Adaptive backlash compensation in upper limb soft wearable exoskeletons

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**Highlights**

- Soft exosuit driven by Bowden cables for human arm assistance.
- Backlash hysteresis in Bowden-cable transmission.
- Nonlinear adaptive controller for backlash compensation.

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**Abstract**

A new frontier of assistive devices aims at designing exoskeletons based on fabric and flexible materials for applications where kinematic transparency is the primary requirement. Bowden-cable transmission is the widely employed solution in most of the aforementioned applications due to advantages in durability, lightweight, safety, and flexibility. The major advantages of soft assistive devices driven by bowden-cable transmissions can be identified in the superior ergonomics and wearability, allowing users to freely move and allocating the actuation stages far from the end-effector. However, control accuracy in bowden-cable transmission presents some intrinsic limitation due to nonlinearities such as static and dynamic friction, occurring between the cables and the bowden sheaths, and backlash hysteresis. Friction and backlash effects are known to be related to the curvature of the flexible sheath, which is not directly measurable and can vary during human motion. In this paper we describe our new wearable exosuit for upper limb assistance and in particular we introduce a mathematical model for backlash hysteresis compensation. The implementation of a nonlinear adaptive controller is described in detail and experimentally tested on the proposed design as a backlash compensation strategy: results report that the adaptive controller improves the accuracy in position tracking (i.e. RMSE in trajectory tracking \( \approx 1^\circ \)) by compensating for time-varying backlash and continuously updating the model parameters. The backlash hysteresis model and the proposed control scheme are validated first on a custom-designed test bench and then applied to control the soft exoskeleton worn by a subject affected by bilateral brachial plexus injury.

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1. Introduction

Soft wearable exoskeletons have been proven to be valid means of assisting human movement. Whilst not being suitable for the application of large forces, their intrinsic compliance, portability and low-power consumption make them ideal for reducing human muscle effort in activities of daily living such as walking [1] and grasping [2,3]. Such kind of solutions allow to overcome the limitations caused by the rigid linkages in conventional exoskeleton devices: these include large output mechanical impedance, misalignment with the user’s joints and unnatural articular stress [4].

One way to overcome the limitations of a rigid wearable robotic device is to rely on the human biomechanics which should provide the “hard” support to bear the loads transmitted by the suit: in such way the function of the rigid structure of a conventional robot is performed by bones and tendons which create the constraints and the degree of mobility to allow human motion.

The actuation is therefore accomplished by mechanical solutions which most of the time comprise tendons, air, or other soft
A new concept of softwearable exoskeleton (exosuit) [1], or exotendon [5]. Adopting this solution further allows to avoid joint misalignment and the associated parasitic torques acting on human joints, and mechanical implementation often result in compactness and lightweight.

Typically, soft exoskeletons combine the use of fabrics and a bowden cable-driven actuation for motion transmission to directly apply torques at the joints level. Being flexible and compliant, this kind of systems allow to relocate the actuation unit away from human articulations (i.e. in a backpack), and the assistive torque can be transmitted via cables from the actuators to the end-effector.

In spite of many significant benefits, the presence of nonlinearities, especially friction [6,7] and backlash hysteresis [8], challenges the system control and limits its performances. Inherent friction and backlash in the bowden cable-driven system impact on control robustness, introducing a delay in the transmission and inaccuracies in force and position tracking. These nonlinearities introduce significant tension losses across the cable and give rise to motion backlash, cable slack, and input-dependent stability of the servosystem [9,10]. In the absence of a transmission model that accounts for these nonlinear behaviours [11,12], control performances are extremely poor. Physical design measures have been shown to help: a PTFE lining on the cables and/or housing can reduce friction phenomena, pre-tensioning of the inner cables has shown to significantly reduce slacking [9] and a high-stiffness or slightly pre-tensioned outer housing reduces backlash-related issues [12]. Nevertheless, these choices can only improve the system performance to a certain degree. To obtain higher accuracy one must rely on effective control algorithms [13].

A wealth of analytical models have been proposed to address the nonlinear characteristics of bowden-cables transmissions. Kaneko et al. [9] presented a parametric lumped mass model for describing the transmission of tendon tension and Palli improved it with the introduction of a dynamic friction model (Dahl model) to account for anomalous behaviour in the stationary condition [6]. Similar approaches were carried out by Tian et al. [14] and Agrawal et al. [13], where a set of partial differential equations are discretized to model the partially-moving, partially-sticking cable motion inside the conduit. However, these approaches still suffer from the discontinuity at near-zero cable velocity and a high degree of complexity. In [13] the authors discussed a method to compensate for the backlash-induced hysteresis in the motion-control of a robotic arm. Their approach was based on “inverse compensation”, where a new desired trajectory was generated by adding the tracking error to the original desired trajectory. This suffers from the limitation of assuming that the required offset to be added is constant and not velocity-dependent. In [15], Kesner demonstrated that a model-based compensation strategy, where the hysteresis profile is analytically modelled, achieves better performance than the inverse compensation one. In addition, Wu et al. [16] introduced a cascaded PID controller to enhance the performance of trajectory tracking tasks in a lower limb exoskeleton driven by bowden cables. However, the relation between the controller and the backlash effect, which is an inherent issue in bowden-cable transmissions, is still missing and the fixed PID gains thus might fail to compensate for the nonlinear variable backlash during motion. Hence a model-based approach is required. Several mathematical formalisms exist for modelling backlash-induced hysteresis [17], but the Bouc–Wen model has been proven to capture a wide range of hysteresis phenomena whilst retaining a low level of complexity and computational effort [18], and has been successfully used for accurate position control of flexible endoscopic systems with the variable geometry [8].

In the present paper, we implement an algorithm based on the Bouc–Wen model to drive a novel soft exosuit for assisting elbow motions [19]. The soft frame is made by fabric garments which provide a more comfortable and compliant interface to the human biomechanics in order to improve the transparency of the device actuators. This relatively new concept is referred in literature as soft wearable exoskeleton (exosuit) [1], or exotendon [5]. Adopting this solution further allows to avoid joint misalignment and the
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