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Design and analysis of a flexible linkage for robot safe operation in collaborative scenarios

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ABSTRACT

One of the most serious security issues for collaborative work between robots and humans is the potential damage caused by unexpected collisions between them. Intrinsically-safe systems are a must in order to assure safety for both, the user and the robot, under the worst-case scenario of a total failure of the control subsystem. This work contributes to the field of passive mechanical system safety. The proposed security system consists in a flexible linkage that splits a robot arm link in two parts. Such a linkage allows the link to remain completely rigid as long as a given torque threshold is not exceeded, with that threshold being configurable according to working conditions and safety considerations. Both theoretical and experimental tests demonstrate a significant reduction in the accelerations and forces generated by impacts between the end effector of a robot arm equipped with the proposed mechanism and a simplified human head model.

1. Introduction

New security systems are required in the design of robots for applications where they share their workspace with humans, with the subsequent risk of accidental collisions, if we are to guarantee the safety of humans and the integrity of machines [1]. The search for intrinsically-safe robot mechanical designs has been already addressed in the literature, focusing fundamentally on the combination of reducing the inertia of robot arms and the addition of flexible components to their structure.

Passive mechanical systems proposed so far exploit the structural flexibility of links [2], joint flexibility [3,4] and soft coverings [5–7]. Among them, the latter approach has demonstrated the best results in reducing impact forces and induced accelerations in the case of an collision between a robot arm and a human head [2]. Joint flexibility, by means of decoupling rotor inertia from the end link inertia, also contributes a safety improvement in the event of an impact. In this sense, there has been interest in Variable Stiffess Actuators (VSAs) [3,8,9] as decoupling mechanisms. However, Haddadin et al. [10] showed that the reduced joint stiffness of robot DLR-LWRIII (mainly due to Harmonic Drive gears) is enough to decouple motor inertia from link inertia, hence any further increase in joint flexibility will not attenuate impact forces during a blunt impact. These results were later confirmed through simulations [2] where, for an ideally rigid link, an ordinary gear transmission was enough to decouple rotor inertia. Finally, the internal flexibility of the robot links also has its own positive effects in damage reduction, although in this case a trade-off must be achieved since excessive flexibility hardens the positioning control of the robot end effector [11].

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A robotic manipulator with the potential of working closely with humans should be able, ideally, to operate with a reduced stiffness whenever it exists any risk of collision (hence, dangerous high forces), while also being able of exhibiting high stiffness in other operations. Following this idea, researchers have proposed VSAs and some flexible mechanisms for robot joints with nonlinear stiffness characteristics. The latter have decreasing stiffness curves, that is, the joint features high stiffness for reduced deformations but quickly decreases after the force reaches some predefined threshold [4,12]. In this respect, Park et al. proposed in [13] a safe link mechanism based on a flexible mechanism amid a robot link. This device includes a double slider mechanism and a spring attached to one of them, such that for a given initial configuration one attains the desired effect of nonlinear stiffness depending on deformation.

Following this concept of introducing a flexible element amid the link instead of at a joint, the present work presents a novel flexible linkage aimed at operation safety. The proposed flexible linkage is located in the middle of a robot link, splitting the link in two, and therefore decoupling the inertia at each side in the event of an impact. The two links remain coupled by means of a mechanism comprising a spring, a cable and a tensor element as will be discussed below. Its main characteristic is the ability to sustain the maximum structural stiffness of the rigid link as long as the external load does not exceed a given threshold value, quickly reducing the stiffness otherwise. In comparison to previous proposals this new flexible linkage features a very simple construction and the ability to easily vary the threshold after which the flexibility of the linkage acts.

The rest of this work is structured as follows. Section 2 firstly introduces the conceptual design, some implementations solutions and the kinematic model. Next, Section 3 presents a mathematical model of the impact between the end effector of a robot arm, including a flexible linkage, and a dummy human head; and analyzes the contribution to safety due to the linkage. Section 4 describes the mechanical implementation of the prototype linkage, the experimental setup devised to assess the performance of the proposed flexible linkage in the context of a robot arm–human head collision, and experimental results. Finally, we conclude with a discussion of the obtained results.

2. Proposed mechanism

In the following we describe the basis of the proposed security flexible linkage, along with a mathematical modeling of its stiffness curve as a function of the angular rotation of the linkage.

2.1. Conceptual design

The linkage comprises two rigid bases placed face to face, perfectly coupled to each other by means of a circular array of equally spaced pockets and spherical protuberances, as illustrated in Fig. 1. Such sphere layout allows the relative rotation of the two bases around an axis contained in the plane described by the center(s) of the sphere(s). The relative rotation may happen either having only one sphere in contact with its corresponding pocket or having two consecutive spheres in contact with their pair pocket. Depending on the number of spheres in contact with pockets, the axis of rotation will be passing through the center of two consecutive spheres or only passing through one. A compression helical spring is supported by the inner face of one of the two base parts, and compressed by a tensor and a steel cable in order to maintain the two parts of the mechanism in contact. As will be discussed below, the external load required to induce the rotation of the two bases depends on the spring preload at rest.

Together with its construction simplicity, the main novelty of the proposed mechanism is the capability of easily changing the load level at which the flexible linkage begins to act, with the particularity of having the same stiffness right after that point regardless of the selected load threshold. Therefore, the arm behaves as if it was a rigid link as long as the load threshold is not exceeded.

Two possible designs of how to dynamically vary the preload of the proposed flexible linkage are shown in Fig. 2. However, it must be noted that the introduction of a tunable preload carries the cost of having to include an electric motor and a transmission system, increasing the overall mass of the system. Fig. 2(a) shows the first design, including a worm gear screw where the cable of the tensor mechanism rolls over the gear shaft. A different solution is shown in Fig. 2(b) where the motor shaft directly drives the tensor screw.

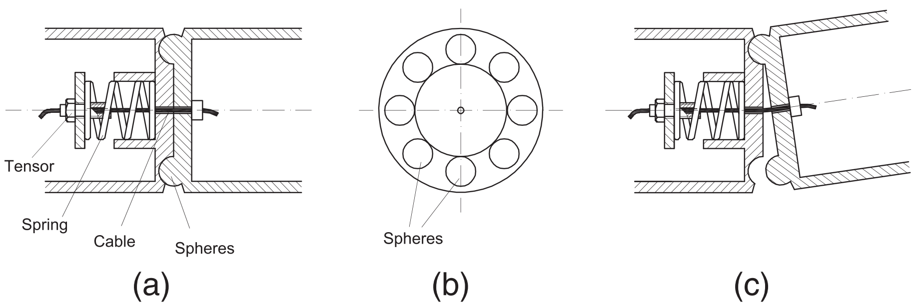

Fig. 1. Sketch of the flexible link, (a)–(b) in its rest configuration and (c) under an external load that forces it to rotate.