A COMPUTATIONAL APPROACH TO THE DESIGN OF MICROMECHANICAL HINGED STRUCTURES

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INTRODUCTION

We are investigating computational aspects of engineering design problems that are amenable to tractable algorithmic solution.

The design process for an artifact can be viewed as a transformation through a series of abstraction spaces that characterize the artifact (Kannapan and Marshek 1991): Requirements, structure, parametrization, geometry, and manufacture space. Design automation aims at algorithmic solutions for these transformations. Our work focuses on the transition from parameter space to geometry space (*parametric design*) for algorithmically tractable subclasses of design problems.

We are currently developing a theory for the design of micromechanical hinged structures. These devices (Pister et al. 1992) are particularly attractive to design automation, because of

- the highly specialized and automated production process, which constrains and guides geometric design,
- the possibly high number of devices produced simultaneously in one manufacturing process,
- and the rather simple geometry and functionality of the devices.

In the following we briefly describe micromechanical hinged structures, and give an overview on our approach for design automation. This approach will use qualitative analysis of the kinematic states of the structure, and fast non-numerical simulation of its behavior. A more detailed description of this approach can be found in (Böhringer 1993).

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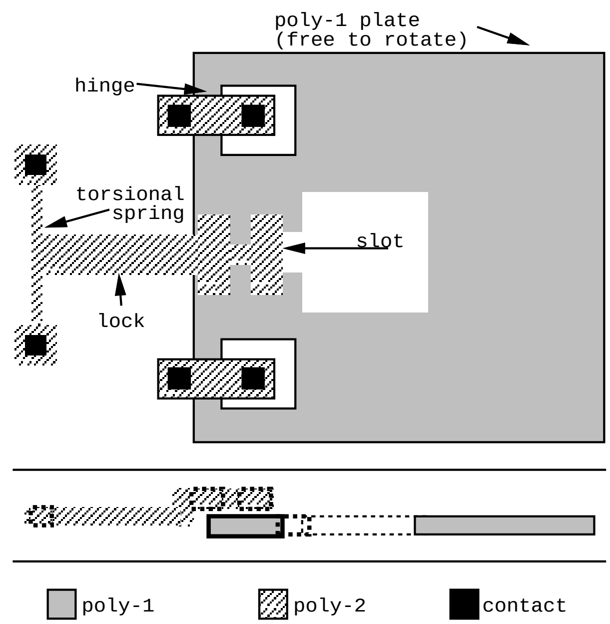

Figure 1: Micromechanical Spring Lock and Hinged Plate (Top and Side View)

MICROMECHANICAL HINGED STRUCTURES

A wide variety of micromechanical structures (devices typically in the micrometer range) have been built recently by using processing techniques known from integrated circuit industry, including micromotors, gears, tweezers, diverse sensors, among others. As a consequence of the production process these structures are essentially two-dimensional. Microfabricated hinged structures (Pister et al. 1992) allow the construction of three-dimensional devices. The basic idea is to make a plate that can rotate about a single axis defined by a pair of hinges. When the plate rotates out of the wafer, it has to push a spring loaded lock out of the way. The lock is designed such that when the plate reaches a certain angle (typically $\pi/2$), the lock snaps down into a slot in the plate (see Figure 1). The structures are rotated into place either by a probe station under the microscope (very labor intensive) or by hydraulic forces, i.e. shaking the wafer under water, such that the random motion of the water moves the parts into their final

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position.

The problem is how to design micromechanical hinged structures. This involves

- satisfying functional requirements for the assembled parts,
- geometric and engineering constraints for the manufacturing process,
- and dealing with physical phenomena like friction, material properties, and liquid flow.

APPROACH

For parametric design we utilize *generalized configuration space*. Besides parameters for each degree of kinematic freedom, generalized configuration space includes design parameters, e.g. the length of a plate. Behavior requirements, simplifying assumptions on geometry and physics, and fabrication constraints are used to reduce the combinatorial complexity of generalized configuration space, such that we can come up with a simple model of the parts to design.

We develop a model of micromechanical hinged structures based on the following assumptions. Assumptions on geometry:

- The parts are a finite sum of rectangular polyhedra. This means that all cross-sections are rectangular polygons. Furthermore a finite (usually small) number of cross-sections completely describes the parts.
- The spring loaded lock and the hinged plate each have one rotational degree of freedom.
- The thickness of the parts is small compared to its total length and width.

Assumptions on physics:

- Quasi-static motion: no inertial or Coriolis forces.
- Instantaneous snap: if the lock snaps off an edge of the plate, the time to reach contact again is negligible.
- Coulomb friction.
- The hydraulic force on the plate is proportional to the dot product of surface normal and liquid velocity.
- The spring force in the lock is proportional to the deviation angle of the lock.

The above assumptions implement constraints imposed by our specific problem domain. We exploit these constraints to develop an efficient algorithm for analyzing and designing hinged structures. First we recognize that the configuration space of a plate-lock pair is $C = [0, \pi]^2$. It can be shown that the conditions for contact can be modeled as low-degree polynomial curves in C, allowing fast exact simulation without numerical integration over velocity (Donald and Pai 1992).

Furthermore the configuration space of the plate-lock pair can be subdivided into a small number of qualitatively equivalent states (Sacks and Joskowicz 1992), each of which represents one edge-edge, edge-vertex, or vertex-vertex contact pair. For example, all configurations where a vertex V of the lock is in contact with an edge E of the plate would form one state. Again, states can be identified by simple algebraic relations on the geometric parameters. All configurations inside a state obey the same equations, while a state change can be seen as a discontinuity in the behavior of the system.

State changes are possible only when their corresponding regions in C-space are adjacent, and the transitions depend on the forces acting on the plate-lock pair (spring, hydraulics, friction). So our model for micromechanical hinges can be represented as a *behavior graph* whose vertices correspond to configurations with equivalent contact, and whose edges describe the conditions for transitions between different states.

The functionality of the structure can be determined by analyzing the behavior graph. Similar designs may have isomorphic graphs, but may differ in the conditions for state transitions, so that the structures differ in properties like stability or ease of assembly. Structures with different graphs may still have similar functionality, as long as start and end state of the graphs are equivalent. When designing these structures, we will make extensive use of the behavior graphs for analysis and simulation of the designed parts. Because the equations governing each state are simple, and fast simulation is possible, we are optimistic about developing algorithms which can optimize design parameters for a given behavior graph, and which search for good behavior graphs of a given parameterized structure.

CONCLUDING REMARKS

We believe that our approach, though still in an early stage, will advance design automation for useful subclasses of design problems. Models that allow fast, exact analysis and simulation of the parts to design seem to be crucial for algorithms that search for good designs. Domain-specific constraints narrow down the high degrees of freedom inherent in design problems and help to come up with an appropriate model. We would like to get a more formal grasp on this process, so that it can be incorporated into automated design. Other current goals are to implement a design system for micro-hinges, to incorporate mechanism dynamics into our model, and to extend our approach to a more general class of design problems.

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