Mechanism and Machine Theory 95 (2016) 114–124

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Design of cam shape for maximum stiffness variability on a novel compliant actuator using differential evolution

Rafael R. Torrealba *, Samuel B. Udelman

Biomechanics and Mechatronics Research Groups, Simón Bolívar University, Caracas 1080A, Venezuela

A R T I C L E I N F O

Article history:
Received 18 December 2014
Received in revised form 2 September 2015
Accepted 5 September 2015
Available online xxxx

Keywords:
Variable impedance actuators
Stiffness variability
Cam shape design
Differential evolution
Knee joint actuator
Bézier curves

A B S T R A C T

In this paper, a particular cam shape was found for maximizing the range of stiffness variability of a novel adjustable compliant actuator called BAFSA. On one hand, this cam shape had to maximize the area corresponding to the curves of the stiffness–torque relationship of such actuator. On the other hand, it had to match with some parameters involved in the design of the BAFSA, in order to guarantee its feasibility of operation as a knee joint actuator on a human exoskeleton. To cope with all these conditions at a time, a differential evolution (DE) technique was applied. A DE algorithm was programmed, introducing a graphical approach based on Bézier curves to define the cam shape. Multiple runs were performed to test up to 10 configurations of the algorithm, progressively applying different constraints and cost functions. Such DE approximation proved to be very effective to design cam shapes, taking into account parameters of the mechanism in which the cam will perform. Finally, the best cam shape was selected from the different cases studied. Such a solution successfully complies with all the design criteria and constraints initially established.

1. Introduction

Variable impedance actuators (VIAs) have emerged as a requirement for robots capable of interacting with humans and cooperating among themselves in a safe way. These particular actuators have been developed in the last years by several research groups worldwide [1–4] and continue to evolve in order to recreate human-like behavior and capabilities [5–8]. Although initially proposed to look for mechanically compliant joints in humanoid robots, the VIAs have also been introduced in exoskeletons for the rehabilitation of paraplegic patients and stroke survivors [9,10]. In such devices, the need for controlling the position and stiffness of the joints is also present; hence, the VIAs are well suited for this application.

This paper introduces a novel VIA that combines the concepts of the floating spring joint (FSJ) and bidirectional antagonistic variable stiffness (BAVS) models presented by Wolf et al. [11] and Friedl et al. [12], respectively. Therefore, it has been called bidirectional antagonistic floating spring actuator (BAFSA). This is part of a project aimed at developing an exoskeleton for rehabilitation of patients with gait disorders, which is currently being carried out by the mechatronics research group (MRG) of the Simón Bolívar University, Caracas, Venezuela. The BAFSA is intended for the knee joint of such a rehabilitation exoskeleton. Its design is grounded on a floating spring located axially between two cam disks, each linked to one motor as pictured in Fig. 1. According to Wolf et al. [11], the proposed FSJ uses two motors with a significant difference in size, one devoted to moving the position of the joint and the other one dedicated to setting its stiffness. Nevertheless, holding into account the motors available for the joints of the exoskeleton being developed by the MRG, the collaborative architecture of the BAVS model was also brought into this design to look for compactness and lightweight. In

* Corresponding author at: Department of Mechanics, Simón Bolívar University, MEU Building, Of. MEU-320D, Caracas 1080A, Venezuela. Tel.: +58 212 9064084.
E-mail addresses: rtorrealba@usb.ve (R.R. Torrealba), samueludelman@gmail.com (S.B. Udelman).

http://dx.doi.org/10.1016/j.mechmachtheory.2015.09.002
0094-114X/

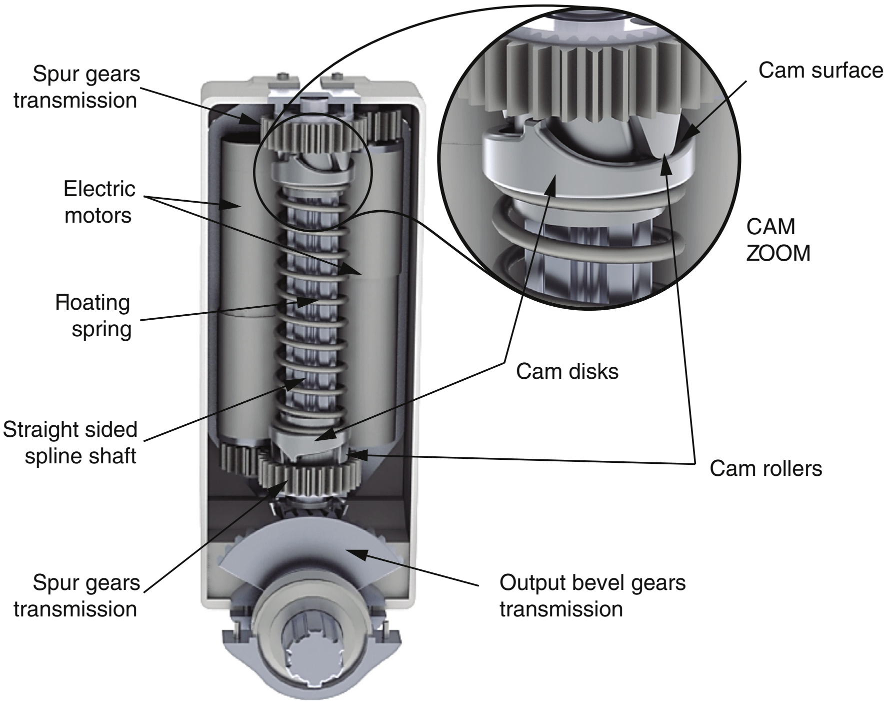

Fig. 1. Design of the BAFSA showing its main parts and a zoom of the cam shape to be designed.

BAVS joints, the output torque is obtained by adding the torque of each motor while stiffness is set by the relative rotation between them.

A cam roller rotates on each cam disk yielding a compression of the floating spring, and thus, the joint stiffness is modulated. The stiffness response of the BAFSA depends on the cam profile, which, as a first approach, could be a simple spline or a mathematical function. However, in this paper, this profile is sought from a different perspective, including different variables related to the mechanism. By using a differential evolution (DE) algorithm that involves these variables to propose a fitted spline, the optimal cam profile for a maximum range of stiffness variability of the BAFSA is pursued [13]. This problem rendered a multi-objective search in a 6—dimensional space of solutions. Recently, DE has shown to be an easy-to-use technique in the family of GAs, which converges to good results in a relatively short time [14–16]. Hence, in this paper, DE is deployed to define the cam shape of the BAFSA.

This paper is structured as follows. In Section 2, an insightful explanation of the mechanism's functioning is presented through the mathematical modeling of the stiffness. Then the setting of the DE algorithm is shown in Section 3, detailing the search parameters, constraints, and cost functions, defined and utilized in the different cases studied. Section 4 presents resulting cam shapes throughout

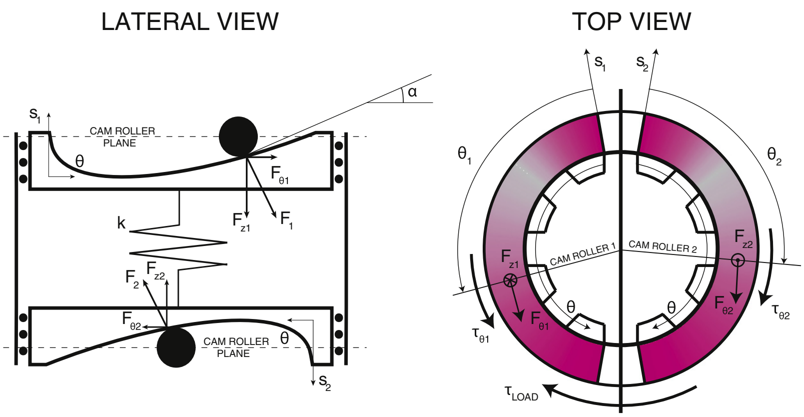

Fig. 2. Model of the BAFSA in 2D: the lateral view (left) shows the cam rollers fixed in their motion planes (by the motors), while the cam disks and the floating spring can move vertically depending on the forces F_{z1} and F_{z2} and the spring constant k; the top view (right) shows how the forces $F_{\theta 1}$ and $F_{\theta 2}$ on the cam disks turn out in the torques $\tau_{\theta 1}$ and $\tau_{\theta 2}$ produced by the variable stiffness mechanism of the BAFSA. Note that each half of the top view represents a cam disk, and the coordinates θ_1 and θ_2 point out the angular position of the corresponding cam roller. In addition, notice that the external torque applied on the actuator τ_{LOAD} is illustrative, as it can actually go in the other direction as well.