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# Study of actuator technologies for a miniature distributed

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# STUDY OF ACTUATOR TECHNOLOGIES FOR A MINIATURE DISTRIBUTED MANIPULATION ENVIRONMENT

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## ABSTRACT

Distributed Manipulation Environment (DME), is a concept based on the overall modularity of a manufacturing system including actuation, sensing, control, computing hardware and software. The basic building block of DME is the Manipulation Module (MM). Each MM may consist of up to three units including processing the unit, actuating unit and sensory unit. The emphasis of this paper is on the actuating unit of the Manipulation Modules used in DME.

The generic features of the actuators suitable for this application are discussed and a review of the motion producing characteristics of the following actuator technologies is presented: electrostatic, electromagnetic, fluid power, shape memory alloys, piezoelectric materials, magnetorestrictive materials, charge sensitive gels and electrorheological fluids.

The conclusion suggests that electromagnetic and fluid power technologies still appear to be the most suitable and practical actuator technologies for miniature DME.


## 1. INTRODUCTION

The advances made in theoretical robotics over the last decade have not been exploited in the production of more robust intelligent robot arms. In spite of extensive work in research laboratories all around the world and impressive achievements, robot arms available commercially have not changed much since they were introduced initially in the late 1970's. Operational constraints of articulated robots, which have slowed progress, include computational requirements and the complexity of integrating robots into the manufacturing system. The Distributed Manipulation Environment (DME), reported earlier, offers a new concept for automation of manufacturing systems and proposes an alternative approach for the design and development of robotic systems.

This paper will describe some technologies which may be used as actuating elements for Manipulation Modules used in miniature DME. The generic features of these actuating elements suitable for this application will be discussed. The results of a survey conducted on various relevant actuator technologies will then be presented. Finally, the conclusion of the work and some guide-lines will be given.


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## 2. DISTRIBUTED MANIPULATION ENVIRONMENT

The concept of DME is based on the overall modularity of the manufacturing system including actuation, sensing, control, computing hardware and software. Modularity has a significant effect on the versatility, maintainability and expandability of the resulting product and the manufacturing system itself. The modular approach exploits this fact and suggests that an alternative strategy is to provide a modular distributed manipulation system spread across the whole production line. The conventional robot arm would then be a high-density integration of these modules.

The modularity of the controlling software and hardware is achieved through a parallel computing platform based on the transputer. This will simplifies the task of software design and development when compared with conventional methods of distributed processing. It also adds the features of flexibility, reconfigurability, versatility, maintainability and expandability to the computing platform.

The basic building block of DME is the Manipulation Module (MM). Each MM may consist of up to three units including a processing unit, actuating unit and sensory unit. The presence or absence of these units in a MM will produce a different type of MM with a particular functional attribute. Furthermore, the MM's interface with each other to form a macro structure. Each MM therefore has mechanical and communication links for interface to others. Communication is provided by the transputer link.

## 3. GENERIC FEATURES OF ACTUATORS

The miniature DME considered in this study may consist of a large number of small actuators. The mechanical relationship between these actuators and the topology of the overall system depends on the specific application in mind. The actuators would be arranged so that they are collectively used to move an object along a trajectory in the horizontal x-y plane with no mechanical link between them. On the other hand, the communication between them is crucial in order to synchronize the operation and achieve the objectives set for the system. Several MMs with sensory units are required to determine the location and orientation of the objects. For micro-manipulation however, depending on the number of degrees of freedom required, two or more of the MM's should be mechanically linked. It is important to avoid complex chained topologies.

In spite of the differences resulting from the application-dependency of the actuators, it is possible to define some common features for them:

i) The controllability of the actuators is of utmost importance. In addition the control strategy required should be simple requiring minimum amount of feedback.

ii) Such an actuator should provide a reasonable amount of driving force.

iii) A fast frequency response is generally required.

iv) Due to the high number of actuators used in the system, the cost per module should be low to make it economical for a wide variety of products and applications.

v) Power consumption and dissipation can be a matter of concern if the number of actuators is high. A low power consumption is then desirable.

vi) High reliability & long life will reduce the maintenance cost.

vii) The manipulation environment may have to be cleaned regularly, particularly if food items are to be handled. The actuators should not be an obstacle in this process

viii) The actuator technology should ideally be generic in nature and be able to be easily manufactured in a range of sizes.

ix) The actuator should be compact while satisfying the other requirements mentioned above.

## 4. ACTUATOR TECHNOLOGIES

### Electrostatic

Electrostatic forces have for a long time been recognized as a viable actuating technology [12]. All actuators and motors rely on the basic principle that a force is produced between two conducting objects held at different electrical potentials. A convenient arrangement for providing this force is two parallel plates of area A, separated by a distance d. In this instance, the force attracting the two plates is given by:

$$F = -4.4\,E\text{-}12\,\frac{A\,V^2}{d^2} \quad (1)$$

Where: V = the potential difference between the two plates
A = plate area
d = distance between plates

A quick analysis of the above equation shows that electrostatic forces tend to become significant for dimensions in the micron range, hence their popularity as micromotors designed on silicon ICs. For example, a simple parallel plate actuator of similar dimensions to a solenoid (a plate area of 1 $cm^2$ and distance between the plates of 4 mm for example) would produce a force of only 2 E - 7 N, in air, with an applied voltage of 100 V. As d is reduced however the force varies as the inverse square of the d. The same actuator with d = 1 $\mu$m for example would yield a force of 8 N, all other parameters being equal. Clearly these tolerances are only achievable using technologies such as those used for IC manufacturer.

Were the magnitudes of electrostatic forces greater this technology would offer excellent possibilities for a low cost array of actuators. One can imagine two sheets of flexible PCB material containing etchings of the parallel plates and interconnect, separated by a thin layer of electrolyte. Unfortunately however, the small forces available leave electrostatic actuators to the realms of the IC designer.

### Electromagnetic

Electromagnetic technology has been commonly employed for small scale actuators. This technology offers good driving force with reasonable ranges of frequency response. The major disadvantages are the non-linear relationship between force and stroke (air gap) and the heat generated in the coil.

The dynamics of solenoids are very complex, however, a good approximation can be obtained from the following equations.[14]

$$ma + bv + kx = 0.5 i^2 dL/dx \quad (2)$$

$$V_o = iR + L(x)\frac{di}{dt} + i\frac{dL(x)}{dx}\frac{dx}{dt} \quad (3)$$

Where: m = moving mass;
a = acceleration of mass
v = velocity of mass
x = position of mass (0 = no air gap)
b = damping constant
k = spring constant
L = inductance of air gaps
i = current

Typically, forces in the 1 to 5 N range are available with solenoids diameters of 14 to 19 mm with a frequency response in the 100 Hz range.

### Fluid Power

This category of actuators have fluid envelopes that expand and contract due to changes in pressure or temperature. Apart from conventional cylinders and motors, recent work has seen the development of simpler "muscle like" actuators. These actuators imitate muscle type actions by contracting in length as the fluid envelope expands.

Several products of this type have been on the market for some time. Most use air as the working fluid and are operated through conventional proportional control valves. Typical dimensions of these actuators are, diameters 7 to 21 mm, lengths 200 to 450 mm. Maximum contractions rates are approximately 20 %, generating a force in the order of 5 kN with an internal pressure of 4.0 $kgf/cm^2$. The frequency response of these actuators is in the order of 10 Hz.[13]

### Shape Memory Alloy(SMA)

Shape memory describes the ability of some alloys to memorize their form after being annealed. If the annealed SMA workpiece is deformed while below its "thermoelastic martensitic transformation"[1] temperature the deformation can be reversibly recovered by heating above the transformation temperature. This recovery can occur over a range of strain exceeding 7% and the associated stress recovery can exceed 250 MPa [1].

Since the mid 1980's several groups, Bergamasco *et al*, Kuribayashi, Ikuta *et al* and others have been developing small actuators using SMA's for robotic & medical applications. [1 & 2] Recent work has concentrated on active elements made from Titanium and Nickel alloys. Bergamasco and his colleagues have published performance data for actuators they have developed which are driven by Ti-Ni coil springs. A general arrangements of these actuators can be seen in the following figure.

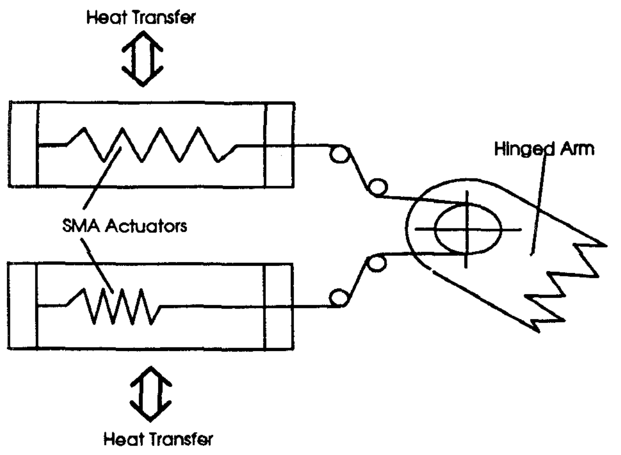


Fig 1: General arrangements of a Bergamasco *et al* style actuator.[1]

The basic operation of the actuator is as follows. The elongated spring has been deformed while below the transition temperature. The contracted spring has relaxed from an elongated state after being heated. When the elongated spring is heated (approx 40 °C for Ti-Ni)[1] it contracts to its relaxed length. This moves the finger through an arc and elongates the previously contracted spring. This operation can be repeated in order to make the finger oscillate.

The physical dimensions of the springs used in the Bergamasco *et al* style actuator are given below. The performance results for this actuator suggest it can recover approximately 3.5 N from being heated from 25 °C to 50 °C and approximately 4.5 N if heated to 100 °C. The frequency response of the above style of actuator is approximately 1 Hz when water cooled.[2]

| | | |
|---|---|---|
| Spring Dimensions: | wire dia of 0.5 mm; | coil dia of 1.5 mm; |
| | length of 7.0 mm; | 14 turns; |
| | mass of 0.08 g. | |

The major limitations are poor efficiency, typically less than 10 %, frequency response of the heating and cooling cycle, and the nonlinear recovery associated with SMA.[3]

Piezoelectric Materials

Over the last few years a variety of micro-actuators have come to market which use piezoelectric material as the active element. Piezoelectric ceramics, which are solid solutions that typically contain: lead, titanium, zirconium, oxygen and other elements, exhibit changes in strain when exposed to electric fields. The magnitude of the change in strain is in the order of 10E-7 mm per volt and can occur with a frequency response exceeding 150KHz.[5]

The types of actuators available can be broadly split into two categories, those using standing waves and those using traveling waves. The stationary wave variety produce motion by allowing a vibrating element to thrust against a moving element with a given period. The traveling wave variety induce a traveling wave in a stator which inturn massages a moving element.[4] Examples of each type are presented in the following paragraphs.

As described above, the standing wave variety of actuator produce motion by periodically thrusting against a moving element. This is analogous to spinning a wheel by periodically giving it a little kick. As the magnitude of the kicks are very small, the moving element must be kicked often to move any appreciable distance. Micro Pulse Systems Inc. of Santa Barbara, CA produce a range single and multi axes actuators and give the performance information shown below.[5]

| Type | Linear | Rotary | Planar |
|---|---|---|---|
| Velocity | 100mm/s | 150 RPM | 12 mm/s |
| Resolution | 20K step/mm | 75K step/rev | ------- |
| Running Force | 1.7 N | -------- | 1.1 N |
| /Torque | -------- | 7.2 Nmm | ------- |
| Clamping Force | 3.4 N | ------- | 4.5 N |
| /Torque | ------- | 14.4 Nmm | -------- |

Traveling wave ultrasonic motors have been developed with a variety of physical configurations. A disk and ring configuration is described in [4] and a linear configuration is described in [6]. These actuators use piezoelectric elements to induce traveling waves in the stationary member. These waves produce local distortions which ripple along the drive surfaces of the stationary member. These distortions then massage the moving element causing it to move in the direction of the induced waves. The following performance information was for the disk type motor presented in [4].

| | | |
|---|---|---|
| Outside Dia 40mm, | Height 10mm, | Mass 60 g, |
| Input freq 72 KHz, | Input Power 3.5 W, | |
| Unloaded rotation 600RPM, | | Torque 100 Nmm. |

In addition to the types of actuators described above, piezoelectric elements have been incorporated in a variety of micro or "Gnat" type robots.[7] Larger displacements have been produced by accumulating the strains of laminated or stacked piezo material and ingenious use of different geometry & interacting arrangements of piezoelectric devices.

Magnetorestrictive Materials

Magnetorestrictive materials exhibit changes in strain when exposed to magnetic fields. The recent emergence of highly Magnetorestrictive alloys, which offer rates of strain in the order of 0.2% (10 times that of piezoelectric material), have generated interest in actuator design using this principle.[8] The material which displays the highest rate of strain at room temperature is an alloy of terbium, dysprosium and iron called Terfenol-D.

The following performance information for Terfenol-D was found in [8]. Strain is approximately proportional to magnetic field strength up to strains of about 0.1%. Further, by suitable compressive preloading of the Terfenol-B, strains of 0.1 % could be achieved with field strengths of 47 A/mm. The force produced can be determined via the conventional stress strain relationship, the modulus of elasticity being 34.5 GPa.[8] The frequency response of the material is for practical purposes limited by the rise time of the magnetic field. Further, the material is not subject to fatigue but can heat up during rapid cycling from induced eddy currents.

This material would appear suitable for use as the active elements in ultrasonic motors like those described in the section on piezoelectric materials. Its advantages over piezoelectric material appear to be higher rates of strain, very high frequency response and simpler electronic excitation systems. However, at present the material cost is considerably higher than piezoelectric material.

### Charge sensitive Gels

Recent work with polyelectrolyte gels [11] has led to the production of a substance which contracts to 4% of its original volume when a current is passed through it. When the direction of the current is reversed, the gel expands again. Figure 2 shows how this gel has been used to construct a novel walking 'gel-looper'.

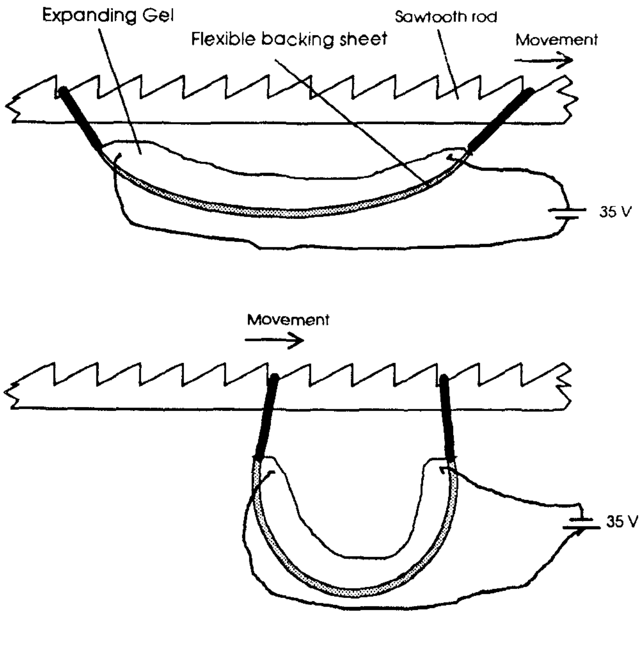


Figure 2 - The Walking 'Gel Looper'

With the device immersed in water a 35V DC signal was applied between the two ends of the gel and the polarity was swapped approximately every two seconds. This gave the device a walking speed of about 15 mm/min.

Potentially these gels offer a very convenient form of technology for an actuator array. The gel is cheap to produce and actuators constructed from it are easily controlled and easily manufactured. The main disadvantage with this technology is its response speed. It may be possible to improve this however since experiments on micro particles of the gel have shown that 1 µm particles can theoretically contract to 4% of their original volume in 0.23 ms.

### Electrorheological Fluids

While not strictly a motion producing technology, electrorheological fluids have potential to control the transfer of motion. Electrorheological fluids can increase their viscosity when placed in an electric field. Prototype applications for these fluids include clutches, solid state fluid valves and "smart" vibration dampers which can adjust to different operating conditions.[9]

The fluids are typically suspensions of micron sized ceramic, polymeric, or graphite particles in a silicon or mineral oil based carrier fluid. When the fluid is not exposed to an electric field the particles exhibit a random orientation and are free to move within the carrier fluid. When the fluid is exposed to an electric field the particles align themselves with the electric field and form "chain like" structures which restrict particle mobility and increases the fluid's viscosity.[10]

In general the fluid's sheer stress increases linearly with applied voltage. Most fluids have a shear strength of about 1 kPa when exposed to a field strength of 4 kV/mm. However sheer strengths of 3.5 kPa at 2 kV/mm can be achieved if a relatively high unexcited fluid viscosity can be tolerated.[9] Other factors which impact on its application are limited working temperature range, approximately 30 $^{o}$C and repeatability problems (caused by particles settling out of suspension). The temperature range limitation is due to changes in electrical properties of the fluid. Typically, the current will double for every 6 $^{o}$C increase in temperature. The frequency response of the viscosity change is almost instantaneous.[9]

## 5. SUMMARY AND CONCLUSIONS

The following table summarizes the merits and demerits of the technologies considered:

The study conducted in this work shows several emerging technologies which, with further development, would offer a practical solution to the problem of finding a cheap, effective actuator which meets the all the requirements listed earlier. Piezo and magnetorestrictive motors for example are good in most respects, except for cost. This situation could change as the technology matures.

Charge sensitive gels are cheap but at present do not have sufficient performance. Again, this situation could change as the technology matures. Electroreheological fluids are another example of a potentially useful product but with performance issues to be addressed.

For the moment the more mature technologies, such as fluid power and electromagnetic devices, still appear to have the best cost/performance ratio. In 5 or so years time however, this situation could be very different.

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| Actuator Technology | Assesment Criteria | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Control - ability | Driving Force | Frequency Response | Cost per Element | Power Consumption | Reliability | Ease of Cleaning | Scalability |
| Electrostatic | Very Good | Very poor | Very Good | Very Good | Very Good | Very Good | Very Good | Very Poor |
| Electromagnetic | Fair | Fair | Good | Good | Poor | Poor | A.D. | Good |
| Fluid Power | Fair | Good | A.D. | Poor | Good | Very Poor | A.D. | Fair |
| SMA | Good | Good | Poor | Fair | Poor | Good | A.D. | Fair |
| Piezoelectric | Very Good | Very Good | Very Good[1] | Poor[2] | Good | Good | A.D. | Good |
| Magnetorestrictive | Good | Very Good | Very Good[1] | Very Poor | Poor | Good | A.D. | Fair |
| Expanding Gels | Good | Poor | Poor | Very Good | Poor | Good | Very Good | Very Good |
| Electrorheological | Fair | Poor | Very Good | A.D. | Fair | Poor | A.D. | A.D. |

1. These technologies respond almost instantly to the applied driving signal. However, because of the small amount of movement produced they normally have to be repeatedly pulsed to produce a practical actuator.

2. Piezoelectric material by itself is very cheap to produce. However, to produce a piezo motor giving reasonable movement and speed is relatively complex. Hence, for now it is relatively expensive.

AD > Application dependent. The ability of the technology to meet the assessment criteria depends on the particular way it is applied.