



## Fuzzy PWM-PID control of cocontracting antagonistic shape memory alloy muscle pairs in an artificial finger

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### ABSTRACT

This paper presents biomimetic control of an anthropomorphic artificial finger actuated by three antagonistic shape memory alloy (SMA) muscle pairs that are each configured in a dual spring-biased configuration. This actuation system forms the basis for biomimetic tendon-driven flexion/extension of the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the artificial finger, as well as the abduction/adduction of its MCP joint. This work focuses on the design and experimental verification of a new fuzzy pulse-width-modulated proportional-integral-derivative (i.e. fuzzy PWM-PID) controller that is capable of realizing cocontraction of the SMA muscle pairs, as well as online tuning of the PID gains to deal with system nonlinearities and parameter uncertainties. The main contribution of this paper is the proposed biomimetic cocontraction control strategy, which co-activates the antagonistic muscle pairs as a synergistic functional unit. It emulates a similar strategy in neural control, called “common drive,” employed by the central nervous system (CNS). In order to maintain a desired position of a joint, the corresponding agonistic muscle pairs are cocontracted by the CNS and stiffen the joint. The synthesis and parametric analysis of the proposed controller are carried out via numerical simulations using a dynamic model of the system. The performance advantage of the cocontracting fuzzy PWM-PID controller over the original PWM-PID controller is shown by both numerical and experimental results. A successful application of the new controller to fingertip trajectory tracking tasks using the MCP joint’s flexion/extension and abduction/adduction is also described.

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### 1. Introduction

Rehabilitative devices can significantly improve hand functionality in people with various hand injuries or conditions. Rehabilitation robotics is a special branch of robotics that aims at building robotic devices as a way to help people who are impaired by accident, or who require assistance due to age or infirmity [1–3]. This field deals with a variety of systems ranging in complexity, from straightforward adaptive tools, to advanced microcontroller-driven mechanisms such as powered orthotic and prosthetic hands. The selection of an actuator, in the case of the latter, requires careful consideration of the following factors: light weight, minimal noise, portable size, sufficient power, rapid response and good positioning accuracy. Shape memory alloy (SMA) actuators have been one of the primary candidates for satisfactorily meeting these criteria as artificial finger muscles [1,4–6]. SMA materials are typically made from nickel–titanium (NiTi) alloys that have demonstrated the

ability to return to some predefined shape or size when subjected to an appropriate thermal procedure. This phenomenon is known as the shape memory effect, and it occurs due to a temperature and stress dependent shift in the material’s crystalline structure between martensite and austenite phases. The use of SMAs as a power source of a device or mechanism has several advantages over traditional actuators including, silent and smooth operation, direct actuation, simple operation as a resistive heating device, compact size and excellent power to weight ratio. Some of the limitations of SMAs, however, are low energy efficiency due to the conversion of heat to mechanical work, slow response and difficulties in motion control [5,7,8]. The latter are mainly due to the complex thermal–electrical–mechanical model needed to correctly represent the behavior of the SMA and its strong dependency on the temperature. When employed in powered orthotic and prosthetic hand applications as biomimetic actuation systems [1,3,9], controllers for SMA actuators need to be robust with respect to parameter variations of the system and environment.

In our previous works [1,4], a new biomimetic tendon-driven actuation system for powered orthotic and prosthetic hand applications was introduced. The actuation system was based on the combination of compliant tendon cables and one-way SMA wires

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