Computer-Aided Micro-Mechanism Design

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Abstract

This paper describes computer-aided design tools for micro-mechanisms that help designers validate correct function, detect design flaws, and assess the effects of part clearances. The domain characteristics of curved geometry, joint play, and higher pairs render traditional software inappropriate. Our software uses configuration spaces to model the kinematic function of micro-mechanisms. It uses the configuration spaces to perform real-time simulation, to compute functional kinematic tolerances, and to support parametric design. Designers can visualize system function under a range of operating conditions, can find and correct design flaws, and can optimize dynamical function. The software is demonstrated on a surface micromachined counter meshing gear discrimination device developed at Sandia National Laboratory.

Introduction

This paper describes computer-aided design tools for micro-mechanisms. Recent advances in fabrication technology make possible the synthesis of complex micro-mechanisms, such as gears, ratchets, and transmissions [8]. Designers need to analyze candidate micro-mechanisms to validate correct function, to detect design flaws, and to assess the effects of part clearances. Traditional computer-aided design software is inappropriate for these tasks. VLSI design software is not meant for moving parts. Finite element analysis is difficult and slow due to the large number of parts, the curved geometry, and the many part contact changes. It is computational overkill for designs that can be modeled as rigid-body systems. Mechanical system simulators offer an efficient alternative to finite element codes, but are limited to systems with permanent part contacts, such as pin joints, prismatic joints, and involute gears. These conditions are unrealistic for micro-mechanisms because the fabrication process cannot produce ideal joints and because changing contacts play a major role in micro-design.

We have developed an interactive computer-aided design program, called HIPAIR, that supports micro-mechanism design. HIPAIR automates kinematic analysis via a novel configuration space computation code [5], performs fast dynamical simulation [7], computes worst-case and statistical kinematic tolerances [6], and supports functional parametric design. Designers can visualize system function under a range of operating conditions, can find and correct design flaws, and can optimize dynamical function. HIPAIR handles planar systems of curved, rigid parts with custom pairs, open and closed kinematic chains, and contact changes.

Micro-mechanism fabrication

Fabrication technologies for micro-electro-mechanical systems can be broadly categorized into three groups: bulk micro-machining, LIGA, and surface micro-machining. Bulk micro-machining technologies make use of the differential etch rates between crystal planes of a bulk material, such as single crystal silicon. These techniques can create high aspect-ratio geometry that is useful as seismic mass, diaphragms, or vibrating elements in inertial or pressure sensors. LIGA is a micro-machining process that can form high aspect-ratio metallic parts with small features. LIGA processes involve making molds using lithographic patterning and etching. The molds are used in electro-plating processes to form the individual parts. Surface micro-machining uses the same tool set as the semiconductor industry, which enables high volume batch fabrication, integration with microelectronics, and definition of mechanical parts with small feature size. Surface micro-machining fabrication involves the repeated deposition, patterning and etching of materials such as poly crystalline silicon (polysilicon), silicon dioxide, and silicon nitride. Most fabrication methods use polysilicon as the mechanical structural material, silicon dioxide as the sacrificial material removed at the end of the process to release the mechanical layers, and silicon nitride as an electrical insulating layer. Surface micro-machining is the only process that can batch fabricate a system. Bulk and LIGA processes produce components that need further assembly, which is very difficult at these scales.

The Sandia SUMMiT process is a surface micro-machining process that can fabricate micro-mechanical devices with four mechanical layers, uses silicon nitride as ground plane isolation, and used silicon dioxide as the sacrificial material. Figure 1 is a schematic cross-section of a pinion gear that has a hub and a pin-joint connection to a linkage. The shape of the mechanical elements is defined via lithography. The reticle for this part is shown at the top of the figure. The color of the closed contours indicates their mechanical levels. The minimum feature size is dictated by the line width/space limitations of the lithography process, which is 1 micron for the SUMMiT process. The formation of a hub and pin-joint is a key element of the process to facilitate the fabrication of movable mechanical linkages. A 0.5 micron layer of sacrificial oxide is used to define the spacing in the hub and pin-joint. A detailed description of the SUMMiT process can be obtained at http://www.mdl.sandia.gov/Micromachine.

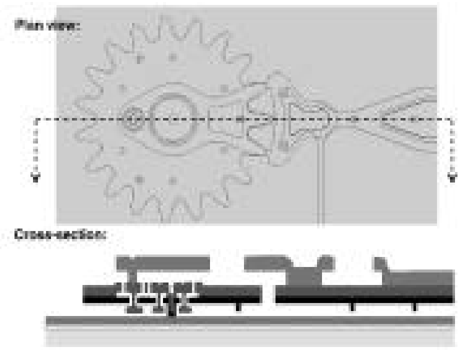
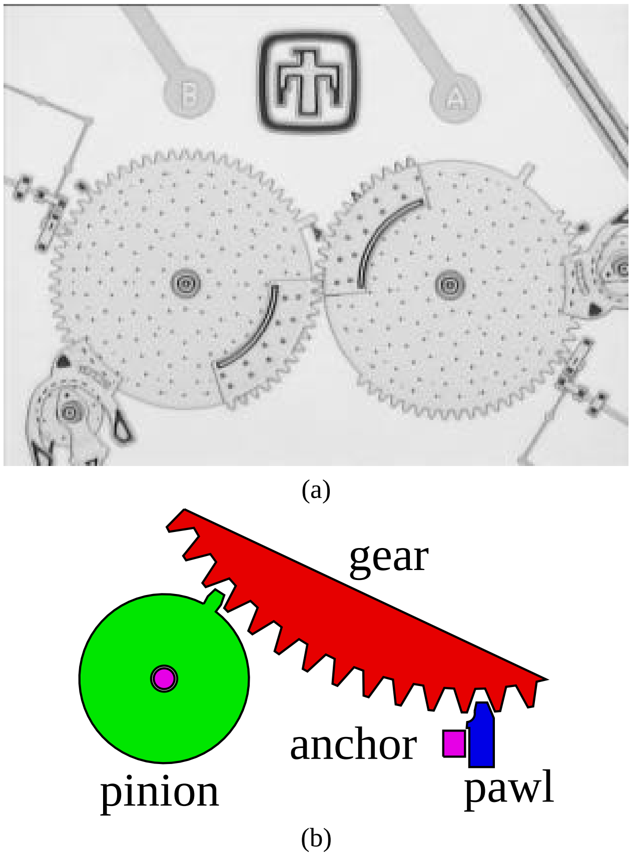


Figure 1: Pinion gear cross-section.

Surface micro-machining enables the fabrication of complex mechanical elements, which has been demonstrated for a number of applications. However, it raises design issues that are different from traditional mechanical design. Since surface micromachining is a batch fabrication method, the mechanical elements must be fabricated in place, which subjects their clearances and tolerances to the limitations of the fabrication process. The clearance and tolerance effects are of three categories: line width/space rules of the lithography, sacrificial oxide space in the hub and pin-joint, and size tolerance (one sided) of the mechanical elements due to release processing.

Design example



(a)

(b)

Figure 2: (a) Photograph of surface micro-machined counter-meshing gear discriminator; (b) Detail of indexing assembly CAD model.

We will illustrate HIPAIR on a prototype micro-mechanism developed at Sandia National Laboratory: a surface micro-machined counter meshing gear discrimination device [3] (Figure 2). The mechanism is a lock based on gears and ratchets. We will focus on the function of the indexing assembly. The pinion and gear rotate on fixed axes, the pawl is attached to the frame by an L-shaped spring, and the anchor is fixed to the frame. The designer intends for the pinion to rotate clockwise and to advance the gear by one tooth per rotation. Counter-clockwise rotation is prevented by the pawl's blocking against the anchor. Clockwise rotation is limited to one tooth per cycle by the damping effect of the strut, which bends as the pawl follows the gear profile.

Configuration space

We represent the kinematic function of the micro-mechanism with configuration spaces [2, 1]. We work with the configuration spaces of pairs of planar parts. Configuration space is a parameter space whose points specify the spatial configuration (position and orientation) of the parts. The part geometry is encoded by partitioning the configurations into three disjoint classes: blocked space where the parts overlap, free space where they do not touch, and contact space where they touch without overlap. Blocked space represents the illegal configurations, free space represents the independent part motions, and contact space represents motion constraints induced by part contacts. The spaces have useful topological properties. Free and blocked space are open sets whose common boundary is contact space. Contact space is a closed set comprised of algebraic patches that represent contacts between part features.

We illustrate these concepts on the gear/pinion pair of the indexing assembly (Figure 3). We assume for the moment that the joints have no play, hence that each part has one, rotational degree of freedom. The configuration space coordinates are the part orientations. Free space is white, blocked space is grey, and contact space is black. Contact space consists of many short contact curves that represent contacts between the pinion and the gear teeth (more precisely, between the geometric features that form the parts). The left part of the configuration space consists of narrow, slanted channels in which the part motions are coupled. As the pinion rotates clockwise, the configuration moves horizontally left until it reaches the nearest channel boundary then follows the boundary up, meaning that the the gear rotates counter-clockwise. The right part of the configuration space represents the rotation of the pinion from when it exits the channel on the left (breaks contact with the gear) until it reaches the right side of the channel above.

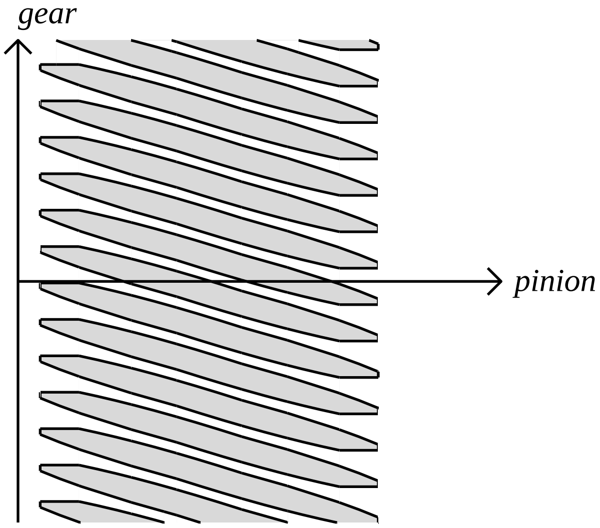


Figure 3: Gear/pinion configuration space.

This analysis ignores a crucial aspect of microfabrication: the 0.5 micron play in every joint. This means that the pinion and the gear each has three degrees of freedom: one micron of horizontal translation relative to its hub, one micron of vertical translation, and unrestricted rotation. We need three-dimensional configuration spaces to model this situation. The configuration space coordinates are the position (u, v) and orientation ψ of the gear relative to the pinion.

Figure 4 shows 1/64 of the gear/pinion configuration space. The shaded surface is contact space, the exterior is free space, and the interior is blocked space. Each of the 3664 contact patches is shaded a different color. Although this figure is extremely complicated, we can derive a complete kinematic analysis from it.

Figure 4: Small portion of gear/pinion configuration space with play.

Design tools

We can validate the indexing assembly function with HIPAIR through kinematic analysis of the interacting pairs, simulation, and visualization. We illustrate this process on the gear/pinion pair.

The first step is to check the configuration space for correct kinematic function. The desired function is that the pinion advance the gear by one tooth per cycle. The contact space shape is consistent with this function. As the pinion rotates, the configuration enters a channel (engagement), follows it (coupled motion), and exits (disengagement) after one gear tooth. Kinematic simulation provides an alternative way of studying kinematic function. We use HIPAIR to compute the gear motion induced by constant, clockwise rotation of the pinion. The simulator computes part motions due to contacts, but ignores dynamical effects, such as friction and inertia [4]. We can animate the simulation to validate the kinematic function or can examine the motion path in configuration space.

The next step is to assess the effects of joint play on the function. We start by examining cross-sections of the configuration space, which quantify the play in key part orientations (Figure 5). The circles mark the range of motion due to joint play. The part play is too small to cause unintended contacts. In the disengaged orientation, the circle lies in free space, which rules out other contacts that could cause chatter, vibration, and wear. In the engaged configuration, the circle center lies on the nominal contact curve and the circle does not intersect any other contact curves, which rules out backlash and jamming.

The next steps are to evaluate the mechanism dynamics via simulation and to study the functional effects of part tolerances. Although we omit these steps for lack of space, they are supported by HIPAIR.

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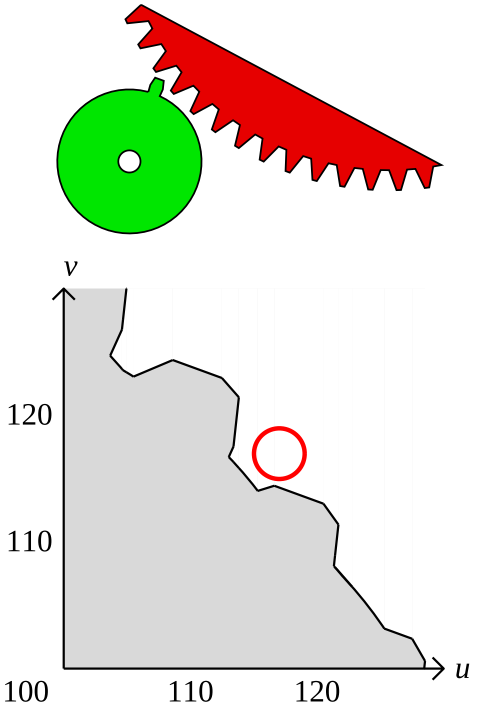

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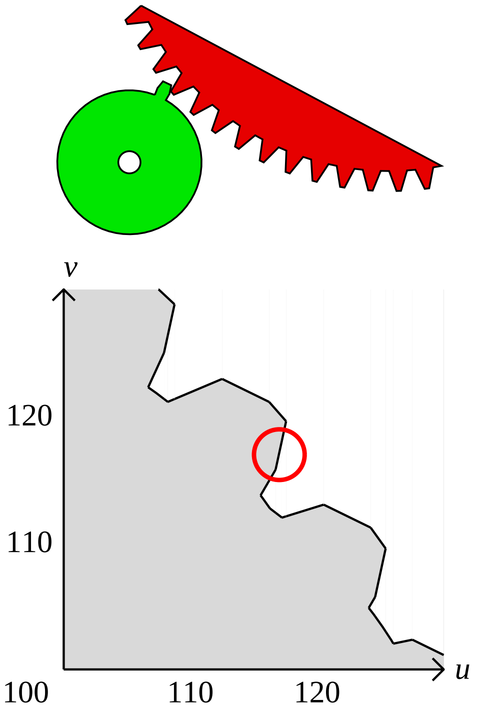

engaged

Figure 5: Cross-sections of the three-dimensional gear/pinion configuration space.

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