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An adjustable gravity-balancing mechanism using planar extension and compression springs

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A B S T R A C T

Passively compensating a payload weight requires a mechanism that can generate a nonlinear torque curve. Existing gravity-balancing mechanisms (GBMs) rely on linear or torsional springs with various principles to generate the required torque profile. This paper presents the design of a novel GBM whose balancing capability can be adjusted. The idea is to employ two linear springs, one extension spring and one compression spring, to synthesize the required nonlinear torque curve. The springs are concentrated on the base joint to reduce the overall size. An optimization formulation is given to maximize the weight compensation capability. The effects of various parameters on the achievable weight are discussed. Low-volume planar springs are specifically designed to serve as the linear springs so that large stiffness can be generated in a limited space. By preloading the springs, the GBM can easily adjust its torque curve to match different payloads. An illustrative prototype is given with experiment verifications to demonstrate the claimed merits of the proposed GBM.

1. Introduction

A robotic manipulator relies on actuators to support and transport its moving links and external payload. Each actuator needs to be large enough to provide sufficient torque. When the actuators are embedded in a manipulator, the heavy actuators would make the manipulator bulky and energy-inefficient. Because the total weight of the payload and the moving links are often known in advanced, gravity-balancing mechanisms have been proposed for the weight compensation. A gravity-balancing mechanism (GBM) can maintain the total potential energy of a manipulator constant by passively transferring the energy in or out of an energy storage element. Statically, no force is required to produce motion. The manipulator shows a zero-stiffness property. Because minimum torque is required for the actuators, the manipulator requires only small actuators and becomes lighter.

Existing weight compensation approaches are mostly based on counterweights [1,2] and spring mechanisms [3–9]. Fig. 1(a) shows the schematic of a counterweighted manipulator. Using a counterweight is simple and can balance all positions. It has been applied for many industrial manipulators. Because a counterweight is usually heavier than the payload, it is not suitable for applications where weight is a concern. Spring mechanisms are more attractive because springs can be assumed weightless. Fig. 1(b)–(e) shows four different spring mechanisms. Each creates a moment arm variation in order to produce the nonlinear torque curve required for gravity balance. The type in Fig. 1(b) is the simplest (e.g., Ref. [4]). To avoid interference with other components, the protruded spring over the links should be avoided. This can be resolved by embedding the spring on the link, as shown in Fig. 1(c). This type requires a large hollow link to store the spring (e.g., Refs. [5,6]). Another way to hide the spring is to use a parallelogram (e.g., Ref. [7]), as shown in Fig. 1(d). This type can be extended to compensate manipulators with multiple degrees-of-freedom. However, the parallelogram

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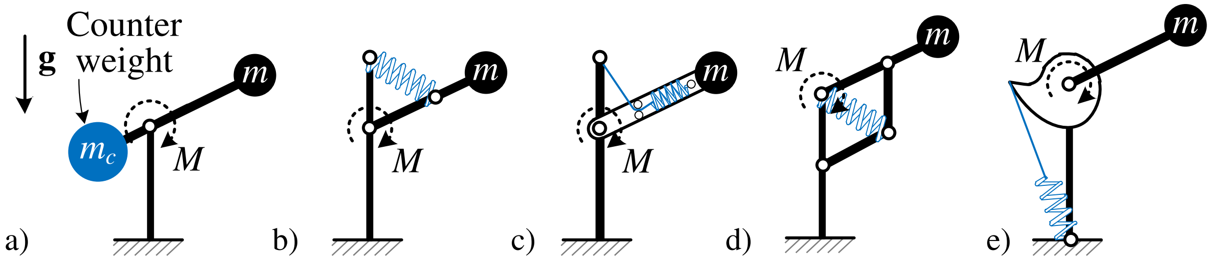

Fig. 1. Different types of GBMs: (a) Counterweight; (b) External spring; (c) Internal spring; (d) Parallelogram; (e) Cable-cam.

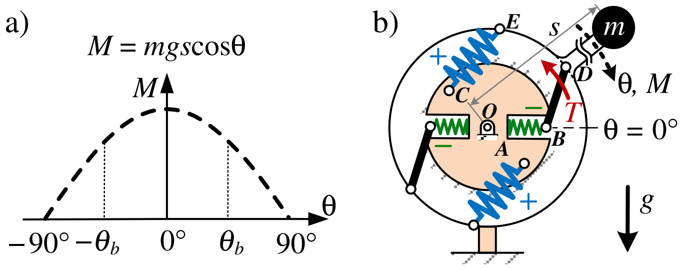

Fig. 2. (a) M–θ curve of a manipulator; (b) Schematic of the proposed GBM.

introduces non-negligible link weight and needs to be large enough to place the spring diagonally. Using a cam can also produce a nonlinear torque curve (e.g., Ref. [8]). The springs used in GBMs are mostly assumed to have zero free length. Because a spring practically has a nonzero free length, wires and pulleys are required to relocate and reorient the springs in order to emulate the condition of zero free length. The additional components would increase the mechanism size.

A major challenge of GBMs is the required complexity to adapt the mechanism to compensate different payload weight. For the spring mechanisms in Fig. 1(b)–(e), these often require adjustment of the spring attachment point or spring stiffness. Adjusting the attachment point is not convenient because it requires extra work in practice. Adjusting the spring stiffness could be achieved via changing the active length of the spring [9]. Because the spring is usually very long, a considerable length change is required in order to significantly change the load capacity. The adjustment mechanism hence becomes larger and occupies a big portion of the GBM. When the spring is loaded, a substantial force is required to change the spring length. An energy-free adjustment method [10] has been proposed to minimize the adjustment force.

In addition to robotic manipulators, GBMs have been applied to design desktop lamps [11], motion stabilizers [12], and support devices [13,14] for disabled people. Recently, they are extended to design passive exoskeletons [15,16] wore on human limbs. When a gravity-balancing exoskeleton is used for limb rehabilitation, the limb weight can be supported such that the weakened limb can move with minimal muscular force. When used for motion assist, the exoskeleton can assist human in strenuous activities. To ensure sufficient wearability, mobility, and safety, an exoskeleton must be compact and free of interference with human motion. However, reducing the size and weight of a gravity-balancing exoskeleton without compromising its compensation capability remains difficult. Most GBMs have protruded components that may collide with human body during operation.

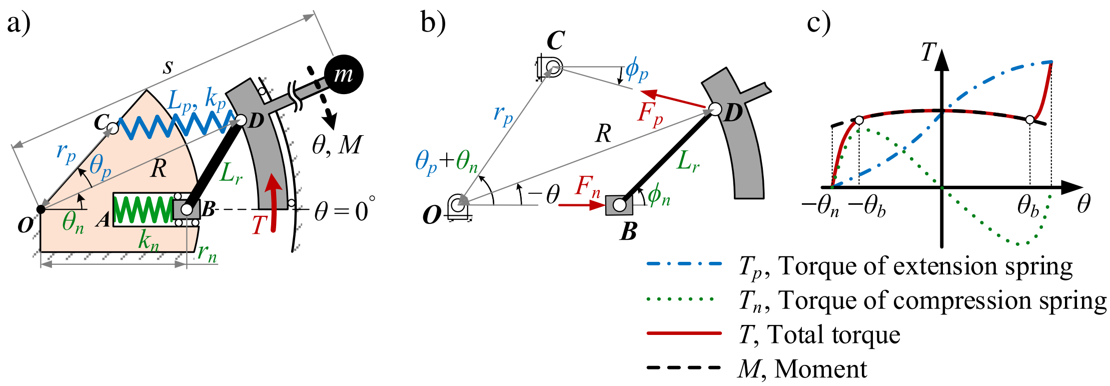

Fig. 3. (a) Design model of the GBM; (b) Free-body diagram of the rigid link and outer rim; (c) Torque and moment curves.