Macro, Mini, Micro and Nano (M^3N) Technologies for the Future

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Microelectromechanical Systems (MEMS), Micro Systems Technologies (MST) and Micromanufacturing are relatively recent phrases or acronyms that have become synonymous with the design, development, and manufacture of "micro" devices and systems. Micromanufacturing encompasses MEMS or MST and, in addition, includes all of the processes involved in the production of micro things. Integration of mechanical and electrical components, including built-in computers, can be formed into systems which must be connected to the macroworld. Macro, mini, micro, and nano technologies are all a part of MEMS or micromanufacturing. At this point in the development of the technology, it is becoming apparent that mini systems, with micro components, could very well be the economic drivers of the technology for the foreseeable future.

Initial research in the fabrication of microdevices using IC processing technology took place over thirty years ago [1]. Anisotropic etching of silicon was used to produce piezoresistive diaphragms. Since the early 60's, there has been gradual progress in MEMS until the early 1980's when worldwode interest in the technology really started to develop. During this time high aspect ratio micromachining using X-rays was started in Germany [2]. In 1987 the concept of a "Silicon Micromechanics Foundry" was proposed [3]. Since then the interest in the U.S., Germany and Japan has increased to the point where hundreds of millions of dollars of research monies are being funneled into the technology (at least in Germany and Japan) and the technology has been classified as critical or as a technology of national importance by the U.S. government.

Projects Utilizing M^3N Technologies

Four areas of concentration will be developed within the Institute for Micromanufacturing at Louisiana Tech University. They are:

- The design and fabrication of microdevices, such as micro-motors, actuators, sensors, pumps, valves, and connectors.
- The design and fabrication of microstructures, such as micro-heat exchangers, filters, distillation columns and supports for micro-devices and systems.
- Research related directly to the manufacturing processes, including fabrication, metrology assembly and testing of the microproducts mentioned above.

- Microsystem research involving the integration of these microdevices/structures and interfacing of these systems with the macroworld.

Several technologies will be developed and used for the fabrication of these micro devices and structures. First, the existing capabilities in diamond bit machining at Louisiana Tech University will be enhanced. Second, conventional photo lithography and chemical etch will be developed and used for the fabrication of low aspect ratio devices and structures. Third, as X-ray lithography technology becomes available at the Center for Advanced Microstructures and Devices (CAMD) in Baton Rouge, Louisiana Tech and LSU researchers will utilize a dedicated beam line to fabricate high aspect ratio devices and structures. Finally, research and development will be performed on small machines that can build these microproducts.

The Institute for Micromanufacturing is currently involved in the integration of different technologies with direct applications. Several examples of this will be detailed. These applications include micro heat exchangers and heat and mass transport at the micro level, smart bearings with self-diagnostic capabilities, advanced ultra-precision air bearings, surface-driven electrostatic micro positioners and shape memory alloy propulsion for micro robots.

Micro Heat Exchangers

There are applications of micromanufacturing where the final device is in the "mini" region but has elements in the micro domain. Such a device is a micro heat exchanger. A micro heat exchanger is hereby defined as a device with a heat transfer surface density (heat transfer surface area divided by active heat transfer volume) above 5000. Typical compact heat exchangers have a surface density of only 1000 to 3000. With such a high surface density, micro heat exchangers have a very high volumetric heat transfer coefficient.

The micro heat exchangers currently under development are based on high conductivity copper and precision diamond machining. For the plate-type cross flow heat exchanger, thin foils of oxygen free (SAE alloy CA122) or electronic grade (SAE alloy CA110) are used to form the plates. These foils are typically 125 micrometers thick. In the surface of these foils, micro flow channels are machined with specially contoured diamond tools. This machining is performed on an air bearing spindle to reduce vibration and improve channel surface finish. The size of the channels can be variable but are typically 85 micrometers deep and 100 micrometers wide at the bottom [4]. A machined foil is shown in Figure 1 and a single flow channel is shown in Figure 2. After machining, the foils are stacked such that each layer has its channels running perpendicular to the adjacent layers, thus forming the cross flow device. The stack is then vacuum diffusion bonded and the faces are diamond machined flat. The device is then ready for use.

The current design is very conservative so that the fabrication and operating variables may be more easily identified. Current testing is with a device composed of a total of 80 layers. Thus each fluid side has 1440 flow passages and the total active volume is 1.64 square centimeters. The surface density for this particular device is 6876 square meters/cubic meter. Filtered water at 20° C and 70° C were used as the working fluids. The mass flow rate was typically 0.02 to 0.04 kilograms/second. These operating parameters gave a 2 to 5 atmosphere pressure drop through the core and a volumetric heat transfer coefficient of 45 megawatts/cubic meter-K (log-mean temperature difference). A design model predicts that a device with a volumetric coefficient over 300 mega-watts/cubic meter-K is easily attainable [5].

Smart Bearings with Self-diagnostic Capabilities

Bearings are the fundamental mechanical components widely used in manufacturing and other industrial branches. Though small in volume, they are highly complex in construction, featuring different parts like rolling-elements, raceways and cages. Depending on the type of applications, bearings are mostly sealed up after machine assembly and often used under extreme conditions such as in cryogenic regions or high temperature, corrosive media or ultra high speeds. In case of overloading or overheating, bearing failure will occur and manufacturing precision will suffer greatly or a critical component may fail endangering human life.

An effective way of preventing such critical situations and thus helping to maintain the manufacturing precision and improve the machine operation security is the on-line, real time supervision of bearing operating environment [6]. The environment mainly consists of the bearing load and operating temperature. This can be achieved by equipping the bearings with self-checking and error reporting functions through integration of sensors and microelectronics into the bearing environment. This concept is shown in Figure 3.

The sensors embedded in the "smart bearings" generate real time electronic signals which correspond to the force and temperature variations in the bearing components. The operating signals will be continuously monitored by microelectronic circuitry located in the bearing housing. The operating signals will be compared with pre-determined "threshold" values which represent a critical loading or temperature condition. Should a critical condition exist, a signal indicating potential damage will be sent from an embedded high frequency data transmitter to the machine control system which then can make corresponding adjustments. In using only an overload signal, the control system is not burdened with a continual stream of data. However, to generate critical "signatures", the real-time data can be monitored and stored for subsequent evaluation which will also be beneficial to improving the existing machine control algorithm. A novel feature of the smart bearing is that for data transmission, no direct cable connection will be needed. This wireless method is especially suitable for applications where the accessibility of the measurand is not easily available. Similarly, the power supply for the embedded transducer will be provided through non-contact voltage induction.

In contrast to traditional methods of manufacturing precision controls which focus on post-error adjustment and compensation, instrumented smart bearings will allow on-line error source location and pre-failure adjustment. This method can be very well applied to the high-tech areas like aerospace and the military or automotive industry, where high precision, reliability and accuracy of manufacturing and operation are required.

Herring Bone Air Bearings for Ultra-Precision Spindles

Air bearings of all types (including linear guides, x-y tables, and spindles) have been widely employed in the ultra-precision engineering field to ensure the extremely high precision requirements of machinery such as in diamond-tool machining. The design optimization of the journal air bearing for precision and high performance applications is currently in progress. Among various self-acting air bearings, the herring bone type shown in Figure 4 has been considered as one of the best bearings for high speed spindles due to its high efficiency and high stability. For the best possible bearing design, the relationship between the design specifications and the bearing characteristics, such as load capacity and stability, must be known. However, the design information available in the literature only give a limited number of design specification sets. This information is, in most cases, insufficient for design optimization. Therefore, the design of herring bone bearings, especially when high speed and stability are required, still depends mainly on testing and the experience of the designer. Because of this, the design of herring bone air bearings is still very challenging.

The Reynolds equation, which governs the performance of the air bearing, has been numerically solved by specially developed finite element method programs. Once the solution, that is the pressure distribution over the bearing surface, is obtained, the bearing performance may be simulated in the computer.

The groove pump-in angle β affects the bearing load capacity W, as well as the stability indirectly through the bearing attitude angle Θ, (which is a divergent angle between the eccentricity and the direction of load), as shown in Figure 5. The eccentricity ratio in the figure is defined as a ratio of eccentricity to average bearing clearance ($\varepsilon = e/h_0$), while Λ is a nondimensional parameter used to express the rotational speed and n is the number of grooves. Through such figures, the influence of the design specifications on the performance of the herring bone bearing over the most common ranges have been discussed. Consequently, the design optimization of the bearing has been made possible [7].

Surface-driven Micro Electrostatic Positioner

In the past several years, there has become a growing need for micro-sized motors and actuators for applications in micromanufacturing and other microelectromechanical systems domain (MEMS). Among other topics, the design and fabrication of micro electrostatic motors have found widespread interests. Compared to conventional electromagnetic motors commonly used in the large-scale motion world, electrostatic equivalents promise numerous advantages like simple structure, small size, high force-to-

-volume ratio and fine motion/step control.

Among different types of electrostatic motors (side-driven, surface-driven and cylindrical harmonic or wobble), the surface-driven version effectively utilizes the whole stator/slider overlapping area so that its force density is the highest. The basic motion principle is that a sequence controlled multiphase excitation voltage pattern (positive, negative and ground) is applied on the electrodes which are either evenly or unevenly pitched on the stator board. This voltage pattern will induce electrical charges in the slider film which is laid on the top of the stator surface. The interaction between the induced electrical charges in the slider film and the applied charges on the stator electrodes results in three types of forces: an upward levitational force which reduces the contact friction between the slider and the stator, a repulsive force between electrical charges of the same polarity and an attractive force between opposite charges. The combined effects of these forces is that each time the voltage pattern is applied, the slider will move a certain length (step), which corresponds to the electrode pitch width, in a certain direction and at a certain speed, depending on the configuration of the excitation voltage pattern. The slider motion will continue when the voltage pattern cycle applied on the electrodes is shifted and repeated. To enable easy modifications and flexible changes of the excitation voltage pattern for any desired slider motion behavior, the electronic circuits are software controlled by a computer. The excitation voltage generation part of the circuits was built with power bipolar and MOSFET transistors. For control unit protection and isolation, opto-couplers were used. In Figure 6, the principle of an electrostatic motor is schematically shown.

The arrangement of the stator electrodes (linear or radial) determines, whether the slider will perform a linear or a rotary motion. The resolution of the motion steps is mainly dependent on the dimensions and manufacturing precision of the electrodes. By appropriate connection of the slider to further mechanism, it can be well expected that high precision positioners, micro conveyors, micro feeders or micro drive systems can be realized which will find wide applications in conventional and micro manufacturing, medical, biochemical, aerospace or other relevant fields.

Biomechanical Micro Swimming Robots Using Smart Materials

The objective of this research is to design and fabricate microrobots with a simple method of propulsion using smart materials instead of electric motors. Such devices can be fabricated at a very small scale and will have a high strength to weight ratio for special applications.

In this study, two types of micro robots will be designed and fabricated with smart materials based on biomechanical similarity principles. The first type, as shown in Figure 7a, is a jellyfish-like robot with an umbrella made of shape memory alloy (SMA) which has the capability of remembering and reproducing its original shape when exposed to a change in temperature. The second type, as shown in Figure 7b, is a tadpole-like device with muscles made of either SMA or piezoelectric materials, which can change dimensions upon electrical stimulation.

The muscles within the umbrella of the jellyfish will be activated by heat generated from an electric current flowing in the SMA, while cooling will come from the liquid through which the robot is swimming. As the umbrella is heated, it will contract and will result in forward movement of the device. As the umbrella cools, it will return to its original position. With proper design, this impulse will provide a forward propulsion. The muscles on the sides of the tadpole will differentially expand and contract causing the tail to move in a sidewise direction. This reversing process will cause the tail to provide a forward propulsion similar to a fish. The main advantage of this robot is that it is easy to fabricate at small dimensions due to its simplicity of design, it should have high reliability due to the simple movement, and it has high efficiency because no mechanical mechanisms are used.

Designs using SMA materials, and the control systems required for the robots, are often complex and difficult to perform because of the lack of appropriate models. In addition, the hysteresis of the material causes added complexity to the design and fabrication and the hysteresis is not properly understood. A dynamic model of the SMA material has been developed to aid the design and control of the robots. The shape memory effect is the result of a crystalline transformation between two phases of the material and so the model is based upon that phenomenon. From this, the physical properties and behavior of the SMA may be computed for a specific configuration and set of parameters. The SMA is divided into the martensitic and austenitic phases, and the behavior of each is computed for variations in the stress and temperature fields.

To confirm the applicability of the model, a comparison between the model and experimentation was made. In the experiment, TiNi50 wire of 0.1mm diameter and 20mm length was loaded with a 360g mass, and then heated. The heating power was supplied as a square pulse and the wire was allowed to cool by natural convection and radiation into the room at 18 °C. Using heat transfer theory for the heating and cooling process, the simulation was developed for the two phase material. Excellent agreement was found between the simulation and experimental results.

Future Directions

The key to future technological applications will be the ability to rapidly and effectively integrate, as necessary, the macro-, mini-, micro-, and nano-world. Basic science is driving the scale down to, and beyond, the nano-domain. These investigations are necessary to understand material properties and behavior at the fundamental level. These studies are also necessary to understand the fundamental interactions between materials and outside influences such as electrical and magnetic fields, gravity, light, and electromechanical driving forces. Although the science learned at this level will greatly aid in the design and control of micro and nano devices, these devices must still adapt to the macro world.

The Institute for Micromanufacturing is dedicated to the integration of these various domains. Total integration will not be possible at the process level because of the large difference in the dimensional orders of magnitude within the domain. Therefore it is necessary to design and fabricate assist-devices so that either humans or their kinematic extensions can grasp, manipulate, position, adjust, and assemble nano-components or attach/integrate nano-components into a macro- or mini-device. In addition, it will be necessary to develop the speed, sensitivity, reliability, and inspection aspects of micromanufacturing so that these curiosities may move from the laboratory to a production environment.

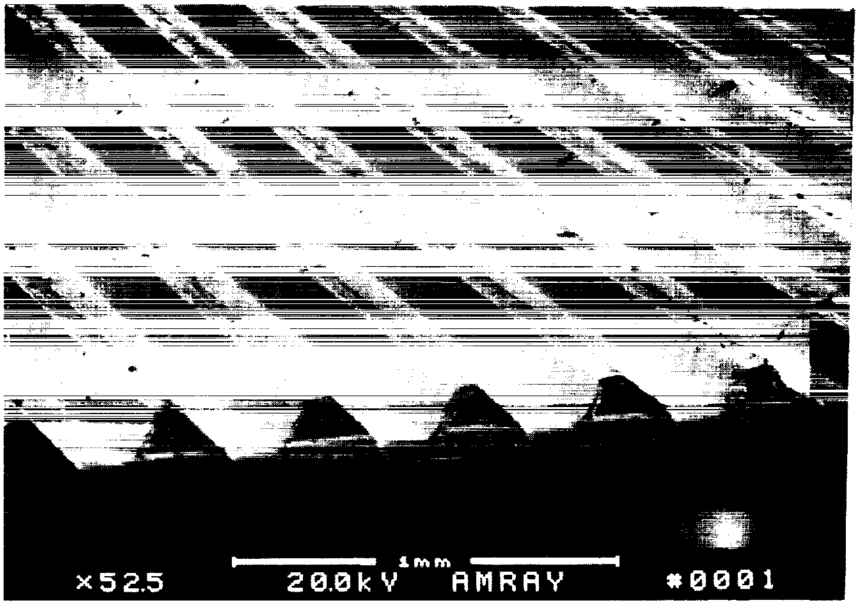


Figure 1. Micrograph of machined flow channels

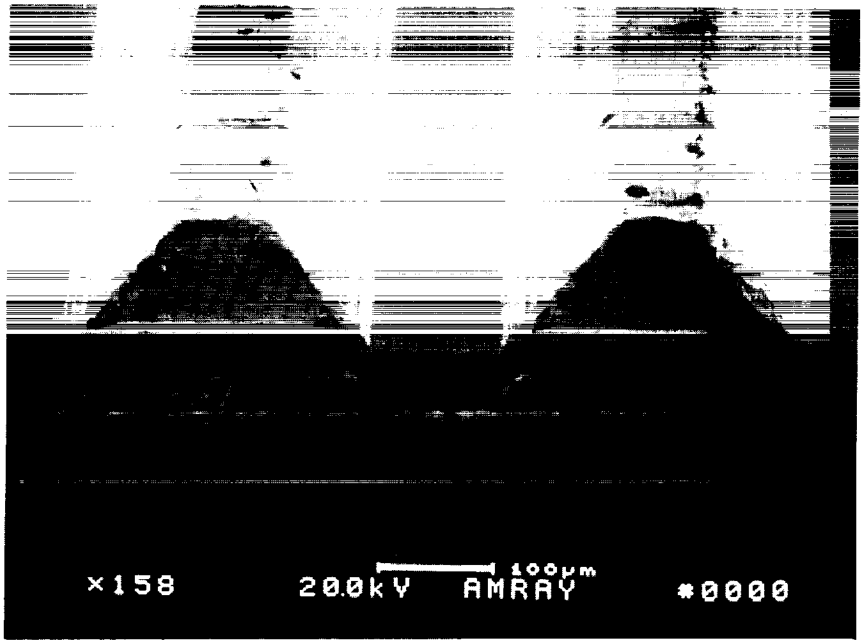


Figure 2. Micrograph of single flow channel (rms roughness 39 nm)

- **Sensitive to force and temperature variations;**
- **Micro size, able to be implanted into bearings environment;**
- **Robust in mechanical construction;**
- **Minimal repercussion on bearings dynamics.**

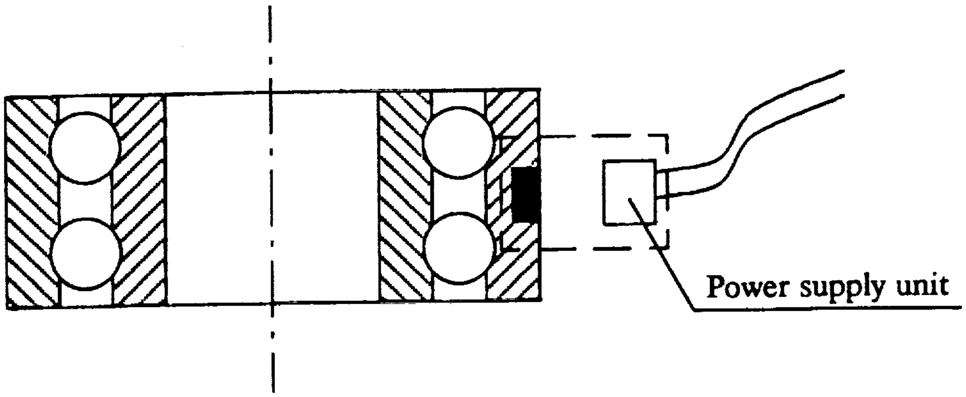


Figure 3. Sensor located in smart bearing

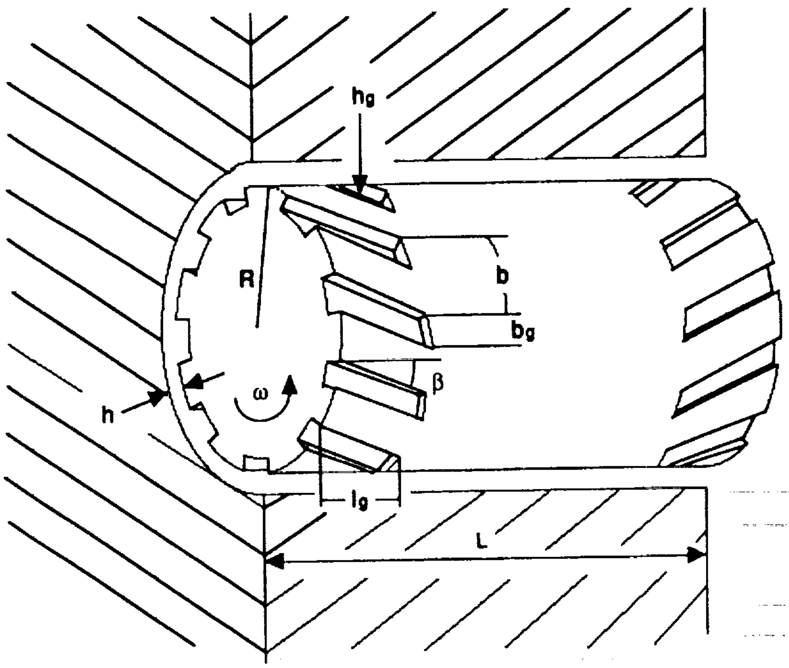


Figure 4. Configuration of a herring bone air bearing

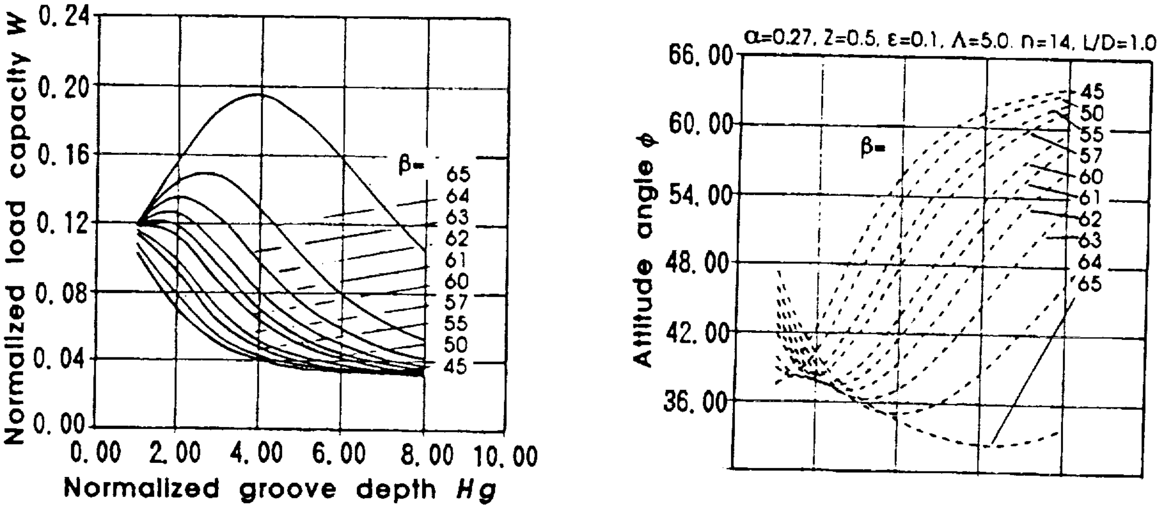


Figure 5. Influence of the groove pump-in angle

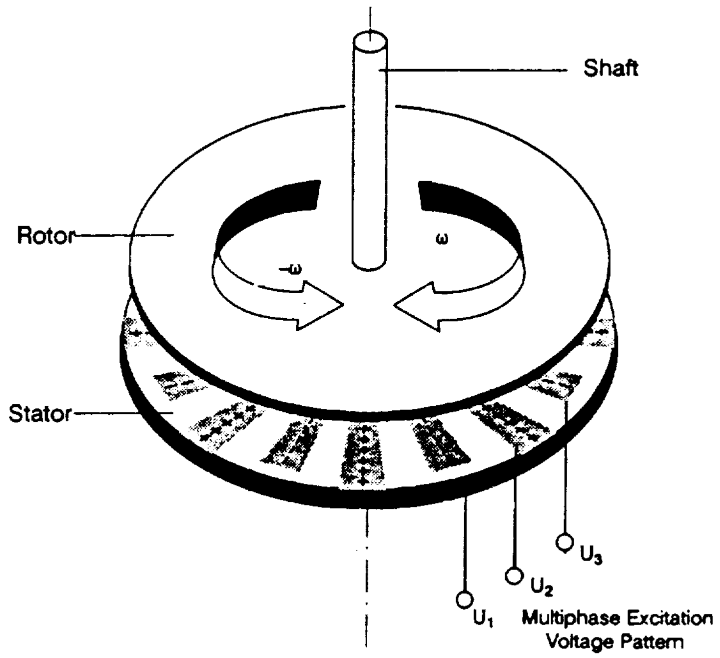
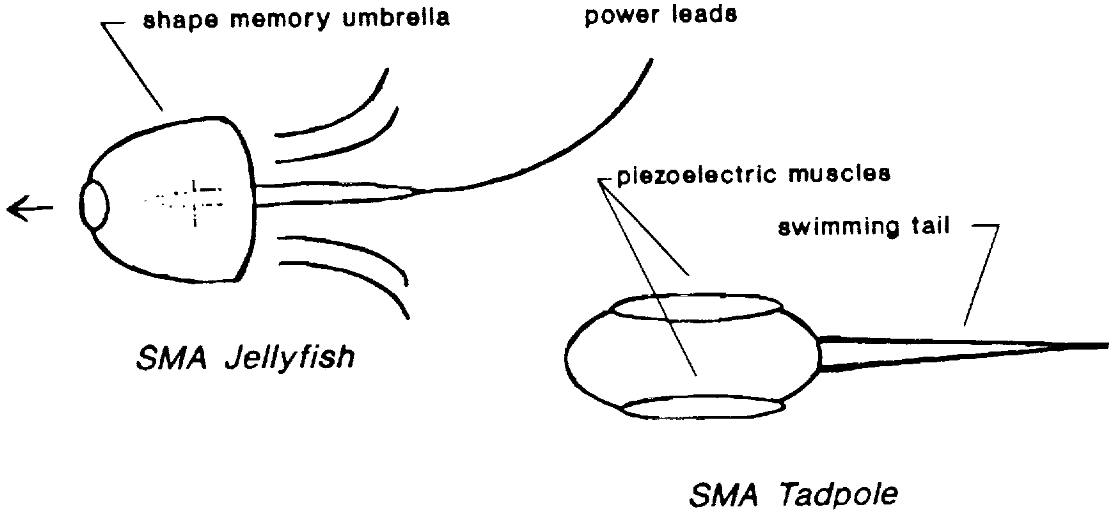


Figure 6. Layout of electrostatic motor



7a. Jelly-fish like robot

7b. Tadpole-like robot

Figure 7. Shape memory alloy robots

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