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Model-based tracking control design, implementation of embedded digital controller and testing of a biomechatronic device for robotic rehabilitation[☆]

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ABSTRACT

In this paper, the tracking control problem of a biomimetic exoskeleton powered by a pair of pneumatic artificial muscles is considered. The antagonistic configuration of the pair of pneumatic muscles, which is biologically inspired, enables safe and reliable actuation in applications of orthopaedic rehabilitation. However, during the inflation-deflation process, the pneumatic muscles introduce nonlinearity and hysteresis which deteriorate the control performance. A model of the antagonistic artificial muscles is adopted to develop a computed-torque control for feedforward compensation of the nonlinear dynamics of the actuated joint. A PID control action is used in combination with the feedforward compensation to achieve fast and accurate tracking control performance. The model, which possesses a reduced set of parameters as functions of the inflation/deflation phase, enables efficient nonlinear compensation. The experimental tests on the biomechatronic device, compared with other state-of-the-art approaches for controlling pneumatic artificial muscles, show better tracking performance in terms of convergence rate and robustness, justifying the convenience of using the proposed control methodology in the design of tracking controllers for exoskeletal biomechatronic devices.

1. Introduction

The emerging field of soft robotics is currently covering novel applications in rehabilitation robotics, prosthetics and surgical robotics and, more in general, several safety-critical applications involving interactions between robots and human operators. The main requirements for safe human-robot interactions [1] can be fulfilled through the inherent (and adaptable) compliance of soft actuators. Moreover, the adaptation mechanisms of the compliance of soft robotic and biomechatronic devices can mimic the behaviour of the biological musculo-skeletal system [2,3].

As an example of biomimetic and soft actuation, pneumatic artificial muscles (PAMs) have been employed in the realization of rehabilitation robots, wearable exoskeleton robots and energy-efficient walking humanoids (see [4–6]). More recently, pneumatic muscle actuation technologies are developed towards the realization of miniaturized biomechatronic devices. For instance, the work [7] focuses on the characterization of pneumatic muscles for set-point regulation of the motion of a biomechatronic finger.

Together with their advantages, PAMs offer some challenges in the design and implementation of the tracking control, since the controller has to handle the strong nonlinearity of the PAMs dynamics.

Some control techniques have been developed to solve the problems of regulation and trajectory tracking for PAMs-driven robots. Prior results focus on variable structure control [8], gain scheduling [9], adaptive backstepping [10], sliding mode [11] and PID neural network control [12]. The sliding mode control strategy recently proposed in [13] is aimed at the enhancement of the safety during collision with obstacles. Therefore, the sliding mode tracking controller is complemented by a joint compliance controller, which meets the safety requirements during collision.

Model-based compensation strategies are originally proposed in [14,15], where the compensation of the hysteresis in the force characteristics of pneumatic muscles is achieved on the basis of generalized models of the hysteresis in the mechanical response of PAMs. A feedforward compensation is implemented into the feedback control schemes of linear positioning stages implementing backstepping [15] and cascade control [14] strategies. More recently, in [16,17], the authors show how the guaranteed-cost control approach can be effectively applied to the solution of a regulation problem for a PAMs-driven robot whose dynamics can be described through uncertain (bilinear and quadratic) systems.

To foster the efficient implementation of model-based control strategies for PAMs-driven robots, lumped parameter models of the

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nonlinear dynamics of PAMs can be exploited. The three-element phenomenological model proposed by Reynolds et al. [18] allows to accurately predict the dynamic response of PAMs; the model parameters can be easily identified through static perturbation tests at several constant values of pressure. More recently, in [19] a series of static perturbation tests have been carried out for the efficient identification of a novel model of the mechanical response of some classes of PAMs.

The main contribution of this work consists in the development and the experimental evaluation of a novel model-based tracking control methodology for a biomechatronic device powered by PAMs in antagonistic configuration. The lumped parameter model by Reynolds et al. [18] is used here to develop a computed torque control for feedforward compensation of the actuated joint via nonlinear inversion. The Reynolds's model provides an efficient description of the variability of the nonlinear dynamics of the PAMs during the pressure cycle. Therefore, the feedforward control action is a function of the model parameters which depend on the phase of inflation/deflation. The compensation loop of the tracking controller is complemented by a PID control action which enables the robust regulation to zero of the tracking error.

To the best of the authors' knowledge, this is the first time that such a combined nonlinear inversion feedforward + feedback PID control methodology has been proposed and experimentally tested for the tracking control of a PAM-based robot. The devised approach improves the tracking performance over the existing approaches in the related literature on the control of PAMs-based robots. The parsimony of the model makes this control approach very suitable for the real-time implementation on embedded microcontroller devices. Therefore, a non negligible byproduct of this work is the microcontroller-based implementation of the embedded control system, whereas the previously published results were tested by means of PC-based implementations.

Some experimental tests are presented to prove the superior control performance achieved by the proposed methodology thanks to the efficient compensation of the nonlinear dynamics. Specifically, the performance of the closed loop control system has been measured in terms of convergence rate, steady-state error and robustness to load disturbance during the tracking of constant and sinusoidal trajectories. Furthermore, the micro-controller based implementation of the proposed control scheme shows the advantages related to the real-time execution, computational resources and customizable constraints on the control action.

This paper is structured as follows. The main technical specifications of the robotic exoskeleton and a model of the dynamics of the actuated robot are presented in Sections 2 and 3, respectively. The model-based tracking control law is derived in Section 4, where the steps of design and implementation of the digital controller on embedded control unit are also described. The experimental tests and the discussion of the experimental results are given in Section 5. Some concluding remarks are eventually left to Section 6.

2. CoRAnT: Compliant Robotic Ankle Trainer

The traditional therapy for stroke and traumatic brain injuries requires long and intensive rehabilitation tasks performed by the physical therapist. Indeed, the quick recovery of neural and motor functions, resulting from cortical reorganization in the motor cortex of the patient, can be achieved under intensive and repetitive exercises. Unfortunately, the required burden of care may contrast with the budget and time constraints.

Thanks to the accuracy and repeatability of the control performance, robotic exoskeletons performing high-intensity physical rehabilitation can offer their potential in the optimization of costs and efficiency of the rehabilitation procedures. Moreover, biomechatronic and robotic devices can collect quantitative data useful for the evaluation of both the patient's motor performance and the progress of the motor recovery.

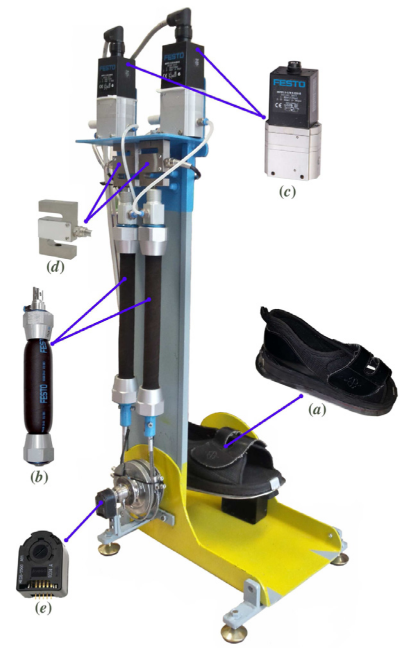

Fig. 1. Overview of CoRAnT. (a) Orthotic shoe. (b) Pneumatic muscle actuator. (c) Pressure regulator. (d) Load cell. (e) Optical encoder.

To obtain a training performance at least comparable to the manual therapy, an essential requirement for biomechatronic rehabilitation is the safe interaction between the patient and the rehabilitation device. During the conventional clinical therapy, the manipulations performed by the therapist are adapted to the resistance force exerted by the patient. Similar adaptation mechanisms, guaranteeing the intrinsic safety of robotic rehabilitation tasks, can be realized through suitable control strategies of biomechatronic devices driven by biomimetic and soft actuators. For instance, the natural compliance of soft actuators, which utilize air as source of energy, enables to absorb potential shocks occurring during the manipulation of the patient.

After the analysis of both the main issues involved in physical rehabilitation and the advantages provided by robotic and biomechatronic technologies, the main specifications are implemented in a robotic exoskeleton for rehabilitation following the design principles of soft and biomimetic robotics. Therefore, CoRAnT is actuated by soft pneumatic muscles, which guarantee safety and comfort for the patient.

The mechanical structure and the main components of the robotic exoskeleton are highlighted in Fig. 1; the pneumatic muscle used for the actuation of the exoskeleton is the fluidic muscle MAS-20-200N by FESTO company.

An orthotic shoe is installed on the rotational joint of the exoskeleton; the joint axis is aligned with the ankle axis of the patient (see Fig. 2).

A couple of PAMs is required for the full actuation of the joint, since a single PAM actively generates motion in one direction. The PAMs are arranged in the bio-inspired configuration of Fig. 3, where the antagonistic setup can mimic the mechanisms of regulation of motion and stiffness of the joints in the human musculo-skeletal system. Therefore, in analogy with the human anatomy, the PAMs act as biceps and triceps, respectively. The conversion of the linear motion of the actuators to the joint rotation is obtained through some cables of diameter 3.5 mm tied together around a pulley of diameter 80 mm.

Position and force sensors are installed on the robotic exoskeleton. An optical rotary encoder (AVAGO HEDM5500 J14) measures the angular position of the joint at 1024 counts per revolution. The encoder provides the measured variable to the tracking controller. Moreover, each PAM is connected to a load cell (Phidgets 3138 S-type). The signals of force and angle can be used for measuring the interaction between