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Research paper

Rotatable cam-based variable-ratio lever compliant actuator for wearable devices

Miha Dežman[a,b,*], Andrej Gams[a,b]

[a] Department of Automation, Biocybernetics and Robotics, Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia
[b] Jozef Stefan International Postgraduate School, Jamova 39, 1000 Ljubljana, Slovenia

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ABSTRACT

This paper presents a novel variable stiffness mechanism based on the combination of a rotatable cam and a variable-ratio lever principle. The proposed configuration results in i) a pseudo-linear torque/deflection characteristics, where ii) the stiffness is varied rotationally and perpendicularly to the external load. The first is convenient for easier mechanism dimensioning and offers a more conventional control design. The second allows for a more energy efficient stiffness variation, thereby enabling the use of a less powerful stiffness variation motor and a reduction of the overall actuator weight and size. The presented mathematical model derivation and theoretical evaluation support both desired mechanism characteristics. Practical use of the mechanism is evaluated through the application of the developed prototype in a fully sensorized variable stiffness actuator intended for a wearable application. The results of the experiments and a comparison to other variable stiffness mechanisms show that the mechanism geometry is convenient for light and compact design.

1. Introduction

Functionality and usefulness of robotic systems are making rapid progress. For example, wearable devices, such as exoskeletons, have progressed to the stage where they can efficiently provide assistance and even augment user performance [1]. While many advances rely on advanced control techniques [2,3], the mechanical design has been just as important. This has been shown in the design of various robotic mechanisms, for example, in humanoid robots [4–6] and jumping robots [7], but also in the aforementioned wearable devices [8–10]. Aspects of mechanical design include the choice and properties of the actuators, which can critically determine the intended application of use.

Among the different actuators, mechanically compliant actuators meet many suitable performance criteria for force-oriented applications [11]. By taking advantage of elastic elements either in a series (series elastic actuator – SEA) or in a parallel configuration (parallel elastic actuator – PEA), increased speed or higher torque can be achieved [12]. Furthermore, utilizing elastic elements can lower the cost and weight of the drive units because it allows the use of smaller and lower precision components and allows the replacement of expensive load cells with a simple spring with position transducers [13]. The latter can even make force measurements less prone to chatter and noise. Higher impedance and higher stiction components in these type of actuators are not detrimental to such use [13].

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[*] Corresponding author.
E-mail addresses: miha.dezman@ijs.si (M. Dežman), andrej.gams@ijs.si (A. Gams).

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While the SEA typically adopts a fixed-compliance elastic element, it can be controlled to render a variable compliance including nearly zero stiffness and a high stiffness up to the inherent mechanism stiffness [14]. The more advanced variable stiffness actuators (VSAs) use a second motor to add the ability of mechanical compliance adaptation. The secondary motor acts on the elastic element, for example through changing its strain [15], or the lever-length it acts on [16], to achieve different behavior. Through this, the VSAs can modulate their natural dynamics [17], or improve SEA power modulation. The latter was, for example, used to achieve greater vertical jumping ability [7] and efficiency [18]. VSA mechanisms can also adapt the stiffness to achieve different assistance levels in rehabilitation tasks based on the progress of the patient [19]. Having two motors and a mechanical system to change the stiffness parameters increases the geometrical complexity of VSA devices, and also makes them heavier and more expensive. However, this also creates the opportunity for simplifications and cost reduction [20] through the mechanical design.

This paper:

- proposes a novel VSA actuator principle with a convenient rotational geometry and potential for future compact units,
- shows the derivation and analyzes its mathematical model,
- presents a prototype drive unit implementing the proposed principle,
- shows the use of the prototype unit to evaluate the mathematical model, its advantages and disadvantages, and
- compares it to other actuators that are most relevant to this work.

The intended application of the proposed mechanism is the actuation of wearable devices, more specifically, a 1 DoF elbow exoskeleton. However, the focus of this paper is on the compliant actuator, and not on the exoskeleton device.

The basic concept of rotational stiffness variation was previously presented and tested with a plastic prototype in a proof of concept [21]. However, it was not appropriate for application use due to a higher mechanical complexity. In this work, the number and diversity, including the mechanical complexity of different mechanical components, were all reduced. The device was made ready for practical applications and was thoroughly evaluated.

The rest of the paper is organized as follows. In the next Section, a short literature review and highlights of the desired VSA actuator are presented. In Section 3, the proposed operational principle of the mechanism, and the derivation and evaluation of its mathematical model, are presented. Section 4 describes the experimental setup with results shown in Section 5. In Section 6.1, the prototype is evaluated in light of other similar VSA actuators, ending with a discussion in Section 6.2. Finally, a conclusion follows in Section 7.

2. Related work

Research on compliance enabling devices has been very extensive. A broad overview of different compliance types, e.g., emulated active compliance, fixed inherent mechanical compliance (SEA) or actuators with mechanically varied compliance (VSA) and different technologies enabling it, is presented in [22]. In the following short overview, the focus lies on the compliant actuators with a mechanical variable stiffness, which represent only a fraction of available compliance enabling technologies.

The favorable properties enabled by mechanical compliance, and the endless possibilities to implement elastic elements into the actuator geometry resulted in a vast amount of architecture structures and variants. The reader is referred to [23–25] for an in-depth review of architectures of such inherent compliance mechanisms.

One can exploit the advantages of both fixed compliance actuators (SEAs) and variable stiffness actuators (VSAs). Considering a gait-assistance device, both SEA and VSA find suitable applications [26]. In many situations, using a VSA would provide only minimal benefits, while needlessly increasing the complexity and the weight. However, a suitable fixed compliance is often not immediately clear, so in research situations, a variable stiffness device is advantageous, because it enables quick and practical stiffness adaptations. Overall, the VSAs are defined by a broader number of parameters than classical actuators or SEAs, e. g. the deflection range, stored energy, stiffness variation speed, etc. These variables are nicely presented in [27] and [28].

Besides design properties from the point of view of achieving variable stiffness, the VSAs are considered in the scope of wearable devices. Here, energy efficiency can mean a longer battery time. A lighter and smaller actuator can, furthermore, reduce the added weight impact and the amount of kinematic obstructions on the user. The suitability of such actuators is correlated with the desired application or task, which also makes the comparison between them difficult.

Three VSA actuator types have had a considerable influence on the field and the presented work. These are the MACCEPA-type VSAs, the DLR (German Aerospace Center) actuators, and the AwAS actuators. They have easily distinguishable operation principles and a high amount of available literature data. Many other VSA variants also exist [29–32], but often use a larger amount of non-standard parts, which increases not only their complexity but also the complexity of their comparison.

The well established MACCEPA VSA principle [33] has a uniquely simple and straightforward way to vary the stiffness. Its compliance is achieved through a third link that deflects and pulls on a steel cable connected to a linear spring. The relative position of the external link to the third link determines the equilibrium position. To change the stiffness, a second motor can pretension the elastic element. Overall, the MACCEPA is known for a large deflection range and its ability to store a lot of elastic energy. Its flat and long structure makes it suitable for wearable applications, since it keeps the hardware close to the limbs, but also makes design of compacter units more difficult.