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Low-cost variable stiffness joint design using translational variable radius pulleys

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ABSTRACT

Robot joints are expected to be safe, compliant, compact, simple and low-cost. Gravity compensation, zero backlash, energy efficiency and stiffness adjustability are some desired features in the robotic joints. The variable radius pulleys (VRPs) provide a simple, compact and low-cost solution to the stiffness adjustment problem. VRP mechanisms maintain a preconfigured nonlinear force-elongation curve utilizing off-the-shelf torsional spring and pulley profile. In this paper, three synthesis algorithms are presented for VRP mechanisms to obtain desired force-elongation curve. In addition, a feasibility condition is proposed to determine the torsional spring coefficient. Using the synthesis methods and the feasibility condition, a variable stiffness mechanism is designed and manufactured which uses two VRPs in an antagonistic cable driven structure. Afterwards, the outputs of three synthesis methods are compared to force-elongation characteristics in the tensile testing experiment. A custom testbed is manufactured to measure the pulley rotation, cable elongation and tensile force at the same time. Using the experiment as the baseline, the best algorithm achieved to reproduce the desired curve with a root-mean-square (RMS) error of 13.3%. Furthermore, VRP-VSJ is implemented with a linear controller to reveal the performance of the mechanism in terms of position accuracy and stiffness adjustability.

1. Introduction

For many years, conventional industrial robot joints have been designed as stiff as possible to increase the position accuracy. These robots can only be operated in restricted and well-known workspaces because they can be harmful to the fellow human workers, considering collision possibilities and impact situations [1,2]. Therefore, recent robotics research has mostly focused on new systems which are able to interact with humans in unknown environments in everyday life. To meet the interaction requirements, as well as having wider perception and decision-making capabilities, mechanical designs of the robots have to be more compliant. As a response to this request, in [3] an elastic mechanical component is used in actuator design to have compliance.

Compliant joints are superior to the conventional systems in terms of impact scenarios, energy consumption, and force interaction. Having a constant stiffness is not enough for most of the robot applications especially working under different modes such as walking and manipulation tasks in humanoid robots. As a consequence, a new concept, variable stiffness or

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in general variable impedance actuator (VSA or VIA), has started to gain the attention of the researchers. There have been several new designs and various applications in robotics area such as MACCEPA [4] and AWAS [5], which are well known VSA designs that change lever arm lengths to adjust the stiffness of the mechanisms. In [6], an alternative approach uses the same principle with the addition of guide blocks to provide rigid motion as well. Another approach to variable stiffness joint design is adjusting the pretension in springs via harmonic drive [7] or cam mechanism [8]. In [9], a tensioning mechanism with a timing belt and three pulleys are utilised to modify the stiffness of the mechanism. The researchers in [10] and [11] benefit from the mechanical behavior of helical springs for the same purpose. A similar idea is used in [12,13], the effective lengths of the leaf springs are adjusted to change joint stiffness. In addition to the combination of electric motor with elastic element together, magnetic [14–16] and pneumatic [17] components are also employed to adjust the stiffness. Various designs are classified and examples are presented in [18,19].

In nature, the biological joint structures are able to adjust their stiffness value. In the biological joints, agonist and antagonist muscle pair co-contraction cause a change in the stiffness value of the joint. Following this way to build such a VSA system, [20] emphasizes the requirement of nonlinear springs. In the human musculoskeletal system, the stiffness of the muscle changes linearly which means desired spring must have a quadratic stiffness characteristic as described in [20]. Additionally, a robot design could require nonlinear springs which have more complicated force-deflection functions. Despite the fact that, some previous spring mechanism designs have been realized to achieve various custom-defined, nonlinear force-deflection functions, they are not easy to calculate and are inaccurate without a feedback compensation [20]. In the same inspiring study, a cam mechanism is designed to mimic biological muscle behavior with quadratic characteristics and is tested in an antagonistic setup. The change in the stiffness by co-contraction is observed as linear. Cam design can be changed in a way that any relation between force and displacement can be performed with this mechanism at least in theoretical terms. However, the resulting mechanism may not be compact enough to be used in small volumes, such as an anthropomorphic robotic arm of a humanoid. Other drawbacks are backlash and friction between the cam and the follower. As an alternative approach, variable radius or non-circular pulley is used both in translational [21,22] and rotational [23,24] way. These designs require less number of moving parts and have a great potential to be manufactured in small sizes with lower friction losses.

VRPs have been used in various areas and are not limited to robotics. They are known as wrapping cam mechanisms, variable radius drums, and non-circular spools. These mechanisms are utilized mostly in studies such as gravity compensation [25–27], VSA [28,29] or specific motion profile generation [30]. It is clear that all of these mechanisms rely on the nonlinear force/torque-deflection relation. The main focus in designing of these mechanisms is the synthesis of the pulley profile. The pulley profile is calculated analytically in [21,27,31] for a given torque-angle relation. In [25], the researchers used a simple and efficient numerical algorithm for this purpose. Synthesis problem is considered as an optimization problem aiming to minimize the difference between the desired torque of the mechanism and torque generated by the elastic component [28]. In [32], a sequential quadratic programming algorithm is used to design the pulley profile so that the energy consumption of the series elastic actuator remains minimum. In [30], analysis and synthesis problems are carried one step ahead where the effects of idler pulleys and thickness of the cable are taken into account.

Aforementioned VRP mechanisms use a translational spring and produce a torque profile with respect to spring elongation. Only in [23,24], a torsional spring is used to create a nonlinear force-elongation profile. The study in [23] focuses on passive noise reduction of proposed actuator design and does not present a detailed analysis of the spring mechanism. A linear guide constrains the motion in one dimension. This increases the size of the mechanism and the friction losses. In [24] synthesizing of translational spring using VRP is presented however the solution is restricted by certain functions. On the other hand, in [31], free design parameters are defined and it is indicated that maximum radius of the pulley grows in an unbounded way. For the implementation, minimum radius is determined as a limit. In paving the path to use the robots in our daily life, the cost is an important issue. Most of the current VSA and VSJ mechanisms have complex structures, requiring advanced manufacturing techniques, also they are difficult and expensive to implement. A big step forward to overcome this problem is presented in [33]. In the study, a modular and low-cost VSA design (VSA-cubebot) is given.

The aim of this paper is to propose a methodology for designing compact translational VRP mechanisms. Three methods are presented to synthesize VRPs in an attempt to extend the existing research in this field. As a remarkable case study, a low-cost, easily customizable, energy-efficient and safe VSJ that is based on translational VRP mechanisms is presented. In the broader context, the proposed methodology and mechanism should be of interest to researchers from the fields of social and humanoid robots design. Additionally, it should also be noted that the use of translational VRP mechanisms is not only limited to robotics field.

This paper is organized as follows: The details of the VRP mechanisms and three methods for synthesizing process are explained in Section 2. Then in Section 3, the proposed mechanism is introduced. Next, the test-beds for force-elongation identification are given in Section 4 together with the details on the conducted experiments. Finally, the conclusion is drawn and the future work is outlined in Section 5.

2. VRP mechanism and synthesizing methods

VRP mechanisms provide a wide range of novel approaches to contemporary robotics research, mainly to soft-robotics area. One of the most important properties of the VRP mechanisms is to have adjustable stiffness characteristics where the springs are principally used to control the rigidity by a cable. Thus, the compliance can also be regarded as the distinctive