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Design of flexure-based precision transmission mechanisms using screw theory

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ABSTRACT

This paper enables the synthesis of flexure-based transmission mechanisms that possess multiple decoupled inputs and outputs of any type (e.g., rotations, translations, and/or screw motions), which are linked by designer-specified transmission ratios. A comprehensive library of geometric shapes is utilized from which a multiplicity of feasible concepts that possess the desired transmission characteristics may be rapidly conceptualized and compared before an optimal concept is selected. These geometric shapes represent the mathematics of screw theory and uniquely link a body's desired motions to the flexible constraints that enable those motions. This paper is significant to the design of nano-positioners, motion stages, and optical mounts. It is also significant to the design of transmission-based microstructural architectures for creating new materials with extraordinary mechanical properties. The microstructural architecture for a material that achieves a negative Poisson's ratio as well as a hand-actuated two degree of freedom (DOF) microscopy stage are designed as case studies to demonstrate the utility of this theory.

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1. Introduction

In this paper we introduce the theory necessary to synthesize multi-input, flexure-based transmission mechanisms like the mechanism shown in Fig. 1, which will be discussed at length near the end of this paper as a case study. If either handle of this mechanism were rotated about its red rotation line shown in the figure, the labeled stage would translate in the direction of the actuated rotation line's axis 429 μm per degree of rotation. Sophisticated transmission mechanisms like the mechanism shown in Fig. 1 may be synthesized by combining parallel flexure modules created using the Freedom and Constraint Topologies (FACT) synthesis approach [1–5]. FACT utilizes a comprehensive library of geometric shapes, like the intersecting blue planes shown in the figure, to enable designers to visualize every way a system may be synthesized with flexible elements for achieving any desired set of DOFs. In this way, designers may rapidly consider and compare numerous concepts without having to apply the time-consuming, rigorous mathematics of screw theory, which is already embodied by the geometric shapes. Note that the flexible constraints, C_1 and C_2, each lie on the surface of one of the intersecting blue planes from Fig. 1.

Flexure-based transmission mechanisms are important to precision engineering because of their ability to amplify or attenuate an input displacement or load on a structure in a repeatable way. As such, they may be used as low-cost solutions for (i) increasing the resolution of a system's actuators, (ii) improving the sensitivity of a systems sensors, and (iii) transforming the nature of a system's inputs (e.g., from rotations to translations). The theory of this paper is, therefore, significant to the design of next-generation nano-positioners, optical mounts, and microscopy stages.

The flexure-based transmission mechanisms enabled by the theory of this paper are particularly important to the creation of new materials that possess extraordinary physical properties such as large negative Poisson's ratios and other transmission-based properties. The micro-structures of such materials consist of a multiplicity of sophisticated, multi-input, flexure-based, transmission mechanisms. These mechanisms interact with neighboring mechanisms to produce the bulk material's desired properties. A microstructural architecture that achieves a negative Poisson's ratio will be designed as a case study later in this paper.

1.1. Previous transmission synthesis approaches

Others have attempted to tackle the challenges of synthesizing compliant transmission mechanisms. The three most common approaches for designing such mechanisms include the pseudo-rigid body model (PRBM), constraint-based design (CBD), and topological synthesis.

Pseudo-rigid body modeling models compliant mechanisms as analogies to rigid-link mechanisms [6–8]. The transmission mechanism shown in Fig. 2A, for instance, was initially designed using

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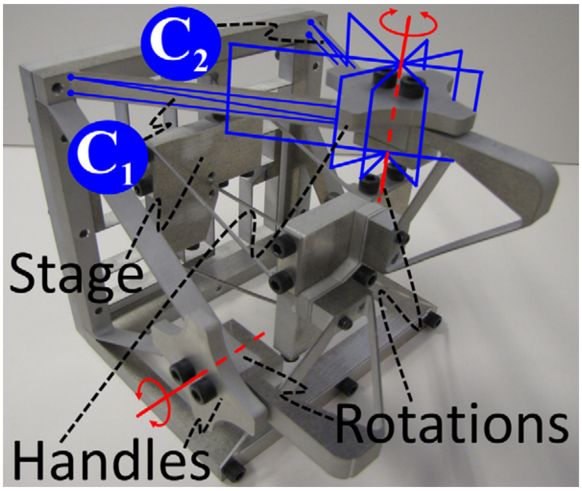

Fig. 1. Example of a complex multi-input flexure-based transmission mechanism synthesized using geometric shapes.

a pinned joint and two rigid stages. The compliant analog shown in the figure was then created by replacing the pinned joint with a flexible hinge. Concepts generated using the PRBM are unfortunately limited by what designers are able to synthesize using rigid-link transmission theories.

Constraint-based designers have developed rules of thumb for synthesizing compliant transmission mechanisms using well known flexible elements as building blocks [9–11]. One such building block consists of flexible constraints with lines of action that intersect a common point called an instant center. Systematic approaches [12,13] exist for combining such building blocks to produce compliant mechanisms, like the one shown in Fig. 2B, that possess the desired transmission characteristics. Many of the concepts

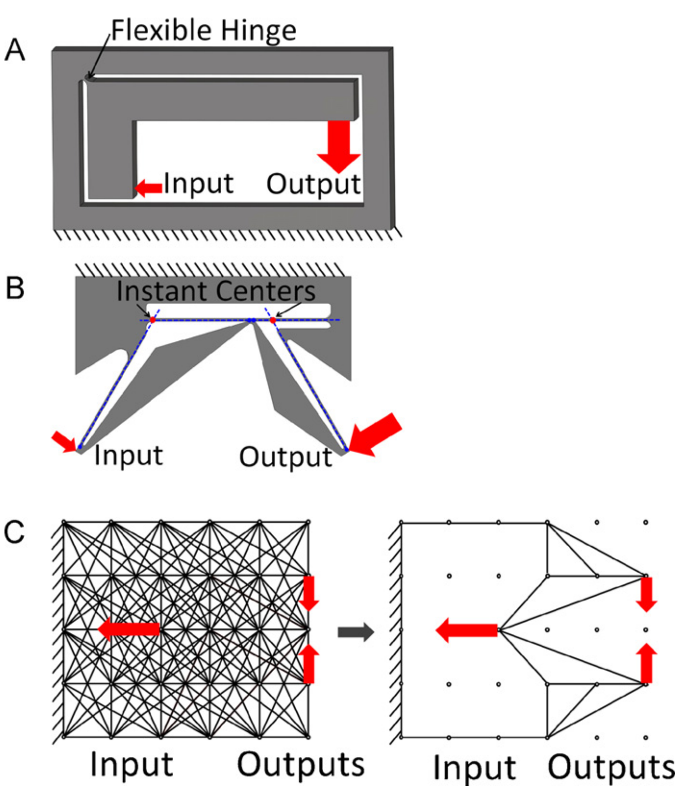

Fig. 2. A compliant transmission mechanism designed using the pseudo-rigid body model (A), constraint-based design (B), and topological synthesis (C).

generated using constraint-based design are unfortunately limited by compliant building blocks that possess simple motions, which are able to be visualized in conjunction with other building blocks.

Topological synthesis utilizes a computer to iteratively construct the topology of compliant transmission mechanisms by satisfying input and output displacement and force specifications using systems of linear beam elements as shown in Fig. 2C [14–17]. In this way, optimized compliant mechanisms evolve to possess the desired transmission characteristics. Unfortunately, many of the concepts generated using topological synthesis are difficult to fabricate and implement because the designer's common sense has no influence on what the computer generates.

All of these approaches have difficulty enabling designers to (i) synthesize non-planar transmission mechanisms with multiple decoupled inputs and/or outputs, (ii) transform input motions into different types of output motions (e.g., translations into rotations), (iii) generate screw motions with specific pitch values, and (iv) consider every solution before selecting the final transmission concept. The theory of this paper enables designers to overcome these challenges and thus synthesize next-generation compliant transmission mechanisms.

1.2. Scope

The mathematics in this paper applies to linear, small-motion kinematics only. This assumption is fitting as we are designing precision transmission mechanisms with stages that move small amounts compared to the overall size of the mechanism. Likewise, this paper's mathematics captures only the instantaneous transmissions of flexure-based mechanisms that have not yet been deformed over a finite range. Such deformations would alter the transmission ratios of the mechanisms in a non-linear fashion. Furthermore, this paper does not consider the effects of thermal fluctuations on the transmissions of the mechanisms designed, nor does it rely on the assumption that constraints are ideal (i.e., infinitely stiff along their line of action). Rather, the elastomechanic behavior of the constraints is fully considered and thus the transmissions predicted in this paper are accurately modeled for constant temperature conditions. Finally, this paper deals only with quasi-static conditions (i.e., it does not account for dynamic vibrations or time dependent inputs or outputs).

2. Fundamental principles

2.1. Parallel flexure systems

In this paper we will demonstrate how parallel flexure systems may be combined to synthesize flexure-based transmission mechanisms. Parallel flexure systems consist of a single rigid stage connected directly to ground by flexible constraints. Examples of such systems are shown in Fig. 3. We will later see that parallel flexure systems that possess screw DOFs are important for achieving transmissions. The DOFs of a parallel flexure system may be represented by geometric shapes called freedom spaces [1–5]. The constraints that permit the DOFs of a parallel flexure system may be represented by geometric shapes called constraint spaces [1–5]. The following sections review the fundamental principles of freedom and constraint spaces and how they may be used to synthesize parallel flexure systems.

2.2. Freedom space

According to screw theory [18–25] there are three types of motions—translations, rotations, and screws. Each of these motions may be modeled using a 6 × 1 twist vector, **T** [1–5,18–25]. In this paper translations are depicted as thick black arrows along which a

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