Chapter Two: Theoretical Background

2.1 Preface

The general area of MEMS is one that has been the subject of speculation and 'futurology' over the past few years, some of which has been quite unhelpful in providing a real appreciation of the huge potential of this technology. In the first days when micromachining became feasible, there were extreme predictions of the potential of the new technology micromachines that would revolutionize every aspect of daily life were predicted, often based more on science fiction that any sober assessment of the capabilities of the technology.

More recently, the futurologists have turned their attention to nanotechnology, MEMS being the old news. Strangely, however, the prediction that MEMS technology would affect our daily lives has turned out to be entirely true, but the effect has been in ways both more subtle and profound than envisaged by the original forecasts. MEMS has indeed proved to be a potent technology and the application of MEMS that has been most important for the realization of this potency has been sensors: sensing, a seemingly prosaic area of technology, has been revolutionized by MEMS to the extent that the basis has been laid for completely new types of engineering systems. There is now the possibility of designing complex MEMS based systems that are sensitive and reactive to their environment and able to respond and adapt to it. In turn, this responsiveness may be used to address some of the large scale engineering problems which are crucial to the major concerns of the world today: efficiency, energy saving and environmental monitoring. This is design concepts and methods that will be necessary to realize these new systems, building from the technological base provided by MEMS sensors [3]. The complexity of MEMS is also shown in the extensive range of markets and applications that incorporate MEMS devices. MEMS can be found in systems ranging across automotive, medical, electronic, communication and defense applications. Current MEMS devices include accelerometers for airbag sensors, inkjet printer heads, computer disk drive read/write heads, projection display chips, blood pressure sensors, optical switches, microvalves, biosensors and many other products that are all manufactured and shipped in high commercial volumes [4].

The field of microelectromechanical systems (MEMS), particularly micromachined mechanical transducers, has been expanding over recent years, and the production costs of these devices continue to fall. Using materials, fabrication processes, and design tools originally developed for the microelectronic circuits industry, new types of microengineered device are evolving all the time-many offering numerous advantages over their traditional counterparts. The electrical properties of silicon have been well understood for many years, but it is the mechanical properties that have been exploited in many examples of MEMS [9].

Microtechnology and, close on its heels, nanotechnology, are set to change many manufacturing and product paradigms. To stay ahead in this competitive world , one need to assess and reassess his options and establish products that have unique value that helps them stand apart from the rest . Microtechnology is one way to go about this, for it brings along small size, low power consumption, low per-unit manufacturing costs in a mass market, low environmental impact for discardable units, and high sophistication when combined with embedded systems . The wide field of technical information processing, electromechanical systems consisting of coupled electrical and mechanical functional elements have a significant importance. Both the design of interfaces between human and information processing mechanisms and the design of interfaces with the material process during metrological data acquisition and actuatory influence of process variables is made possible by these electromechanical systems [4] .

2.2 Micro-electromechanical systems (MEMS) :

Micro-electromechanical systems (MEMS) is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. MEMS devices have critical dimensions in the range of 100 nm to 1000 µm (or 1 mm). MEMS technology is a precursor to the relatively more popular field of Nanotechnology, which refers to science, engineering and technology below 100 nm down to the atomic scale. Occasionally, MEMS devices with dimensions in the millimeter-range are referred to as meso-scale MEMS devices. Figure (2.1) shows relevant dimensional scale alongside biological matter. These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale.

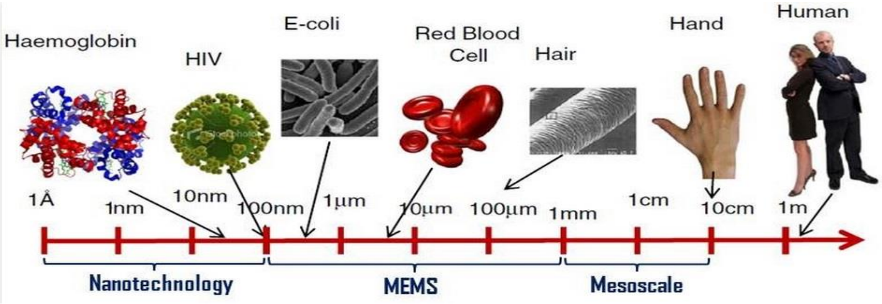
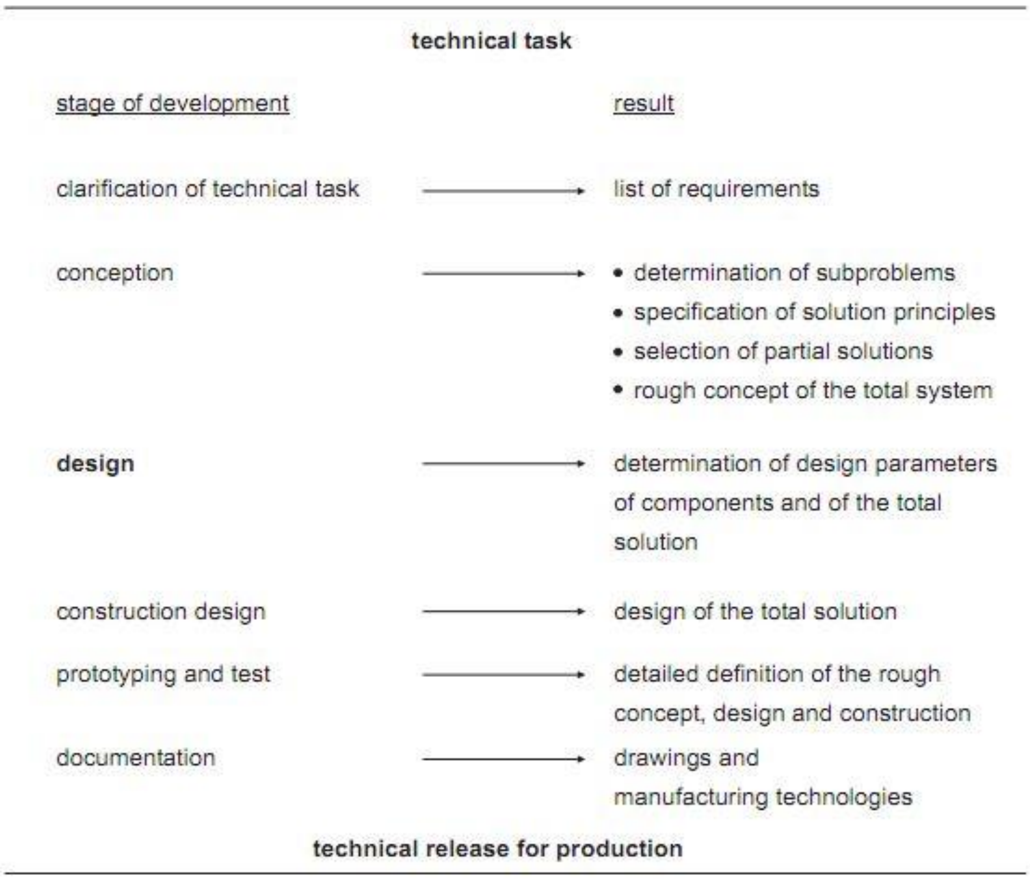


Figure 2.1: shows relevant dimensional scale alongside biological matter

2.3 Design of Electromechanical Systems:

The aim of modeling is the calculation of the parameters design parameters of the designed solution for a technical product. Thus, the design phase is of central importance within the product development process of mechatronic, electromechanical and microelectromechanical systems. The design phase is especially distinct, both with ” the V-Model” [8] of mechatronic systems and the development models of microsystems technology [9]. In Table 2.1, the phases of the product development process of an electromechanical system are specified as rough stage model according to [10].

Table 2.1. Classification of design in the technical product development process



technical task

stage of development		result
clarification of technical task	→	list of requirements
conception	→	• determination of subproblems • specification of solution principles • selection of partial solutions • rough concept of the total system
design	→	determination of design parameters of components and of the total solution
construction design	→	design of the total solution
prototyping and test	→	detailed definition of the rough concept, design and construction
documentation	→	drawings and manufacturing technologies

technical release for production

The design phase follows the conception of the total solution and forms the basis of the subsequent preparation of constructional documents. A physical model of the designed solution forms the basis of the conception (quantitative technical parameter definition for the designed solution). The calculation of the model parameters design parameters is based on different description methods . The aims of these simulations are either the covering of predetermined characteristics design characteristics of the electromechanical system or the fulfillment of special optimization criteria like minimum energy consumption, minimum available space and mass or maximum operating frequency range, respectively. The appraisal verification of simulation results with the parameters of the requirement specification completes the design phase in Figure. 2.2. If the result differs strongly from the target values with respect to the defined limits, the simulation will be repeated with changed parameter sets. If no convergence can be obtained, a validation of the model approach will be necessary.

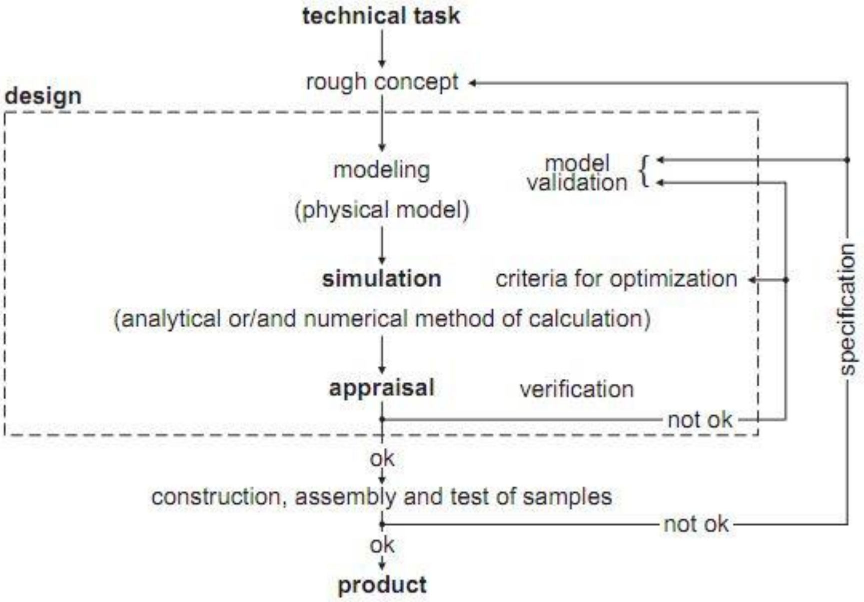


Figure. 2.2. Design workflow for electromechanical systems

The improvement of the design process results in a decrease of experimental testings in order to evaluate development parameters. Simultaneously, the number of samples is reduced resulting in shorter periods of development and lower development costs. The practical relation, the applicability for engineers and the detailed description of simulation methods are decisive for the design improvement that is to be always aspired.

2.4 mechatronics system :

Sensors and actuators are two critical components of every closed loop control system. Such a system is also called a mechatronics system. A typical mechatronics system as shown in Figure 2.3 consists of a

sensing unit, a controller, and an actuating unit. Sensing unit can be as simple as a single sensor or can consist of additional components such as filters, amplifiers, modulators, and other signal conditioners. The controller accepts the information from the sensing unit, makes decisions on the basis of the control algorithm, and outputs commands to the actuating unit. The actuating unit consists of an actuator and optionally a power supply and a coupling mechanism [19].

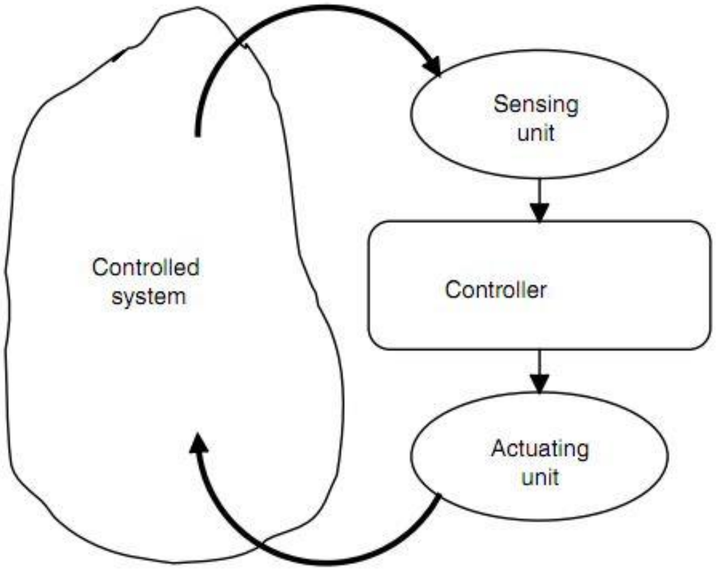


Figure 2.3 A typical mechatronics system.

2.4.1 Transducer:

A transducer is a device that transforms one form of signal or energy into another form. The term transducer can therefore be used to include both sensors and actuators and is the most generic and widely used term in MEMS.

The market for micromachined mechanical transducers has, in the past, had the largest slice of the pie of the overall MEMS market. This is likely to be the case in the immediate future as well. The main emphasis of this text is on mechanical sensors, including pressure, force, acceleration, torque, inertial, and flow sensors. Various types of actuation mechanism, relevant to MEMS, will also be addressed together with examples of the fundamental techniques used for mechanical sensors. The main methods of sensing mechanical measure and have been around for many years and are therefore directly applicable to microsensors. There is, however, a significant effect that must be accounted for when considering mesoscale devices (i.e.,those that fit into the palm of your hand) and microscale devices. This is, of course, scaling. Some physical effects favor the typical dimensions of micromachined devices while others do not. For example, as the linear dimensions of an object arereduced, other parameters do not shrink in the same manner. Consider a simple cube of material of a given density. If the length l is reduced by a factor of 10, the volume (and hence mass) will be reduced by a factor. There are many other consequences of scaling that need to be considered for fluidic, chemical, magnetic, electrostatic, and thermal systems . For example, an interesting effect, significant for microelectrostatic actuators operating in air. This states that the voltage at which sparking occurs (the breakdown voltage) is dependent on the product of air pressure and the separation between the electrodes. As the gap between two electrodes is reduced, a plot of breakdown voltage against the gap separation and gas pressure product reveals a minimum in the characteristic. The consequence is that for air gaps of less than several microns, the breakdown voltage increases.

2.4.2 sensor :

The emergence of the first thermostat in 1883 is considered by some to be the first modern sensor. Innumerable forms of sensors have since emerged, based on a variety of principles. Early sensors were simple devices, measuring a quantity of interest and producing some form of mechanical, electrical, or optical output signal. In just the last decade or so, computing, pervasive communications, connectivity to the Web, mobile smart devices, and cloud integration have added immensely to the capabilities of sensors, as shown in Figure 2.4.

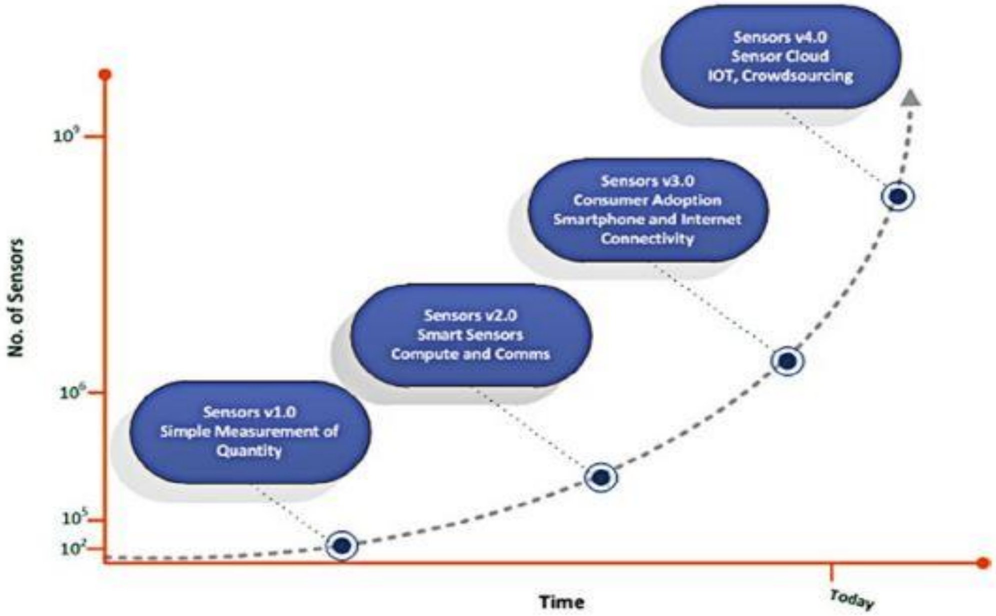


Figure 2.4 Evolution of sensors reflecting the integration of ICT capabilities and consumer adoption

Sensors can be used to measure or detect a vast variety of physical, chemical, and biological quantities, including proteins, bacteria, chemicals, gases, light intensity, motion, position, sound and many others, as shown in Figure 2.5. Sensor measurements are converted by a transducer into a signal that represents the quantity of interest to an observer or to the external world. In this section, we will review the most commonly used sensing techniques for our target domains.

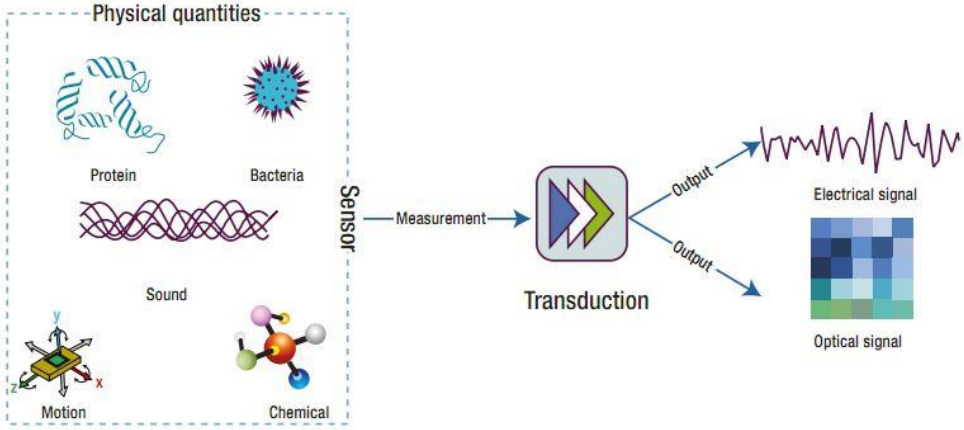


Figure 2.5. The sensing process.

For any given quantity, there is usually more than one form of sensor that can be used to take a measurement. Each sensor type offers different levels of accuracy, sensitivity, specificity, or ability to operate in different environmental conditions. There are also cost considerations. More expensive sensors typically have more sophisticated features that generally offer better performance characteristics. Sensors can be used to measure quantities of interest in three ways:

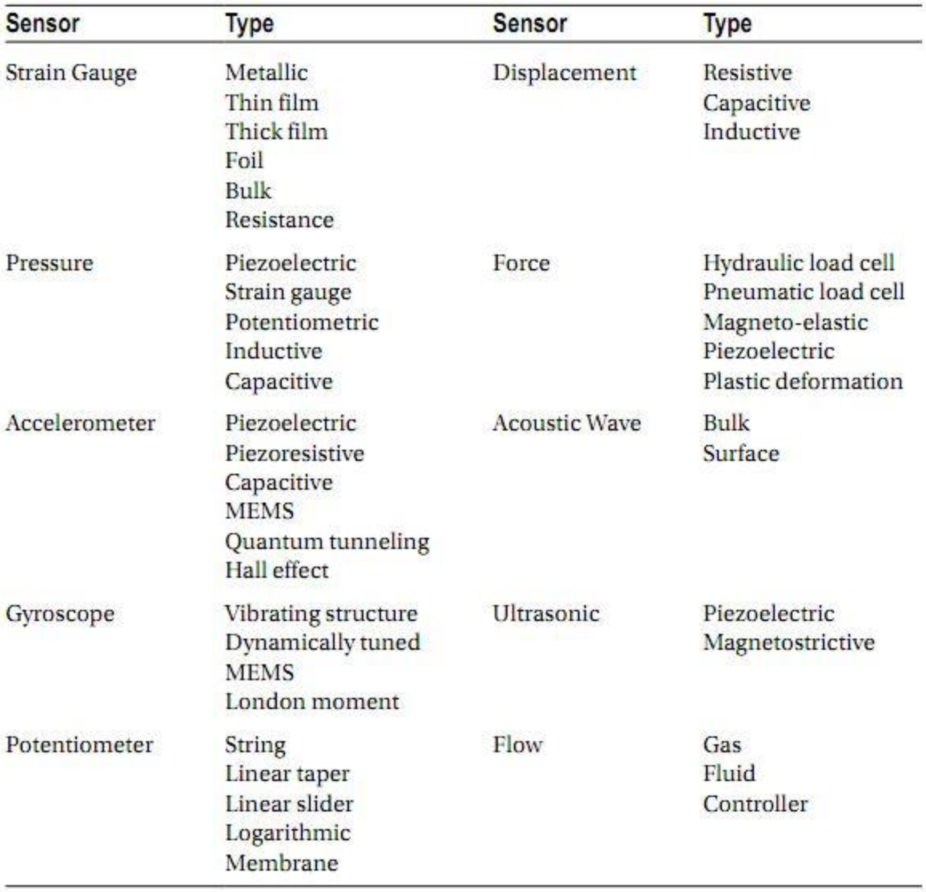
- Contact: This approach requires physical contact with the quantity of interest. There are many classes to sense in this way liquids, gases, objects such as the human body, and more. Deployment of such sensors obviously perturbs the state of the sample or subject to some degree. The type and the extent of this impact is application-specific. Let us look at the example of human body-related applications in more detail.

- Noncontact: This form of sensing does not require direct contact with the quantity of interest. This approach has the advantage of minimum perturbation of the subject or sample. It is commonly used in ambient sensing applications—applications based on sensors that are ideally hidden from view and, for example, track daily activities and behaviors of individuals in their own homes. Such applications must have minimum impact on the environment or subject of interest in order to preserve state. Sensors that are used in non-contact modes, passive infrared (PIR) , for example, generally have fast response times.
- Sample removal: This approach involves an invasive collection of a representative sample by a human or automated sampling system. Sample removal commonly occurs in healthcare and environmental applications, to monitor E. coli in water or glucose levels in blood, for example. Such samples may be analyzed using either sensors or laboratory-based analytical instrumentation.

2.4.2.1Mechanical Sensors

Mechanical sensors are based on the principle of measuring changes in a device or material as the result of an input that causes the mechanical deformation of that device or material . Inputs, such as such motion, velocity, acceleration, and displacement that result in mechanical deformation that can be measured. When this input is converted directly into an electrical output, the sensor is described as being electromechanical. Other possible output signals include magnetic, optical, and thermal .The common mechanical and electromechanical sensing approaches as described by the IEEE Sensors Council are shown in Table 2.2.

Table 2.2. Common Mechanical and Electromechanical Sensors



Sensor	Type	Sensor	Type
Strain Gauge	Metallic Thin film Thick film Foil Bulk Resistance	Displacement	Resistive Capacitive Inductive
Pressure	Piezoelectric Strain gauge Potentiometric Inductive Capacitive	Force	Hydraulic load cell Pneumatic load cell Magneto-elastic Piezoelectric Plastic deformation
Accelerometer	Piezoelectric Piezoresistive Capacitive MEMS Quantum tunneling Hall effect	Acoustic Wave	Bulk Surface
Gyroscope	Vibrating structure Dynamically tuned MEMS London moment	Ultrasonic	Piezoelectric Magnetostrictive
Potentiometer	String Linear taper Linear slider Logarithmic Membrane	Flow	Gas Fluid Controller

Strain gauges are one of the most common mechanical sensors and come in many forms and types. They have been used for many years, and are the key sensing element in a variety of sensors types, including pressure sensors, load cells, torque sensors, and position sensors. Measurement is based on a change in resistance due to strain on a material or combination of materials. A common strain gauge implementation uses a grid-shaped sensing element, which comprises a thin metallic resistive foil (3 to 6 mm thick) bonded onto a thin plastic film backing (15 to 16 mm thick). The entire structure is encapsulated within a protective polyimide film. Strain gauges generally have nominal resistance values ranging from tens of ohms to thousands of ohms, with 120, 350, and 1,000W being the most common. An excitation voltage (typically 5V or 12V) is applied to the input leads of the gauge network and a voltage reading is taken from the output leads. The output readings in millivolts are measured by a measurement circuit normally in the form of a Wheatstone bridge, as shown in Figure 2.6 . As stress is applied to the strain gauge, a change in resistance unbalances the Wheatstone bridge. This results in a signal output, related to the magnitude of the applied stress. Both strain gauge elements and bridge resistors can usually be purchased in an encapsulated housing. This form of package is commonly called a load cell.

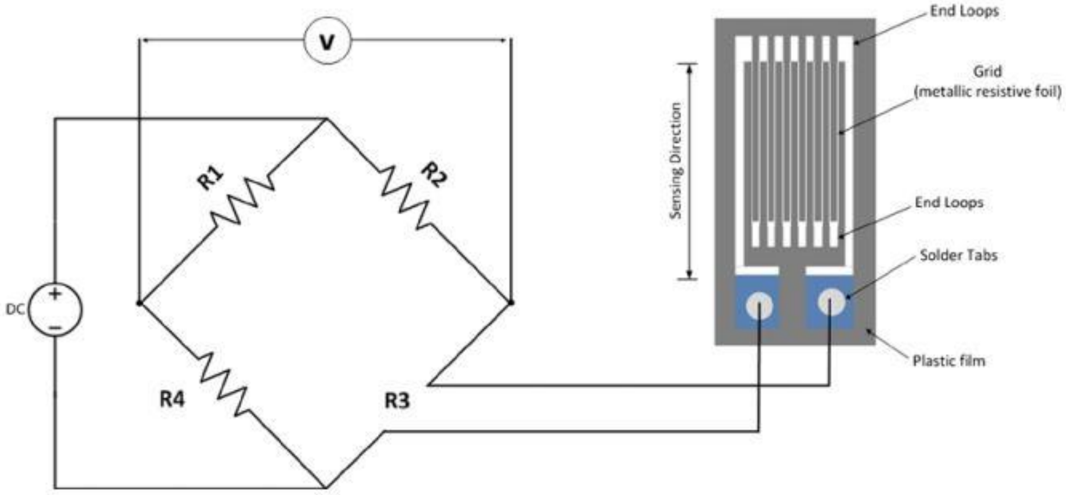


Figure 2.6 . Foil strain gauge attached to a wheatstone bridge

Another common form of strain gauge is based on the piezoelectric (production of electricity when certain materials are subjected to mechanical stress) properties of some semiconductor materials, such as silicon or germanium. These were first used in the car industry during the 1970s, before being applied in other domains, including sports. This form of strain gauge is smaller, has higher unit resistance and sensitivity, and is lower in cost than grid-style strain gauges.

A key problem with strain measurements is that of thermal effects. Changes in temperature cause expansion or contraction of the sensing element, resulting in thermally induced strain. Temperature compensation is required to address the problem and this can be built into the Wheatstone bridge. Piezoelectric strain gauges have even greater sensitivity to temperature variation and greater drift characteristics, which must be compensated for during use by regular recalibration. Strain gauges are used in a variety of sporting and healthcare applications, including clinical dynamometers that measure grip strength .

Over the years, this information has been categorized in terms of the type of energy domains but MEMS devices generally overlap several domains or do not even belong in any one category.

These energy domains include:

- Thermal - temperature, entropy, heat, heat flow
- Chemical - concentration, composition, reaction rate
- Radiant - electromagnetic wave intensity, phase, wavelength, polarization reflectance, refractive index, transmittance
- Magnetic - field intensity, flux density, magnetic moment, permeability
- Electrical - voltage, current, charge, resistance, capacitance, polarization .

2.4.3 Actuators:

An actuator is a device that converts an electrical signal into an action. It can create a force to manipulate itself, other mechanical devices, or the surrounding environment to perform some useful function [11]. Actuators are basically the muscle behind a mechatronics system that accepts a control command (mostly in the form of an electrical signal) and produces a change in the physical system by generating force, motion, heat, flow, and so forth. Normally, the actuators are used in conjunction with the power supply and a coupling mechanism as shown in Figure 2.7. The power unit provides either ac or dc power at the rated voltage and current. The coupling mechanism acts as the interface between the actuator and the physical system. Typical mechanisms include rack and pinion, gear drive, belt drive, lead screw and nut, piston, and linkages.

Actuators can be classified on the basis of the type of energy as listed in Table 2.3 The table, although not exhaustive, lists all the basic types. They are essentially of electrical, electromechanical, electromagnetic, pneumatic, or hydraulic type. The new generations of actuators include smart material actuators, microactuators, and nanoactuators.

Actuators can also be classified as binary and continuous on the basis of the number of stable state outputs. A relay with two stable states is a good example of a binary actuator.

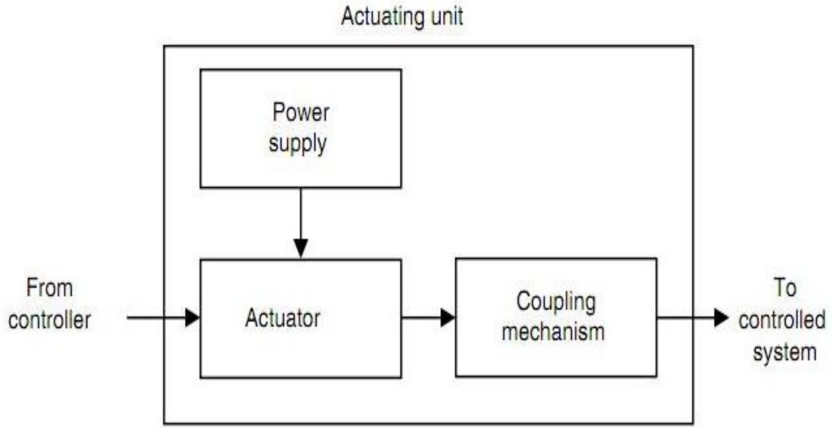
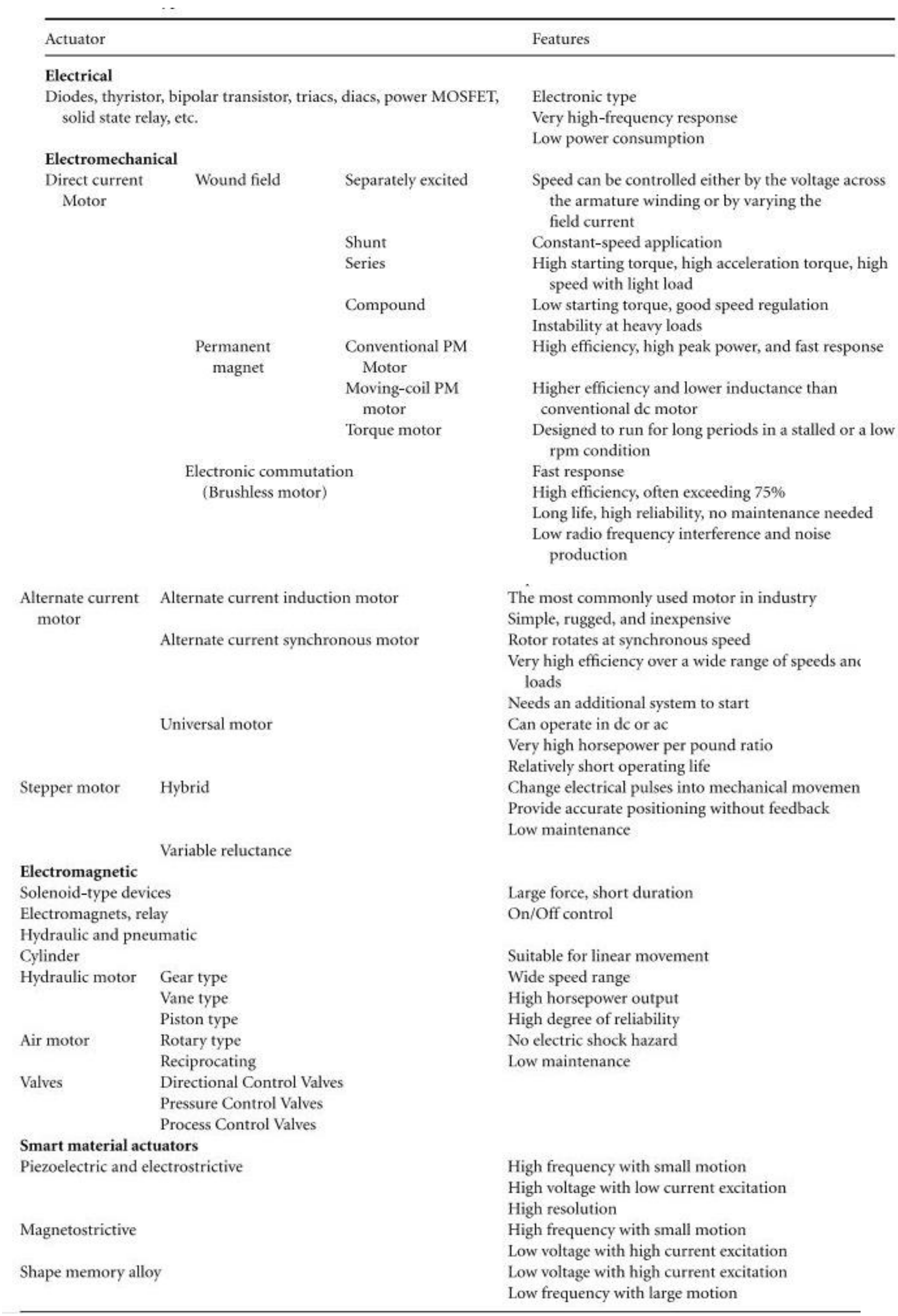
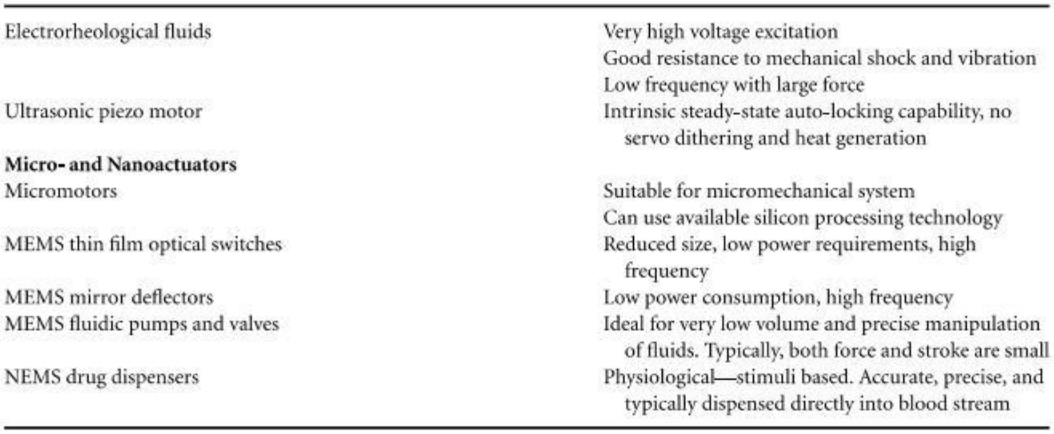


Figure 2.7 A typical actuating unit.

Table 2.3 types of Actuators and their Features



Actuator			Features
Electrical			
Diodes, thyristor, bipolar transistor, triacs, diacs, power MOSFET, solid state relay, etc.			Electronic type Very high-frequency response Low power consumption
Electromechanical			
Direct current Motor	Wound field	Separately excited	Speed can be controlled either by the voltage across the armature winding or by varying the field current
		Shunt	Constant-speed application
		Series	High starting torque, high acceleration torque, high speed with light load
		Compound	Low starting torque, good speed regulation Instability at heavy loads
	Permanent magnet	Conventional PM Motor	High efficiency, high peak power, and fast response
		Moving-coil PM motor	Higher efficiency and lower inductance than conventional dc motor
		Torque motor	Designed to run for long periods in a stalled or a low rpm condition
	Electronic commutation (Brushless motor)		Fast response High efficiency, often exceeding 75% Long life, high reliability, no maintenance needed Low radio frequency interference and noise production
Alternate current motor	Alternate current induction motor		The most commonly used motor in industry Simple, rugged, and inexpensive
	Alternate current synchronous motor		Rotor rotates at synchronous speed Very high efficiency over a wide range of speeds anc loads Needs an additional system to start
	Universal motor		Can operate in dc or ac Very high horsepower per pound ratio Relatively short operating life
Stepper motor	Hybrid		Change electrical pulses into mechanical movemen Provide accurate positioning without feedback Low maintenance
	Variable reluctance		
Electromagnetic			
Solenoid-type devices			Large force, short duration
Electromagnets, relay			On/Off control
Hydraulic and pneumatic			
Cylinder			Suitable for linear movement
Hydraulic motor	Gear type		Wide speed range
	Vane type		High horsepower output
	Piston type		High degree of reliability
Air motor	Rotary type		No electric shock hazard
	Reciprocating		Low maintenance
Valves	Directional Control Valves		
	Pressure Control Valves		
	Process Control Valves		
Smart material actuators			
Piezoelectric and electrostrictive			High frequency with small motion High voltage with low current excitation High resolution
Magnetostrictive			High frequency with small motion Low voltage with high current excitation
Shape memory alloy			Low voltage with high current excitation Low frequency with large motion



Electrorheological fluids	Very high voltage excitation Good resistance to mechanical shock and vibration Low frequency with large force
Ultrasonic piezo motor	Intrinsic steady-state auto-locking capability, no servo dithering and heat generation
Micro- and Nanoactuators	
Micromotors	Suitable for micromechanical system Can use available silicon processing technology
MEMS thin film optical switches	Reduced size, low power requirements, high frequency
MEMS mirror deflectors	Low power consumption, high frequency
MEMS fluidic pumps and valves	Ideal for very low volume and precise manipulation of fluids. Typically, both force and stroke are small
NEMS drug dispensers	Physiological—stimuli based. Accurate, precise, and typically dispensed directly into blood stream

2.5 Glucose meters :

A glucose meter (or glucometer) is a medical device for determining the approximate concentration of glucose in the blood. It can also be a strip of glucose paper dipped into a substance and measured to the glucose chart. It is a key element of home blood glucose monitoring (HBGM) by people with diabetes mellitus or hypoglycemia. Typical glucometers are shown in Figure (2.8). A small drop of blood, obtained by pricking the skin with a lancet, is placed on a disposable test strip that the meter reads and uses to calculate the blood glucose level. The meter then displays the level in units of mg/dl or mmol /l.

Since about 1980, a primary goal of the management of type 1 diabetes and type 2 diabetes mellitus has been achieving closer-to-normal levels of glucose in the blood for as much of the time as possible, guided by HBGM several times a day. The benefits include a reduction in the occurrence rate and severity of long-term complications from hyperglycemia as well as a reduction in the short-term, potentially life-threatening complications of hypoglycemia.

Figure 2.8: Some glucometer types

There are several key characteristics of glucose meters which may differ from model to model:

a- Size: The average size is now approximately the size of the palm of the hand, although hospital meters can be the size of the remote control of a TV set. They are battery-powered.

b-Test strips: A consumable element containing chemicals that react with glucose in the drop of blood is used for each measurement. For some models this element is a plastic test strip with a small spot impregnated with glucose oxidase and other components. Each strip is used once and then discarded. Figure (2.9) shows a glucose meter with a test strip. Instead of strips, some models use discs, drums, or cartridges that contain the consumable material for multiple tests.

Figure 2.9: A glucose meter with a test strip

c- Volume of blood sample: The size of the drop of blood needed by different models varies from 0.3 to 1 μm. (Older models required larger blood samples, usually defined as a "hanging drop" from the fingertip.) Smaller volume requirements reduce the frequency of unproductive pricks. The volume of a droplet blood sample is shown in figure (2.10)

figure 2.10: The volume of a droplet blood sample

d- Alternative site testing: Smaller drop volumes have enabled "alternate site testing" pricking the forearms or other less sensitive areas instead of the middle of the fingertips; pricking the sides of the fingertips is actually the least uncomfortable method of testing. Although less uncomfortable, readings obtained from forearm blood lag behind fingertip blood in reflecting rapidly changing glucose levels in the rest of the body.

e- Testing times: The times it takes to read a test strip may range from 3 to 60 seconds for different models.

2.6 MEMS Applications :

There are numerous possible applications for MEMS . As a breakthrough technology, allowing unparalleled synergy between previously unrelated fields such as biology and microelectronics, many new MEMS applications will emerge, expanding beyond that which is currently identified or known. Here are a few applications of current interest:

2.6.1 Medical

The MEMS in biomedical applications holds the promise of improving patient care in a minimally invasive manner while simultaneously reducing health care costs .The biomedical applications of microsystems fall broadly into the two categories of diagnostic and therapeutic systems. Diagnostic applications include DNA diagnostics, systems on a chip, and cell and molecule sorting. Therapeutic systems include drug and gene delivery, tissue augmentation/repair , micro/minimally invasive surgical systems, and biocapsules. These categories are necessarily broad, and the applications listed are by no means exhaustive: A tremendous number of biomedical microsystems have been proposed and are under development. Further, with increased opportunities and capabilities to integrate functionality on microsystems , the advent of devices that bridge these is likely to be seen . Significant opportunities exist to leverage the capabilities of microsystems in therapeutic applications.

There are a wide variety of applications for MEMS in medicine. The first and by far the most successful application of MEMS in medicine (at least in terms of number of devices and market size) are MEMS pressure sensors, which have been in use for several decades. The market for these pressure sensors is extremely diverse and highly fragmented, with a few high-volume markets and many lower volume ones. Some of the applications of MEMS pressure sensors in medicine include:

- MEMS pressure sensors are used to measure intrauterine pressure during birth. The device is housed in a catheter that is placed between the baby's head and the uterine wall.
- During delivery, the baby's blood pressure is monitored for problems during the mother's contractions.

- MEMS pressure sensors are used in hospitals and ambulances as monitors of a patient’s vital signs, specifically the patient’s blood pressure and respiration.

-The MEMS pressure sensors in respiratory monitoring are used in ventilators to monitor the patient’s breathing.

- MEMS pressure sensors are used for eye surgery to measure and control the vacuum level used to remove fluid from the eye, which is cleaned of debris and replaced back into the eye during surgery.

- Special hospital beds for burn victims that employ inflatable mattresses use MEMS pressure sensors to regulate the pressure inside a series of individual inflatable chambers in the mattress. Sections of the mattress can be inflated as needed to reduce pain as well as improve patient healing.

- Physician’s office and hospital blood analyzers employ MEMS pressure sensors as barometric pressure correction for the analysis of concentrations of O_2, CO_2, calcium, potassium, and glucose in a patient's blood.

- MEMS pressure sensors are used in inhalers to monitor the patient’s breathing cycle and release the medication at the proper time in the breathing cycle for optimal effect.

- MEMS pressure sensors are used in kidney dialysis to monitor the inlet and outlet pressures of blood and the dialysis solution and to regulate the flow rates during the procedure.

- MEMS pressure sensors are used in drug infusion pumps of many types to monitor the flow rate and detect for obstructions and blockages that indicate that the drug is not being properly delivered to the patient.

The contribution to patient care for all of these applications has been enormous. More recently, MEMS pressure sensors have been developed and are being marketed that have wireless interrogation capability. These sensors can be implanted into a human body and the pressure can be measured using a remotely scanned wand.

Another application are MEMS inertial sensors, specifically accelerometers and rate sensors which are being used as activity sensors. Perhaps the foremost application of inertial sensors in medicine is in cardiac pacemakers wherein they are used to help determine the optimum pacing rate for the patient based on their activity level. MEMS devices are also starting to be employed in drug delivery devices, for both ambulatory and implantable applications. MEMS electrodes are also being used in neuro-signal detection and neuro-stimulation applications. A variety of biological and chemical MEMS sensors for invasive and non-invasive uses are beginning to be marketed. Lab-on-a-chip and miniaturized biochemical analytical instruments are being marketed as well.

2.6.2 Communications

High frequency circuits are benefiting considerably from the advent of RF-MEMS technology. Electrical components such as inductors and tunable capacitors can be improved significantly compared to their integrated counterparts if they are made using MEMS and Nanotechnology. With the integration of such components, the performance of communication circuits will improve, while the total circuit area, power consumption and cost will be reduced. In addition, the mechanical switch, as developed by several research groups, is a key component with huge potential in various RF and microwave circuits. The demonstrated samples of mechanical switches have quality factors much higher than anything previously available. Another successful application of RF-MEMS is in resonators as mechanical filters for communication circuits.

2.6.3 Inertial Sensing

MEMS inertial sensors, specifically accelerometers and gyroscopes, are quickly gaining market acceptance. For example, MEMS accelerometers have displaced conventional accelerometers for crash air-bag deployment systems in automobiles. The previous technology approach used several bulky accelerometers made of discrete components mounted in the front of the car with separate electronics near the air-bag and cost more than $50 per device. MEMS technology has made it possible to integrate the accelerometer and electronics onto a single silicon chip at a cost of only a few dollars. These MEMS accelerometers are much smaller, more functional, lighter, more reliable, and are produced for a fraction of the cost of the conventional macroscale accelerometer elements. More recently, MEMS gyroscopes (i.e., rate sensors) have been developed for both automobile and consumer electronics applications. MEMS inertial sensors are now being used in every car sold as well as notable customer electronic handhelds such as Apple iPhones and the Nintendo Wii.

2-7 Biosensor :

A biosensor is commonly defined as an analytical device that uses a biological recognition system to target molecules or macromolecules. The great development of biosensors for numerous diagnosis of infectious diseases, detection of oxidizing of free radicals in saliva [12] , glucose determination and also stress measurements [13], has lead to the technological advancement of microsensors for biological sensing. Biosensors can be coupled to physiochemical transducers that convert this recognition into a detectable output signal. Typically biosensors are comprised of three components: the detector, the transducer and the output system which involves amplification and display the output in an appropriate format.

Biosensors use biochemical mechanisms to identify an analyte of interest in chemical, environmental (air, soil, and water), and biological samples (blood, saliva, and urine). The sensor uses an immobilized biological material, which could be an enzyme, antibody, nucleic acid, or hormone, in a self-contained device see Figure 2.11. The biological material being used in the biosensor device is immobilized in a manner that maintains its bioactivity. Methods utilized include membrane (for example, electroactive polymers) entrapment, physical bonding, and noncovalent or covalent binding. The immobilization process results in contact being made between the immobilized biological material and the transducer. When an analyte comes into contact with the immobilized biological material, the transducer produces a measurable output, such as a current, change in mass, or a change in color. Indirect methods can also be utilized, in which a biochemical reaction occurs between the analyte and sensor material, resulting in a product. During the reaction, measurable quantities such as heat, gas (for example, oxygen), electrons, or hydrogen ions are produced, and can be measured.

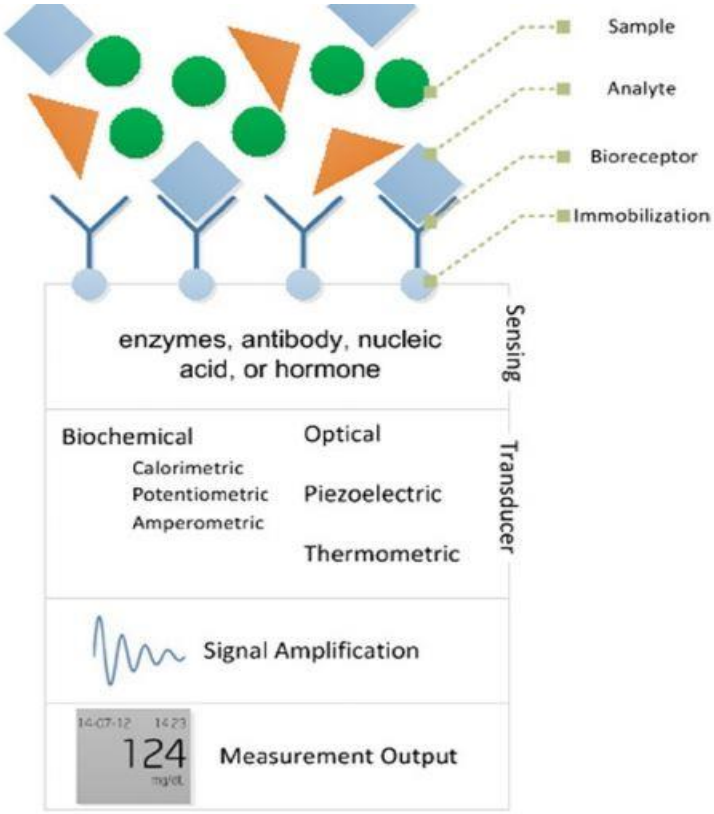
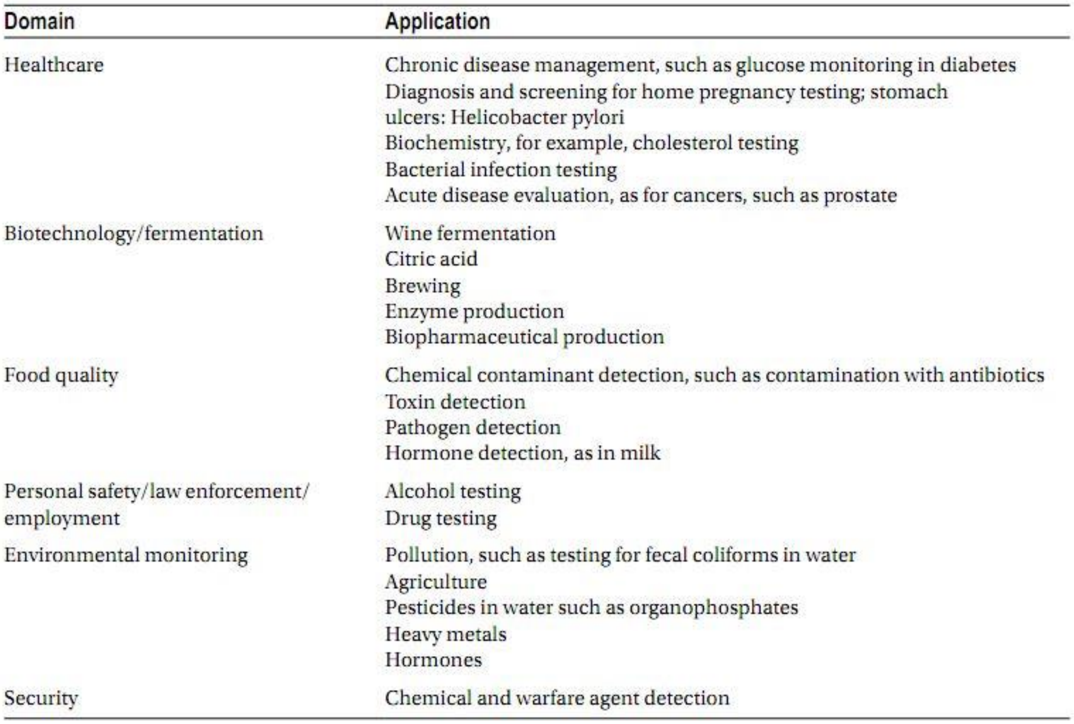


Figure 2.11 . The biosensing process

The use of biosensors has increased steadily since Yellow Springs Instruments produced the first commercially successful glucose biosensor in 1975 . Biosensors are now available over the counter for a large variety of consumer applications, including cholesterol measurement, fertility monitoring, ovulation status, bacterial infection or exposure (such as Heliobacter pylori), allergies, and STD detection. A report by Global Industry Analysts (GIA) estimates that the biosensors market will be worth approximately USD 16.5 billion by 2017 . Biosensors have also found niches in domains outside of healthcare. The key biosensor application domains are summarized in Table 2.4.

Table 2.4. Key Biosensor Application Domains



Domain	Application
Healthcare	Chronic disease management, such as glucose monitoring in diabetes Diagnosis and screening for home pregnancy testing; stomach ulcers: Helicobacter pylori Biochemistry, for example, cholesterol testing Bacterial infection testing Acute disease evaluation, as for cancers, such as prostate
Biotechnology/fermentation	Wine fermentation Citric acid Brewing Enzyme production Biopharmaceutical production
Food quality	Chemical contaminant detection, such as contamination with antibiotics Toxin detection Pathogen detection Hormone detection, as in milk
Personal safety/law enforcement/ employment	Alcohol testing Drug testing
Environmental monitoring	Pollution, such as testing for fecal coliforms in water Agriculture Pesticides in water such as organophosphates Heavy metals Hormones
Security	Chemical and warfare agent detection

2.8 Microcantilever :

Is a device that can act as a physical, chemical or biological sensor by detecting changes in microcantilever bending or vibrational frequency. Microcantilevers are being used for chemical and biological sensors for detection in medical fields. These sensors have a wide range of applicability in defense and medical fields These micro-scale sensors utilize a receptor, which is specific to a single chemical or biological target . for immobilizing the species of interest and then using a wide variety of physical and chemical mechanisms for detection and transduction, leading to a recordable signal response .

In addition to silicon and polymers, some new materials also used in these types of sensors. Microcantilever sensors can be operated in air, vacuum or in liquid. The damping effect in a liquid medium, however, reduces the resonance response of a microcantilever . In most liquids , the observed resonance response is approximately an order of magnitude smaller than that in air. The bending response, however, remains unaffected by the presence of a liquid medium. Therefore, the feasibility of operating a microcantilever in a solution with high sensitivity makes the microcantilever an ideal choice for its use as chemical sensors and biosensors.

2.9 Piezoresistive sensors:

Piezoresistive derives its name from the Greek word piezin, meaning “to press.” It is an effect exhibited by various materials that exhibit a change in resistivity due to an applied pressure. The effect was first discovered by Lord Kelvin in 1856, who noted that the resistance of copper and iron wires increased when in tension. He also observed that iron wires showed a larger change in resistance than those made of copper. The first application of the piezoresistive effect did not appear until the 1930s, some 75 years after Lord Kelvin’s discovery. Rather than using metal wires, these so-called strain gauges are generally made from a thin metal foil mounted on a backing film, which can be glued onto a surface. A typical metal foil strain gauge is depicted in Figure 2.12.

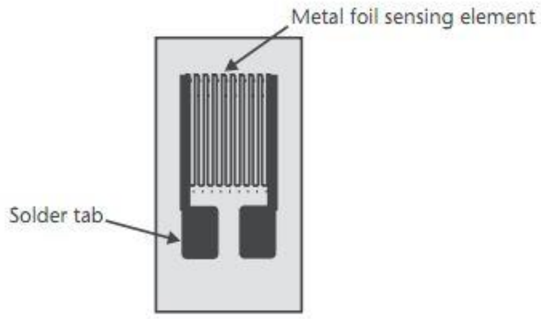


Figure 2.12 Illustration of a metal foil strain gauge.

The piezoresistive effect of semiconductors has been used for sensor devices employing all kinds of semiconductor materials such as germanium, polycrystalline silicon, amorphous silicon, and single crystal silicon. Since silicon is today the material of choice for integrated digital and analog circuits the use of piezoresistive silicon devices has been of great interest. It enables the easy integration of stress sensors with Bipolar and CMOS circuits. This has enabled a wide range of products using the piezoresistive effect. Many commercial devices such as pressure sensors and acceleration sensors employ the piezoresistive effect in silicon. But due to its magnitude the piezoresistive effect in silicon has also attracted the attention of research and development for all other devices using single crystal silicon. Semiconductor Hall sensors, for example, were capable of achieving their current precision only after employing methods which eliminate signal contributions due the applied mechanical stress.

2.10 Material for MEMS :

MEMS devices and structures are fabricated using conventional integrated circuit process techniques, such as lithography, deposition, and etching, together with a broad range of specially developed micromachining techniques. Those techniques borrowed from the integrated circuit processing industry are essentially two dimensional, and control over parameters in the third dimension is only achieved by stacking a series of two-dimensional layers on the work piece, which is usually a silicon wafer. There are practical and economic limits, however, to the number of layers that can be managed in such a serial process, and therefore, the expansion of devices into the third dimension is restricted. Micromachining techniques enable structures to be extended further into the third dimension; however, it has to be understood that these structures are simply either extruded two-dimensional shapes or are governed by the crystalline properties of the material. True three dimensional processing would allow any arbitrary curved surface to be formed, and this is clearly not possible with the current equipment and techniques. An important aspect of MEMS is to understand the limitations of the micromachining techniques currently available. Although the range of these techniques is continually being expanded, there are some core techniques that have been part of the MEMS toolkit for many years. This chapter deals mainly with these core techniques, but also with those process techniques borrowed from integrated circuit manufacturing.

New technologies tend to originate with new materials and manufacturing processes that are used to create new products. The current technologies used in producing MEMS and microsystems are inseparable from those of microelectronics. The close relationship between microelectronics and microsystems fabrication is due to a common belief that the two are indeed interchangeable . It is true that many of the current microsystem fabrication techniques are closely related to those used in microelectronics. Design of microsystems and their packaging, however, is significantly different from that for microelectronics. Many microsystems use microelectronics materials such as silicon.

2.10.1 Silicon (Si) :

Silicon (Si) , is an elemental semiconductor that is found periodic table. In its monocrystalline form, it is lighter and harder than steel. Its electrical properties can be altered by introducing impurities . Silicon occurs naturally in abundance and also forms hard insulating oxides (glass) and nitrides.

In MEMS, silicon is found in both monocrystalline and polycrystalline forms. As these names suggest, in the former, all the atoms are aligned in the same crystal lattice arrangement. In the latter case, the material is made up of many smaller crystals of silicon . The silicon wafers used as a substrate for micromachining are all of the monocrystalline form.

2.10.2 Polysilicon :

Polysilicon is produced from metallurgical grade silicon by a chemical purification process . At the component level, polysilicon has long been used as the conducting gate material in CMOS processing technologies. For these technologies it is deposited using low-pressure chemical-vapour deposition (LPCVD) reactors at high temperatures and is usually heavily doped n-type or p-type.

2.10.3 Borophosphosilicate glass (BPSG) :

The use of boron and phosphorus dopants in silicate glass as inter-layer dielectric films has become quite prevalent in recent years. The addition of these dopants lowers the temperature required to soften or flow the glass layer. The lowering of this temperature minimizes the diffusion of contaminates in underlying layers, and minimizes defect sites and warpage. Consistent and uniform deposition of the chemical vapor deposition (CVD) glass ensures higher device yield.

The technique of phosphosilicate glass (PSG) and borophosphosilicate glass (BPSG) analysis on the relationship between the absorbance height of the amount of a particular material present. Consider the spectrum of a BPSG on a silicon . The proportional relationship between the height of these bands and the amount of material present creates the possibility of using absorption as a quantitative measure of these parameters.

2.10.4 Silicon nitride (Si_3N_4):

Used as excellent barrier to diffusion to water and ions, it has ultra

strong resistance to oxidation and many etchants make it superior material for masks in deep etching, also used as high strength electric insulators [20].

2.11 Design and simulation of MEMS device:

The design phase follows the conception of the total solution and forms the basis of the subsequent preparation of constructional documents. A physical model of the designed solution forms the basis of the conception .

To verify that the devices function, the designer has to model the MEMS. The modeling involves writing the equations of motion or physical modeling of the performance of the device; finite-elements techniques are used to solve these modeling equations.

There are a variety of computer aided design (CAD) tools to aid the designer in the simulation and modeling of the device such as ANSYS, COMSOL. In a very fundamental way, these tools are more complicated than the software for design of either solely ICs or solely mechanical devices. This is due to the close coupling of both electrical and mechanical effects within many MEMS. Consider a micro cantilever that is pulled down by electrostatic forces, its simulation has to take into account both the flow of electrical charge and mechanical elasticity and self consistent fashion. Models can be generated from the finite-element model or from written analytical equations; behavior models symbolic view can be generated [21].

2.11.1 The Finite Element Method :

The FEM is a numerical procedure that can be used to solve a large class of engineering problems including mechanics of structures, heat transfer, electromagnetism, fluid flow and , as well , so called coupled fields problems (e.g. electro-thermal). In the simplest description, the method involves dividing the geometrical model of the analyzed structure into very small, simple pieces called finite elements**,** connected by nodes(such as the ones shown in Figure (2.13) . The behavior of the element is described by adequate physical laws. An unknown quantity (e.g. temperature, displacement vector, electrical potential) is interpolated within an element from the nodal values using specially defined polynomials. The procedure leads to set of simultaneous algebraic equations with the nodal values being unknown. In stress analysis these equations are equilibrium equations of the nodes. During the solution process the nodal values (DOF of the model) are found first and then all interesting quantities (strains, stresses) are calculated within the elements. Finally the results may be presented in the required graphical form, as shown in Figure (2.14) . The method was developed in 1950s for solving complex problems of stress analysis for aeronautical industry. This development was strictly connected with the progress in digital computers and numerical techniques. Today the method is considered as the most powerful analysis method for problems described by partial differential equations.

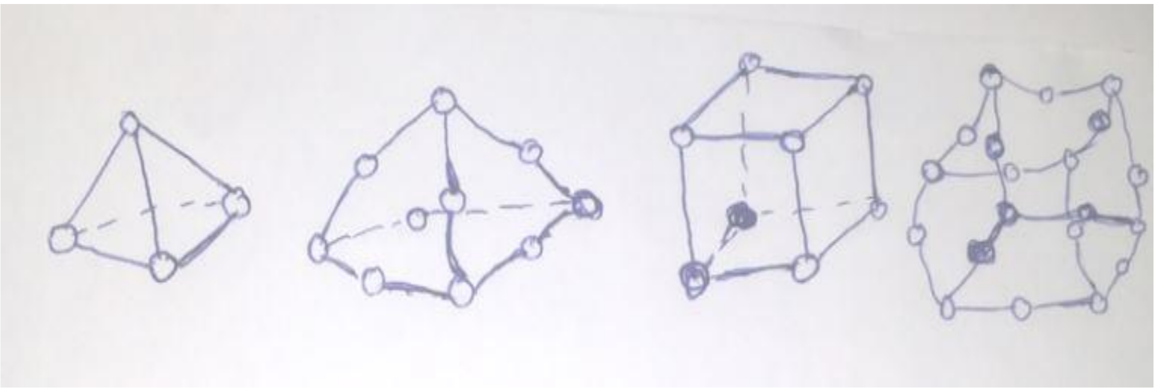


Figure 2.13 : 3D finite elements

2.11.1.1Basic Steps In The Finite Element Method:

a- Preprocessoring phase

In the preprocessing phase the problem is described in the numerical, discrete form.Tasks performed are:

1- Definition of the analysed domain (geometry analysis ,and material properties).
2- Boundary conditions (loads and constraints).
3- Meshing (dividing the domain into the finite elements of the reauired density distribution)

b-Processoring (solution phase)

In this phase the user of FEM program defines type of analysis (static, linear or nonlinear, dynamic, buckling ......) and other details decribing the method of calculations and solution process. FEM performs the calculations and writes the results in the adequate files.

c- Postprocesoring (phase) :

In this phase it is possible to present the interesting results in different forms: plots, graphs, animations, listings e.t.c. The user can create the pictures, tables, graphs and generate the reports.

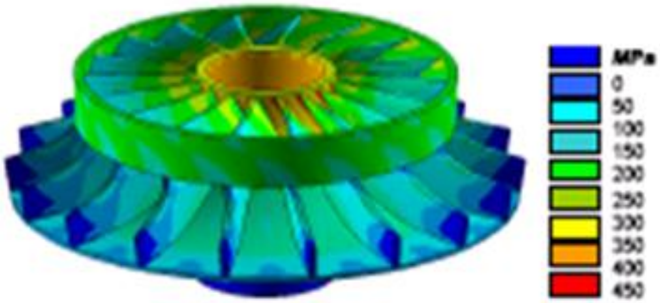


Figure (2.14) Von – Misis stress distribution

2.11.2 ANSYS:

ANSYS is a general purpose software, used to simulate interactions of all disciplines of physics, structure, vibration, fluid dynamics, heat transfer and electromagnetic for engineers. ANSYS, which enables to simulate tests or working conditions, enables to test in virtual environment before manufacturing prototypes of products. Furthermore, determining and improving weak points, computing life and foreseeing probable problems are possible by 3D simulations in virtual environment. ANSYS can work integrated with other engineering softwares on desktop by adding CAD and FEM connection modules.

ANSYS can import CAD data and also enables to build the geometry with its "preprocessing" abilities. Similarly in the same preprocessor, finite element model which is required for computation is generated. After defining loadings and carrying out analyses, results can be viewed as numerical and graphical. ANSYS can carry out advanced engineering analyses quickly, safely and practically by its variety of contact algorithms, time based loading features and nonlinear material models.

2.12 Piezoresitive Microcantilever :

Cantilever sensors are based on relatively well known and simple transduction principle “A simple cantilever beam can be used as a sensor for biomedical, chemical and environmental application. Figure(2.15) shows a target biochemical species adsorbing on a functionalized surface of the cantilever beam.

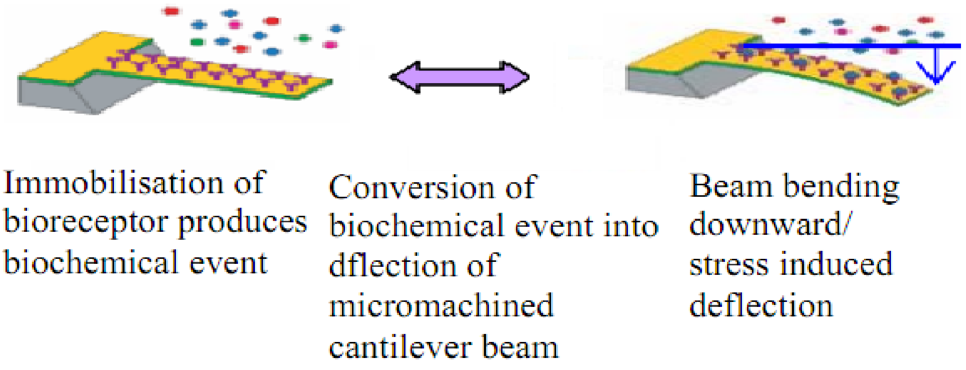


Figure 2.15: The microcantilever beam response

The changes in the surface properties of the microcantilever through absorption or adsorption of analytes to receptor molecules will influence its surface stress. This causes the deflection of microcantilever and it is proportional to the analyte concentration. Usually the deflection is in micrometers and can be detected by several method such as Optical and capacitive detection. There is increasing concern that the requirement for external devices for deflection measurements such as lasers, optical fibers or capacitors is the disadvantages of these techniques where the alignment and calibration of these external elements are required.

However, by integrating piezoresistive material, the disadvantages can be avoided where Piezoresistive microcantilevers can detect the changes in surface stress due to cantilever deflection upon adsorption or absorption. This research uses finite element analysis to simulate the geometrical parameters for polysilicon-based piezoresistive microcantilevers by using Coventorware. The displacements and the ΔX/X changes of the cantilevers were also discussed[18].

2.12.1 Deflection calculations :

Figure 2.16 shows the schematic for a microcantilever beam subjected to a concentrated moment on its free and while the other end is fully constrained.

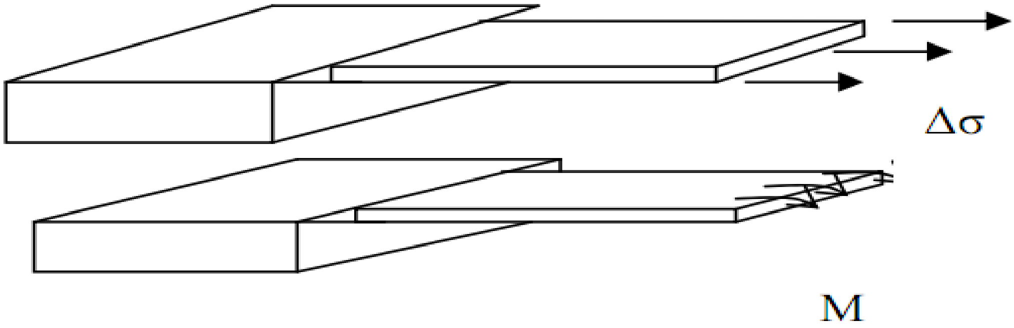


Figure 2.16 Fixed- free end Microcantilever beam

Based on the Stoney equation assumption, the surface stress bends the microcantilever beam with uniform curvature into the concentrated moment induced bending and the following curvature relation is given by [1]:

$$K = \frac{M_0}{EI} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

K = the gauge factor of piezoresistor.

M_0= the applied concentrated moment.

E = the modulus of Elasticity.

I = the moment of inertia of the beam.

By comparing with the curvature relations, the following relation between the surface stress and the moment per unit length can be established as

$$M_0 = \frac{\Delta\sigma t}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}$$

M_0= the applied concentrated moment.

$\Delta\sigma t$ = differential surface stresses on the surface of the microcantilever .

Since the moment is directly proportional to the induced surface stress and the microcantilever beam geometry property, the above can be further simplified as.

$$z = \frac{2(1-\upsilon)\Delta\sigma}{EI}\left(\frac{1}{t}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}$$

v = the Poisson’s ration .

Which is a well known form of Stoney equation commonly used to measure the deflection caused by residual surface stresses in thin films .

is the differential surface stresses on the surface of the microcantilever, E the is the Young’s modulus, v is the Poisson’s ration, r and h are the radius of curvature and thickness of microcantilever beam. For piezoresistive microcantilever in Figure 2.8 , the relationship between the surface stress and the relative change in resistance ΔX/X for a piezoresistor is given by[18];

$$\frac{\Delta X}{X} = -K\left\{\frac{1}{E_1H_1+E_2H_2} + \frac{Z_T^2}{E_1H_1\left(\left(Z_T-(H_1-H_2)+\frac{H_1}{2}\right)^2+\frac{1}{3}\left(\frac{H_1}{2}\right)^2\right)+E_2H_2\left(\left(Z_T-(H_1-H_2)+\frac{H_2}{2}\right)^2\right)}\right\} \ldots\ldots\text{(2.4)}$$

v = the Poisson's ration .

h , x = the radius of curvature and thickness of microcantilever beam.

E_1 = the Young's modulus of the polysilicon cantilever beam.

h_1 = thickness of the polysilicon cantilever beam.

E_2 = the Young's modulus of the piezoresistor.

H_2 = thickness of the piezoresistor.

Z_T = the distance from neutral axis to top of the cantilever beam. containing piezoresistor.

$\Delta\boldsymbol{\sigma}_s$ = differential surface stresses on the surface of the microcantilever.