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Designing coupling behaviors using compliant shape optimization[☆]

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ABSTRACT

A wide set of assembly blocks such as attachments, connectors, joints, and supports rely on the principle of passively coupling two objects using structural compliance. However, only a limited variety of configurations are prevalent in daily use (*e.g.* snap fits) due to the challenge of extending the appropriate mechanical behavior to arbitrary object pairs. In this work, we present a method for computationally designing the mechanical coupling behavior between a rigid object and a compliant enclosure based on high-level specifications such as the ease of engagement and disengagement. At the heart of our approach is the use of deformation profiles as the means to describe and optimize physical coupling characteristics. In particular, we introduce a method that maps the shape parameters of the compliant object onto sequentially observed coupling descriptors such as the grip, insertion and removal forces that develop as the rigid object is engaged. Using this formulation, we present a method for optimizing the rest shape of the compliant object to produce the desired coupling behavior. We demonstrate our approach through a variety of designs and validate it with 3D printed physical prototypes.

1. Introduction

Mechanical coupling, defined as attaching two objects to one another, is a fundamental notion that underpins the realization of all types of connectors, joints, fixtures and attachments, which enable the creation of complex assemblies and mechanisms [1]. In daily use, a large class of couplings are intended to be *readily separable* with as few parts as possible as a way to facilitate temporary affixing, quick assembly and maintenance, and general ease of use. To this end, passive coupling of objects through structural compliance is a widely used method involving minimal number of parts and mechanical complexity, as part engagement is primarily enabled by elastic body deformations over coupling rigid objects. For designing monolithic compliant structures, topology optimization is a widely used approach that allows a tuning of force–displacement characteristics at prescribed end states [2,3], or to achieve structures that satisfy strength or compliance requirements under specified load configurations [4].

However, only a limited variety of configurations are prevalent in daily use (*e.g.*, snap fits) due to the challenge of extending the appropriate mechanical behavior to arbitrary object pairs. In particular, the compliant structures and their rigid counterparts are typically tailored such that either there exist known and permanent contact points that do not change during coupling [5], or the contact points involving the maximally deformed state can be known a priori [6]. Realizing these limitations, Koyama et al. [7] in an inspiring work present a data-driven approach for designing compliant attachments using parameterized basic geometries such as cylinders and rectangular prisms. However, the analysis does not extend to arbitrary free-form objects, necessitating rigid, multi-part solutions for such instances.

In this work, we present a physics-based method for designing the mechanical coupling behavior between a rigid and a compliant object such that the engagement and disengagement forces during the process of coupling, as well as the grip forces that lock the object pair together can all be customized by optimizing the shape of the compliant object (Fig. 1). Given an arbitrary rigid and compliant object, we use deformation profiles as a means to describe and optimize physical coupling. We introduce a method that maps the compliant object's shape parameters onto sequentially observed coupling descriptors such as the grip, insertion and removal forces that develop when the compliant object engages the rigid object. Using this formulation, we present a method for optimizing the rest shape of the compliant object to produce the desired coupling behavior.

A distinguishing feature of our approach is that it allows coupling behaviors to be designed for part interactions that may not be known a priori. In particular, our approach does not rely on the knowledge of known contact points or deformed states, thereby extending prior work on compliant attachments to scenarios involving arbitrary object pairs.

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Fig. 1. We introduce a method for designing coupling behaviors between an arbitrary compliant structure and an arbitrary rigid object. Resulting structures exhibit the desired coupling behavior such as ease of engagement/disengagement and grip.

Our main contributions are

- The use of deformation profiles to describe and optimize mechanical behavior.
- A physics based shape optimization method for compliant coupling behavior design involving two-part interactions.
- A practical insertion simulation based on collision elimination for computing deformation profiles.

2. Related work

Fundamentally, our approach involves mechanical behavior control through shape optimization. Below, we review the works that are foundational to our work.

Deformation behavior control. Deformation control through shape and structure optimization has been addressed in various ways including (1) Material distribution optimization [8–10], (2) Multi-material distributions [11], (3) Wireframe thickness optimization [12], and (4) Nonlinear material design through prescribed stress–strain curves [13]. Xu et al. [14] introduce model reduction to design heterogeneous deformable materials to achieve prescribed displacements and forces. Chen et al. [6] explore rest shape optimization to account for the deformations due to prescribed forces to obtain desired deformed states.

We extend these works to scenarios involving a coupling process with part contacts between a compliant and a rigid object rather than relying on forces known a priori. We formulate a broader problem where the compliant object acquires its final (steady) state through a progression of contacts where neither the location of the contact, nor the resulting contact forces can be known in advance. Additionally, it is not possible to prescribe the final deformed configuration in advance, as the contact forces deforming the object cannot be known explicitly a priori. Finally, each new hypothesis for the compliant object during its design likely produces new contact configurations. This necessitates shape design and contact analysis to be performed conjointly.

Computational design for fabrication. There exists a large body of work for structure design to enable prescribed functional objectives such as kinematic goals [15–17], strength improvements [18–21], or other physical qualities of interest [22–24]. Closely related to our work [7] create automatic connectors between object pairs involving parameterized primitive geometries such as cylinders and rectangular prisms using a data-driven approach informed by a battery of physical experiments, or use partitioned rigid connectors to accommodate free-form objects. Our work extends their work by formulating compliant mechanical coupling design as a conjoint shape optimization and physics-based contact simulation. This allows our method to transform arbitrary free-form objects into pairs that can be made attachable to one another.

Compliant mechanisms. Compliant mechanisms exploit flexible and continuous joint structures [25]. Typically, compliant mechanisms are structurally optimized for input/output displacement or force transfer ratios [2,3], for matching the displacement path of a compliant mechanism for an input actuation [26], or for enabling gripping behavior through known input force points [27–31]. Our compliant structures are not externally activated through prescribed contact points. Instead, deformations are generated through part interactions that are unknown a priori.

Bruns et al. [30] present a designer guided topology optimization method for generating a snap-fit mechanism to mount onto walled openings. However, contacts are deterministic as they follow imposed boundaries such as continuous sliding across a line. Lawry et al. [32] present a topology optimization method that produces a snap fit pair starting from objects with perfectly matching boundaries (*i.e.*, one object is a complement of the other). The aim is to optimize harmonic separation forces without considering grip. Optimization of connectors for simple pin geometries has been shown in [33,34]. Our approach builds on these ideas to make arbitrary geometries attachable to one another rather than fine-tuning existing snap fit configurations. With our formulation, engagement and disengagement forces as well as grip tightness can be designed in a decoupled way, thereby enabling the creation of couplings that require weak engagement forces but result in tight grips. Moreover, our work extends the above works in 2D to 3D.

Contact simulation. Our approach seeks to optimize the compliant object so as to produce the desired deformation behavior in the form of deformation profiles. The deformation, however, depends exclusively on the interaction between the current shape of the compliant object and the rigid object, thus necessitates a heavy use of contact simulations throughout the shape optimization process. Kloosterman [35] provides a detailed review of the large body of research in contact simulations. Voxmap Point Shell [36] models the environment as a map of voxels for penetration calculations and computes virtual penalty forces to eliminate penetrations. This method works for rigid object contacts but it is also extended to deformable objects in [37]. Kaufman et al. [38] presents a method that can model the frictional contact between deformable objects. Complex contact scenarios in dynamic simulations are studied in [39]. Continuous penalty force approach is presented in [40]. Based primarily on these works, we formulate our insertion simulation as a friction-free penetration elimination problem using distance fields.

3. Fundamentals and overview

Given a compliant structure $\mathcal{A}$ and a rigid object $\mathcal{O}$ to be inserted, we optimize the rest shape of $\mathcal{A}$ (Fig. 2). We use deformation profiles to understand and characterize the coupling between $\mathcal{A}$ and $\mathcal{O}$ for the current hypothesis of $\mathcal{A}$.