MEMS Functional Validation Using the Configuration Space Approach to Simulation and Analysis

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Abstract

We have developed an interactive computer-aided design program that supports mechanical design of devices fabricated in surface micro-machining processes. The program automates kinematic analysis via a novel configuration space computation code, performs real-time simulation, 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 performance. We used the program to detect and correct a design flaw in a micro-mechanical indexing mechanism fabricated at Sandia with the SUMMiT process.

Keywords: MEMS, micro-mechanical design, configuration space, Summit.

Introduction

We have developed an interactive computer-aided design program that supports mechanical design of devices fabricated in surface micro-machining processes, such as the Sandia SUMMiT technology. Typical devices include gears, ratchets, and transmissions [1]. Surface micro-machining technology poses significant design and analysis challenges that do not arise in traditional, macroscopic devices. It is a batch fabrication method, so 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 fall into three categories: lithography line width and space rules, sacrificial oxide spacing, and unilateral size tolerances on the mechanical elements due to release processing. These factors often influence the device kinematics and dynamics in complex ways. Comprehensive simulation is needed to assure correct function without excessive prototyping, which is extremely slow and expensive.

Traditional computer-aided design softwares is inappropriate for micro-mechanism design because of the curved geometry, contact changes, and large clearances. 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 contact changes (higher kinematic pairs) are common.

Our program automates kinematic analysis via a novel configuration space computation code [2], [3], performs real-time simulation [4], 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 performance. The program handles planar systems of curved, rigid parts with custom pairs, open and closed kinematic chains, and contact changes. This paper explains how we used the program to detect and correct a design flaw in a micro-mechanism fabricated at Sandia with the SUMMiT process.

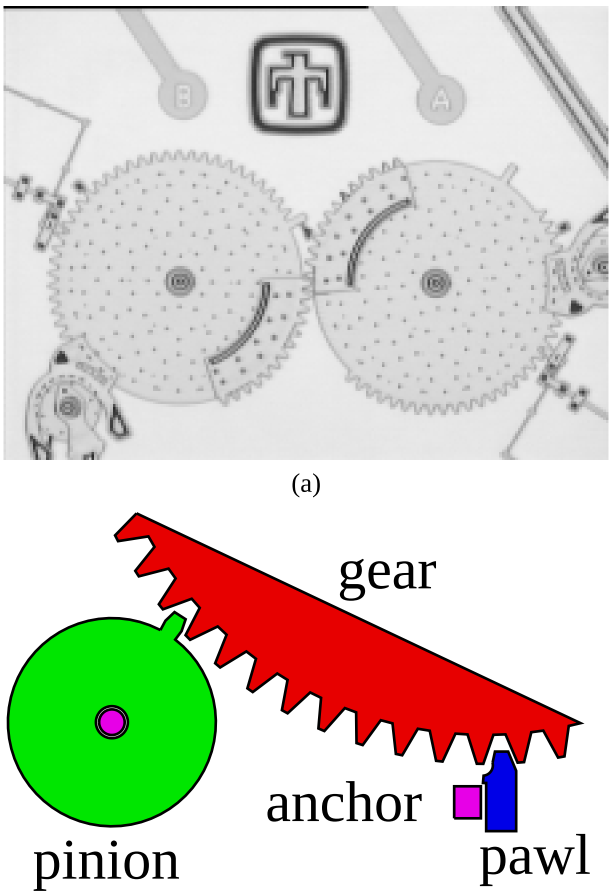
Indexing micro-mechanism

The mechanism is a lock based on gears and ratchets (Figure 1). We will focus on the function of the indexing assembly. The designer intends for the pinion to rotate clockwise and to advance the gear by one tooth per rotation. Reverse rotation is prevented by the pawl blocking against the anchor. Forward 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

Kinematic analysis is performed by constructing configuration spaces for the interacting pairs of parts. These spaces encode the part interactions in a uniform geometric format that supports simulation and parametric design. The configuration space of a pair is a manifold with one coordinate per part degree of freedom. We assume for now that the pinion and the gear rotate around their hubs without play. This yields a two-dimensional configuration space whose coordinates are the orientation angles p of the pinion and g of the gear (Figure 2). We compute three-dimensional configuration spaces for the gear/pawl and pawl/anchor pairs because the pawl has three degrees of freedom. These pairs will not be discussed further because they are irrelevant to the design flaw.

The part contacts are encoded by partitioning configuration space into three disjoint classes: blocked space (grey) where the parts overlap, free space (white) where they do not



(a)

(b)

Figure 1: (a) Photograph of surface micro-machined mutilated pinion indexing device; (b) Indexing assembly CAD model.

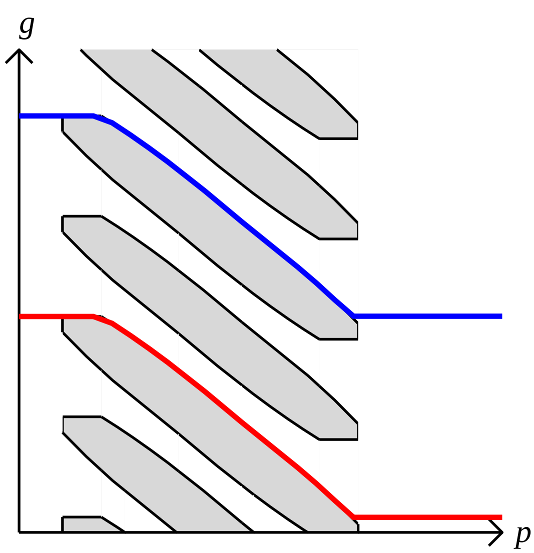


Figure 2: Pinion/gear configuration space.

touch, and contact space (black) 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. Blocked space consists of 63 regions (one per gear tooth) bounded by closed loops of contact curves. The loops consist of many short contact curves that represent contacts between features (points, line segments, and arcs) of the pinion and the gear teeth.

As the parts move, their configurations trace a path through the configuration space, which is shown as a thick line. The horizontal segments of the path represents the rotation of the pinion from when it breaks contact with a gear tooth until it makes contact with another tooth. These segments lie in free space, since the parts do not touch. They are horizontal because the gear does not rotate unless the pinion moves it. The diagonal segments of the path represent the pinion rotating the gear. They lie in contact space (on the right sides of the contact space loops) because the parts touch.

Simulation

Configuration space analysis reveals the kinematic constraints due to contacts among the parts of the micro-mechanism. We combine this analysis with dynamical simulation to predict the system function. The major factors are driving forces, contact forces, friction, stiction, and impacts. Kinematic analysis is a prerequisite for simulation because contacts create forces that effect part motion. The simulator needs to know which part features touch at every instant and when contact changes occur. Given this information, it can compute the contact forces, combine them with the external forces, compute the part accelerations from Newton's laws, and numerically integrate them to obtain the part configurations and velocities at the next time step. Manual kinematic analysis is practical for systems with permanent contacts, called multibody systems, and is implemented in commercial simulators [5], [6], but automated analysis is crucial for systems with many contact changes.

We have developed a simulator that uses configuration spaces for automated kinematic analysis [4]. The configuration spaces of the interacting pairs are computed before the simulation. At each time step, the simulator queries them for the contact data for contact force computation. It tests for part collisions and contact changes between steps by querying the configuration spaces for transitions between free and contact space or between contact patches. When these occur, it backs up to the change time and updates the contact equations. Running on a personal computer, the simulator handles systems with tens of moving parts at interactive speeds.

Results

We analyzed the pinion/gear configuration space to test the kinematic function. Figure 3 shows the nominal part dimensions. The correct function is for the gear to advance

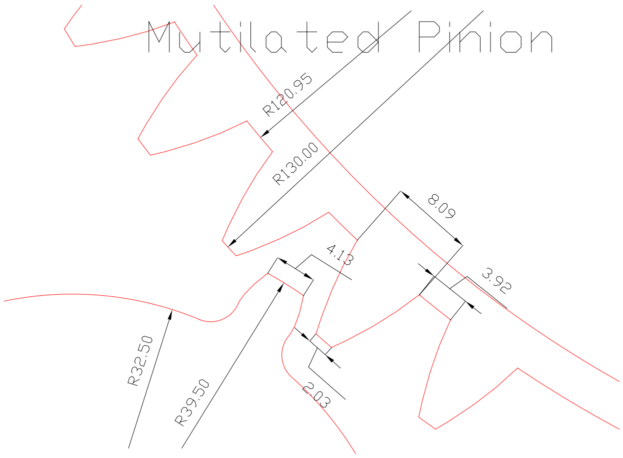


Figure 3: Nominal dimensions of pinion/gear pair.

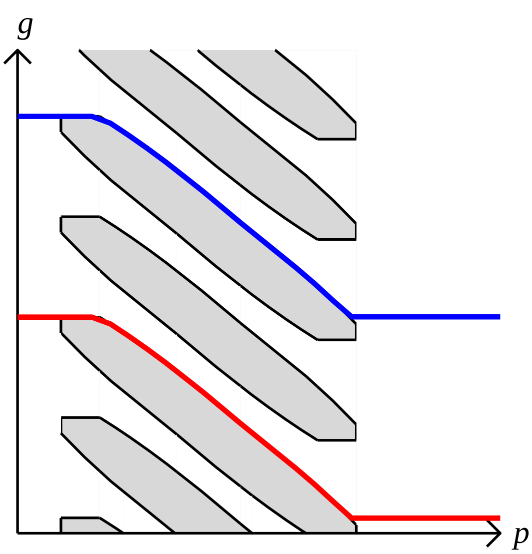


Figure 4: Pinion/gear configuration space.

by one tooth per pinion rotation. In configuration space terminology, consecutive diagonal segments of the motion path must lie on adjacent contact space loops. Figure 2 shows this behavior, so the nominal function is correct. The configuration space does not account for hub play, which allows the distance between the parts to differ by one micron from the distance between the hub centers (167.5 microns). When the parts are closest together, the configuration space shows incorrect kinematic function (Figure 4). The gear advances by two teeth per pawl revolution.

Configuration space analysis does not account for inertial, impact, and frictional forces. We performed rigid-body dynamical simulation to assess these factors. The material properties and frictional coefficients are from Sandia measurements. The simulation suggests that the two-tooth gear advance is masked by the pawl/gear impact, which reverse rotates the gear by one tooth. The fortuitous correction fails at other driving velocities and is sensitive to small variations in the part geometry and mass. Optical microscopy confirms this behavior.

The configuration space analysis shows that increasing the distance between the hub centers to 168 microns guarantees correct kinematic function despite hub play. Simulation suggests that the dynamical function is correct. To test this analysis, we designed a suite of mechanisms with distances between 167 and 169 microns. They are awaiting fabrication at Sandia.

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