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Computer Aided Design Tools in the Development of Surface Micromachined Mechanisms

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Abstract

This paper describes a number of computer aided design (CAD) tools that are used in the development of surface micromachined mechanisms. It investigates the application of parametric or constraint-based CAD in the design of these mechanisms. Parametric CAD facilities are compared with conventional CAD facilities in this paper. The advantages and limitations of conventional and parametric CAD are illustrated by describing their application in designing an electrostatically actuated crescent pump mechanism, which was fabricated in five levels of silicon using Sandia's Ultraplanar Multilevel Micromachining Technology (SUMMiT-V). The paper also describes the application of visualization and motion simulation tools in designing surface micromachined mechanisms.

Keywords: CAD, MEMS, Surface Micromachining, Parametric Constraint-Based CAD.

1. Introduction

The past few decades have witnessed the emergence of the field of microelectromechanical systems (MEMS) as an outgrowth from the silicon revolution. MEMS systems are produced from the integration of mechanical elements with electronics on a common silicon substrate through microfabrication. The electronics on a MEMS system perform arithmetic, logical and intelligence functions and are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes). On the other hand, the mechanical components perform sensing and/or actuation functions and are fabricated using photochemical lithographic processes that selectively etch away parts of the silicon wafer, or add new structural layers to form the mechanical and electromechanical devices. A number of MEMS mechanisms have been developed for applications ranging from accelerometers to mirror arrays [1-3]. More complex mechanisms have been developed for systems such as lab on a chip and micropumps [4-9]. These systems and are expected to impact disciplines such as biology, medical sciences, and others.

One particularly promising MEMS technology is surface micromachining [10], which leverages on the highly developed IC fabrication toolset, and provides the ability of batch fabricating hundreds to thousands of MEMS devices, together with drive and control electronics fully assembled on a single silicon substrate. In this technology, MEMS devices are built from a number of stacked polycrystalline silicon (polysilicon) films, consecutively deposited and patterned on top of a silicon wafer. Layout and visualization CAD tools traditionally used for IC fabrication were employed in surface micromachined mechanism design [11, 12]. However, the increased number of mechanical layers, and the mechanical complexity of surface micromachined mechanisms, increased the demand on the MEMS mechanism designer. Unlike an IC designer, a MEMS mechanism designer must visualize the three dimensional geometry, and motion of the target device from a set of planar mask patterns, besides verifying its conformity with the proposed fabrication process.

The paper describes the facilities provided by the generic and customized layout and visualization CAD tools in developing surface micromachined mechanisms and investigates the application of parametric constraint-based CAD in surface micromachined mechanisms design. As a case study, the advantages, limitations and improvement prospects of these tools are illustrated by describing their application in designing an electrostatically actuated crescent pump mechanism, which was fabricated in five levels of silicon using Sandia's Ultraplanar Multilevel Micromachining Technology (SUMMiT-V) [9]. Section 2 provides an overview of the fabrication and design of surface micromachined mechanisms. Section 3 outlines the design, operation and fabrication of the surface micromachined crescent pump used as a case study in this work. Section 4 describes the application of conventional layout tools in the design of surface micromachined mechanisms and section 5 investigates the potential benefits of parametric CAD in

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*Corresponding author. malkilani@kfu.edu.sa the design of those mechanisms. Section 6 describes the visualization and motion simulation tools in surface micromachined mechanisms.

2. Overview of the Fabrication and Design of Surface Micromachined Mechanisms

Surface micromachined MEMS are built from a number of stacked polycrystalline silicon (polysilicon) films, consecutively deposited and patterned on top of a silicon wafer. The standard building-block fabrication process consists of depositing and photolithographically patterning alternate layers of low-stress polycrystalline silicon as the structural material and silicon dioxide as the sacrificial material. The sacrificial layers provide a temporary standoff for the structural layers and are selectively etched away in hydrofluoric acid (HF) at the end of the process, leaving the free-standing polysilicon layers. Holes etched through the sacrificial layers provide anchor points between the mechanical layers and the substrate. The use of the center-pin and the flange processes [13], [14] allow creating a revolute joint between two of the polysilicon levels. The result is a system of mechanical polysilicon structures capable of producing complex mechanical movement involving linear and angular translation, reciprocation, oscillation and continuous rotation.

Sandia's Ultra-planar Multi-level MEMS Technology (SUMMiT) is a standard surface micromachining process [15]. It uses five levels of stacked polysilicon films labelled POLY0 through POLY4 as structural material, and four levels of intervening silicon oxide layers labelled SOX1 through SOX4 as sacrificial material. Each sacrificial SOX*n* film resides between a POLY*n* and a POLY*n-1* film and gets etched away in the final release process. This allows creating elaborate structures due to the great design freedom in defining the in-plane shapes of the structural and sacrificial films, and the provision of revolute joints between the POLY1 and POLY2 films. Freely rotating elements and free-spinning gears can be created. SUMMiT devices ranging from pressure sensors and gas sensors to complex gear trains and microengines have been demonstrated [16, 17].

The design of a device that is to be fabricated via SUMMiT fabrication process requires the designer to produce the layout drawings for the mask of each patterning step of the fabrication process. Depending on the number of structural and sacrificial levels used in the device, as many as 14 masks may be needed to produce a design. These include 9 masks for the structural polysilicon and the sacrificial oxide levels and 5 masks to produce dimples or pin joint cuts between the structural polysilicon levels. Pin joint cuts allow rotational freedom between two polysilicon levels, while dimples allow for creating protrusions to prevent the polysilicon films fro sticking to one another during movement. A mask is a two-dimensional design representation that will be patterned and etched into the structural or sacrificial material to produce the desired artefact. The mask set is the interface between design engineer's information (i.e., design), and the fabrication process.

The SUMMiT design tool suite utilizes the two-dimensional geometric layout capabilities of AutoCAD, which has the full set of geometric entities to facilitate complex mechanical design. To help the designer verify that the masks conform with the fabrication process, a number of design rules were developed. These rules are a set of requirements and advisements for the designer. Design rule checking tools were also developed and added to MEMS CAD systems [18]. These tools analyze the MEMS layout and examine if the size, spacing and overlap of geometry are correct for the fabrication process. After executing the design rule check, the results are loaded into the drawing session. Advisory rule violations and mandatory rule violations are displayed, and the design must be modified until no mandatory rules are violated.

3. Design, Operation and Fabrication of a Surface Micromachined Crescent Pump

The conceptual design and operation of the crescent pump used as a case study in this work may be described with reference to Figure 1. The pump utilizes a ring gear driven through teeth on its outer surface to drive the pumping mechanism through the triangular teeth on its inner surface. The outer teeth of the ring gear are not shown in the illustration of Figure 1. The inlet and outlet ports are located inside the ring gear and the pumped fluid is maintained in the inner vicinity of this gear. The ring gear has internally cut teeth, which mesh with the teeth of an externally cut idler gear that is set off-center from the ring gear. The crescent is fixed and divides the flow between the idler gear and the rotor. As the ring gear and the idler rotate in the counter clockwise direction, the gear teeth come out of mesh in the left side of the pump. This motion creates a partial vacuum, which draws fluid into the pump. The fluid is transferred to the right side of the pump between the rotating gear teeth and the fixed crescent. As the rotating gears mesh together in the right side of the pump, they generate an increase in pressure that forces the fluid into the outlet line. A gear pump can discharge fluid in either direction, depending on the direction of the gear rotation. Crescent pumps have two advantages. First, they can operate with no valves, simplifying their design and improving their reliability, and second, fluid is contained in the vicinity of the ring gear and is naturally sealed from the outer devices.

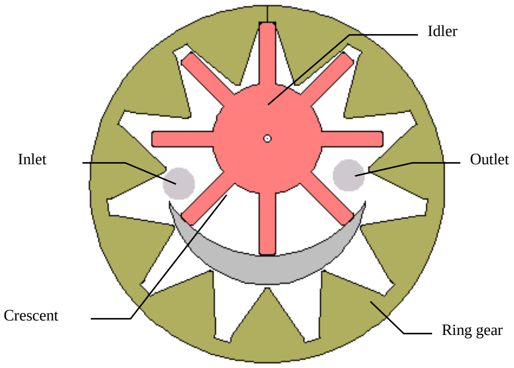


Figure 1. Crescent pump concept

A surface micromachined crescent pump fabricated from five levels of polysilicon is shown in Figure 2. The pump was produced using Sandia National Laboratory's Sandia Ultra-planar, Multilevel, Micromachining Technology (SUMMiT V) process and utilized all five layers of the technique. A torsional ratchet actuator in the bottom of the figure combined with a transmission gear train provides the power needed to actuate the ring gear of them pump. Figure 3 illustrates the mask layouts for the five structural polysilicon levels used in the crescent pump mechanism shown in Figure 2.

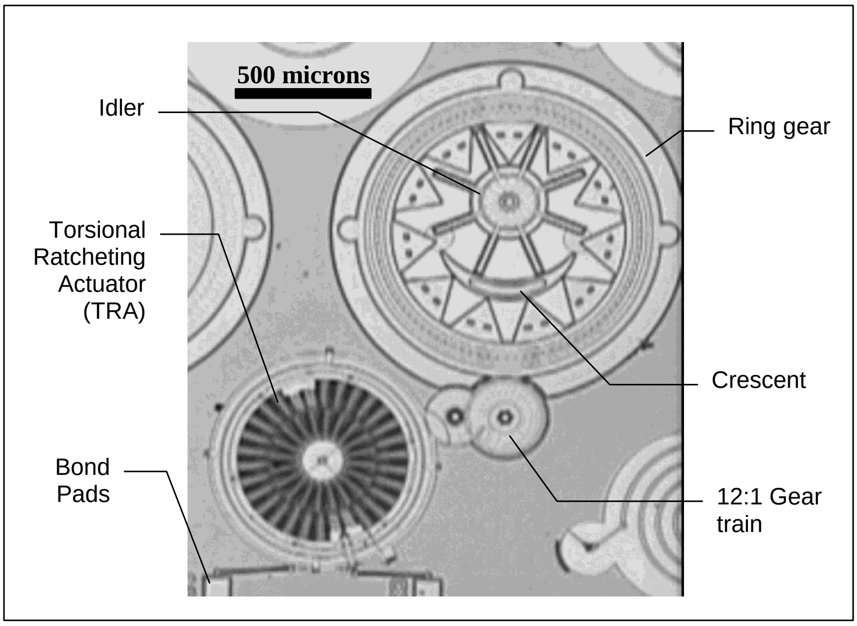
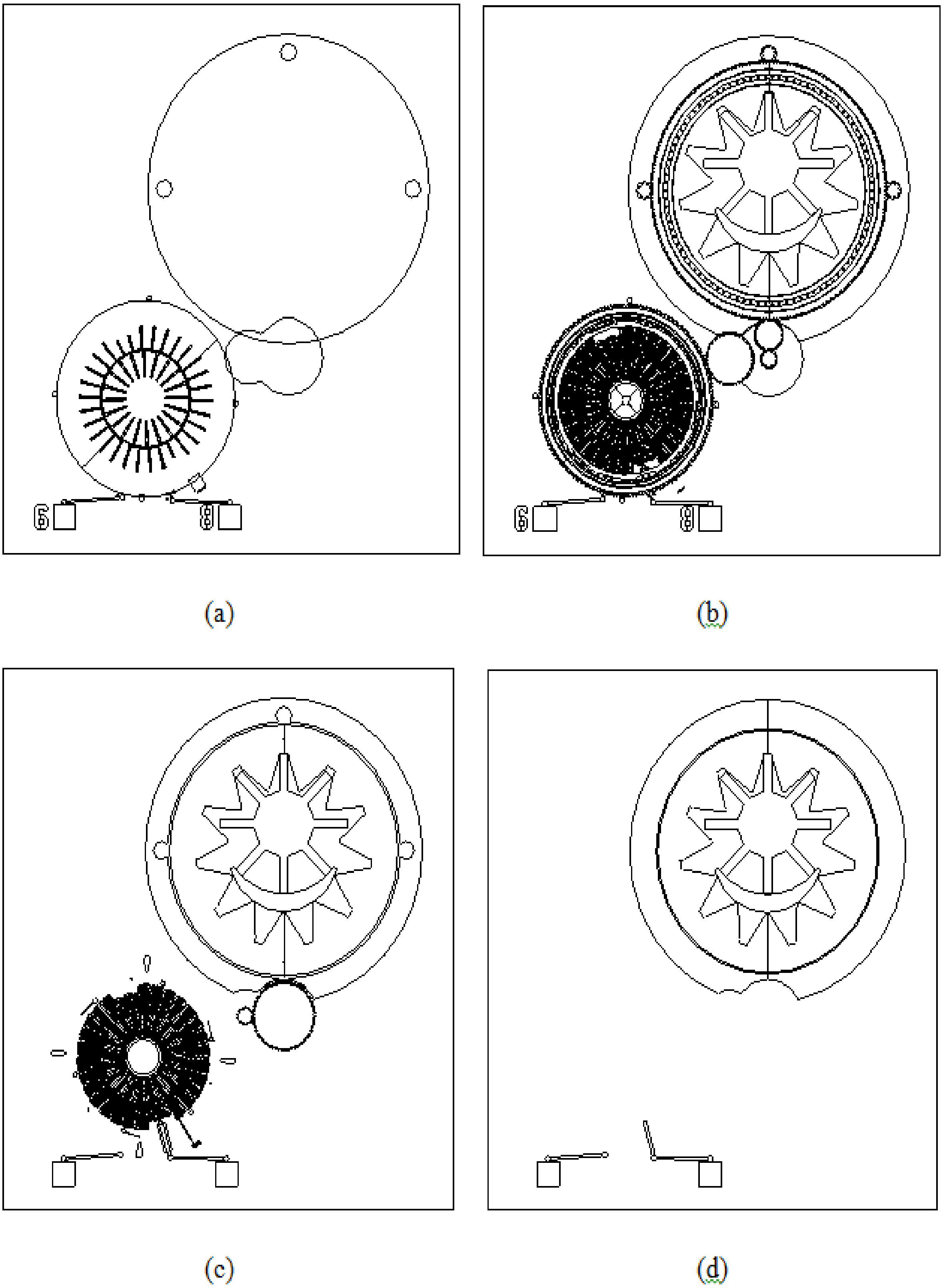


Figure 2. A Crescent mechanism fabricated in SUMMiT

4. Conventional Layout of Surface Micromachined MEMS

Construction, modification, inquiry and organization layout tools found in conventional CAD systems allow the creation of the geometric patterns in the masks of surface micromachined mechanisms. Construction commands are used to create the various geometric entities into the drawing database, including the lines, circles and arcs. Modification commands, such as scale, erase, move, array, etc. allow for the interactive modification of patterns to reach the desired mask layout. Inquiry commands are used to obtain information from the system on the locations, distances, angles, lengths and areas pertinent to the created geometry, and are useful for checking the correctness and accuracy of the design.

Organization tools allow the designer to group and/or separate certain geometric entities for the purpose of construction, modification or visualisation. Typical organization tools include layer tools and compound entity or block tools. Layer tools allow the designer to separate the design into different layers, which may be turned on or off, or assigned different colours or line types. One useful strategy in organizing surface micromachined MEMS is to group the entities belonging to each mask pattern on a different layer and assign different colour for that layer. Thus, a designer can edit, and examine each mask pattern separately, and can examine the pattern in relation with any other pattern or group of patterns on the complete mask set. In creating the mask layout for the crescent pump mechanism, geometric entities belonging to each polysilicon level or sacrificial oxide level were assigned to a different layer.



(a) (b)

(c) (d)

Figure 3. Mask layouts of the structural polysilicon levels for the pump in Fig. 2 (a) level 0 (Poly 0), (b) level 1 and level 2 (Poly 1 and Poly 2), (c) level 3 Poly 3 and (d) level 4 (Poly 4)

Compound entity tools of current CAD layout systems allow grouping a number of geometric entities together to create a new entity, which may be inserted into the drawing and manipulated as a single entity. This facility allows for the creation of standard component libraries for repeatedly used items and provides a convenient pick and place capability for such components. Current surface micromachined MEMS layout environments provide an assortment of library items for standard parts refined over the years by component designers. Selecting an item from the library automatically generates the entire mask layouts needed to produce that component on the wafer. This liberates the designer from 'reinventing' these components. Library items encompass a significant amount of design expertise, refined over the years by component designers. For a surface micromachined mechanism designer, a library component saves time and works as an important tool of experience sharing between designers.

Once in the drawing database, a library component may be translated and/or rotated according to the design requirements while still generating the mask layouts for the component in the new location, and without violating any of the design rules pertaining to the process. Scaling a library component in a traditional CAD system, however, would scale all the dimensions uniformly, which may result in violating the minimum line/space design rules, and leads to missing, undersized, oversized or fused features.

A standard components library, integrated into the SUMMiT's design interface, was used in defining some of the basic components of the crescent pump mechanism of Figure 2. The gear train, the torsional ratcheting actuator (TRA), and the bond pads were accessed from that library. This helped ensure the correct operation of these components in the assembly.

When the design contains internal cuts or holes, it is convenient to place them on a negative mask layer in order to simplify the production of the needed layout. Consider for example the layout for the POLY2 level of the idler of the crescent pump mechanism. The idler has an annular cut for hub clearance and 12 etch release holes symmetrically located around its axis of rotation. Setting the complete layouts of the idler in one positive mask, requires the designer to define the shape of the idler as a number of solid parts, which when joint together would produce the desired hole or internal cut, as illustrated in Figure 4. In this case, the symmetry of the shape was utilised and a polar array of four elements was invoked to produce the desired region with the holes and cuts inside as shown in Figure 4(c).

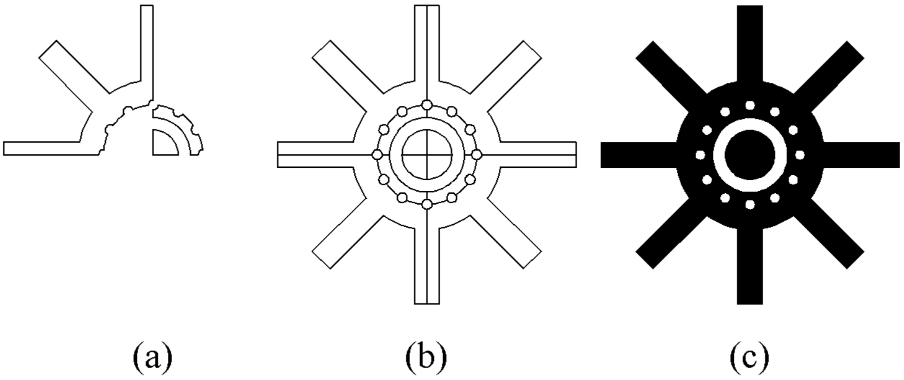


Figure 4. Defining the mask layout for the idler gear using only a positive mask set.

(a) positive mask regions. (b) polar array and (c) resulting region

Note that the polar symmetry property of the idler gear was utilized to simplify the generation of the layout in Figure 4. The production of this layout would be much more difficult if a larger number of etch release holes were needed and if polar symmetry did not exist. It is common to use as many as 100 etch release holes in some designs.

To deal with such cases, positive and negative masks would be conveniently used. As seen in Figure 5, the etch release holes and the hub clearance are defined in the negative mask and the external body of the idler is defined on a positive mask. The resulting mask shown in Figure 5 (c) is the same as that of Figure 4, but the construction procedure is simpler.

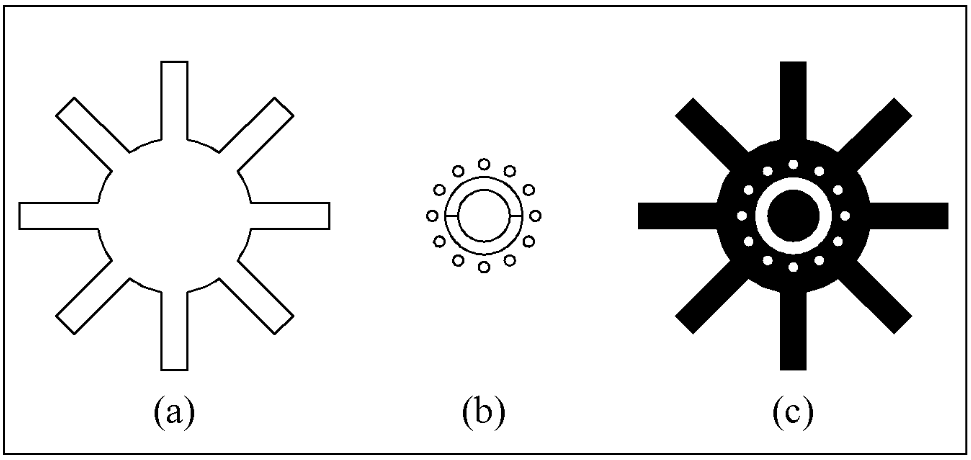


Figure 5. Defining the mask layout for the idler gear using positive and negative mask sets.
(a) positive mask regions. (b) negative mask and (c) resulting region

Some CAD systems provide facilities for converting closed polygons and circles into topological regions in order to perform union, difference and intersection operations. These operation can be employed as an alternative to using positive and negative mask sets. The result of applying a cut to the polysilicon level can be obtained by subtracting the regions of the cut from those on the body, resulting in the desired shape layout.

When laying out the design of a surface micromechined mechanism, the designer needs to verify that the resulting layout conforms with the proposed fabrication process. To help ensure the greatest possibility of successful fabrication, a number of design rules have evolved, which are a set of requirements and advisements for the designer defined by the capabilities of the individual process steps. In general, these rules are defined by the resolution and alignment capabilities of the lithography system. Both mandatory and advisory rules exist, and they define the minimum feature sizes and spaces for all levels and minimum overlap and spacing between relevant levels. The minimum line widths and spaces are mandatory rules. Violation of these rules will result in missing, undersized, oversized or fused features. Minimum overlap (enclosure, cut-in and cut-out rules) requirements reduce the effect of large topographies and prevent unnecessary etching of underlying layers. Minimum spacing between levels guarantees that features of two different levels can be delineated by photolithography and etch.

To help the designer confirming to the posted rules, design rule check tools were developed. The MEMS layout includes 2D polygons, arcs and circles placed on predefined layers, and a design rule check may be invoked in order to check that the developed design does not violate any of intended process design rules. As many of the rules are concerned with eliminating the overlap between the different polysilicon or sacrificial oxide layers, Boolean operations may be utilized in checking the validity of the design. Boolean operations may be invoked to check if an overlap exists, and its extent.

5. Parametric Layout of Surface Micromachined MEMS

When constructing the layout in a conventional CAD system, the user specifies the location of the individual entities in the drawing in absolute coordinates, or relative to other entities in the drawing, which the user can select on the screen using various snap techniques. The system stores only the absolute coordinate of the resulting entity with respect to a global or Word coordinate system. These coordinates are stored in the model’s database and are used for editing, printing and other purposes. Besides storing absolute or relative coordinates, parametric CAD systems create and maintain a set of constraints between the geometric entities created by the designer. Tangency, perpendicularity, parallelism, concentricity, and other relations may are recognized [19, 20]. The internal representation of constraints may be expressed as a network of equations or predicates. A constraint solver is then used to evaluate the absolute coordinates of all the entities in the network.

When creating a layout in a parametric design system, the designer first defines the topology of each shape in the layout by sketching lines, arcs and other entities in approximate coordinates. The designer then creates a number of geometry or dimension constraints in order to accurately define the geometry of the sketch. Constraints may be applied to an individual entity such as the length of a line or the radius of a circle, or may be applied as a relation that defines a dependency between two or more of the sketched entities such as constraining two lines to be parallel, or three circles to be concentric. Relations between the entities in the sketch reduce the number of free dimensions needed to completely define it, and the remaining free dimensions are called *parameters* that the user is allowed to manipulate to complete the sketch. The designer may edit the shape by changing one or more of its defining parameters.

As an introductory example, consider the layout of the rectangle in Figure 6(a). In a parametric system, the rectangle may be defined by four lines and three perpendicularity constraints. Note that only three perpendicularity constraints are needed as the perpendicularity condition between the right and bottom sides of the rectangle is implied due to the fact that the sum of the internal angles of a quadrilateral is equal to 360 degrees. The three constraints leave two free parameters, the length of the rectangle, d_1, and its width d_2, to to fully define it. When the three perpendicularity constraints are enforced, the designer can create rectangles of different lengths and widths by simply changing the values of d_1 or d_2. If an additional equality constraint is imposed between the right side and the bottom side of the rectangle, as shown in Figure 6(b), the shape is further constrained to become a square, fully defined by specifying the length of its side.

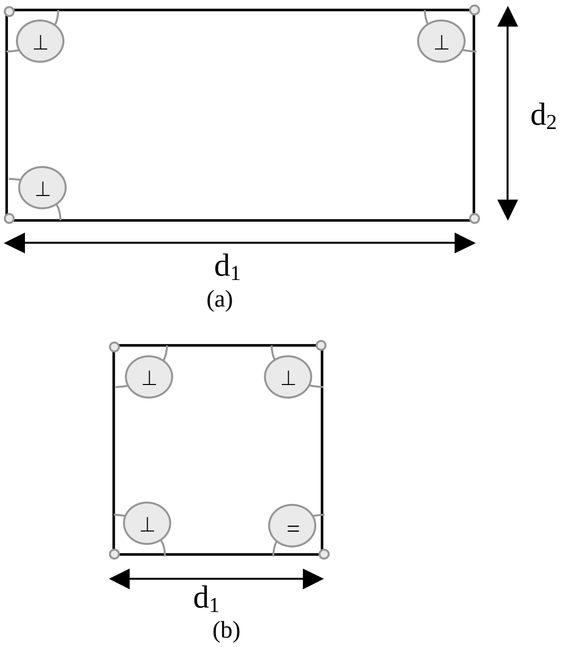


Figure 6 (a) Rectangular shape and (b) Square shape defined in a parametric CAD systems

The advantages of using a constraint based design system include faster creation of shapes because the designer specifies approximate rather than exact coordinates. Further editing and changes to the design is simplified because it is performed by changing few key parameters, while the constraints are observed. This reduces error possibility by propagating relations to other shapes in the design across layers.

A component is modified in those systems by changing one or more of its defining parameters, and the constraints will be observed in the result. This paradigm allows editing operations to be performed without running the risk of violating the design rules imposed. Additionally, a parametric or constraint-based design system affords an explicit representation of design rules in the item definition, leading to a richer and more transparent form of knowledge representation. Explicit constraints allow the designer to specify the mandatory or advisory rules in the form of constraints between its graphical entities. The designer can then change design parameters while the rules are satisfied.

An example of the application of parametric constraint-based layout tools in surface micromachined mechanisms design may be illustrated with reference to the layout of the idler gear of the crescent mechanism of Figure 5. The hub clearance needed to provide the rotational freedom of the idler's hub consists of the two half rings adjacent to one another as seen in the Figure. The minimum spacing between the outer arc and the inner arc is specified in the design rules to be 3 microns, and we assume the designer has used a design with this minimum spacing. If the designer adjusts the inner radius in a conventional layout setting, he needs to explicitly adjust the outer radius while making sure that the minimum spacing condition is not violated. Attempting to scale down the ring will scale the spacing between the two arcs and the design rule will be violated. A parametric layout system, however, allows specifying the radius of the outer arc in terms of the inner arc. The constraint relationship may be $r_o = r_i + 3$, where r_o and r_i denote the outer radius, and the inner radius, respectively. The resulting layout for the hub clearance is thus effectively defined in terms of one parameter. If the inner radius is changed, the outer radius is updated based on the constraint imposed, and vice versa. Propagation of this parameter to other elements in the design, and may also be defined in terms of other elements.

Library components of surface micromachined design environments have evolved after many design iterations involving experimentation, modification and refinement. Employing a parametric design paradigm in a component library significantly increases its experience sharing value. Consider the process of scaling a library component without violating the design rules. This requires preserving the relational constraints embodied in these rules. In parametric CAD systems, the component designer can define a set of constraints on the dimensions of the group, and these constraints will be observed whenever the component is edited, which would allow scaling the component without violating the design rules. Additionally, the relations, associations and constraints defined in a parametric design system allows capturing a deeper form of design expertise into the component, significantly increasing the knowledge sharing value of the component libraries.

6. Visualization and Motion Simulation

The increased number of mechanical layers, and the mechanical complexity of surface micromachined mechanisms increases the demand on the designer, who is needed to visualize the three dimensional geometry, and motion of the target devices from a set of planar mask patterns, besides verifying its conformity with the proposed fabrication process.

MEMS designer needs to combine the fabrication process information with two-dimensional mask geometry to visualize the target MEMS device. The 2D mask set does not reveal the true three-dimensional structure of the target MEMS device, and the result is highly dependent on the employed process sequence. Custom-made visualization tools help the designer visualize the target MEMS structure during the design stage, and before fabrication by applying the process sequence to the mask set to produce a representation that reveals the target device to the designer. Commonly used visualization tools include cross-section visualizers and geometry modellers. A cross-section visualizer generates a cross sectional view of the target MEMS structure at a location specified by the designer on the mask set. A geometry modeller generates a 3D solid model from the 2D mask layout allowing the designer to examine the target device from different angles and viewpoints. Those tools extracts 2D mask geometry from the design layout and apply the process sequence to the mask set resulting in a representation that reveals the target device to the designer. A 2D visualizer generates a cross sectional view of the target MEMS structure at a location specified by the designer on the mask set. A 3D geometry modeller, on the other hand, generates a 3D solid model from the 2D mask layout allowing the designer to examine the target device from different angles and viewpoints

Figure 7 demonstrates a cross sectional view for the crescent mechanism at the idler's centreline generated by a cross-section visualizer custom made for SUMMiT [21]. The section shows the different polysilicon levels used on the idler's body, and illustrate the formation of a hub in the central region of the idler to form a pin joint between the idler and the substrate. The cross section is generated from the entities on the layout and confirms that the idler will be physically separated from the hub, and free to rotate.

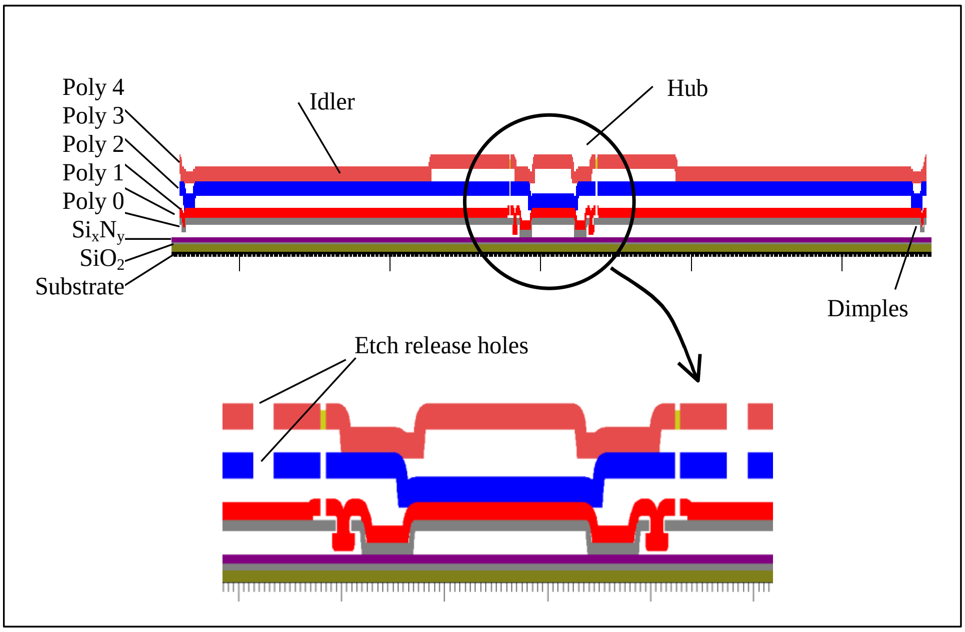


Figure 7. A section through the idler generated by A Cross Section Visualizer.

A geometry modeller generates a 3D solid model for the target MEMS device from the 2D mask layout [22]. Like a section visualizer, a geometry modeller works by interpreting the design layout based on the process definitions. The resulting interpretation is a 3D solid model of the target MEMS device which allows visualizing the true 3D geometry of the MEMS device. An example solid model generated for the crescent pump mechanism using a 3D geometry modeller is shown in Figure 8. The model shows the ring gear, the idler, the crescent, and the inlet and outlet holes. Because it generates a complete representation of the target MEMS device, a geometry modeller is capable of predicting process artefacts including stringers and trapped oxide.

Geometry modellers are convenient tools which help visualize the 3D geometry of the target MEMS device. An additional benefit of the generated solid model is that it can be used for finite element analysis, kinematic and dynamic simulation, rapid prototyping, and other downstream activities. This capability requires a complete and seamless integration between the geometry modeller and the different analysis programs.

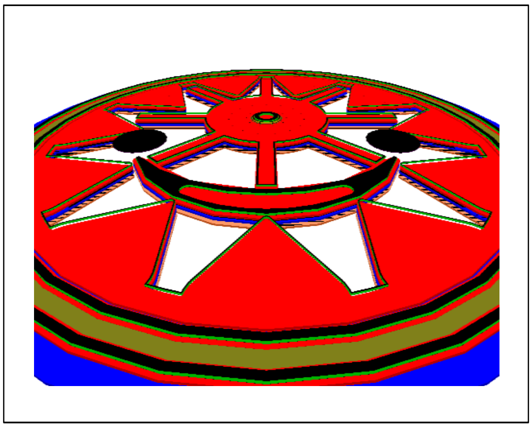


Figure 8. A model for the crescent mechanism generated by a geometry modeller

To help the surface micromachined mechanism designer visualize the motion of the target mechanism, motion simulation software tools are used. These are particularly useful when the mechanism includes revolute joints and gear pairs for continuous rotation. Object geometry may be imported into the simulation tool from the layout drawings and the designer specifies motion constraints. The software can then simulate the resulting motion, which may be displayed in animation showing possible interference, jamming, or loss of contact between meshing objects.

Crescent mechanism operation relies on the continuous rotation of a ring gear, which has internally cut teeth that mesh with the externally cut teeth on the idler. Ensuring proper operation of the gears is complicated by the fact that non-standard gear form was used to increase the capacity of the pump. A 2D mechanical motion simulation was generated during the design phase of the crescent mechanism to ensure that continuous meshing between ring gear and the idler gear is maintained, and that no interference, jamming, or loss of contact takes place during the pumping cycle. The simulation was generated using the Working Model 2D® dynamics software, (MSC Software Corporation, Redwood, CA, USA). The mask patterns for the ring gear, the idler and the crescent were imported into a 2D macroscale simulation package from the POLY2 level of the respective items, and the appropriate motion constraints were added.

The simulated motion and the actual motion of the crescent mechanism are shown in Figure 9. The top part of the figure shows four frames of the generated motion clip. The frames depict the engagement-disengagement of one pair of teeth between the idler and the ring gear during operation, and are repeated for each pair of teeth engagement. At the design stage, this simulation verified continuous meshing between the ring gear and the idler with no interference or jamming. The simulated motion was found to be in good agreement with that of the actual fabricated pump shown in the bottom of Figure 9.

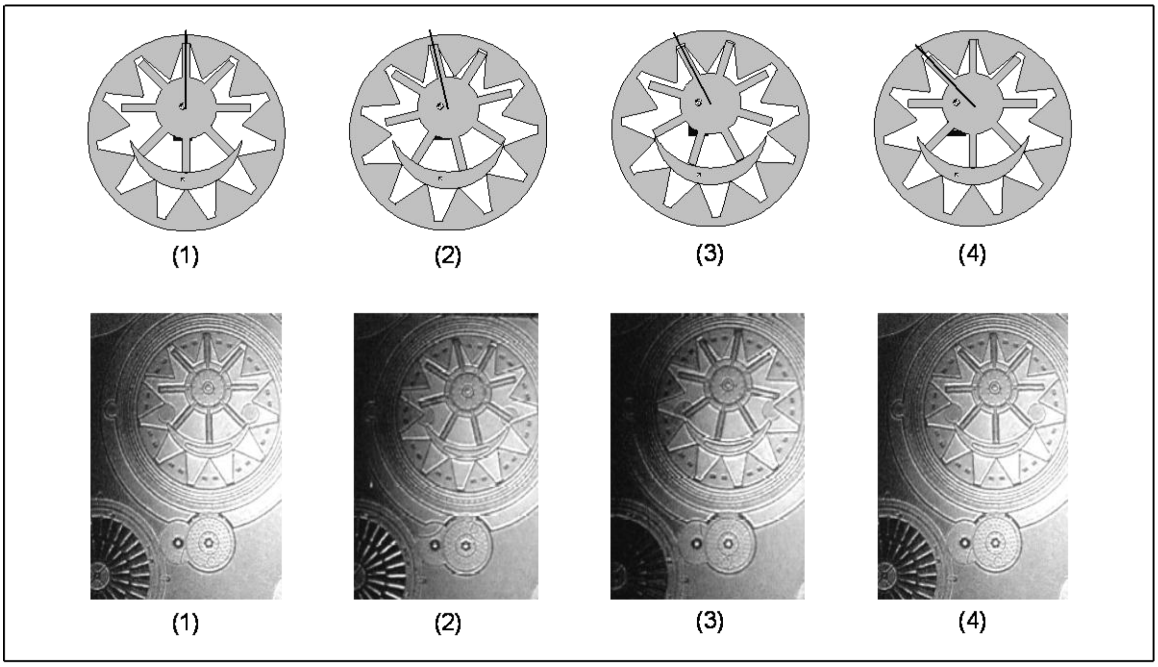


Figure 9. Crescent mechanism motion. Simulated (top) and actual (bottom)

2D motion simulation proved to be valuable in confirming the correct operation of the crescent pump mechanism. However, The POLY2 dimensions on which the simulation was based represent only the nominal dimensions of the crescent pump components, and the vertical topography resulting from additional SUMMiT layers were not included in the model. The cross section visulizer was used at different critical location on the mask layout to ensure that these artefacts cause no interference or jamming during actual motion. To show such effects, 3D motion simulation of surface micromachined mechanism is needed. This requires the integration between the 3D geometry modeller and the motion simulation routines and is not yet available.

Motion simulation confirms the kinematic correctness of the model, but does not include the dynamic effects of the forces and torques acting on the microstructure in operation. The software, for example would not calculate the forces acting on the components from the actuator used, neither would it confirm that power available by the actuator is enough to overcome the friction forces resisting the motion. The designer must rely on his own judgment and experience in answering such questions. A physical model for the forces and torques developing during operation, which includes the forces of stiction, friction and surface tension, would help ensuring that the drivers used are adequate and would produce the intended motion of the designed mechanism.

7. Conclusions

The paper described the application of CAD tools used in the development of surface micromachined mechanism design and illustrated the utilization of these tools in the design of a crescent micropump mechanism. The potential benefits of parametric constraint-based CAD systems in surface micromachined mechanism design are discussed.

Construction and editing facilities provided by current layout CAD systems are convenient for producing the lithographic masks of surface micromachined MEMS. Boolean operations may be used to expedite the layout process, and help in visualizing the result of using positive and negative lithographic masks in the design.

Parametric CAD systems allow imposing a set of constraints on the design, which may be derived from the mandatory or advisory rules of the fabrication process. This allows editing operation to be performed without running the risk of violating these rules. The explicit representation of design rules in parametric design systems leads to a more transparent form of knowledge representation, and allows for storing a deeper level of design expertise in library items.

Visualization tools help visualizing the target MEMS structure during the design stage, assuring the conformity of the mask to the intended process. Mechanical motion simulation tools may be adapted to microcmechanism design to predict the kinematic behaviour of the mechanisms. A comprehensive surface micromachined design system requires integrating layout, visualization and motion simulation functions; a capability that may be provided by modern feature, based associative design systems. This would allow 3D motion simulation which considers vertical topography issues associated with the process artefacts. Additionally, these systems may provide a link to other downstream design activities including finite element analysis and rapid prototyping.

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