Design and investigation of a multi-material compliant ratchet-like mechanism

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Abstract

We present the design of a new compliant ratchet mechanism using a multi-material additive manufacturing technology. The design enables the elimination of springs and global movement of the pawl or gear that typically exist in classical ratchets. It is also taking advantage of recent advances in 3D printing technology to replace traditional mechanisms with multi-material mechanisms. This design is evaluated with computational finite element (FE) simulations and verified with physical tests of motion in two opposite directions. We also present a parametric study of the geometric and material properties of our current design and discuss how this basic design concept can be customized for specific applications.

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1. Introduction

The ratchet device (Fig. 1), is one of the classical designs in mechanical engineering which limits either rotary or linear motion to a single prescribed direction. Typically, the mechanism is composed of a pawl and a gear with asymmetrical teeth geometry at a contact area that allows a sliding motion in one direction and a locking behavior in the opposite. The classical ratchet mechanism has been applied to various everyday objects such as bicycle conveyor belts, zip ties, wrenches as well as to more complex systems of overrunning clutches and turnstiles [17].

In the classical approach where a ratchet is constructed from a homogeneous stiff material, the mechanism requires space for either the pawl or gear to move near perpendicular to the ratchet motion during the slide insertion. This perpendicular motion is generally controlled by an extra component such as spring. Here, we propose a new multi-material compliant ratchet mechanism with the following advantages: (1) eliminating springs, reducing part count, and therefore easing of assembly, (2) elimination of space required for the global perpendicular motion of pawls during insertion, and (3) tuning of the mechanical behavior.

Compliant mechanisms transfer or transform motion, force, or energy by gaining at least some of their mobility from the deflection of elastic members rather than from rigid body motion and mechanical joints (Larry L. [8]). Compliant mechanism consists of a mixture of the stiff parts with integrated flexible materials in selected segments in order to control the force or displacement of the mechanism [3]. The advantages of compliant mechanisms in comparison to traditional mechanisms include the reduction of number of parts and elimination of assembly processes [11], no requirement for lubrication (L. L. [9]; Larry L. [8]), stress relief from contact-induced loads [13], and storage of potential energy within the structure ([3];...
Larry L. [8]). Moreover, some progresses have been made in the areas of design and analysis [7] and fabrication methods [15] of compliant mechanisms in the last decades.

Compliant mechanisms have also been investigated in tandem with other mechanisms or other components of an existing device design. For example, Gouker et al. improved the connectivity between compliant hinges and rigid parts within a rotor head [7] and Bejgerowski et al. have fabricated multi-material hinge-links for a prototype flapping wing of a micro air vehicle (MAV) [3]. Leylek et al. also controlled the flight dynamic of an unmanned aircraft by using multi-material compliant hinges in their design [12]. Moreover, some researchers used compliant mechanisms in design and fabrication of bio-inspired robots [5] and small-scale robots (Vogtmann et al., 2011).

Furthermore, the emergence of new manufacturing methods such as multi-material additive manufacturing (MMAM) technologies has contributed to the rapid development of compliant mechanisms in different fields of research [3,18,21]. The ability of additive manufacturing in generating complex parts coupled with multi-material capabilities makes this process ideal for devices of arbitrary geometry and varying material compositions. As a result, the whole part including the compliant mechanism can be fabricated as a single monolithic geometry [2,6,21]. This has been manifested in the work of Meisel et al. to create a topology-optimized compliant mechanism using Polyjet 3D printing [6]. Moreover, Bailey et al. and Cham et al. have investigated the technique of Shape Deposition Manufacturing in the fabrication of robotic legs with integrating soft polyurethane as the joint flexures [2,4]. Although it is possible to create a mechanism using compliant joints made from a single material, in the current study, we have proposed an alternative approach that is made possible by recent advances in multi-material 3D printing technology to replace traditional mechanisms with multi-material mechanisms by creating a large-displacement mechanical effect through material properties. This alternative approach has advantages of simpler geometry of the joint and the possibility of fabrication in smaller sizes where creating the thin ligaments for compliant joints in other designs is complicated. Furthermore, this approach would easily be embedded into the design of complex structures containing it as a working mechanism, and fabricating the whole structure in a single process.

In this work, we apply the concept of compliant mechanisms to the classical ratchet mechanism and design a new multi-material ratchet mechanism and prototype it using multi-material additive manufacturing technology. This design is then evaluated both experimentally and computationally to determine the force-displacement behavior of the mechanism in two opposite directions. These analyzes illustrate how this mechanism allows the motion in one direction while restricting motion in the opposite direction. It is worth mentioning that in our investigations we analyzed one tooth design as the key element to study the phenomena however, this understanding is transferable to the other designs combining more teeth. Furthermore, this new design, as we explain further in the following sections, has the capability of being tailored for different applications by changing different material and geometrical parameters. Therefore, the effects of these parameters such as, elastic modulus of flexible region, thickness of flexible region, and the slope of wedges on the insertion and locking performance of this mechanism are investigated computationally and presented in this study.

The proposed multi-material ratchet mechanism in this study could be used in different applications such as interlocking joints for fastening 3D printed parts together or as a captive fastener for assembly of furniture parts or attaching panels in automotive and building industries. The capacity of embedding the proposed design as a region of other components and fabricating the entire part with multi-material additive manufacturing technology has made the proposed design significant and different from other compliant ratchet mechanism such as zip-tie. Furthermore, the strategic use of multi-material mechanism and the flexible base in the mechanism could be used to prevent vibration when using in high speed situations or as a system to cause energy absorption. Finally, the multi-material printing approach gives us more ability to tailor the desired load-displacement behavior of the mechanism due to the high control we have over the material layout and geometry.
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