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Exploratory design of mechanical devices with motion constraints

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ABSTRACT

Mechanical devices are ubiquitous in our daily lives, and the motion they are able to transmit is often a critical part of their function. While digital fabrication devices facilitate their realization, motion-driven mechanism design remains a challenging task. We take drawing machines as a case study in exploratory design. Devices such as the Spirograph can generate intricate patterns from an assembly of simple mechanical elements. Trying to control and customize these patterns, however, is particularly hard, especially when the number of parts increases. We propose a novel constrained exploration method that enables a user to easily explore feasible drawings by directly indicating pattern preferences at different levels of control. The user starts by selecting a target pattern with the help of construction lines and rough sketching, and then fine-tunes it by prescribing geometric features of interest directly on the drawing. The designed pattern can then be directly realized with an easy-to-fabricate drawing machine. The key technical challenge is to facilitate the exploration of the high dimensional configuration space of such fabricable machines. To this end, we propose a novel method that dynamically reparameterizes the local configuration space and allows the user to move continuously between pattern variations, while preserving user-specified feature constraints.

We tested our framework on several examples, conducted a user study, and fabricated a sample of the designed examples.

1. Introduction

Toy of the Year in 1967, the Spirograph is a simple-to-use family of interlocking cogs and teethed rings allowing to draw a great variety of patterns. Although many other mechanical drawing tools preceded and followed it (see Fig. 1), this modest set of gears has marked a generation, and remains one of the most well-remembered today. As a product of the relationship between art and technology, drawing machines are still popular across artists [1], enthusiastic inventors [2], and makers [3]. The simplicity of the mechanical parts involved makes them easily fabricable with modern personal fabrication devices, which in turn open the door to a level of customization leading to new and fascinating patterns. Beyond this goal, the inverse problem of finding the machine tracing out a specific trajectory has numerous applications (see e.g., Coros et al. [4]).

Designing such machines, however, is particularly challenging. First, many mechanical devices transform an input rotation into a more complex cyclic output by combining oscillations of different periods and amplitudes. To produce a closed end-effector curve, the radii of mating gears (or equivalently, the number of teeth) need to have rational ratios. It is easy to enforce this constraint by restricting radii to natural numbers; the size of the pattern can still be controlled by a global scaling factor. The downside is that the design space becomes much more complex to explore: as the period is governed by modular arithmetic between radii, the visual output can radically change from one value to the next. Furthermore, the number of design parameters obviously increases with the number of parts. While this greatly enriches the space of possible curves, manually refining a design becomes difficult with as little as three continuous parameters. Indeed, nonlinearities make the influence of each control hard to grasp, and each one possibly influences the bounds of the others, making the space harder to explore.

In this paper, we propose a constraint-based exploration framework to design complex mechanical trajectories by interacting directly with the output pattern. In contrast to previous work [5], we focus on: (i) highly structured curves, which would be tedious to edit point by point, and (ii) allowing the continuous exploration of local design variations, rather than recomputing a new solution

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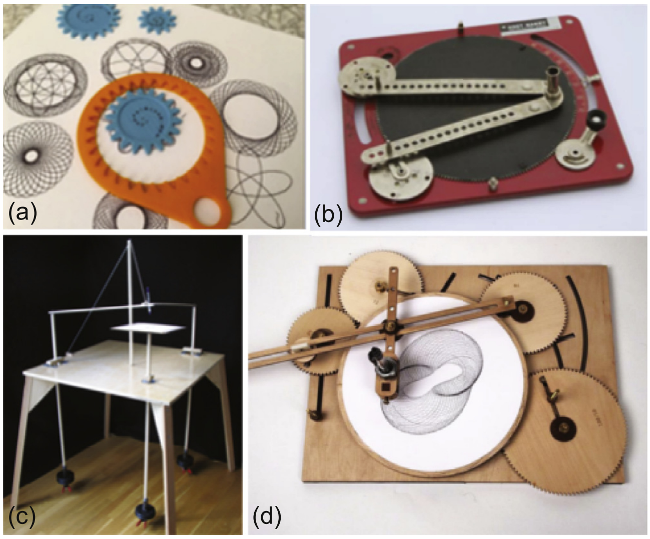

Fig. 1. Some examples of drawing machines: (a) Spirograph, (b) Hoot-Nanny, (c) Harmonograph, (d) Cycloid drawing machine.

after each curve edit. Indeed, the latter has the disadvantage that modifications made in one place of the pattern may result in unexpected changes somewhere else. Our method, on the other hand, allows the user to define visual preferences and explore the resulting constrained subspace.

Our exploration workflow consists in a coarse-to-fine definition of visual preferences that progressively refine the choice of curves. First, as an entry point into the design space, the user draws a coarse sketch that defines the global properties (e.g., order of rotational symmetry) and appearance of the desired pattern. After selecting an initial curve among suggestions proposed by the system, changes can be made via sliders within a domain that respects the feasibility constraints of the corresponding mechanism. When one slider is moved, the bounds of the others are automatically updated. As a key interaction, the user can define *visual preferences* directly on the drawing. These take the form of special points on the curve that can be constrained according to their geometric properties. The user can then explore local variations closest to these specifications via new handles that are automatically generated. Once the user is satisfied, the shape of the mechanical parts is automatically generated and exported for laser cutting fabrication (see Fig. 2).

Technically, we enable the above key interaction with a novel dynamic reparameterization method that locally samples the high dimensional configuration space of a given mechanism, measures closeness to the user-defined preferences, approximates the closest subspace, and exposes new parameters to navigate this subspace.

We evaluated the effectiveness of our design tool on several test scenarios, conducted a user study, and fabricated several physical prototypes able to draw patterns created by the users. Overall, we found that dynamic reparameterization allowed users to reliably make meaningful fine scale adjustments to their pattern designs.

This paper extends the previous conference work [6] by significantly extending the pattern retrieval step (including a novel technique to reduce the search space), providing new figures, a more detailed explanation of the fabrication process, and a virtual extension to a mechanical character to demonstrate the generality of our method.

2. Related work

Drawing machines have a long history in mathematics [7], art [8], and as toys. Before the computer era, they were the only way to accurately draw certain curves, with applications in architecture, astronomy, engineering, etc. [9]. While simulating such machines is nowadays relatively easy, the inverse problem of mapping an arbitrary end-effector trajectory to a reasonably simple mechanism remains a challenge. One of the most fundamental results in this regard is Kempe's universality theorem [10], which states that for any arbitrary algebraic plane curve, a linkage can be constructed that draws the curve. The constructive method proposed by Kempe, however, produces mechanisms with so many links that they are impossible to fabricate in practice. There have been many endeavors since then; to cite only one, Liu and Michael McCarthy [11] recently proposed a method to reproduce trigonometric plane curves with either Scotch yoke mechanisms or serial chains. Robotic arms and CNC machines have not made this problem obsolete, since there are situations where size is an issue (e.g., MEMS or nano applications), or electric power is unavailable or undesirable.

The following paragraphs discuss related advances in computational design and fabrication, with different application settings, both for inverse modeling and design exploration.

Computational design from target motion.

In the context of automata design, researchers have investigated replicating target motion using an arrangement of mechanical parts in a classic instance of inverse problem setup. The general approach involves sampling configurations from a library of components to retrieve a local arrangement of parts, and then refining the shape parameters using a gradient-descent based optimization to fit the target motion. For example, Zhou et al. [12] and Coros et al. [4] design automaton characters, while Ceylan et al. [13] design automata to replicate mo-cap sequences.

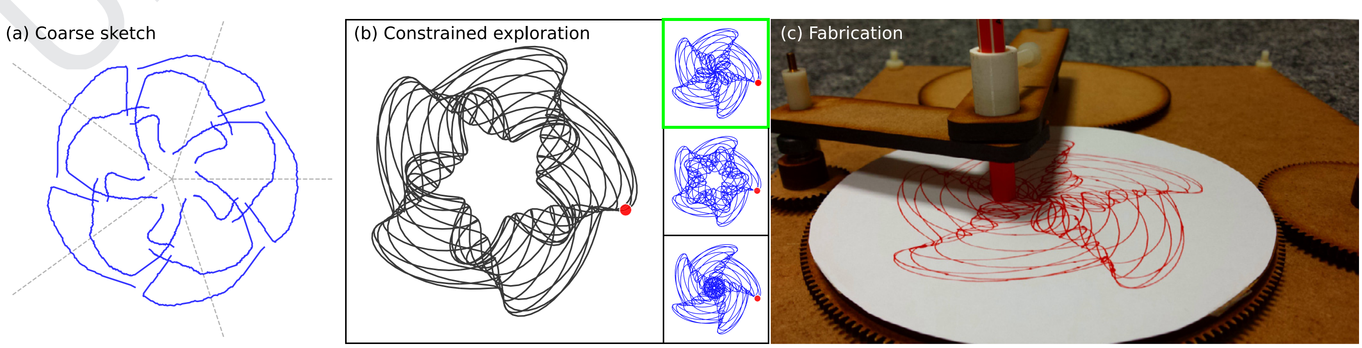

Fig. 2. Overview of our design workflow. The user first selects a mechanically feasible drawing by providing a rough sketch (a), and is then able to interactively explore local alternatives (b) by defining visual constraints directly on the pattern (here, the cusp position). The resulting machine is automatically exported to laser cutter profiles for fabrication. (c).

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