The Art and Signs of a Few Good Mechanical Designs in MEMS

G. K. Ananthasuresh

1 Introduction

Mechanical design is a triple helix intertwining geometry, material, and manufacturability. Geometry mostly decides the functionality of a device; materials dominantly determine the performance; and manufacturability arguably dictates the economic viability. While this is true of any field, it is particularly relevant where movable elements are involved. *Microelectromechanical Systems* (MEMS) field is unique in this respect. MEMS devices combine sensing, actuation, processing, control, communication, and power within a minute volume. It is important to note that miniaturized mechanical elements have made this possible. Some MEMS devices have nearly a million moving parts that are individually controllable (e.g., tilting mirrors of Digital Light Processor used in projectors)—a feat unmatched by any engineered mechanical systems in the macro world.

Mechanical design of MEMS has not been easy because MEMS designs, at the inception of the field, had to be made using the same unit processes that were available for making electronic circuits, and using the same materials. This continued along the same lines while a few more processes and materials were added to the repertoire [1]. Thus, design and fabrication are tightly integrated to achieve the desired functionality within the constraints. There aren't many other instances of such integrated systems other than biological cells and unicellular organisms. It is therefore pertinent to reflect on the role of mechanical design in MEMS.

When a MEMS researcher was asked to list a few good mechanical designs, the reply was that commercially successful devices have good designs. Furthermore, it was noted that great MEMS designs are those that actually made it into useful products and concurrently diverged from concepts that are routinely used in meso- and macro-sized devices and systems. This is indeed true. Some mechanical designs

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in MEMS are so clever that there were no such designs before in other disciplines. Some, of course, were taken from other disciplines to fulfill a need in MEMS. In this chapter, we consider a few good designs of both kinds. As we examine them, it might reinforce the idea that design is mostly an art. But that is not entirely true. There are systematic methods to obtain novel designs that are elusive to human designers [2]. And there are logical extensions of elegant concepts that point to new designs. It is thus important to notice the characteristics of good designs. Therefore, several mechanical designs used in MEMS are presented with an eye toward nine indicative attributes of good designs:

Simplicity
The "wow" factor
Ubiquity
Ease of making
Optimality
Modularity
Generality
Economy
Hierarchy

The collage of a few MEMS devices is depicted in Fig. 1. When seen in their microfabricated and assembled form, the intrinsic merit of these is not easily apparent. So, they are broken down into components that have the essential quality that defines a device. This helps us to adapt and use the design concept in other applications.

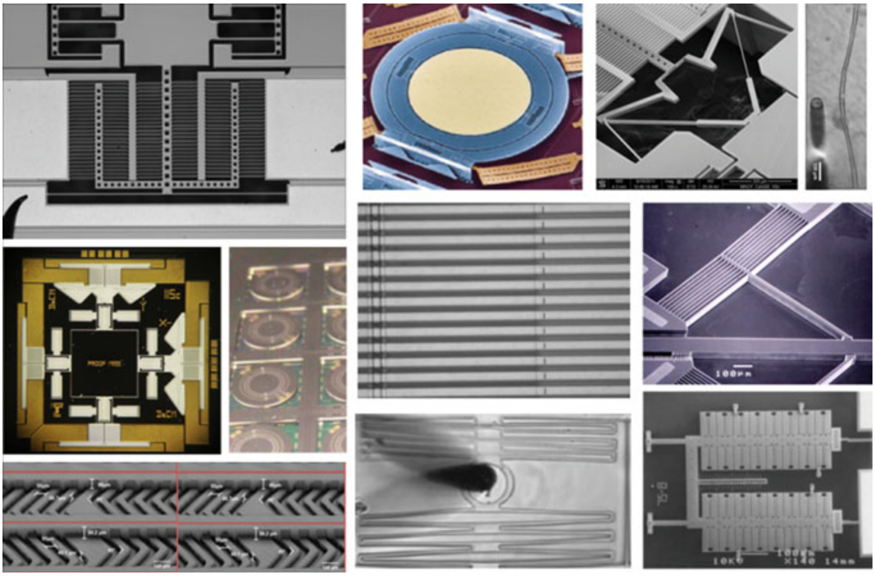


Fig. 1 A collage of a few good mechanical designs used in MEMS. Starting from top-left, and moving left to right row-wise: a folded-beam suspension and an electrostatic comb drive actuator [3], Agere two-axis tilting mirror array used in optical cross-connects [4], a Displacement-amplifying Compliant Mechanism (DaCM) that helps simultaneously increase sensitivity and bandwidth of a capacitive accelerometer [5], a two-axis in-plane accelerometer that mechanically decouples and amplified motion in *x*- and *y*-directions [6], an ultra-sensitive ring gyroscope [7], an array of flat beams in a polychromator [8], a bent-beam thermal actuator array [9], a herringbone fluidic mixture [10], a cell stretcher [11], and an array of heatuators that enhance effective electrothermal expansion [12]

2 *Simplicity* of a Folded-Beam Suspension

Joints are essential components of any mechanical device with moving parts. MEMS field got its recognition at the inception of the field when researchers showed that hinges and sliders could be made at the micron scale with polysilicon by incorporating a sacrificial layer in microelectronic fabrication processes [13]. Electrostatic micromotors [14], which could spin about an axis perpendicular to the silicon wafer, had used cleverly-crafted revolute joints, i.e., hinges. Similarly, prismatic joints (i.e., sliders) too were realized using silicon. Sacrificial layer process was the key to those developments. Years later, Sandia laboratory made a miniature revolute joint with a seven-layered process called SUMMiT [15], Sandia Ultra-planar Multi-level MEMS Technology. The geometry of the Sandia micro-hinge can be argued to be more complex than that of a macro-scale bearing. The relative tolerances were not stringent in those miniature revolute joints even though absolute values of tolerances were only a few microns. If MEMS field limited itself to such kinematic joints that merely imitate macro-scale joints, the field would not have attained the sophistication we see today. The key was simplicity offered by compliant design [16].

In *compliant design*, elastic deformation is utilized instead of kinematic joints such as hinges and sliders, to achieve relative motion. A compliant hinge can be as simple as a short beam segment or a narrow flexure that enables a body attached to it to rotate about a point. But this has three drawbacks: (i) the effective center of rotation keeps shifting during the rotation; (ii) the range of motion is limited because of stress in a deforming body; and (iii) there is inevitable resistance to motion because some effort is needed to deform a body. So, a compliant hinge cannot come close to a revolute joint in terms of functionality and performance. The situation is better with a compliant slider.

A kinematic sliding joint needs a guideway in which a block moves to provide relative translation. Such a moving block has zero resistance, barring friction, in the direction of translation; it has infinite resistance in all other directions, namely, two other translational directions and all three rotational directions. Resistance in a compliant slider is due to elastic stiffness. Therefore, a compliant slider should have as low a stiffness as possible in the intended translating direction and as high a stiffness as possible in all other directions. A pair of beams achieves that to some extent as can be seen in Fig. 2a.

Note that a cantilever beam has high stiffness in the axial direction and low stiffness in the transverse directions. So, we can use a beam to translate a body. But a block attached at the free tip of a single cantilever beam would rotate. On the other hand, a block attached to a pair of beams does not rotate much. So, it becomes a compliant slider. But then, we notice in Fig. 2a that the moving block experiences slight motion in the direction perpendicular to the intended translatory motion. This is avoided by using a folded-beam suspension [17] shown in Fig. 2b. The transverse motion of one pair of beams is perfectly compensated by that of another pair because of the folded-beam configuration. Figures 2c, d show the solid model and deformed configuration of a folded-beam suspension, respectively.

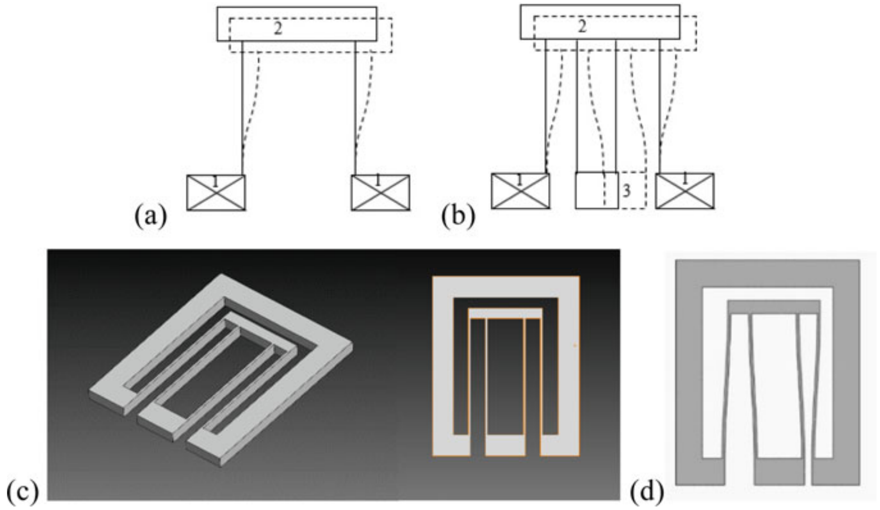


Fig. 2 The design principle of a compliant slider that uses a folded-beam suspension. **a** A parallel-beam suspension; while block 2 translates parallel to the anchored block 1, it also moves closer in the transverse direction; **b** the downward motion of block 2 is compensated by the upward motion of block 3 relative to block 2 because of the extra folded-beam pair; **c** a solid model of the folded-beam suspension in isometric and planar views; **d** the deformation of the compliant slider as obtained using finite element simulation

The folded-beam design for a compliant slider was borrowed by MEMS researchers from the precision mechanisms field that needed backlash-free precise motion not offered by kinematic joints.

A folded-beam suspension, which serves as a compliant sliding joint, has simple yet remarkable design. It enables one body to perfectly translate relative to another. The stiffness in the translating direction is much lower than that in the other directions. This is especially true when the height of the beams is larger than the in-plane width. Even more interesting is the fact that the stiffness in the translating direction is nearly constant over a long range of motion. Its range of motion is limited by the spacing of the beam when it is made in a single layer. The range can be extended when it is made of two or three layers.

In summary, the functionality of pure translation without any offset motion of a folded-beam suspension arises because of the flipping of one pair of beams. The performance parameters, such as the stiffness, maximum stress, range, etc., can be easily calculated using elementary beam theory. Finite element analysis can also be used if accurate nonlinear behavior is to be captured. The simplicity of this design enables it to be made using a single releasable layer in microfabrication. Its simplicity is also because the dimensions (length and cross section of the beams and their spacing) would not alter the characteristic behavior much. Furthermore, it uses distributed compliance [18] and thus keeping the stress low and hence increasing the range of motion. This design is commonly found in micromachined accelerometers, electrostatic comb drive actuators, and other MEMS devices.

3 *Ease of Making* of a Compliant Two-Axis Gimbal

When Micro-Opto-Electro-Mechanical Systems (MOEMS) started to emerge, researchers needed an array of tiny mirrors to reflect and steer light beams. Texas Instruments (TI) pioneered a tilting mirror, which could rotate about a single axis parallel to the silicon wafer. It used a short beam segment that twists to provide rotation. It was a simple design and served its purpose then. When it came to mirrors that needed to rotate about two orthogonal axes, more ingenuity was required. Such a need is depicted in Fig. 3. A light ray from any single input optical fiber in an input bundle needs to the directed to any fiber in an output bundle. For this, two arrays of mirrors were used by Agere Systems [4]. Each mirror was expected to tilt about two in-plane orthogonal axes. And the mirrors should almost fill the space in a plane, which means that the suspension of the mirror should be as compact as possible. The design question was this: How do we obtain a two-axis gimbal design that has a large range of rotation about both axes and one that can be compactly microfabricated in a single releasable layer? The answer can be seen in Fig. 4a–c.

A short beam of the kind used in the TI mirror does not give much rotation; it is severely limiting because the stress in a beam that twists a lot is very high. The alternative is to use bending using slender beams, which embody the concept of distributed compliance [18]. This concept is shown in Fig. 4d where a serpentine beam that is anchored at both the ends can be seen. When one end is fixed to a frame

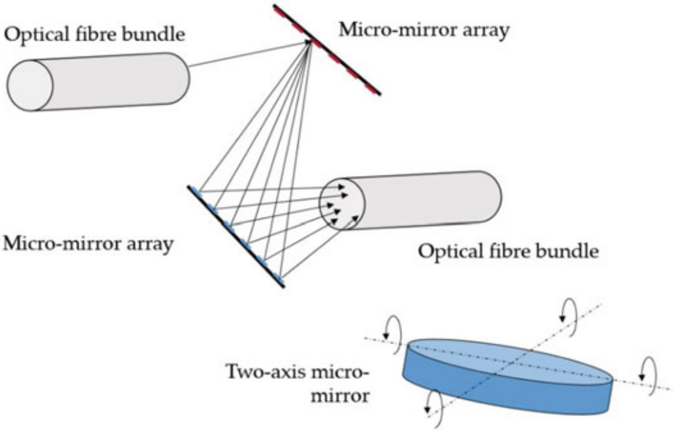


Fig. 3 The schematic of Optical Cross-Connect (OXC) developed at Agere Systems in early 2000s [4]. Each mirror in the two planar arrays should be tiltable about two axes in order to steer light from any fiber in the input bundle to any fiber in the output bundle

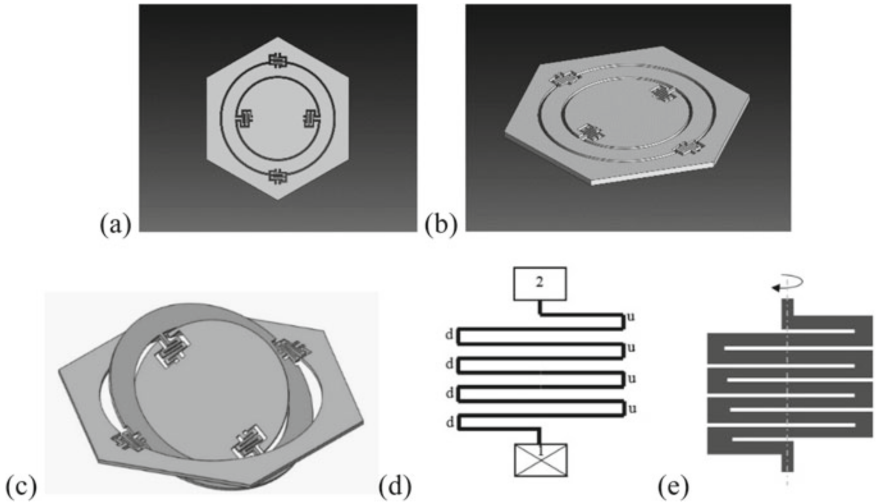


Fig. 4 A two-axis micro-mirror: **a**, **b** top and isometric views of a hexagonal block with two pairs of torsional hinges compactly arranged to give two-axis gimbal; **c** two-axis rotation of the mirror; **d** serpentine beam serving as a rotational hinge: when it twists, those marked with “u” move out of the plane and those with “d” move into the plane; and **e** a simple way to realize the serpentine beam rotational hinge using a few slits etched in a rectangle

and the other end is connected to a body that is required to rotate, the beams bend alternately up and down. This is indicated with letters “u” and “d” in Fig. 4d. When the serpentine beam *twists* by bending about the axis as shown in Fig. 4e, the beam segments marked with “u” move up and those with “d” move down. The longer beam segments deform accordingly, also up and down. A simple way to realize a serpentine beam in a single layer can be understood from Fig. 4e: We just need to etch a few narrow rectangular slits. As shown in Fig. 4a, b, such slits can be etched in a hexagon along with annular slots. The result is an amazing disk at the center with the capability to rotate about two in-plane orthogonal axes and by large angles. Once again, the distributed compliant design with bending of slender beams keeps the stress low. Furthermore, the rotational stiffness of the rotary joint in this design is quite low. The range of rotation and the rotational stiffness is limited by the microfabrication process. If lithography permits 1-μm-wide slits, many beams can be incorporated into the serpentine beam of a given size. However, even with a 5-μm-wide slit, substantial range of rotation with sufficiently low stiffness is possible with this design. Thus, ease of manufacture is a remarkable trait of this design that gives a rather complex functionality. This design is so simple and elegant that its ingenuity can be appreciated only if one contemplates alternative designs that surpass this.

4 *Generality* of an Electrostatic Comb Drive Actuator

Electrostatic force is a fundamental force. It exists between any pair of conductors that hold electric charge. It is also a large force as compared to another fundamental force, the gravitational pull. The magnitude of electrostatic force is large enough to cause sizeable motion at the micro-scale. It is inversely proportional to the gap between the conductors and directly proportional to the area of the conductor-surface patches that face each other. This is best understood when we consider two parallel plates shown in Fig. 5a.

When two parallel plates of overlapping area, $w \times l = wl$, of surfaces that face each other, are separated by a gap, g_0, and with a potential difference, V, the force in the gap direction between them is given by $\frac{\varepsilon_0 w l V^2}{2g_0^2}$, where ε_0 is the permittivity of free space. When the two plates come together with a reduced gap (Fig. 5b), the force increases a lot because of the inverse-square relationship. When the two plates displace along the width direction (Fig. 5c) or the length direction (Fig. 5d), the force is approximately constant. The force in the width direction is given by $\frac{\varepsilon_0 l V^2}{2g_0}$ and that in the length direction is $\frac{\varepsilon_0 w V^2}{2g_0}$. This simple principle is used for conceiving the comb drive actuator. Incidentally, if we use capacitance which has a similar relationship, it becomes the principle of a capacitive sensor.

The electrostatic comb drive uses the parallel-plate capacitor displaced in the length direction (Fig. 5d). As per the formula for the force, $\frac{\varepsilon_0 w V^2}{2g_0}$ is large when the gap is small. The gap is decided by the lithography limit of the microfabrication process used. If the process does not allow a small gap, a way to get around this problem is to use many pairs of parallel plates. This leads to the comb drive actuator shown in Fig. 6.

A comb in the comb drive actuator has many fingers. There are two combs, one is an anchored comb and another a moving comb. In Fig. 6, we see two anchored combs and two moving combs. The moving combs are attached to a shuttle mass. It is called a shuttle mass because it shuttles between two extremes limited by the suspension. The suspension here is the folded-beam suspension that acts like a compliant slider.

The electrostatic force between the moving shuttle mass and the fixed comb can be enhanced by packing many fingers into a given space. As said earlier, the narrower the gap between the fingers, the more the force. The range of displacement is limited by that of the compliant slider. It can be seen that the force of the comb drive actuator

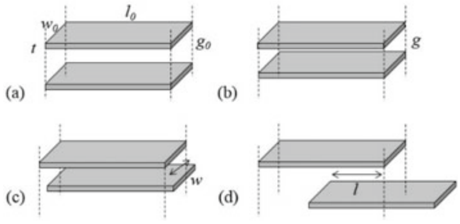


Fig. 5 Parallel-plate capacitor. **a** complete overlap in width and length separated by a gap; **b** reduced gap; **c** reduced width of overlapping surface; **d** reduced length of overlapping surface

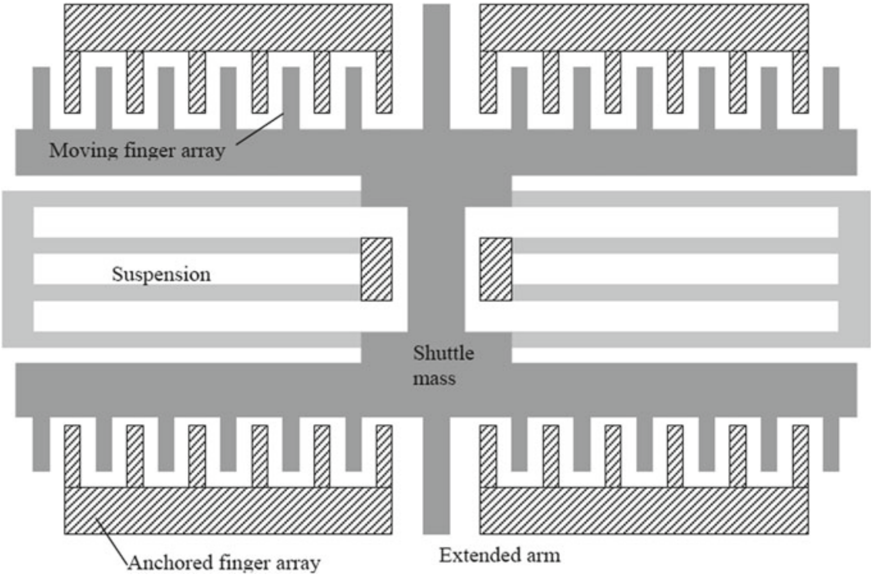


Fig. 6 Schematic of an electrostatic comb drive actuator. The hatched regions are anchored to the substrate, while the shaded regions are suspended above the substrate. The lighter shaded region indicates the folded-beam suspension. The moving comb fingers are attached to the shuttle mass that moves with the help of a compliant slider (i.e., the folded-beam suspension)

has to overcome the force required to deform the folded-beam suspension. So, the available output force tapers off with the stroke of the actuator. Most often, the force of a comb drive actuator is just sufficient to move the shuttle mass. So, it is useful in sensor applications (e.g., resonant sensors that need a mass to move back and forth). It is indeed a *prime mover* for microsensors and some micromechanisms. Sandia National Laboratories used a pair of comb drive actuators to turn a wheel continuously (not unlike a piston-crank mechanism) and called it a *microengine* [19].

Even though the force of a pair of fingers does not vary with their relative displacement in the length direction (to first order as the formula cited earlier neglects the fringing fields), the force is not constant due to the folded-beam suspension. This can be overcome by shaping the fingers. That is, one can vary the gap nonlinearly to increase the force with the displacement in the length direction [20]. However, this is not common because rarely MEMS applications need a constant force over a large distance.

As can be discerned from Fig. 6, the comb drive actuator needs a single releasable layer, which most microfabrication processes can provide. A small complication arises if the bond pads within the device are not possible (e.g., SOIMUMPs [21]). In such a case, the folded-beam suspension can be turned inside out to move the bond pads out to the periphery of the device.

The design of a comb drive actuator is simple, and it is easy to microfabricate. There is another feature in it that makes it general. Myosin motor, which is the fundamental building block for skeletal muscles, has the same interdigitated design [22]. The thick and thin myosin filaments have an arrangement similar to the comb drive design. It is hard to say, however, that myosin filaments inspired the comb drive. Nevertheless, the comb drive actuator is a general feature of many MEMS devices. It is the most widely used actuator in MEMS. This design is here to stay.

5 The *"Wow" Factor* of a Polychromator-Beam Mechanism

Sometimes a brilliant idea calls for a new design, and another brilliant idea is needed for practical realization of that design. An example of this is a polychromator [23], a MEMS device that is a miniaturized version of a correlation absorption spectrometer to identify a substance from a distance. The brilliant idea was to use diffraction of light to generate light of any wavelength from broadband white light, for the reference spectrum, using an array of long beams suspended above the substrate. The idea is illustrated in Fig. 7. Imagine a grating cell composed of an array of beams separated from one another in the top view and set at different heights above the substrate. If the gap between the beams and the substrate is of the same dimension as the wavelength of light, the gaps can be adjusted by applying electrostatic force using individually addressable drive electrodes. Then, the light rays reflecting from the top surfaces of the beams and the substrate underneath diffract to give out light of a particular wavelength. Different patterns of gaps give out diffracted light of desired spectral content.

The design question then is: How do we make the beams move up and down continuously for achieving any gap without distorting the beam? Since it is an optical

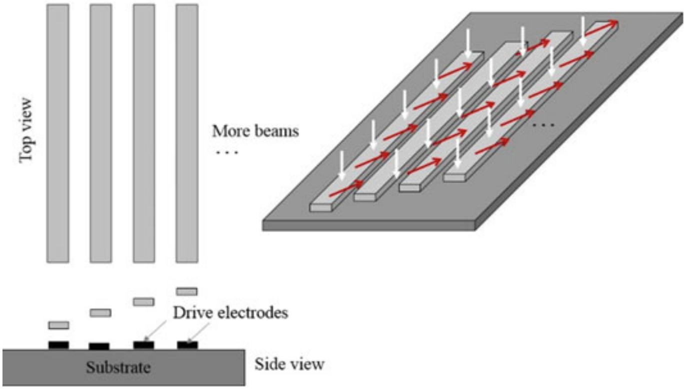


Fig. 7 An array of diffracting beams that can generate diffracted light of desired spectral content by adjusting the vertical gaps between beams and the substrate

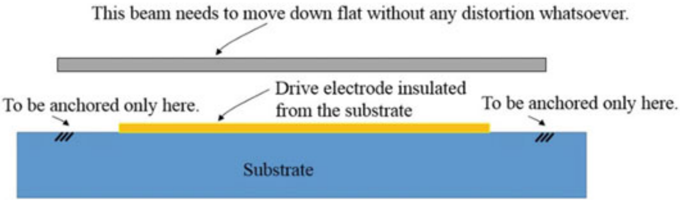


Fig. 8 An unusual requirement of an electrostatically actuated beam: How should the beam at the top be anchored to the substrate at the two points so that it moves down without bending, under the influence of the electrostatic force from the drive electrode?

application, the beam should not deform at all. But then, as in any microfabrication using photolithography, the beam has to be anchored to the substrate. The driving electrode ought to be underneath to pull the beam down. This situation is shown in Fig. 8. Those who know about elastic deformation of beams know that when a beam is anchored at the ends, it will deform. But here, we want the beam to not deform but still move down in the transverse direction. Much creative thinking is necessary to solve this unusual design problem. A reader is urged to spend at least 15 min before looking at the solution.

An ingenious solution to the problem posed in Fig. 8 was reported in [8]. As shown in Fig. 9, it uses a two-layered structure sandwiching a sacrificial layer. This design uses the well-known fact that a fixed–fixed beam under symmetric transverse load deforms with zero slope at the midpoint. Therefore, by attaching a short segment at the midpoint to the top beam, we get its downward motion without any bending whatsoever. This basic idea is further extended by concatenating two beams so that any tilting or vibration is also avoided. This is shown in Fig. 10, which shows a two-segment design in undeformed and deformed configurations. Figure 11 illustrates how an array of such designs can be realized to form a grating element, wherein each beam can be set at a different height, as desired by the intended wavelength of light.

The simple and elegant design of a polychromator serves its function really well. It maintains bending-free transverse motion of a long beam. It is the kind of a design that might occur quickly to a creative person in a flash or perhaps might occur (or not) to anyone after much thought. In any case, when we see it, we get the "wow" feeling. If it does not appear as an amazing design to a particular reader, he/she

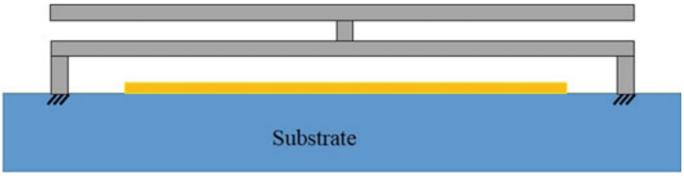


Fig. 9 An ingenious design that makes a long beam move down without bending when actuated from underneath and anchored at either end with an intermediate beam

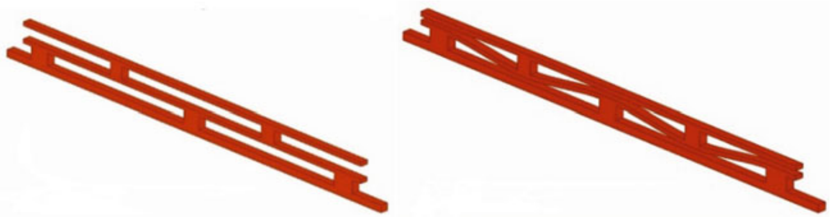
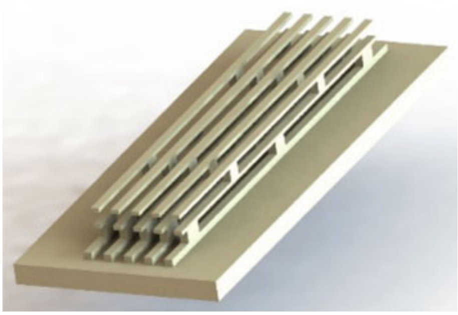


Fig. 10 A two-segment version of the design in Fig. 9 to make a longer beam stay flat. Undeformed and deformed configurations are shown

Fig. 11 A diffracting cell using an array of beams used in a polychromator



should contemplate a similar design in Sect. 7 wherein it is wrapped around a circle for even more amazing functionality.

6 *Optimality* of a Displacement-Amplifying Compliant Mechanism

The design discussed in the preceding section was most likely intuitively conceived. It was a remarkable example of human ingenuity. Those who use optimization techniques or those who develop them tend to think that algorithms too can give rise to clever designs. Designs generated by optimization algorithms can be counterintuitive. They are often beyond the grasp of human creativity. Thus, designs obtained using optimization algorithms are sometimes superior. Additionally, they are also optimal for the conditions set in formulating the optimization problem unlike intuitive designs that could be further tweaked and optimized. We illustrate this using an amplifying mechanism.

A lever, immortalized by Aristotle, comes to mind when we think of a mechanical amplifier. When a pin joint (i.e., a revolute joint) is not practically viable (as is the case with microfabrication), a simple lever is not a preferred choice. A flexure that replaces a pin joint is also not a good choice because of high stress and limited range of rotation. Furthermore, for large amplification ratio of output and input displacements, a lever needs a large space. The question, therefore, is how one can design a displacement-amplifying mechanism in a given compact space. A solution for this, given by a topology optimization algorithm [24], is shown in Fig. 12a. The squares in the top-left and top-right corners are anchors. When a force is applied vertically up on the flat segment at the bottom, the point in the middle of the top part of the compliant mechanism moves down by a large amount. This can be understood from Fig. 12b. First, the motion of this mechanism is counterintuitive: when we push a point up, another point of the mechanism comes down. Second, this design was optimal in the sense that algorithm that generated this satisfied the conditions of optimality set for it. Third, it is often difficult to argue which part of the mechanism or which beam segment is contributing to the amplifying behavior of this compliant mechanism.

Another Displacement-amplifying Compliant Mechanism (DaCM) is shown in Fig. 13. It is also obtained using a systematic design method and an optimization algorithm [6, 25], but it is more intuitive than the one shown in Fig. 12 but one that a human designer might not be able to conceive easily. Such mechanisms are

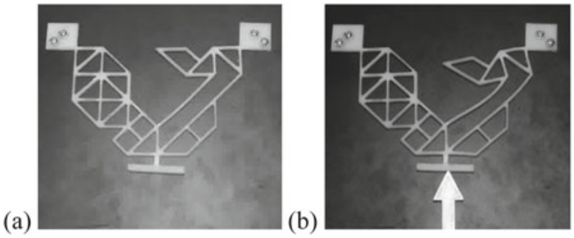


Fig. 12 A displacement-amplifying compliant mechanism designed using a topology optimization algorithm. **a** Undeformed, **b** deformed

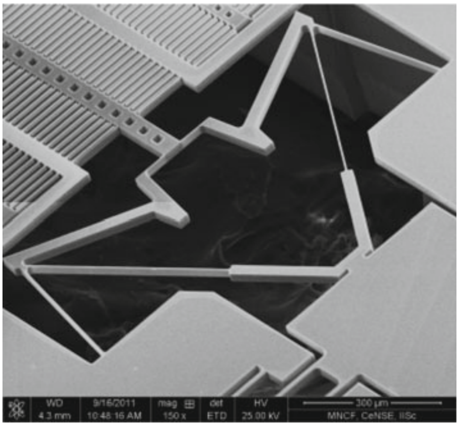
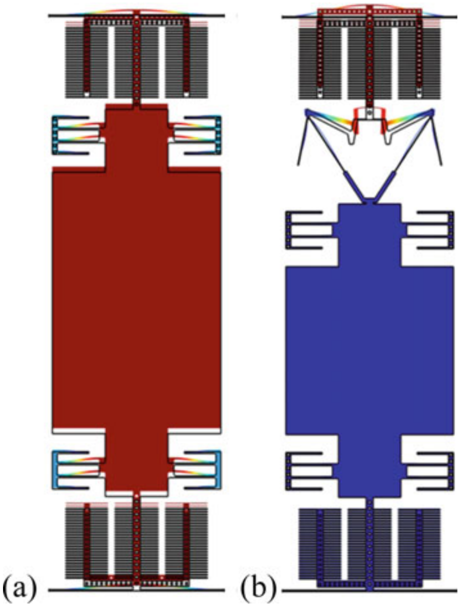


Fig. 13 A displacement-amplifying compliant mechanism microfabricated with silicon [26]

Fig. 14 Two designs of a micromachined accelerometer **a** without a DaCM, and **b** with a DaCM



designed with a purpose because an optimization problem with an objective function and some constraints would have been formulated. The purpose of the DaCM shown in Fig. 12 is shown in Fig. 14. Figure 14a, b shows the simulation of two capacitive micromachined accelerometers [6].

In Fig. 14a, one can see the familiar components of an accelerometer. It has a proof mass held by a compliant slider mechanism on the top and bottom. There are also electrostatic comb drives for the purpose of estimating the displacement of the proof mass indirectly through capacitance measurement. The design in Fig. 14b occupies the same footprint. For the same applied acceleration, the sensing combs at the top in Fig. 14b have larger displacement than that in Fig. 14a. This is because of the DaCM in the latter. Here, it can be seen that even with a smaller proof mass, we get larger displacement. It was also shown in [6] that the resonance frequency of the design with the DaCM is larger than that of the one without it.

Optimal designs, such as the DaCM just discussed, too have multiple uses as do intuitively conceived designs. Generality is indeed a common trait of good designs. The DaCM used in an accelerometer was also used in a micro-newton force sensor [26]. In this, the force applied at the input point of the DaCM results in amplified displacement at the output point. With optical measurement of the output displacement using a digital microscope, a DaCM becomes a force sensor. It is illustrated in Fig. 15. Thus, if a design is indeed optimal for a specific purpose (here, amplification of displacement) and could be used for other purposes, it falls into the category of good designs.

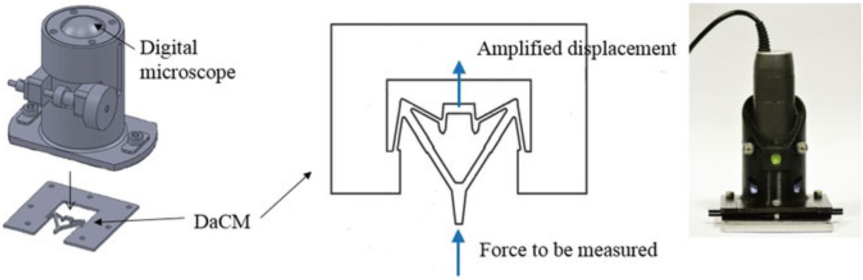


Fig. 15 A micro-newton force sensor using a DaCM and a digital microscope [26] and its product version (bendflex.in)

7 *Economy* of Material and Manufacturing

Benefits of minimalism are well known. It rings true for structural design as embodied in the adage: *the more you think, the less material you need*. Sometimes it also means *the less material you cut*. Serving a function well with a design that occupies a small footprint and minimal manufacturing effort is a goal in MEMS devices because the "real estate value" on a wafer is very high. And there are such MEMS designs that use almost all the material in a compact footprint and serve a useful function.

Shown in Fig. 16a is a rectangular layer patterned with a few slits indicated in white lines. What is left with these slits is a highly flexible spring. The width of the slit can be as small as a microfabrication process allows. The narrower the slit, the more flexible the spring is. This is because what we see here is an array of springs in series wherein each spring is a pair of two fixed-guided beams forming a rectangular box. It is indeed economical use of material and manufacture. Such a stack of springs has many uses.

Figure 16b shows two such springs (white and gray colors interchanged from Fig. 16a with white representing beams here) with a central ring. If the central ring is moved to one side, one spring expands and the other contracts. This structure was used as a cell stretcher [27]. As illustrated in Fig. 17a, b, when biological cells

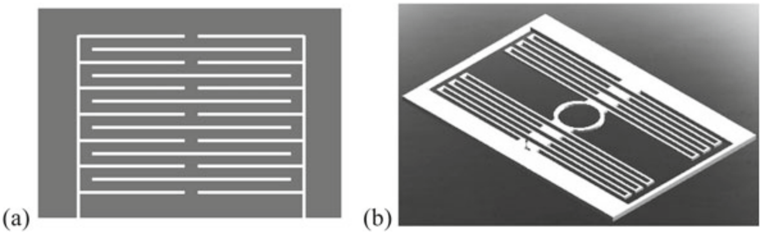


Fig. 16 An example of economy material and manufacture: **a** a very flexible spring is realized by cutting out a few slits (white lines); **b** a stack of two such springs on either side of the central ring

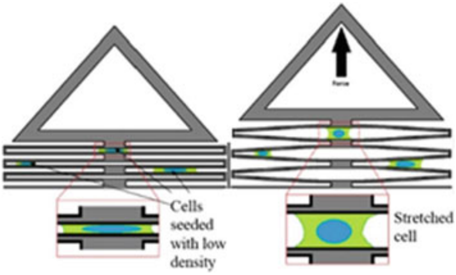


Fig. 17 A single-axis cell stretcher in unstretched and stretched configurations (adapted from [27]) using the spring shown in Fig. 16

are seeded on a patterned polymer layer, SU-8, in particular, cells are stretched by applying a force to stretch the spring. In fact, the stiffness of the spring is so low that cells themselves would stretch the spring, paving the way to measure forces applied by the cells [27].

There is another significant use for this kind of a spring. To see that, let us recall the concept of a micromachined ring gyroscope [28]. In a ring gyroscope, a ring is connected to a central post with spokes. In [28], semicircular spokes were used, see Fig. 18a. The ring is set into resonant motion by applying electrostatic force around it by using one set of electrodes on the periphery. The resonant mode shapes are two ellipses, as shown in Fig. 18b, c. The ring has degenerate mode shapes, which are inclined at 45° to each other. When the substrate to which the central post is attached rotates, then the ring starts to vibrate in the second elliptical mode shape. This motion is capacitively measured by the second set of electrodes on the periphery. This design, although worked well, could not compete with the resolution of the macromachined hemispherical-shell gyroscopes. One of the reasons for this is that the spokes connecting the ring to the central post distort the mode shapes. The second reason is that the actuation force and the change in capacitance were low.

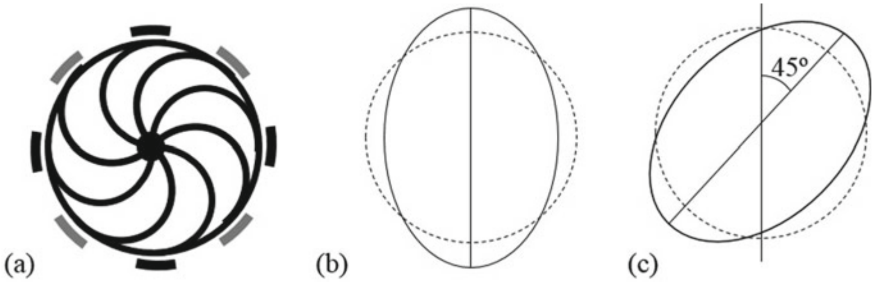


Fig. 18 Ring gyroscope concept. **a** A ring gyroscope with semicircular spokes attached to the central anchor with two sets of arc-shaped electrodes around, one to actuate the ring electrostatically and another to sense the change in capacitance as the ring deforms; **b** the first degenerate mode shape; and **c** the second degenerate mode shape

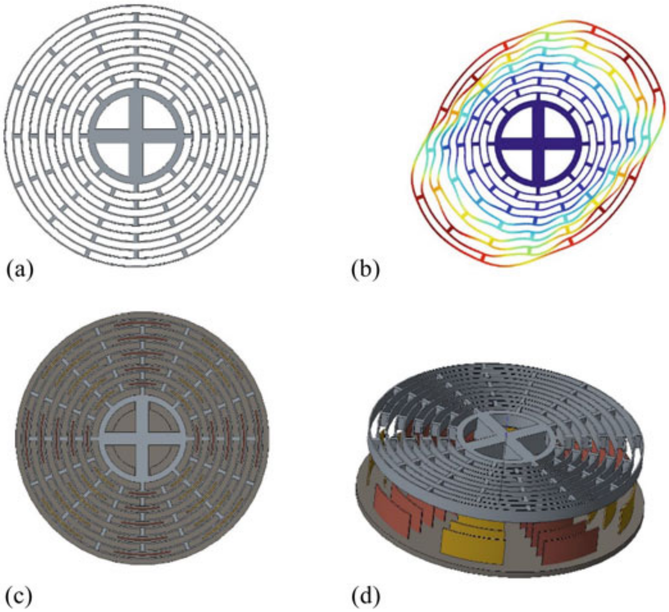


Fig. 19 A multi-concentric ring gyroscope that combines the features of polychromator design in Fig. 10 and the compactness of the very flexible spring of Fig. 16a. It also embodies the principle of the ring gyroscope shown in Fig. 18 in terms of placing the electrodes in two groups, but with more concentric electrodes for resonance actuation and capacitive sensing

These two limitations were overcome to a large extent with a clever and economical design [7], as explained next.

Figure 19a shows concentric rings where adjacent ones are connected to each other in a staggered manner. Compare this with the designs in Figs. 10 and 16a. The design in Fig. 19a inherits the features of these two designs. Consequently, the stiffness of the concentric ring structure is made low, and the distortion at the midpoints of the arc beams is reduced (see Fig. 19b). In Fig. 19c, d, the electrodes for actuation and sensing are shown in top view and isometric views. This design of the micromachined gyroscope achieved resolution better than 0.01 °/h [29]. It is a great example of economical use of material with minimum etching of material resulting in superior performance.

8 *Ubiquity* of Electrothermal Microactuators

Electrostatic actuators, comb drive actuator being the prime example, are widely used in many MEMS sensors. But the force they generate is rather small—barely moving themselves and only occasionally moving something else. Electromagnet-based and electrothermal actuators, on the other hand, can generate much larger force.

Between these two, it is easier to design electrothermal actuators and much simpler to fabricate. They are increasingly used in MEMS devices where force is needed to move components other than themselves. The force can be an order of magnitude larger than that generated by electrostatic force. Hence, they are preferred actuators when large force is needed, and high speed of actuation is not very important. Common among them are two building blocks: bent-beam electrothermal actuator [9] and heatuator [29]. These two designs are ubiquitous in electrothermal actuators.

The extreme simplicity of a bent-beam actuator is apparent from Fig. 20a. It is simply a fixed–fixed beam with a slight kink—it is essentially a wide V-shaped beam. There are anchors, which also serve as bond pads for voltage application, at either end. As shown in Fig. 20a, upon application of a voltage difference between the two anchors, current flows through the bent beam. Consequently, Joule heating ensues. Heated beam expands. Since it is anchored at both the ends, it has no other way than push itself in the transverse direction. This is the basic principle of a bent-beam electrothermal actuator. The 3D view of a bent-beam actuator is shown in Fig. 20b. Just so that the beam does not move much in the out-of-plane direction, it is important to make it taller. Large thickness makes it strong as the area of cross section is large. Since the beam has to be sufficiently narrow in the in-plane direction in order to bend, height should be large.

A single bent-beam actuator cannot generate much force, but an array of them can. This is shown in Fig. 21. In such an array, individual bent-beam actuators are in parallel arrangement and hence their forces add up. This is also an example of economy of material and manufacture because very little space is left empty in the rectangular block. A microfabricated bent-beam actuator array is shown in Fig. 22.

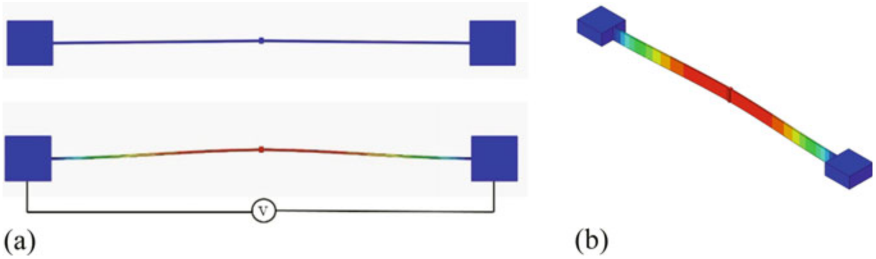


Fig. 20 A bent-beam electrothermal actuator: **a** in unactuated and actuated states; **b** 3D rendering of the same

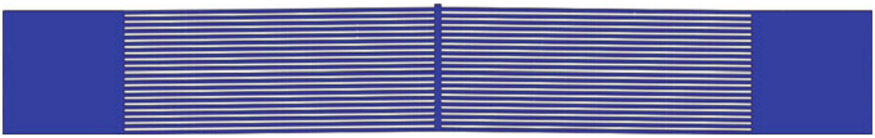


Fig. 21 An array of bent-beam actuators that adds up the force

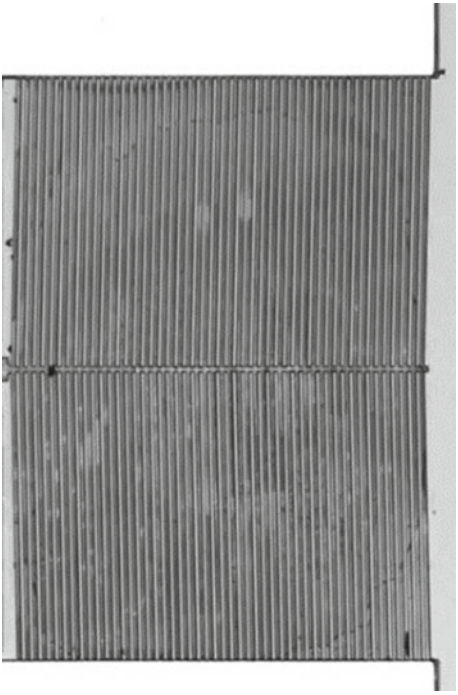


Fig. 22 A microfabricated array of bent-beam electrothermal actuators; the material is single-crystal silicon

The second building block of electrothermal actuators is called a *heatuator*, a portmanteau of heat and actuator [29]. Two versions of it are shown in Fig. 23 on the left and right sides. Both are ingenious designs. The one on the left side is the original heatuator conceived by Henry Guckel and his team [29]. It is a folded beam with one half much wider than the other. Two beams in the fold are connected with a short segment, and the other ends of the narrow and wide beams are anchored to bond pads. When a voltage difference is applied between the two anchor pads, current flows through the narrow and wide beams. Both heat up but the narrow beam gets hotter as the current density is higher in it. Consequently, it expands more than the wide beam. In order to achieve equilibrium under the ensuring thermal loads, the folded beam bends up as shown in the figure on the left side of Fig. 23. The principle of this actuator is similar to that of a bimorph [30] but there is a clever twist: a bimorph needs two materials with dissimilar coefficient of thermal expansion but here it is made of a single material. The disparity in the cross-sectional area is utilized here. Like the bent-beam actuator, it is also easy to realize in microfabrication as it needs a single releasable layer.

The figures on the right side of Fig. 23 show a variant of the original heatuator. Here, the wide and narrow beams are arranged electrically in parallel [12]. Therefore, the current flowing through them is different. The wide beam has more current than

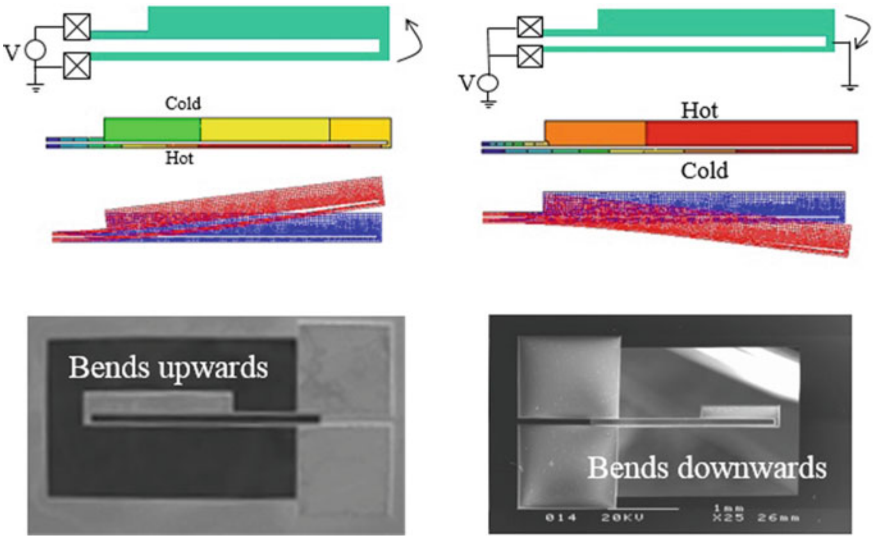


Fig. 23 Heatuators in series (left column) and parallel (right column) electrical connection

the narrow beam because the former has less electrical resistance than the latter. Therefore, now the wide beam gets hotter than the narrow beam. Of course, the length and cross-sectional areas have to be chosen suitably so that overall heating in the wide beam is more than that in the narrow beam. With the wide beam expanding more than the narrow beam, the same folded beam now bends downward as shown in the right-hand side of Fig. 23. As we will see later, there are many uses of this parallel electrical connection. But first, we should take note of the fact that both series and parallel versions have the same mechanical construction and that there is a short flexure that enables the wide beam to rotate. Also to be noticed is how parallel electrical connection could be given to a heatuator in the layout of microfabricated components.

As in the bent-beam actuator, many series heatuators can be made into an array to generate large force [12]. But we can do more with the parallel heatuators. This is shown in Fig. 24. In Fig. 24a, we see an expanding actuator that has four parallel heatuators. When voltage is applied between its two anchor pads at the bottom, they remain stationary but the movable pad at the top moves upward. Notice how the wide and narrow beams are arranged in order to achieve the upward or expanding motion, which can be seen in Fig. 24b. On the other hand, the narrow and wide beams are switched, and the heatuators on either side are kept at an angle, as shown in Fig. 24c. Now, we see a contracting actuator as can be discerned from Fig. 24d. The possibilities for design are almost unlimited with electrothermal actuation. It paves the way for topology optimization involving multiphysics simulation [31–33]. Analysis of electrothermal actuators is challenging because three simulations—electrical, thermal, and elastic—are to be performed in a sequence. Conduction,

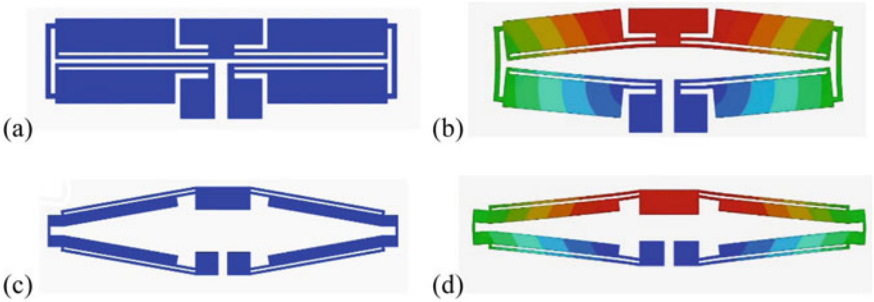
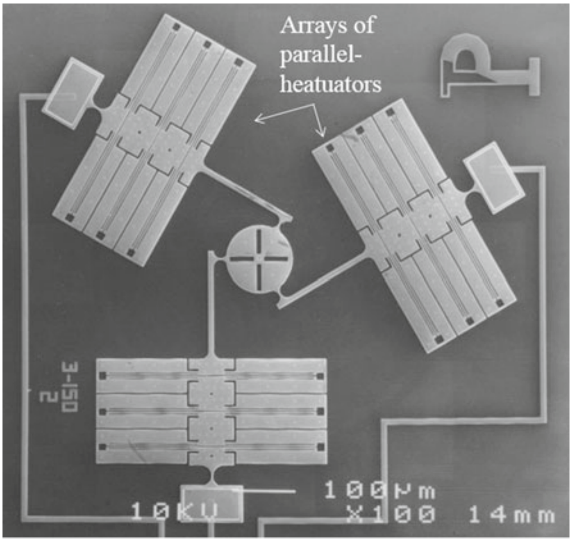


Fig. 24 Four parallel-connection heatuators forming expansion building block (top row) and contraction building blocks (bottom row)

convection, and radiation effects as well as temperature-dependent properties are to be accounted for in simulation and design [34]. Both intuition and systematic optimizations can lead to interesting designs. Shown in Fig. 25 is a planar robotic platform that uses three arrays of expanding parallel heatuators.

The bent-beam actuator and heatuator building blocks are used in arrays or in special arrangements. We see them in many actuators that use electrothermal principle. They are thus ubiquitous—the same principle used in many places.

Fig. 25 A microfabricated planar platform actuated with electrothermal expansion building blocks (adapted from [12]): by applying different voltages at the three anchor pads, the central problem can be positioned in the plane. The orientation is not independently controlled here as there are only two independent voltage differences among the three pads



9 *Modularity* in a Compliant xy-Stage

Many designs illustrated so far have modular construction: a building block repeated in different ways in a specific arrangement to serve a function that is beyond what the building block does. The two-axis gimbal mechanism, comb drive actuator, polychromator, cell stretcher, concentric ring gyroscope, bent-beam actuator, and expanding and contracting heatuator blocks—all of them used building blocks. Modularity is thus a feature of a good design. It makes design and fabrication easy. The modules need not be identical. Even when they are identical, their interesting arrangements can lead to novel functionality. We illustrate novel arrangements of identical and non-identical building blocks, in this section.

Consider the compliant slider (or, the folded-beam suspension) once again. The slider and its schematic are shown in Fig. 26a, b. Shown in Fig. 26c is an arrangement of eight sliding joints connected in a specific arrangement to give the platform at the center two translational degrees of freedom. The platform of this kind cannot rotate. It is an *xy*-stage. By examining the motion of the platform in the *x*- and *y*-directions, one at a time, it can be seen that there is perfect decoupling of the two translatory motions in the plane. That is, when the platform moves in the *x*-direction, four sliders oriented in the *x*-direction move without disturbing the other four. The same is true

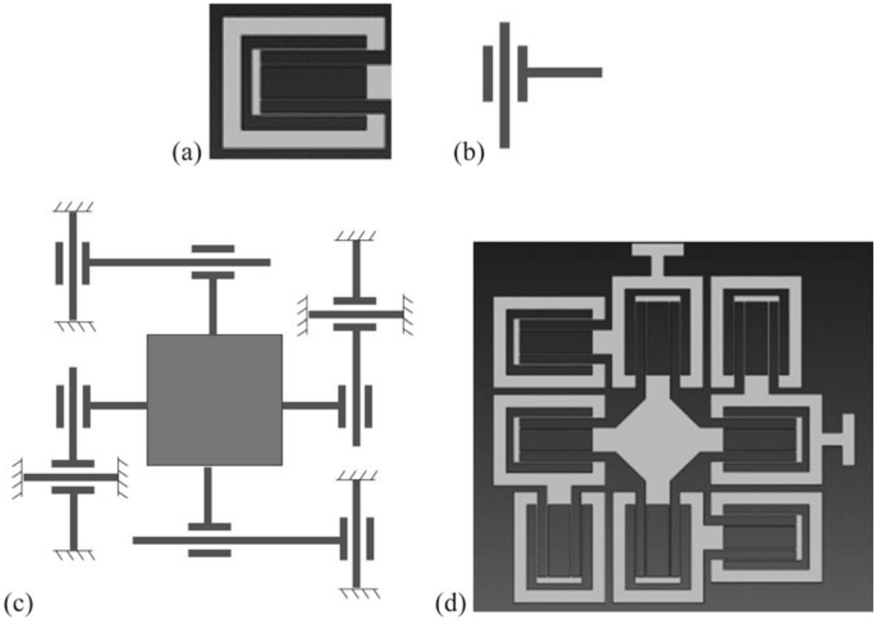


Fig. 26 A single-layer compliant stage with independent motion in *x*- and *y*-directions: **a** a compliant slider; **b** schematic of a compliant slider as a sliding joint; **c** an arrangement that illustrated how independent in *x*- and *y*-movements can be conceived; and **d** compliant version of the scheme in **c**

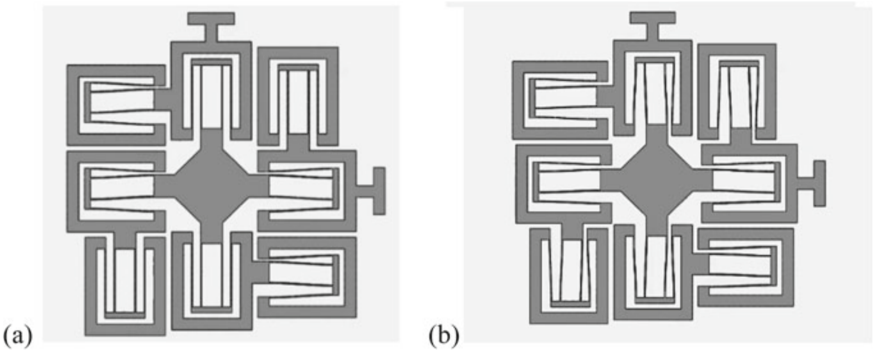


Fig. 27 **a** Movement of the compliant xy-stage of Fig. 26d in the *y*-direction; notice that only four compliant sliders are deforming; **b** movement in *x*- and *y*-directions

for the motion in the *y*-direction. Now, consider the equivalent compliant mechanism where the eight sliding joints are replaced with compliant sliders, as shown in Fig. 26d [35]. Perfect decoupling is preserved in this conversion. This is thus a single-piece compliant mechanism that can be made in a single layer—a feature that makes it perfect for MEMS.

When the central platform in Fig. 26d is moved in the *y*-direction, only four sliders oriented in the *y*-direction deform as shown in Fig. 27a. Notice that there is no motion of the platform in the *x*-direction. Likewise, there is no motion in the *y*-direction for the T-shaped extension on the right-hand side of the mechanism. When the platform is moved in *x*- and *y*-directions simultaneously, the T-shaped extension at the top undergoes only the *y*-motion and that on the right only the *x*-motion. Thus, decoupling of the central platform can be clearly discerned in Fig. 27b. If we think of the combined motion of the platform in *x*- and *y*-directions as a combined signal, this mechanism can split that into two separate signals. Thus, it is mechanical signal amplifier. So, we see how a building block can be cleverly used to achieve a unique functionality.

Figures 28a, b show another arrangement comprising 12 compliant sliders and 12 DaCMs separated equally in two layers stacked one above the other. This *xy*-stage enhances the motion of the central platform when the rectangular extensions on the four sides are actuated [36]. This is because of the DaCMs. As compared to Fig. 26d, we need 12 building blocks here to achieve decoupling of the two axes and amplification along both the axes. This two-layered design can be used as an *xy*-stage with enhanced range of motion without sacrificing the dynamic characteristics. This is an example of two different kinds of building blocks used to create a unique new arrangement.

The design in Fig. 28 is a two-layered structure. Therefore, it is not easily amenable for microfabrication. A variant of this was used in [6] to make a single-layered mechanism without losing much in terms of functionality. Figure 29 shows such a design. It is a dual-axis, in-plane, capacitive accelerometer that has enhanced sensitivity

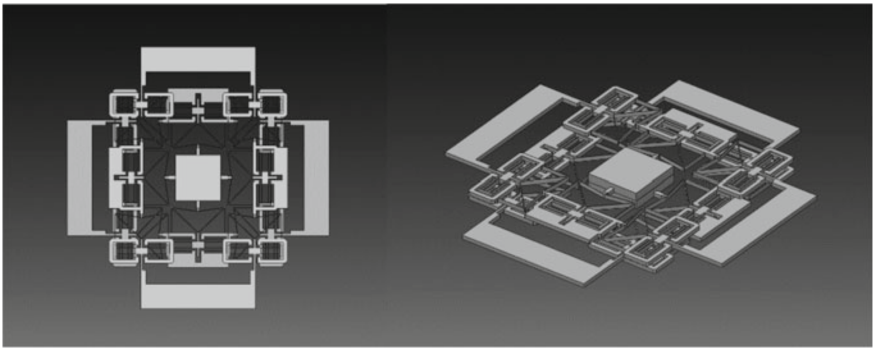


Fig. 28 Two-layered design of a compliant stage with DaCMs and compliant sliders. This design has decoupled as well as amplified motion of the stage in *x*- and *y*-directions

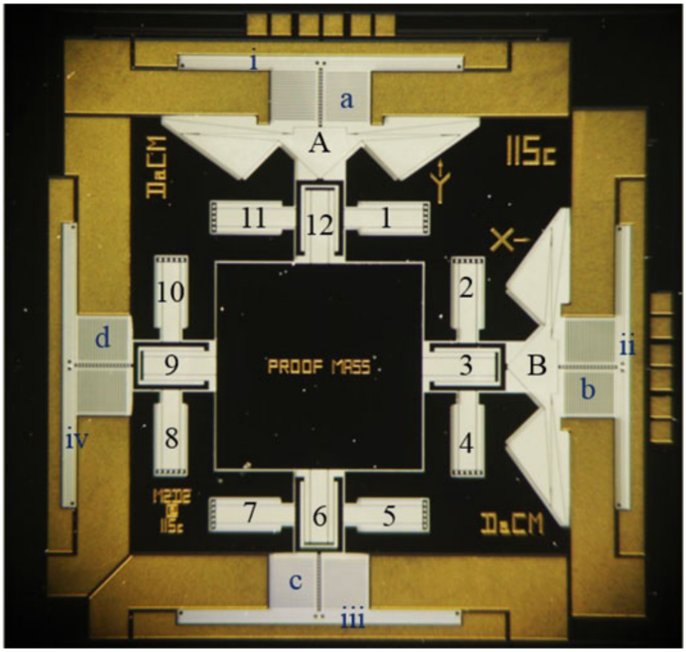


Fig. 29 A single-layer planar design of Fig. 28 with 12 compliant sliders, four compliant sliders, and two DaCMs. Here, the movement of the proof mass is amplified at the output points of DaCMs to enhance the sensitivity and bandwidth of the accelerometer

because of DaCMs. It does not use 12 DaCMs; it uses only two. To compensate for off-axis motion, it uses additional compliant sliders. As can be seen in Fig. 29, it has 12 compliant sliders of one kind (marked 1 to 12), four compliant sliders of another kind (marked i to iv), two DaCMs (marked A and B), and four electrostatic comb drives (marked a to d). Thus, it is modular design with four kinds of building blocks. Two DaCMs amplify the motion of the proof mass at the center. The purpose of 12 compliant sliders is to decouple the movements of the proof mass in x- and y-directions and transmit that to two sensing combs (a and b) though two DaCMs. Four more compliant sliders prevent the motion of the sensing combs in unintended directions. The other two combs (c and d) are used for self-test through actuation. Once we see the intent of each building block, the function of the entire device becomes clear and the interoperability of this modular design becomes clearer. It also makes it easy to arrive at the parameters of all the building blocks.

10 *Hierarchy* in Flow Paths and Solid Structures

What holds true at one size scale might change slightly or a lot at another size scale. Scaling arguments are popular in MEMS and nanotechnology [36, 37]. That line effects (e.g., surface tension) and surface effects (e.g., heat exchange) dominate over volume effects (e.g., inertia) at micro- and nano-scales is well known. Quantitatively speaking, length is the largest at the small scales as compared to area, and area looks larger than volume. This reversal of sequence as compared to the macro-size brings in interesting consequences in many physical and chemical phenomena [38]. There is much more to size effects within a given MEMS device. That has to do with hierarchy in a design.

Hierarchical design is most evident in Nature. The circulation paths of blood flow comprise a prime example. From the big aorta, the arteries multifurcate into small vessels and end up in small capillaries, only to unite later to veins and then vena cava. It is a tree structure. A big flow path divides into small, and then smaller flow paths. They combine in reverse. Andrian Bejan calls it *constructal law* [39]. A tree is another example. From the trunk up, branches emerge and then divide into sub-branches and twigs and then to leaves. Trunk down, the root system too has this hierarchy. For flowing from one source point to multiple points with least resistance requires a hierarchical tree structure [40]. Such a design also helps in mixing because microflows are known to have extremely low Reynolds number and hence are hard to mix otherwise. As we go down a tree structure, the cross-sectional area of the flow path decreases. This has to be calculated carefully; optimization helps and also points what is optimal under what conditions [40].

Hierarchy in structural design is much older and dates back to at least Gustave Eiffel [41, 42]. Eiffel exploited structural hierarchy by making his designs optimally *porous*. That is, he used beam segments crisscrossing with another rather than using a solid piece. If we examine the Eiffel tower, we see cross-beams with smaller cross-beams inside them. It resembles fractal-like design. While Eiffel took it to three levels of hierarchy in the famous tower in Paris, Nature has exploited it up to five levels [41]. Trabecular bone is made of collagen molecules making fibrils, fibrils combining to become fiber, fibers forming lamella, and lamella leading to cancellous bone. All five size scales have their own unique design unlike Eiffel's hierarchy where the same design exists at three different size scales, albeit with reduced cross-sectional sizes like in the flow paths. Solid structures at the macro-scale are replete with hierarchical designs (e.g., bridges and towers) but MEMS structures are yet to exploit it. Nevertheless, it is a trait of good design that leads to economic and efficient use of material.

11 Prospects for MEMS Design

In the last nine sections, we elaborated on nine traits of good MEMS designs with examples. As can be seen here, good designs share one or more traits. Simple designs are easy to make. Many of them are general in the sense that they can be used in other design situations.

A few simple designs serve as building blocks so that modular structures can be conceived. The “array” principle dominates MEMS designs. Just like a single transistor is not useful in itself unless millions of them combine to give a processor chip, the MEMS field uses arrays of single or multiple elements. Many examples presented in this chapter illustrate this. This is not as widely seen in macro-mechanical systems.

It is fair to conclude that MEMS designs depended on intuition and experience at the inception of the field. Later, optimization was used to aid intuition and somewhat automate the design process. There is much more to do in optimal design. It poses challenges as most MEMS devices operate in multiple energy domains [38, 43]. Therefore, multiphysics leading to coupled partial differential equations make design a challenging task. Several examples of optimizing in multiphysical domains were reported in [2].

Enhancing the quality factor of MEMS structures is a continuing challenge and a great opportunity to come up with innovative designs. Many modes of dissipation exist. Many clever designs that minimize dissipation are reported [44, 45]. Systematic study of the phenomena and how we can gain insights into their design are exciting avenues for further research on MEMS design.

Incorporating multiple materials in a single design and finding interesting combinations is also a future prospect in MEMS. Finally, many MEMS devices are focused on sensors. Actuators and mechanisms are far fewer. While we can argue that the demand drives designs (i.e., we needed microsensors more than microactuators), good designs can create demand. Upcoming areas of micro- and nano-robotics surely will venture into actuators and mechanisms, thus giving rise to new designs. Good designs in the future might have more than nine traits that are discussed in this chapter. Many consider design as an art. And there are surely some revealing signs to spot good designs also to conceive them either intuitively or systematically.

Finally, it is important to note that a design conceived in one situation for one application could be used by others in another situation. An example is that of a continuous-membrane mirror of [46] used in [8] for an array of beams that move down without distortion, as discussed in Sect. 5. Good designs are always recognized and used even if they are obscurely buried in the literature. Sometimes, reinvention of good designs happens and that is inevitable despite the widespread availability of research publications.

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References

1. Muller, R.S. (ed.): Microelectromechanical Systems: Advanced Materials and Fabrication Methods. NMAB-483, National Academy Press (1997)
2. Ananthasuresh, G.K. (ed.): Optimal Synthesis Methods for MEMS. Kluwer Academic Publishers (2003)
3. Tang, W.C., Nguyen, T.-C., Howe, R.T.: Laterally driven polysilicon resonant microstructures. Sens. Actuators **20**(1–2), 25–32 (1989)
4. Aksyuk, V.A., Pardo, F., Bolle, C.A., Arney, S., Giles, C.R., Bishop, D.J.: Lucent Microstar micromirror array technology for large optical crossconnects. In: Proceedings of the SPIE, MOEMS and Miniaturized Systems, vol. 4178 (2000). https://doi.org/10.1117/12.396503
5. Krishnan, G., Ananthasuresh, G.K.: Evaluation and design of compliant displacement amplifying mechanisms for sensor applications. J. Mech. Des. **130**(10), 102304, 1–9 (2008)
6. Khan, S., Ananthasuresh, G.K.: Improving the sensitivity and bandwidth of in-plane capacitive micro-accelerometers using compliant mechanical amplifiers. IEEE J. Microelectromech. Syst. **23**(4), 871–887 (2014)
7. Challoner, A.D., Ge, H.H., Liu, J.Y.: Boeing disc resonator gyroscope. In: IEEE/ION Position, Location, and Navigation Symposium—PLANS 2014 (2014)
8. Hung, E.S., Senturia, S.D.: Extending the travel range of analog-tuned electrostatic actuators. J. Microelectromech. Syst. **8**(4), 497–505 (1999)
9. Que, L., Park, J.-S., Gianchandani, Y.B.: Bent-beam electrothermal actuators-part i: single beam and cascaded devices. J. Microelectromech. Syst. **10**(2), 247–254 (2001)
10. Yang, Y.-J., Liao, H.-H., Huang, K.-H., Huang, Y.-Y., Lin, C.-W., Yang, L.-J., Jaw, F.-S.: Novel designs of herringbone chaotic mixers. In: Proceedings of the 1st IEEE International Conference on Nano/Micro Engineered and Molecular Systems (2006)
11. Kollimada, S., Balakrishnan, S., Malhi, C., Raju, S.R., Suma, M.S., Das, S., Ananthasuresh, G.K.: A micromechanical device for in situ stretching single cells cultured on it. J. Micro-Bio Robot. **13**, 27–37 (2018)
12. Moulton, T., Ananthasuresh, G.K.: Design and manufacture of electro-thermal-compliant micro devices. Sens. Actuators Phys. **90**, 38–48 (2001)
13. Fan, L.-S., Tai, Y.-C., Muller, R.S.: Intergrated movable micromechanical structures for sensors and actuators. IEEE Trans. Electron Devices **35**(6), 724–730 (1988)
14. Mehregany, M., Bart, S.F., Tavrow, L.S., Lang, J.H., Senturia, S.D., Schlecht, M.F.: A study of three microfabricated variable-capacitance motors. Sens. Actuators **A21**(22/23), 173–179 (1990)
15. Sandia Ultra-planar Multi-level MEMS Technology (2020). https://www.sandia.gov/mesa/_assets/documents/design_documents/SUMMiT_V_Dmanual.pdf
16. Kota, S., Ananthasuresh, G.K., Crary, S.B., Wise, K.D.: Design and fabrication of microelectromechanical systems. J. Mech. Des. **116**(4), 1081–1088 (1994)

17. Smith, S.T., Chetwynd, D.G.: Ultraprecision Mechanism Design. Gordon and Breach (1992)
18. Yin, L., Ananthasuresh, G.K.: Design of distributed compliant mechanisms. Mech. Based Des. Struct. Mach. **31**(2), 151–179 (2003)
19. Miller, S.L., Sniegowski, J.J., LaVigne, G., McWhorter, P.J.: Performance trade-offs for a surface micromachined microengine. In: Proceedings of the SPIE, Micromachined Devices and Components II, vol. 2882. (1996). https://doi.org/10.1117/12.250702
20. Ye, W., Mukherjee, S.: Design and fabrication of an electrostatic variable gap drive in micro-electro-mechanical systems. Comput. Model. Eng. Sci. **1**, 111–120 (2000)
21. Silicon-on-insulator Multi-user MEMS Processes (SOIMUMPs) (2020). http://www.memscap.com/products/mumps/soimumps
22. Howard, J.: Mechanics of Motor Proteins and the Cytoskeleton. Oxford University Press (2005)
23. McAllister, A., Smith, M., Zafirou, K., Day, D., Butler, M.: Apparatus and Method Providing a Hand-held Sprectrometer. US Patent US20070194239A1 (2007)
24. Saxena, A., Ananthasuresh, G.K.: On an optimal property of compliant topologies. Struct. Multidiscip. Optim. **19**(1), 36–49 (2000)
25. Kota, S., Rodgers, S.M., Hetrick, J.A.: Compliant Displacement-multiplying Apparatus for Microelectromechanical Systems. US Patent US6175170B1 (2001)
26. Baichapur, G.S., Gugale, H., Maheshwari, A., Bhargav, S.D.B., Ananthasuresh, G.K.: A Vision-based micro-Newton static force sensor using a displacement-amplifying compliant mechanism. Mech. Based Des. Struct. Mach. **42**(2), 193–210 (2014)
27. Kollimada, S., Khan, S., Balakrishnan, S., Raju. S.R., Suma, M.S., Ananthasuresh, G.K.: A micro-mechanical compliant device for individual cell-stretching, compression, and in-situ force-measurement. In: Proceedings of the International Conference on Manipulation, Automation, and Robotics at Small Scales. Montreal, Canada (2017)
28. Putty, M., Najafi, K.: A Micromachined vibratory ring gyroscope. In: Proceedings of the Hilton Head Workshop on Solid State Sensors and Actuators (1995)
29. Guckel, H., Klein, J., Christenson, T., Skrobis, K., Laudon, M., Lovell, E.G.: Thermomagnetic metal flexure actuators. In: Technical Digest of Solid-State Sensors and Actuators Workshop, Hilton Head Island, SC, 1992, p. 73 (1992)
30. Timoshenko, S.: Analysis of bimetal thermostats. J. Opt. Soc. Am. **11**, 233–255 (1925)
31. Yin, L., Ananthasuresh, G.K.: A novel topology design scheme for the multi-physics problems of electro-thermally actuated compliant micromechanisms. Sens. Actuators A **97–98**, 599–609 (2002)
32. Mankame, N., Ananthasuresh, G.K.: Topology synthesis of electro-thermal-compliant mechanisms using line elements. Struct. Multidiscip. Optim. **26**, 209–218 (2004)
33. Sardan, O., Petersen, D.H., Molhave, K., Sigmund, O., Boggild, P.: Topology optimized electrothermal polysilicon microgrippers. Microelectron. Eng. **85**(5–6), 1096–1099 (2008)
34. Mankame, N., Ananthasuresh, G.K.: Comprehensive thermal modeling and characterization of an electro-thermal-compliant microactuator. J. Micromech. Microeng. **11**(5), 452–462 (2001)
35. Awtar, S., Slocum, A.H.: Constraint-based design of parallel kinematic XY flexure mechanisms. J. Mech. Des. **129**(8), 816–830 (2006)
36. Dinesh, M., Ananthasuresh, G.K.: Micromechaical Stages with enhanced range. Int. J. Adv. Eng. Sci. Appl. Math. **2**(1), 35–43 (2010)
37. Baglio, S., Castorina, S., Fortuna, L., Savalli, N.: Scaling Issues and Design of MEMS. Wiley-Interscience (2008)
38. Ananthasuresh, G.K., Vinoy, K.J., Gopalakrishnan, S., Bhat, K.N., Aatre, V.K.: Chapter 9 in Micro and Smart Systems: Technology and Modeling. Wiley, New York (2012)
39. Bejan, A., Zane, J.P.: Design in Nature: How the Constructal Law Governs Evolution in Biology, Physics, Technology, and Social Organization. Anchor Reprint Edition (2013)
40. Yan, S., Wang, F., Sigmund, O.: On the non-optimality of tree structures for heat conduction. Int. J. Heat Mass Transf. **122**, 660–680 (2018)
41. Lakes, R.: Materials with structural hierarchy. Nature **361**, 511–515 (1993)
42. Sundaram, M., Ananthasuresh, G.K.: Gustave Eiffel and his optimal structures. Reson. Sci. Educ. J. **14**(8), 849–865 (2009)

43. Senturia, S.D.: (2001) Microsystem Design. Springer
44. Pratap, R., Mohite, S., Pandey, A.K.: Squeze film effects in MEMS devices. J. Indian Inst. Sci. **87**(1), 75–94 (2007)
45. Candler, R.N., Duwel, A., Varghese, M., Chandorkar, S.A., Hopcroft, M.A., Park, W.-T., Kim, B., Yama, G., Partridge, A., Lutz, M., Kenny, T.W.: J. Micromech. Syst. **15**(4), 927–934 (2006)
46. Bifano, T.G., Mali, R.K., Dorton, J.K., Perreault, J., Vandelli, N., Horenstein, M.N., Castanon, D.A.: Contunuous-membrane surface-micromachined silicon deformable mirror. Opt. Eng. **36**(5), 1354–1360 (1997)