Chapter 2
Miniaturization and Microsystems

Abstract Current trends of miniaturization and its need are presented. The impact of miniaturization on design principles for micromechanisms is discussed. The important role microsystems and miniaturization will play in the impending 3rd industrial revolution is also discussed in brief.

Keywords Miniaturization · Third industrial revolution · Microsystems

2.1 Miniaturization

To appreciate the subject of this volume 'Micromechanisms and Microactuators', it is desirable to first recognize the importance of the topic miniaturization as per the current trend of technological development. The matter of miniaturization is, in fact, closely related to the impending paradigm shift slowly taking place. A paradigm shift in technology brings overwhelming transformations in the society affecting almost all spheres of activities. In the recorded history, only twice such changes took place. These are usually termed as 'Industrial Revolution'.

The first industrial revolution took place during the period 1775–1830 when steam engines appeared in the scene as the first prime movers. Once steam power took over manufacturing became an important activity controlling, the world economy and technology became the most important factor in deciding world power. To recognize the phenomenon in a quantitative manner, the yearly pig iron production was taken as the estimating parameter. Figure 2.1 shows the growth of pig iron production, and the sudden increase in the rate is quite visible.

The second industrial revolution started in the 1960s and reached its maturity towards the turn of the millennium. Emergence of microelectronics, computers, communication systems, knowledge-based industry and the information technology transformed the society which we are lucky to experience personally. All these became major factors in the world economy. If one takes up the GDP of the western European countries and plots it over the years, one gets a figure as shown in

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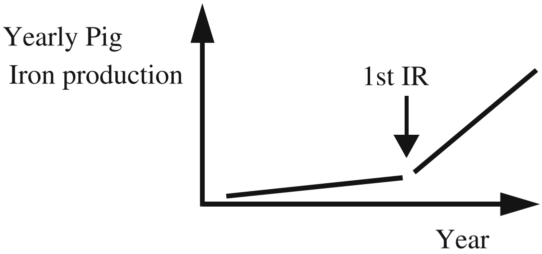


Fig. 2.1 Change in iron production rate due to onset of first industrial revolution

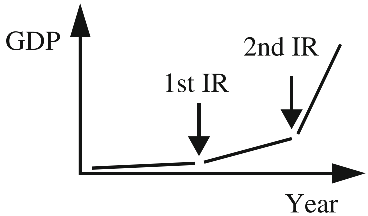


Fig. 2.2 Onset of the first and second industrial revolutions as indicated by the GDP growth

Fig. 2.2. The sudden changes in the slopes clearly indicate the revolutionary changes and paradigm shifts. The onset of the 2nd industrial revolution is very clearly visible.

It is well known that the revolutionary developments of the computer-based system took place primarily through a process of miniaturization of the electronics involved. Because of this, not only the size, but more importantly the cost has crashed down to every ones reach. However, in the 2nd industrial revolution, miniaturization was restricted to only two-dimensional electronic circuits, the primary function of those being manipulation of information. But it is slowly being recognized that three-dimensional miniaturization of devices and systems which physically interact with objects in the surrounding has far more potential to bring revolutionary changes in our society. It is predicted by many that economically viable technology to minimize 3D objects will form the basic foundation for the forthcoming 3rd industrial revolution.

2.1.1 Current Trend

Because of the progress of miniaturization technology, many devices are now produced in very small sizes. In fact, the progress in microelectronics technology has given birth to a new field—microelectromechanical systems (MEMS). As the VLSI chips are becoming more advanced, the fabrication facilities for old chips are becoming obsolete. Instead of dismantling the old set-ups, these are being effectively used in fabricating MEMS devices which require somewhat lesser degree of miniaturization than that for electronic chips. These readily available fabricational facilities have given excellent boost to the development of MEMS technology.

The current trend of technological development arises out of two major requirements. The modern and advanced systems are being provided with greater degree of intelligence and autonomy, and the other trend is towards making the physical devices smaller in size. In some cases, both objectives are being combined for producing miniaturized autonomous devices. Figure 2.3 depicts these trends symbolically. The technology for material manipulation is also advancing continuously, and smaller levels for material manipulation are being achieved.

Figure 2.4 shows how with time the capability to manipulate material is reaching lower and lower levels. Currently, technologists have acquired the capability to operate at nanometre levels and that is why ‘nanotechnology’ is drawing so much attention. It may not be a long time when the technologists will be in a position to control and manipulate individual atoms at least the trend is very clear.

As mentioned in the previous paragraph, one of the objectives of development is to make the futuristic systems more intelligent and autonomous. To a large extent the degree of intelligence with which a device can function depends on the availability of information. This will increase the requirements of sensing ability to many orders of magnitude more than the present systems. Thus, very large number of sensors will be essential for operation and this will make it mandatory to make the sensors miniaturized. Similarly, the actuators for the future devices will have to be composed of very large number of miniaturized actuators all working in parallel. In general, this massive parallelism will be a key feature of machines of the future, and this can be done only if economic miniaturization is achieved. Thus, it is very clear that miniaturization will be essential for not only making microsized objects but for microsized devices also.

Fig. 2.3 Trend of autonomy and reduction in size of devices

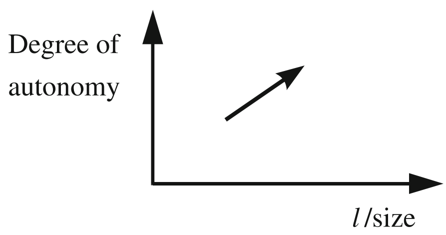
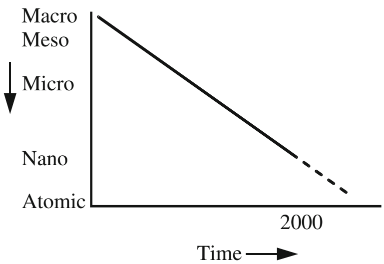


Fig. 2.4 Progress of miniaturization



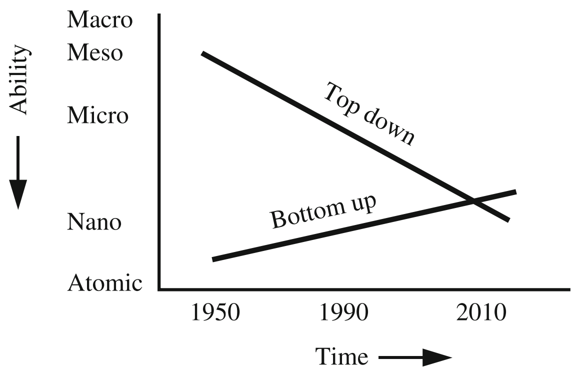


Fig. 2.5 Trends of process capabilities of top-down and bottom-up fabrication technologies

The real challenge, therefore, is the economic way to fabricate miniaturized devices. It is expected that a major shift may be experienced by the basic approach. In many situations, the technologists adopt 'bottom-up' approach along with 'self-assembly' of material for microfabrication in place of traditional 'top-down' batch production approach. Figure 2.5 represents the trend of change in fabricating miniaturized systems through the new capability for manipulating material at micro, nano and molecular levels. It is also not very difficult to recognize that if only a 'self-assembly' technique is adopted, miniaturized products can be produced by 'bottom-up' approach economically.

2.1.2 Miniaturization: Advantages and Impact on Design

The necessity of miniaturization has been discussed in the previous subsection. It may be a good idea to identify the major advantages of miniaturization before proceeding further at this stage.

One major advantage of miniaturization is the drastic reduction in cost. Though sometimes one may think reduction of size is the real important matter, the reduction in cost influences the social impact. If the central processor chip of a personal computer were ten times bigger in area, not much would have changed, but if the cost of the unit were ten times more, computer technology (or mobile communication) would have hardly been able to invade common households. Of course with reduced size, a very large number of units can be packed in a small area (or volume) which is essential for imparting intelligence to some degree.

Miniaturization also drastically reduces the consumption of energy and material. This helps in better conservation of resources and reducing the adverse effect on environment. Microsized objects have very small inertia (as will be seen) because of scaling laws, and their response is fast and can even reach the level of electronic systems.

Miniaturization is excepted to have an extremely important impact in health care technology. In many situations, revolutionary solution can be achieved in invasive health care, drug delivery, diagnostics and prosthesis. It is also very convenient for the miniaturized devices to be disposed of.

Finally, on a more subtle level, miniaturization can lead, in some cases, to taking advantage of the new laws of physics and chemistry which starts playing a predominant role in the small scales due to scaling effect.

Miniaturization will substantially influence various aspects of futuristic systems, and these needs to be considered while designing and fabricating futuristic systems involving miniaturized devices. These are represented below in a classified manner:

- *Configuration and design*—Machines are usually multicomponent devices. At the microscopic level, it is extremely difficult and uneconomic to fabricate and assemble the miniaturized components. Besides, at the microscale, the role of friction becomes predominant when members slide against one another. To avoid both these difficulties, miniaturized mechanisms should be monolithic structures in a majority of cases. The hinges are replaced by flexure joints to provide localized compliance (Fig. 2.6).
  Under some circumstances, the whole mechanism may be a compliant device and the elastic deformation of the whole unit provides the necessary movements. In cases where it is relevant, a unit may be composed of a very large number of miniaturized units all functioning is parallel.
- *Material*—Presently, Si is used for most micromechanisms as the lithographic micromachining techniques are employed to manufacture most MEMS devices. However, in more advanced systems of the future, bottom-up self-assembly-based fabrication technique may be used. In such cases, material of the unit will be typically much softer because of the requirement of self-assembly as will be seen later. Even otherwise, softer materials may be preferred in many cases for the requirement of the necessary degree of compliance.
- *Actuation*—Actuators for micromachines of the future may be very different from the conventional systems. In most cases, the actuators may be integrated with the mechanisms from the very initial stage of fabrication. In some cases, a member of the device may also act as actuator. This can be achieved by using smart materials for the elements of a micromechanism. Many exotic new ideas for microactuators are emerging, and out of all these, the concept of using molecular motors looks very promising. A number of ideas are being taken from the living world for actuating microdevices of the future, and some progress has

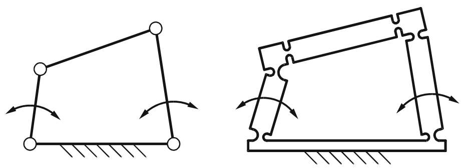


Fig. 2.6 Replacement of hinges by flexure joints

been made in developing artificial muscle type of material to drive microsystems.

- *Sensing and control*—A major difference with the conventional systems in this regard is the fact that in many situations, sensors will be integrated with the functional elements of a micromechanism. Some smart materials themselves can act as transducers. So an element in case of advanced micromechanism can have multiple tasks to achieve.
- *Energy source*—Energy source also can be of very different nature in the futuristic advanced microdevices. Unlike the conventional macroscopic systems, the energy source may not be isolated and limited in number. The energy source can be distributed over the system. One important consideration will be to reduce the distance between the energy source and the actuators. Though, till now, electrical energy is the chief source of energy, thinking has started if biochemical source of energy can be integrated with microdevices. Though it sounds like science fiction, but in future, it may be possible to operate microdevices using photosynthesis!
- *Fabrication*—Design of a system is always closely linked with the fabrication process involved. In case of micromechanisms, the fabrication technique is lithography-based micromachining. Thus, currently most such devices are primarily of 2 dimensions with thickness varying between 50 and 200 μm. Surface micromachining can make parts with mobility. More sophisticated techniques like self-assembly are still to come to reality except in a very few special situations. Some other types of fabrication processes based on generative principles may be also employed in special situations. For developing features of nanometre size, focussed ion beam (FIB) machining can be also used with which 7-nm-level feature size can be achieved. However, any process that cannot be adapted to batch manufacturing cannot be very popular because of the cost considerations.

2.2 Microsystems

Traditionally, micromechanisms represent those devices which enable some links (or elements in general) to undergo prescribed movements when input signal is applied. This movement accomplishes the desired task that can be of immense variety. The input movement is generally provided by a device called actuator as mentioned in a previous section. However, in some cases with the use of smart materials, this input motion can be generated by a member of the mechanism itself. Under many situations, the movements and associated functions of a micromechanism are controlled by signal generated by some sensing elements. In some cases, the objective of a sensor is to activate the mechanism for performing the assigned task, and in some situations, the operation of the mechanism requires feedback control, the feedback being generated by the sensors. In any case, like actuators,

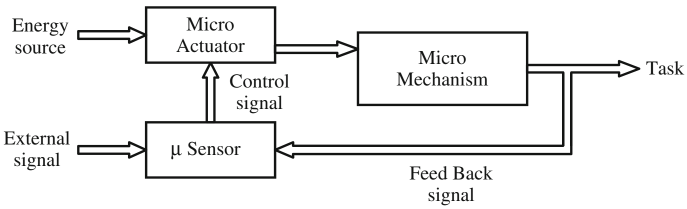


Fig. 2.7 Basic scheme of a microsystem

sensors also form an essential part of a microsystem as indicated in Fig. 2.7 symbolically. This diagram represents the structure of a typical microsystem.

Rarely, it is found desirable (or, even feasible) to totally delink the various elements of a microsystem. It is difficult to assemble all the different elements at microscale, and the system cannot be mass or batch manufactured. Besides, such separate existence may not ensure reliable functioning of the whole system under certain circumstances. Thus, the trend is to integrate all the elements forming the microsystem. These systems are so designed and the materials are so chosen that the whole system becomes monolithic and integrated. Furthermore, the design is done in a manner so as to facilitate the microfabrication of the whole unit simultaneously. In recent times, smart materials are finding increasingly more frequent usage and these materials do not only form the basic body of the micromechanism, but the same bodies can act as the actuating elements. In a truly advanced situation, the members can also play the role of the sensor elements. Such total integration provides better robustness, higher reliability and lower cost.

As the time progresses, the engineers and scientists are becoming increasingly aware of the excellent lessons from the nature, particularly the living world. This has led to a new concept in engineering—biomimetics that is based upon, imitating the biological world. In a substantial number of cases, engineers designing micromechanisms find excellent solutions to their problems from the study of insects (the branch is called entomology). One can design efficient microrobots or micromachines learning from the insect world about their methods of locomotion and movements, manipulation of objects and sensing arrangements.

While designing micromachines, a direct downward scaling of the design of a corresponding system at macroscopic scale is generally not possible, the primary reason being the scaling effects. As the relative predominance of different physical phenomena depends on the scale, a system designed for a macroscopic scale may not function at all when miniaturized isotropically. In many cases, a designer also makes decisions using his/her macro intuition. Since this capability cannot be acquired from the experiences on day-to-day encounters, a careful study of mechanics at microscale is essential. A careful study of the scaling laws is very helpful in this regard, and the next chapter of this volume is devoted to that purpose.

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