Shape Morphing Structures via Intercalation Compounds

by

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ABSTRACT

Recent research has allowed the use of electrode-active materials as actuators by harnessing reversible volumetric change due to intercalation during charging and discharging. These actuators provide a relatively large strain, 2-3%, while requiring less than ten volts to operate with a cycle time on the order of one hundred seconds. This technology can be used in any moderate bandwidth, high-force, high-strain application, including shape-morphing helicopter blades, boat hulls, satellites, and any other structure that benefits from shape change.

An analysis is performed on the state of the technology, the intellectual property held, and the potential markets that exist. A recommendation is made to pursue the technology, while cognizant of the fact that it is still in a seed stage and requires significant time and financial investment before entering production. Two business models are proposed and rough market calculations are also presented.

The basis of this project is work done at the Massachusetts Institute of Technology by Professor Yet-Ming Chiang and Professor Steven Hall. Industrialists, including but not limited to, William Fallon and Dan Ursenbach of Sikorsky Aircraft in Stratford, Connecticut are also involved in the project.

Thesis Supervisor: Yet-Ming Chiang
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1.0 Introduction

Recent advances in moderate bandwidth, high-force, high-strain actuation materials in the form of intercalation compounds has brought large-scale, shape-shifting structures into the realm of possibility. Piezoelectric and magnetostrictor materials that are available today have relatively low energy densities and a reversible strain limit of about 0.2%. Shape-memory alloys have a much higher energy density and strain limit, but require temperature control and are intrinsically slower due to the necessity for phase transformations.

Electrode-active materials, such as those in rechargeable batteries, undergo reversible strain when charged and discharged due to intercalation (reversible inclusion of a molecule between two other molecules). In the context of batteries, this is an undesirable side-effect and a source of degradation [1]. However, this effect can also be harnessed as an electrochemical actuator.

Unlike piezoelectrics and magnetostrictors, which are both appropriate for high frequency and low strain applications, these electrode-active materials fill the need for moderate frequency, high-strain applications. Intercalation compounds studied thus far offer reversible strains of 2-3% in approximately 100 seconds, compared to 0.1-0.2% strains in piezoelectrics [1][2].

These properties allow entrance into a new regime of large-scale applications, where mechanical strength is critical. Four such applications will be examined in section 3.2. However, for any large-scale use of this technology to be considered, its commercial viability must also be proven. Section 4 of this paper will consider the business case for pursuing this technology. This is not to say that the small-scale application potential of this material should be dismissed. Being a solid-state, single-component actuator lends to devices' durability and performance. However, micro-scale applications will not be investigated in detail here.

2.0 The Technology

It is well-known within the field of ion storage materials that intercalation causes lattice constant and volumetric changes in the crystal, as schematically shown in Figure 1. In a graphite-based electrode with lithium ions as the intercalation species, shifts of lithium ions into graphite planes cause approximately one percent strain parallel to the plane and on the order of ten percent strain transverse to the plane. However, due to the physical and kinetic constraints, measured values vary. Nevertheless, when a material such as those in electrodes of lithium ion batteries is charged and discharged, and there are no external constraints on the material, it undergoes extension and contraction.

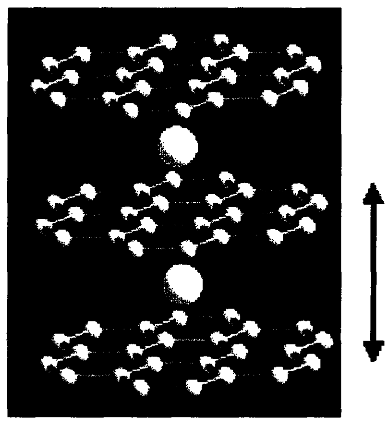

Figure 1: A schematic of atomic intercalation of lithium in graphite. The yellow atom represents lithium and the white atomic planes represent graphite [3].

2.1 Prior Work: Material

In 1992, K. Takada *et al.* showed that intercalation of silver in electrodes of silver vanadium oxide ($Ag_xV_2O_5$) mixed with silver iodide tungsten oxide ($Ag_6I_4WO_5$) can be utilized to generate approximately 2% free volume change of the electrodes. Takada *et al.* used a reflection-based displacement meter to measure strains as the electrodes were charged and discharged. The actuation of the material was noted as well as the fact that the materials' strain states remained unchanged during "rest periods," or the time when no charging or discharging was occurring [4]. However, no loads were placed on the electrodes, so the ability to perform actual work was not documented.

T.E. Chin, Y. Koyama, and others have since demonstrated that these materials can, in fact, support large mechanical loads [1][2]. Chin *et al.* used commercially available prismatic lithium ion batteries, all utilizing $LiCoO_2$ as the cathode and graphite as the anode. Volumetric changes were measured by the displacement of silicone oil up a capillary, corrected for thermal expansion. Free volumetric strains were measured to be only 1.25-1.55%, several times smaller than the 6.9% theory had predicted – though the theoretical value doesn't include the packaging of the active material. Uniaxial strains were measured at 2-3%, larger than the 2.2% predicted for an isotropic system because expansion is greater through its thickness than in other directions (i.e. the material is not isotropic). Stresses up to 9400 psi (65 MPa) were applied before internal shorting gradually prevented actuation of the material. With approximately 1500 psi (10 MPa) of load, the strain still exceeded 1.5% [1].

Both of above-mentioned studies also tested application of a cyclic potential, resulting in cyclic strain. In addition to the cyclic strain expected in response to the applied voltage, the absolute strain during each cycle also varied due to the material's viscoelasticity, as seen in Figure 2. This viscoelastic behavior can be explained, at least partially, by deformation of the porous structure of the specimen – a cell with approximately 30 volume percent active material – being tested. It can be reduced by pre-stressing the material [1].

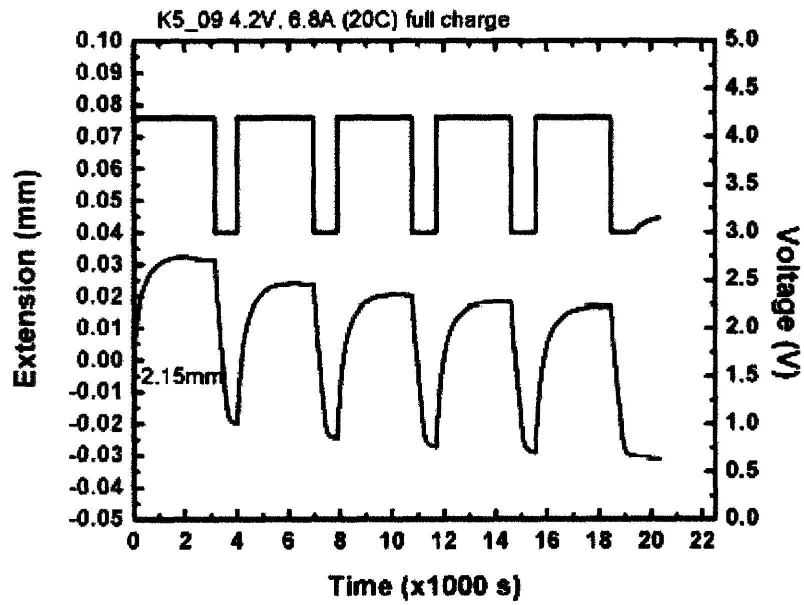

Figure 2: A plot of extension varying with a cyclic voltage [3].

2.2 Comparison with Other Material Types

The material's extension is governed by diffusion's effect on the lattice constant, thus the bandwidth of its reaction to an applied voltage is limited. Current materials require on the order of 100 seconds in order to effectively actuate. As discussed in section 1, intercalation compounds offer reversible strains of 2-3% in approximately 100 seconds, approximately ten times the strain offered by the best piezoelectric materials on the market today.

In addition to the strain and bandwidth, there are other key differences between piezoelectrics and intercalation compounds. The former operates at hundreds of thousands of volts and the latter at fewer than 5 V. The density of a lead-zirconium-titanate (PZT) piezoelectric ceramic is approximately 7500 kg m^{-3} and that of a graphite intercalation compound is 2100 kg m^{-3}.

Assuming stress state does not affect lithiation saturation, the elastic energy density, $\frac{1}{2}E\varepsilon^2$, can be calculated using a theoretical cycle in which an intercalation compound is actuated, then compressed to its original dimension. The stored energy of lithiated graphite (taking E = 35GPa, ε = 10% at saturation of LiC_6) equates to 175,000 kJ m^{-3}. This value is over 1,000 times that of a lead-zirconium-titanate piezoelectric ceramic. Figure 3 shows a comparison of energy densities of various classes of materials.

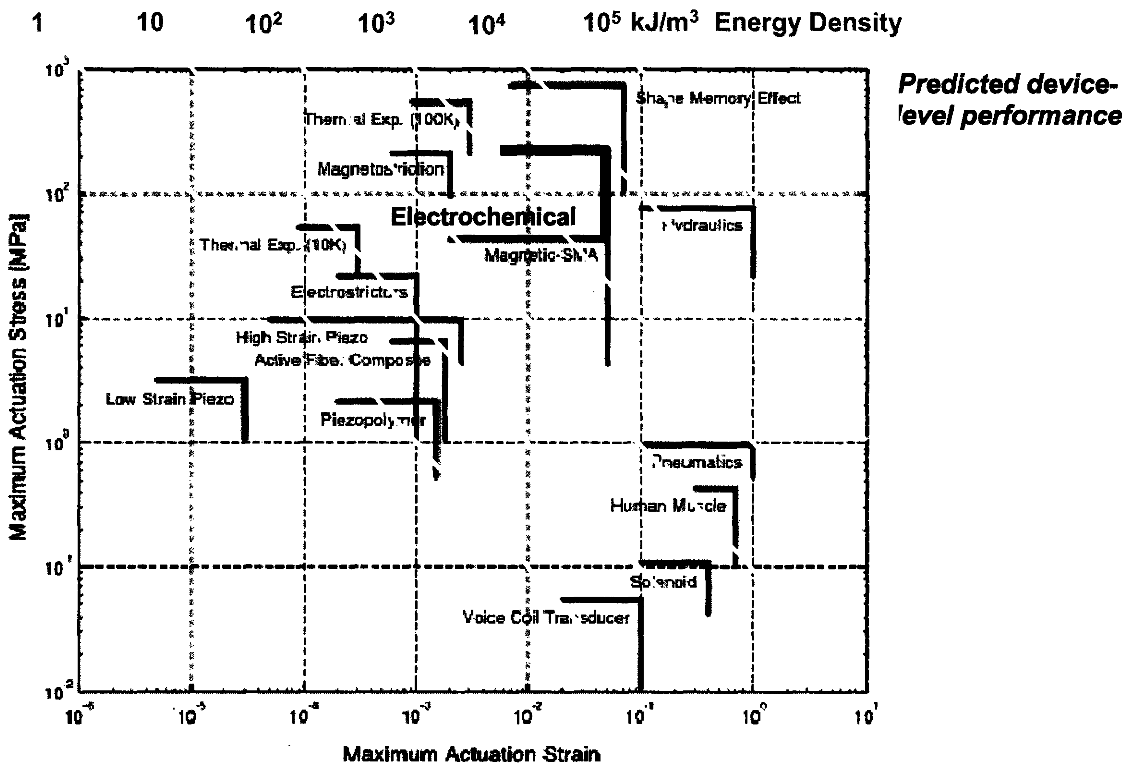

Figure 3: Comparison of energy densities of various classes of materials and devices [5].

2.3 Devices Characteristics

Hydraulics and shape memory alloys have higher energy density than intercalation compounds, but their applications are limited by other factors. Hydraulic devices are generally heavy, and as in the rotorcraft example discussed later, do not operate well in the presence of centrifugal forces. Shape memory alloys require temperature control, and are thus restricted to either small-scale or well-insulated devices in order to be efficient. Recent work on compounds containing $LiCoO_2$ for lithium extraction and graphite for lithium insertion has shown high energy densities using conventional materials, preventing the need for expensive, novelty materials [2][6].

Use of intercalation compounds as actuators has the additional benefit of possible "set-and-forget" characteristics, where an open-circuit condition will maintain the material's state of strain. Thus, energy requirements for devices that are not in frequent motion are low. For example, the boat hull example discussed later will normally only be required to actuate a few times per trip.

If the material is appropriately positioned in the actuator, some of the energy from the material's discharging can even be used to actuate itself. Consider two actuators placed in opposing directions: during an actuating event, the discharge from one can be used to charge the other while both are providing force in the same direction.

2.5 State of Technology

Looking at the state of this technology in a normal development timeline, as defined by E. Fitzgerald [7], it is clear that the first technological barrier has been surpassed. Several proof-of-concept prototypes, including a laser-machined micro-actuator and a helicopter rotor blade section, using intercalation compounds have been created and tested [2],[6]. The next, and largest foreseeable, barrier to production is choosing a material with proper stiffness and rates for practical use. Materials exist with each of these properties separately, but choice of a compromise material or combination of several materials is necessary. Whether this qualifies as a second, much larger, technological barrier is questionable. For the purpose of this analysis, we argue that it does not, and thus the second barrier does not exist.

The second, larger, technological barrier would normally become apparent during the attempt to use a technology to fabricate a useful device. In the case of intercalation compounds, an operational rotor blade section has already been built [6]. It can be argued that the prototype is sub-scale and at a component level, but the device's complexity should also be considered. Aircraft parts are mechanically complex, with stringent weight and design requirements. If such a prototype can be built, then a simpler device should not pose any insurmountable technological barriers.

In the initial phases of the technological discovery, there was a very high perceived value. Two well-known MIT professors – Chiang and Hall – were collaborating, the first prototypes were fabricated, and news articles were written [8]. Several other groups around the world were also working on related technologies [3][9][10]. These projects have since faded more into the background of public view, thus we can expect that the technology has progressed beyond the false start point. There are still several barriers before practical application of the technology, so there is some investment opportunity at the current time, but not the large gap between perceived and real values that often arises later in the development timeline.

This technology has not undergone a spike of activity in the field – perhaps because the technology was developed when an individual/group saw the opportunity to take what was regarded as an unwanted side-effect and create a product of value. That is, electrode strain during charge-discharge cycles of batteries was utilized to create a functional actuating device. Figure 4 summarizes the state of this technology with respect to technological barriers, monetary value, and activity in a schematic form.

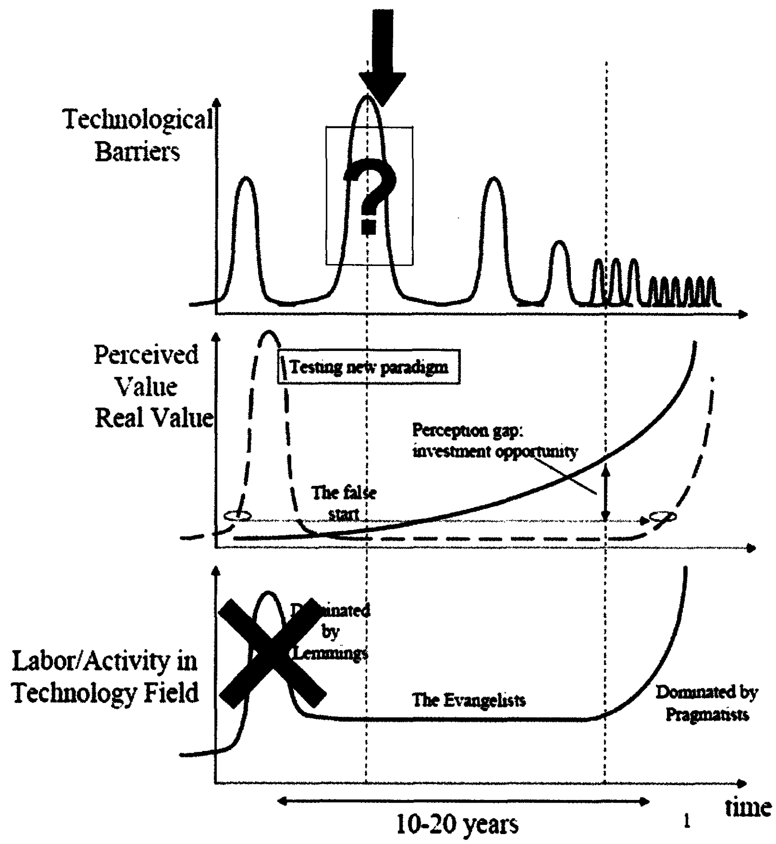

Figure 4: Schematic of technology development timeline. The arrow indicates current state of the technology of interest [7].

2.6 Intellectual Property (IP)

A key element of the high-technology sector of the economy is the patent. While trade secrets and so-called "tribal knowledge," or experience, can give one company a competitive edge over another, ultimately intellectual property in the form of patent protection is the basis of long-term risk reduction and growth. Whether the patents are owned or licensed, having a well-planned out strategy for use of intellectual property is important to success of a business.

2.6.1 Intercalation Compounds' IP

A search of both the *United States Patent and Trademark Office's* and *Free Patents Online's* databases showed that a strong position is held with intellectual property by Y. Chiang *et al.*, assuming that the patent is issued without complications [11],[12]. The patent application, number 20060102455, claims methods, devices, and structures using electrochemical actuation mainly through the use of intercalation or alloying [13]. Among the claims are actuators, consisting of electrodes with active material, that change dimension or volume upon the application, or cessation, of voltage due to intercalation in the active material.

Also claimed are a number of variations of such an actuator, however the concept is similar in each: an applied potential causes intercalation, leading to mechanical motion. The electrodes are usually in solid form, though they can also be powdered, stacked, and/or rolled. In each case, the device will perform some useful physical action when a potential is applied. The electrodes in such a device can also be donor or acceptor of the intercalation species; however those applications are not covered in this paper.

The most basic embodiment of intercalation compound devices include a positive and a negative electrode, with intercalation species, that performs useful work on a physical load when an electric potential is applied. The same concept is used in a series of stacked positive and negative electrodes. If a positive and a negative electrode are laminated and rolled, then the applied voltage can be used to wind or unwind the coil, producing torque. Electrodes in the form of long filaments can be used to perform work or used to form composites. Actuators can be used to amplify stresses or strains, direct or pump fluids, produce movement in a nastic structure, or in many other applications.

Analyzing every potential application in detail is not the intent of this paper. The above is meant only to give a broad overview of the patented technology available to the inventors. Several applications are chosen for further discussion in section 3.2. Refer to [13] for further details, if desired.

2.6.2 Potentially Competing Technologies' IP

Other, potentially competing, actuating technologies were also investigated. Several interesting methods of manufacturing and applications of these materials are discussed, but because this paper seeks to analyze intercalation compounds and their applications, discussion here will be limited to overlapping applications and properties. Keiskue Oguro *et al.* have patented a particular method of ion exchange that bows/deforms a membrane by application of an electric field. However, the application is limited to an "ultra-small actuator element" and the membrane must contain water [14].

A patent by R. Baughman *et al.* entitled "actuators using double-layer charging of high surface area materials" lists several macro-scale applications, including actuating optical fibers and use in artificial muscles [15]. Although both Chiang and Baughman's materials are able to convert electrical energy into mechanical energy, they utilize different mechanisms. Chiang's uses intercalation; Baughman utilizes high surface areas, such as that available when utilizing carbon nanotubes, to allow for charge injection, as shown in Figure 5. A power source is used to form a layer of charge in the nanotube surfaces and compensating charges are supplied by the electrolyte. Thus, a double-layer of charge is formed, allowing control of various mechanical and electro-magnetic properties [15][16]. Although intercalation also contributes to the actuation of the material, it is not the primary device of actuation. Other applications, such as attenuation of electromagnetic radiation will not be discussed here for reasons listed above.

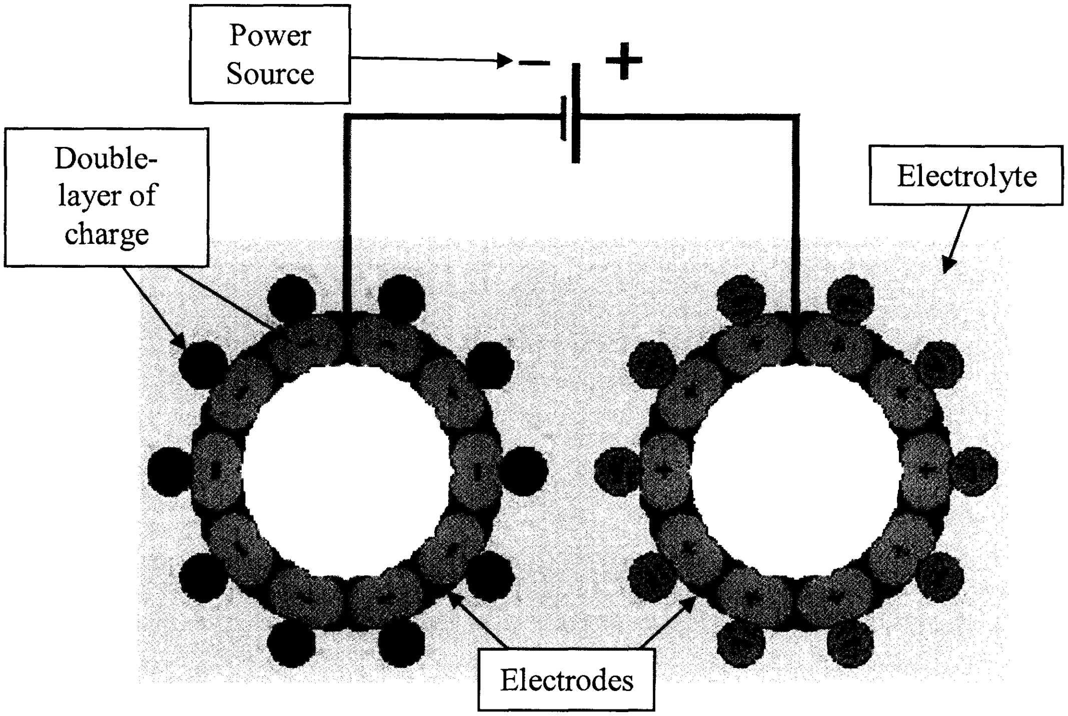

Figure 5: Mechanism of actuation in patent number 6555945 [15][16].

The "quantum chemical-based expansion due to double-layer charging" nanotube-based material that Baughman's patent was likely submitted to claim theoretically has higher energy density, faster actuation rates, larger strains, and similar voltage requirements to Chiang's material [16]. However, these materials will require significant time before they can be used in practice because current nanotube sheet manufacturing capabilities are not yet able to produce the properties required for such devices. Even recent research shows a maximum real strain of only 0.2% [9]. Because the physical/chemical method of actuation is different and the available strain levels are limited by an immature complementary technology, there is no direct conflict between these two sets of materials.

D. Suh recently filed a patent application partially utilizing a concept published by J. Weissmüller *et al.* on using electric charge to actuate nano-porous platinum [17][10]. Weissmüller induced reversible strains up to 0.15% on platinum with a continuous network of nanometer-sized pores by applying a voltage relative to an electrolyte that was impregnated in the material. Figure 6 shows a schematic of a similar process, where an array of metal nanoparticles was immersed in the electrolyte and a resulting double-layer of charge is formed. Suh's patent application claims mainly the ability to retain the unit cell volumetric changes in electrolyte-free materials, thereby affecting electric, magnetic, and optical properties. However, it does also claim high strain and high rate actuators. However, the aqueous electrolytes used restrict the applied voltage, and rates are still governed by diffusion [18]. In other words, a significant amount of time and research is still required before practical actuators can be produced from this technology.

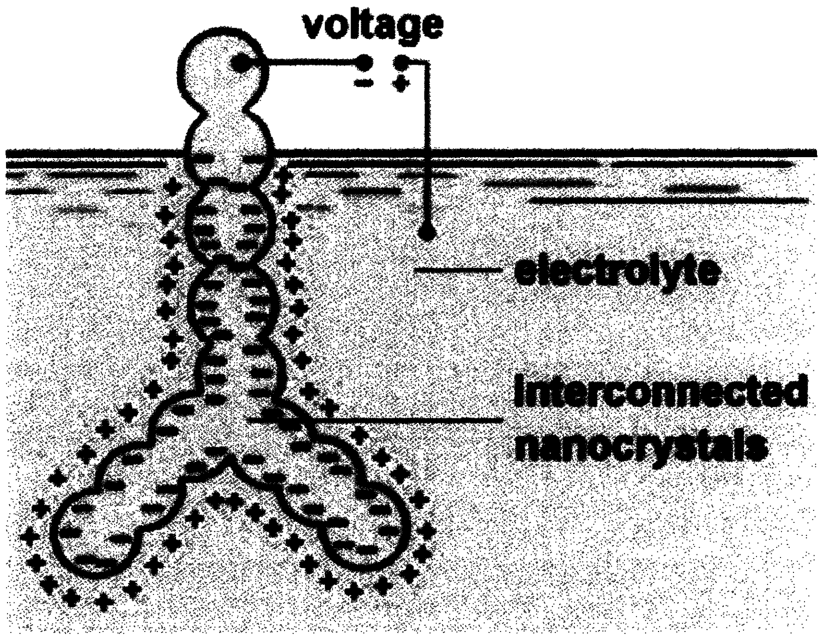

Figure 6: Schematic of array of nanoparticles immersed in an electrolyte [10].

Yuichi Ishida *et al.* have two patents filed relating to intercalation compounds. The first, *Solid-state displacement element, optical element, and interference filter*, uses a layered structure to create – as the title suggests – an actuator, an optical element, and an interference filter. The actuator, however, is driven not by a voltage, but rather a controlling light [19]. The second *Driving System and Actuator* refers to using intercalation to actuate fiber, film, or plate shaped elements. However, these are driven by a change in its surrounding solution and are more useful for applications such as artificial and robotic muscles [20]. Although Chiang's material can also be developed for use as fibers and muscles [13], it would likely require much more research and time than practical for use under existing patents.

Several other similar technologies exist. For example, Marinus Dona used silver electrodes and a silver iodide electrolyte to create micropositioners [21]. Helmut Bauer *et al.* and Dean Hopkins both use gas pressure produced by electrodes to produce actuation devices [22][23]. As expected of all technologies that incorporate fluid as an inherent part of an actuation device, low moduli and energy densities are difficult to overcome. While all of the technologies discussed here are somewhat related, none is similar enough to overlap in practical applications with the devices discussed in this paper.

3.0 Applications

Intercalation compounds provide a class of materials with 2-3% strain and a cycle time on the order of 100 seconds, allowing for realization of "smart" or adaptive structures. It should be noted, however, that use of intercalation compounds need not be restricted to large-scale applications; smaller, e.g. MEMS, devices can be designed using these materials. They can also be applied in biological or medical devices, e.g. valves, stints, etc. Here, several devices that have already been fabricated and tested are reviewed, followed by discussion of potential applications.

3.1 Prior Work: Devices

Three actuators are summarized here: a micro array of graphite posts, a laminated stack of $LiCoO_2$ and graphite electrodes, and a woven actuator device. This section is meant for familiarization of prior work at a high level; the reader is encouraged to refer to the original sources for details of these devices.

3.1.1 Micro Array Actuator

Koyama *et al.* used single piece of highly oriented pyrolytic graphite (HOPG) and laser micromachining to create a micro array of posts, which were incorporated into an actuating device, as shown in Figure 7. Maximum strains and work were measured and calculated while the actuator was under various stresses.

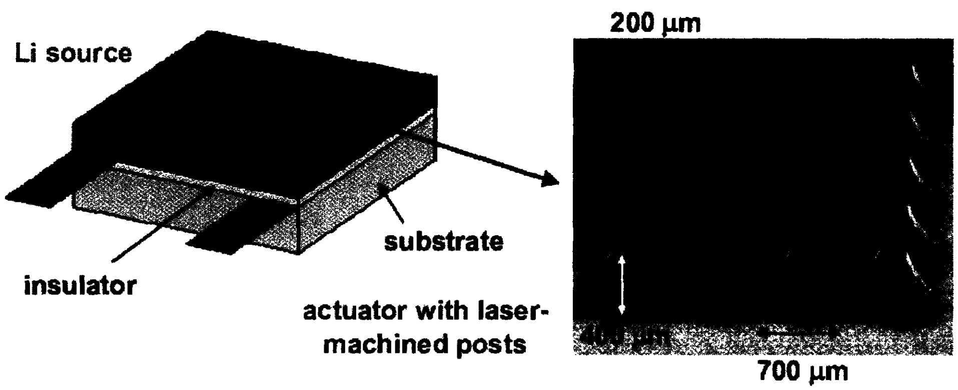

Figure 7: Schematic and image of actuator produced by Koyama *et al.* for mechanical testing [2].

As the applied stress was increased the work performed also increased, but the charge capacity decreased, suggesting transport kinetics are slowed by stress. To prevent shorting, the 15 ksi (100 MPa) and 29 ksi (200 MPa) conditions were performed on a second actuator, similar to the first, but with the substrate also made of HOPG (i.e. the micro array was machined directly onto the HOPG). This device allowed for faster testing rates, but lower absolute values of ion concentration. The results are summarized in Table 1.

Table 1: Results from graphite micro array testing [2].

Applied Stress	Strain	Work Performed
1.5 ksi (10 MPa)	6.7%	8.1 ft-lb_f in^{-3} (670 kJ m^{-3})
4.4 ksi (30 MPa)	4.3%	15.6 ft-lb_f in^{-3} (1290 kJ m^{-3})
7.3 ksi (50 MPa)	3.5%	21.2 ft-lb_f in^{-3} (1750 kJ m^{-3})
15 ksi (100 MPa)	1.3%	15.7 ft-lb_f in^{-3} (1300 kJ m^{-3})
29 ksi (200 MPa)	0.7%	16.9 ft-lb_f in^{-3} (1400 kJ m^{-3})

3.1.2 Laminated Actuator

Koyama *et al.* also tested a set of laminated $LiCoO_2$ and graphite electrode actuators. These devices were similar in design to the prismatic lithium ion batteries discussed in section 2.1. A few weight percent of poly(vinylidene fluoride)-based binders and conductive carbon additives were included in the electrode suspension-castings. Although still low, the 29-44 ksi (200-300 MPa) electrode stiffness was higher than those in commercially available batteries.

The linear strain measured with the electrode under 145 psi (1 MPa) was 4.1%, almost twice the theoretical 2.2% for isotropic electrodes, even though the cell was only charged to 86% of its theoretical capacity. At least two factors contributed to this discrepancy. The first was an anisotropic casting; the preferred orientation of the electrode material combined with the anisotropic expansion of graphite led to anisotropic properties in the device. The second factor may be the mechanical restrictions (i.e. clamps) placed on the device in the non-gage directions during testing. Under 1.5 ksi (10 MPa) of stress, the strain dropped to 2.3%; and under 2.5 ksi (17 MPa) of stress, the strain was 1.8%. These numbers are still promising considering that minimal engineering of the active material was performed [2].

3.1.3 Woven Actuator

The third, more elaborate, device was built and tested by F. Tubilla Kuri *et al.* The goal of this device was threefold: de-amplify strain for efficient application in structures that cannot handle large deformations; convert strain from the through-thickness to the in-plane direction; and increase the stiffness of the actuator. The design consists of fibers woven around a group of cells that are enclosed in rounded caps, as shown in Figure 8. The entire device is placed under pre-load in order to keep the fibers taught and to enable actuation in both directions. Out of convenience, steel wires and commercially available rechargeable cells were used.

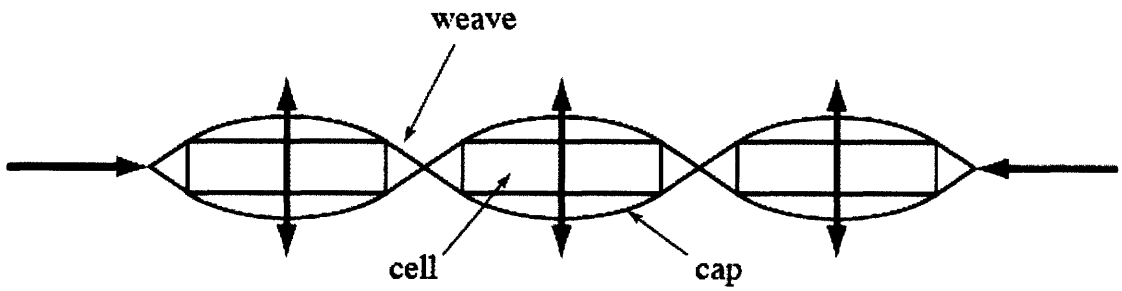

Figure 8: Schematic of the woven actuator [6].

Testing showed a maximum actuator strain of 0.40% with the corresponding cell strain of 1.48%, after discounting creep behavior. The device was under 400 pounds-force (1800 N) of pre-load. It is interesting to note that the instrumentation showed the device to creep more than the cells. Ceramic fibers in conjunction with a stronger adhesive to bond the caps to the cells were suggested as simple and readily available improvements to the device [6]. While not itself a practical device, the woven actuator did show that fabrication of useful devices in the near future is in the realm of possibility.

3.2 Potential Applications

Airplane wings have a different optimal shape for take-off and for cruising. Wings made from intercalation compounds can change between these two shapes during flight to improve efficiency. Next generation wings can potentially morph continuously to adapt to every flying condition. This same concept can be extended to helicopter blades, boat hulls, satellite solar arrays, and any other structures that benefit from shape changes. Here we investigate four such structures.

3.2.1 Stopping Flow

Perhaps one of the simplest devices that can be made is a stopper. Not as glamorous as the later applications, this one is meant simply to demonstrate a usable device. Whether removing a press-fit bushing or pulling the cork out of a wine bottle, a small change in diameter equates to a large difference in effort required to remove the article. In the case of metallic bushings, the difference in dimensions between a loose-fit and a (tight) press-fit bushing with a 0.750 inch diameter is less than one percent – or on the order of one thousandth of an inch [24].

Even in more compliant materials a few percent change in diameter is usually enough to greatly ease the burden of movement. For example, a typical cork in a wine bottle has an elastic modulus (E) and is under a radial stress (σ) [25]. Utilizing the definition of modulus,

$$E = \frac{\sigma}{\varepsilon} \qquad \text{Equation 1,}$$

the strain, ε, is calculated to be approximately 0.04. The coefficient of friction, μ, can also be calculated using the force required to pull out the cork, P, and the surface area of the cork in contact with the bottle, A, by

$$P = \mu \cdot \sigma \cdot A \qquad \text{Equation 2,}$$

where σ is the same stress from Equation 1. Again, taking typical values for P and A from [25], μ equates to 0.5. A summary of cork properties is shown in Table 2.

Table 2: Typical properties of a wine bottle cork [25].

Elastic modulus, E	1100 psi
Radial stress, σ	45 psi
Pull-out force, P	65 lb_f
Surface area contacting glass, A	3 sq. in.
Diameter of cork, d	0.75 in

Assuming a cylindrical geometry of active material in the center of the cork with a diameter half that of the cork and a 3% strain capability, as schematically shown in Figure 9, the step down in force required to remove the cork can also be approximated. Taking the modulus as a constant, any change in strain must be directly compensated by a change in stress. A three percent change in the active material's diameter is equivalent to a 1.5% change in the cork diameter because the active material has a diameter half that of the cork. This yields a new cork strain, ε', equal to 0.025. Substituting E and ε' into equation 1 yields a new radial stress, σ', of 28 psi.

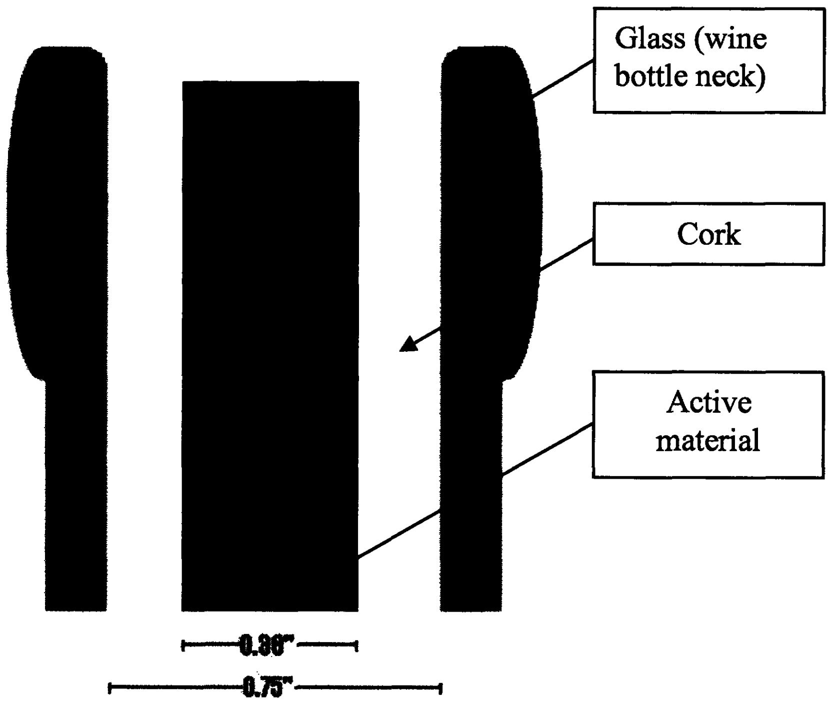

Figure 9: Schematic of a stopper with imbedded active material.

Finally, substitute μ, σ', and A into equation 2 to obtain the new force required to pull out the cork, $P' = 40$ lb_f, a forty percent decrease from the original value. Of course, several assumptions have been made, including that the strains of the cork and active material are simply additive and the modulus of the cork device not changing with the addition of active material. However, as an order of magnitude approximation, the addition of an intercalation compound device has significant impact on the ease of wine cork removal, without sacrificing the cork's seal. The assumption of 3% strain is reasonable considering the relatively low stresses on the active material.

For the average bottle of wine, cost restrictions would likely eliminate such a device, however this example was chosen because a low modulus material is also the most difficult case due to the high levels of strain present. If we had considered a metallic wine bottle stopper, the 1.5% change in diameter would have been more than sufficient to allow the stopper to slide out without any force. Although a metallic wine bottle stopper is impractical for many unrelated reasons, the metallic bushings discussed above operate in the same way, as do a number of other vacuum seal and pressurized chamber stoppers. These may also not have the same price restrictions as commodities like wine bottle corks.

3.2.2 Focusing a Lens

On an intermediate size scale between MEMS and airplanes, lenses, such as those used in microscopes and cameras, can be positioned using this active material. A lens which has a curved surface with a spherical shape has a focal length, *f*, given by

$$\frac{1}{f} = (n-1)(\frac{1}{r_1} + \frac{1}{r_2}) \qquad \text{Equation 3,}$$

where *n* is the refractive index of the glass, and r_1 and r_2 are the radii of curvature of the first and second surfaces, respectively [26]. Each lens has a specific focal length depending on its size and shape.

In microscopy, this distance is normally changed by the user with manual controls, which do not cause a large inconvenience. However, in photography, setting this distance is one of the most important elements in taking a high quality photo. An inexpensive, or low resolution, camera will usually have a fixed-focus lens that will produce a sharp image for objects that are at least eight feet away from the lens. A somewhat better camera will have a lens adjustable to focus objects as close as three feet away, and will often have a mechanism to automatically adjust the lens ("auto-focus") [27].

Thus, there is an opportunity for using intercalation compounds as a means of actuating the lens. Current cameras utilize a variety of devices to perform this function, most of them with multiple moving parts forming a complex system. An active material device would reduce the number and complexity of components, while functioning effectively in the low-power environment of the portable device.

Moving forward, the next generation active material device may include a transparent intercalation compound material. As can be seen in equation 3, not only is the focal distance determined by the shape of the lens, but the shape of the lens can also affect the focal distance. A lens that changes its radii of curvature can stay in the same position relative to the film (or digital media) and produce a sharp image, similar to the lens in a human eye.

3.2.3 Boat Hulls [28]

A boat hull's shape is important in determining the vessel's maximum speed, ride comfort, and fuel consumption. When a round bottom boat goes through the water, it creates waves from bow to stern called bow waves. As the speed of the boat increases, the waves grow closer together until the boat rides on the two waves created – one on the port and the other on the starboard side. After this point, adding more power to the engine only increases the size of the waves. The maximum speed is approximated by:

$$V_{\max} = 1.34\sqrt{L} \qquad \text{Equation 4,}$$

where L is the waterline length. This type of hull provides a smooth ride and is very economical in fuel consumption, but is relatively slow because it is limited by the waterline length, as seen in equation 4.

An alternative design is the planing hull. When this type of boat increases its speed, it rises on the water and rides on its own bow wave. As power is added to its engine, its speed continues to increase. Also, since it skims the water, there is less friction. This type of hull provides a high speed, but a very bumpy ride as the boat hits the surface of the water at each natural wave. It also requires much larger amounts of fuel.

The compromise is a 'V' shape forward and a flatter aft boat hull, as can commonly be seen in many types of water vessels. Figure 10 shows a summary of the advantages and disadvantages of each type of boat hull.

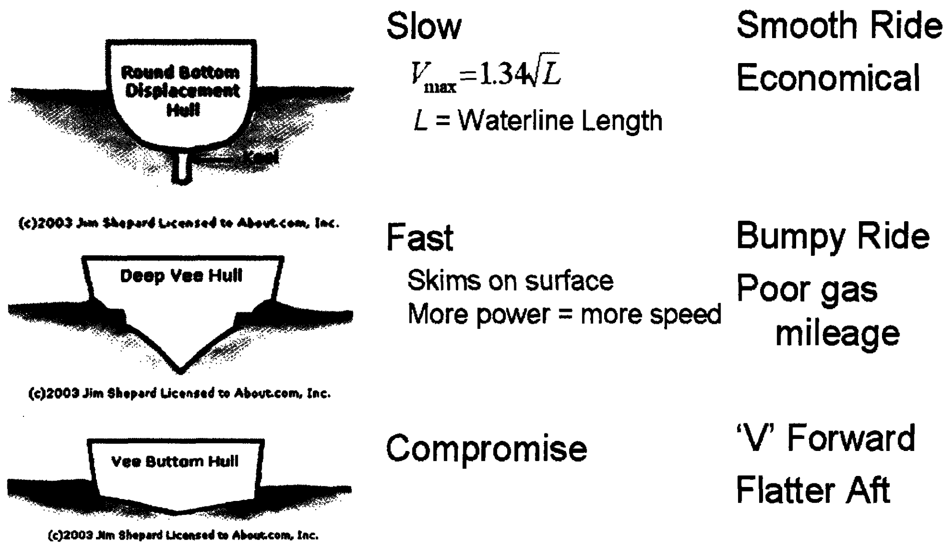

Figure 10: Summary of various types of boat hulls [28].

Intercalation compounds provide a method to produce a vessel that can morph between these two types of hulls. For example, application on a recreational fishing vessel would allow fast transport to the destination, economical cruising during fishing, and fast transport back to the dock. It would also allow adaptability to water and weather conditions.

3.2.4 Helicopter Blades

Unlike airplanes, which produce lift by moving atmosphere over its airfoils (wings) by moving the entire aircraft, helicopters produce lift by moving their airfoils relative to the aircraft (rotor blades). Thus, helicopters can hover as well as maneuver. Just as the optimal angle of attack of airplane wings are different for take-off and cruising, helicopters have a different optimal angle of attack for hover and forward flight.

A rotor blade's linear twist can be designed for blades to have optimal hover performance, or designed to minimize vibration during forward flight. Blade twist in current rotor designs is a compromise between the two, as shown in Figure 11.

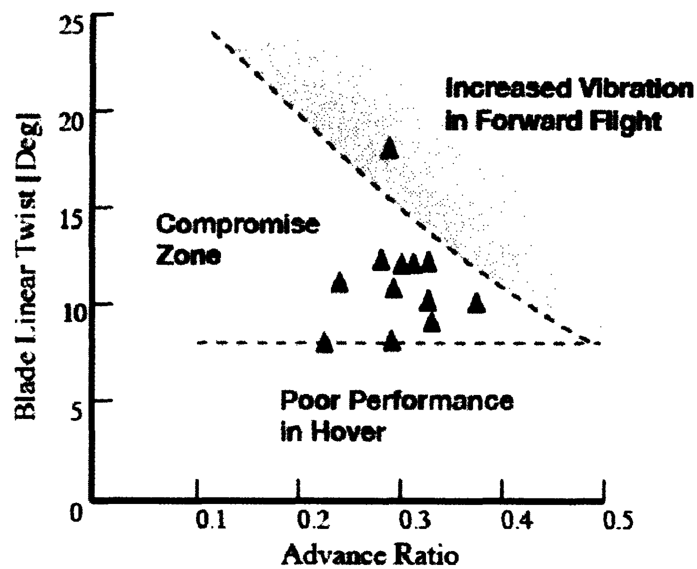

Figure 11: Current helicopter rotor blade designs incorporate blade linear twists that are a compromise between optimal hover performance and minimal vibration during forward flight [3].

It is very difficult to actually change the twist of a blade during flight because of the large aerodynamic and centrifugal forces present. However, the effective twist can be changed by adding a flap to the trailing edge of the airfoil, a schematic of which can be seen in Figure 12. A device actuated by intercalation compounds is used to move the flap and change the effective twist. Note that more traditional methods, such as hydraulics, are impractical because the large centrifugal forces (>50,000 pounds) on the rotor blades render them uncontrollable. Other devices (refer to Figure 3) would not have the energy density required. Shape memory materials have a large energy density, but temperature control of the blade is impractical. Use of these materials would require insulation of the airfoil, which then makes it difficult to change the airfoil's temperature, affecting the available bandwidth.

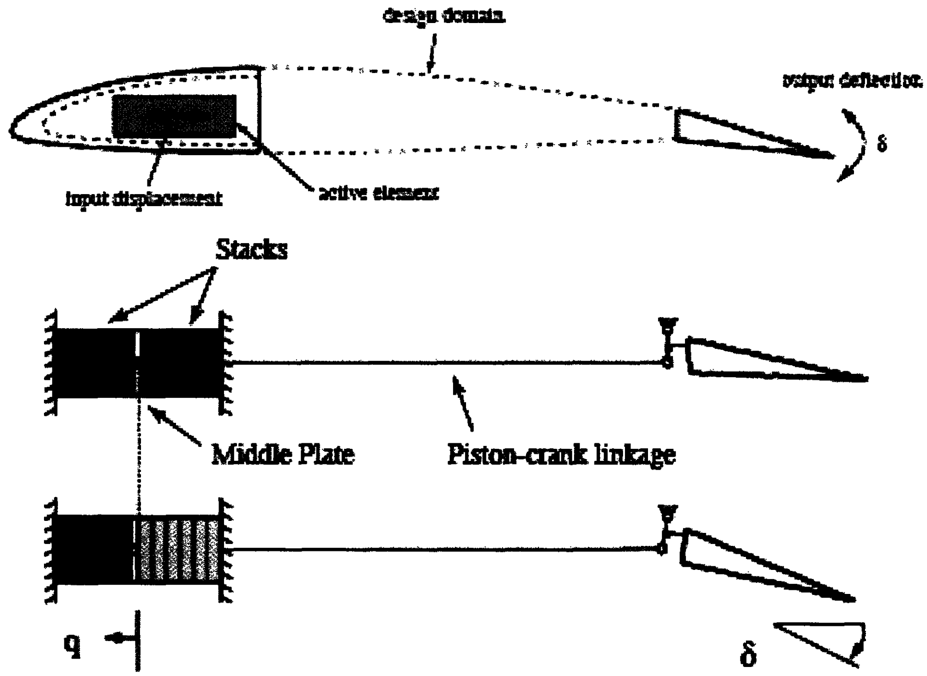

Figure 12: Schematic of morphing airfoil with intercalation compound actuator [6].

In order for this technology to be viable in rotor blades, it must increase the hover figure of merit by 1%, the equivalent to a two person payload increase, and add less than 10% of mass per unit span of blade [3].

A prototype of a helicopter main rotor blade section has been created by Prof. Yet-Ming Chiang's and Prof. Steven Hall's groups (of MIT's Materials Science and Aeronautics & Astronautics Engineering departments, respectively). However, as of today, this technology is not commercially available in any industry.

4.0 The Business

Here we choose helicopter blades to be our first focus for development both because it is familiar to the developers and because initial work has already been performed in this area. Basing the technology on the NASA Technology Readiness Level (TRL) scale, a level 6 would be a full-scale, working rotor blade. A level 5 is a reasonable assumption for prototype of a blade cross-section [29]. With sufficient funding, it normally takes 5-7 years for technology to progress to a TRL of 9, which is integration into a helicopter. Approximating an annual investment of $0.8M - 1.0M gives a total investment of $4M - $7M before a viable product is available.

4.1 A Business Model

After considering the most probably route to the most economically sound return, one possible business model is explored in detail here. The business would be a combination of product manufacturing and a licensing company. Actuators and simple peripheral attachments, such as hinges, levers, etc., would be manufactured. Figure 13 shows two potential manufacturing items. However, it doesn't make sense to build an entire boat company in order to build hulls, thus licensing to existing companies will also be a part of the business.

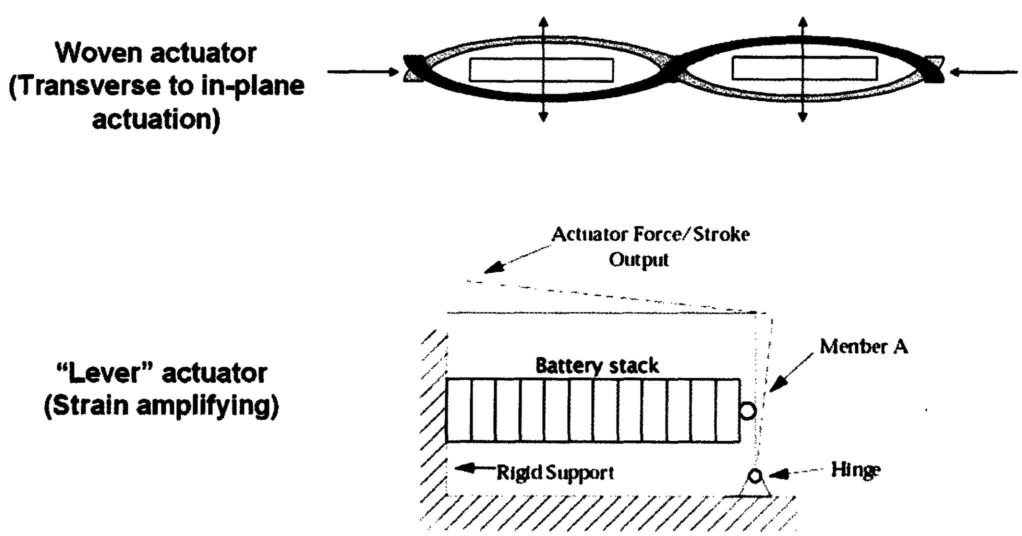

Figure 13: Two potential items for manufacture. These are mechanically simple and would be in the company's core competency [5].

In this type of business model, the company would be at the device-level, as shown in Figure 14. Thus, at a minimum, financial gain for both materials suppliers and interface designers must be considered if the business is to succeed. This is addressed in section 4.3 with the market.

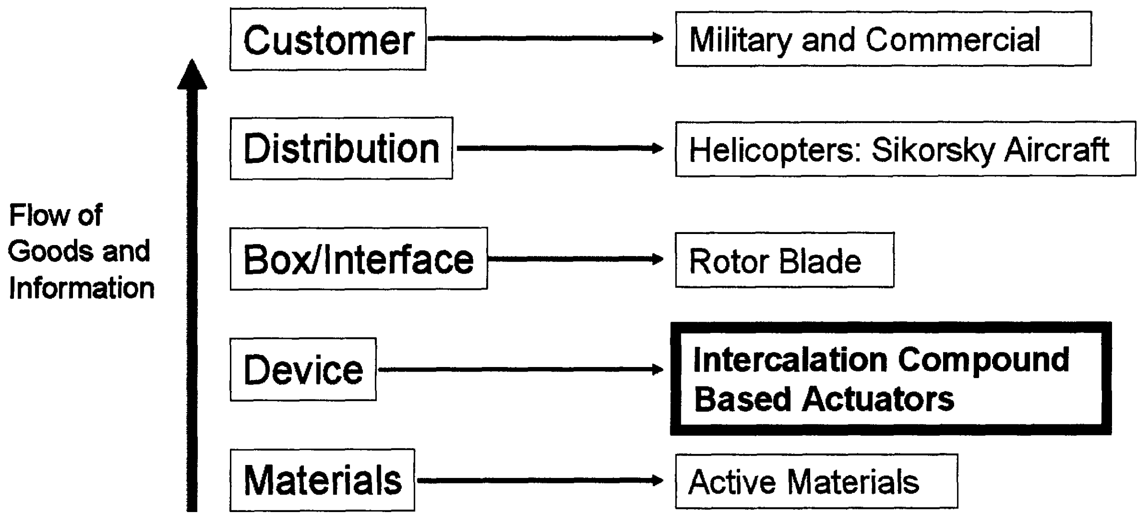

Figure 14: Schematic of various levels of production leading to a final product. The business model discussed here places the company in the device level [7].

4.2 Cost Model

Based on current material, labor, and capital costs, in addition to market projections discussed in section 4.3, a cost model has been developed for the first year of production. The full details of the cost model can be seen in Appendix A, but some of the key assumptions and results are discussed here, and can be seen in Table 3.

Table 3: Key assumptions used in the cost model

Market share	→	5% or 336 blades
Location	→	Industrial region of U.S.A.
Labor Cost (based on location) [30]	→	\$20 /hr
Cost of active material	→	Similar to the best rechargeable battery electrodes
Amount of active material required	→	1 pound per actuator
Scrap rate	→	5%

As will be discussed in section 4.3, a five percent market share is assumed, and a plant with capacity for a 30% market share is built because the marginal cost of having a larger plant is small until this point. A larger plant requires higher capital costs for equipment and space. The plant is assumed to be in an industry rich section of the United States. Although labor, land, and other prices are higher in these regions, many potential customers will also be in close geographic proximity.

Intercalation compounds are assumed to have a cost similar to that of the newest rechargeable battery electrodes – approximately fifty cents per watt-hour. Compare this to the common two-dollar, 18650 cell. At 2.2 A and 4 V, this typical cell costs about twenty-five cents per watt-hour. The 100% premium is added to the price to account for the fact that it is a specialty material. A typical battery's energy density is approximately 100 watt-hours per pound, thus a cost of $50 per pound of active material is assumed.

The amount of active material required is back-calculated from the weight of a typical blade – approximately 300 pounds for a medium lift helicopter. As discussed in section 3.2.4, addition of intercalation compound actuators results in a ten percent increase in weight. This equates to 30 pounds of total weight, of which approximately two-thirds is accessory weight and one-third is active material weight. With actuators spaced two feet apart on a twenty foot long blade, ten actuators are required per blade with 1 pound of active material per actuator.

Using these inputs, the cost model showed total operating costs, including both fixed and variable, for one year to be $1.2 M. This value includes a 5% scrap rate, which is on the high side of industry standards and thus a conservative estimate for this cost model. In the Appendix A, per blade and per device costs can also be seen, as well as fixed and variable costs. An economy of scale exists, as shown in Figure 15, although prices drop down quickly with production volume because fixed costs are low when compared to variable costs. The unit cost of actuators begins to level off once a 40-60 kit – each kit containing 10 actuators, enough for one blade – production rate is reached. With annual production at the projected 336 kits, fixed costs amount to only $42, as compared to $306 of variable cost, per actuator produced.

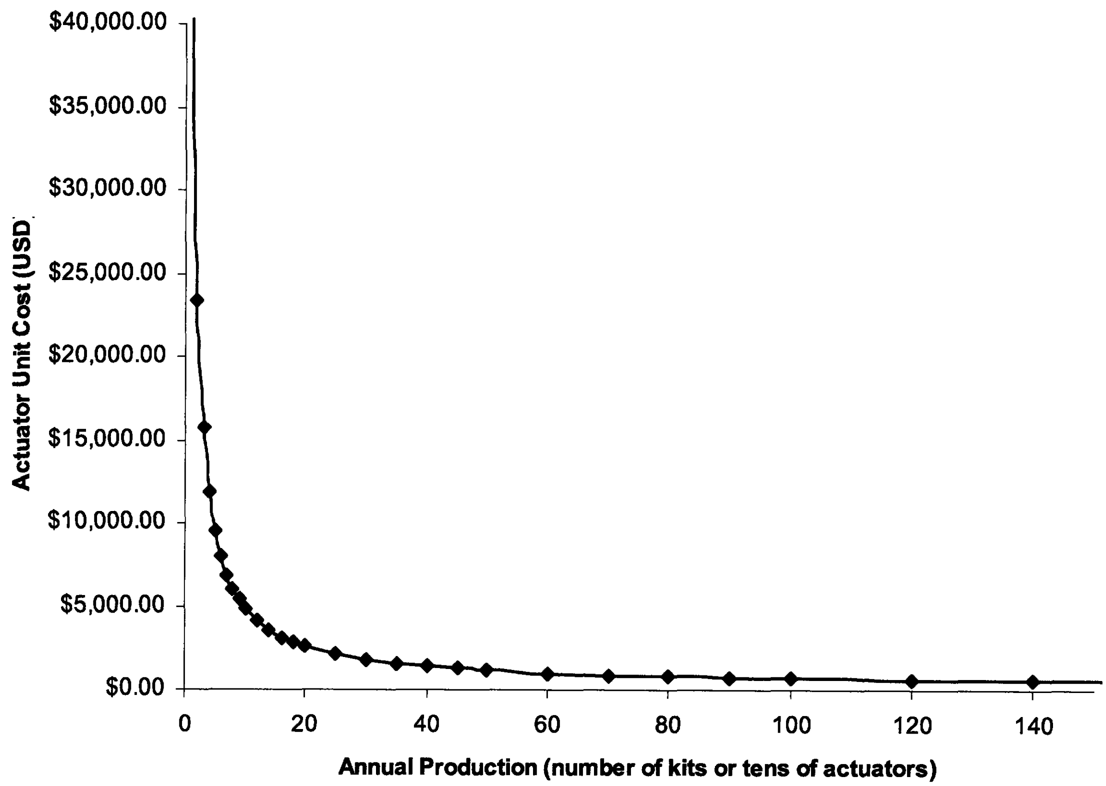

Figure 15: Cost model shows economy of scale.

4.3 The Market

Worldwide, there are approximately 56,000 helicopters in flight today [29]. Several basic assumptions are made, such as a three percent fleet growth per year for 1,680 new helicopters annually. Also, there exists a finite number of production helicopter models. If there are 15-20 models that are currently being manufactured in the world at a significant rate, and one model uses this technology, then a five percent market share is a reasonably conservative estimate.

Two more key, but equally reasonable, assumptions are made. The first is that the market will tolerate a 10% rotor blade price increase for a 1% aircraft performance increase. At $100,000 per blade, 4 blades per helicopter, and 1,680 new helicopters per year, this yields $3.4M in new blade revenues. The second assumption is that this new revenue will be split between costs, profit for blades producers, and profit for the new electrochemical actuator company. The cost model showed a projected $1.2M in cost. Thus 35% of the new revenue will be for cost. For a major aerospace business, 20% is a comfortable profit margin. This leaves 45%, or $1.5M, profit for the actuator company in the first year. Table 4 shows a summary of the market model.

Table 4: Summary of the Market Model.

# of helicopters in flight	→	56,000 worldwide
3% fleet growth per year	→	1,680 new helicopters
4 blades per helicopter	→	6,720 blades
5% of market	→	336 blades
$100k per blade	→	$34M Revenue (Assume market tolerates 10% price increase for 1% performance increase)
$34M *10%	→	$3.4M new revenue
Revenue breakdown:		
50% cost (including supplier profits)	→	$1.2M
15% profit for blade manufacture	→	$0.7M
45% profit	→	**$1.5M**

If we assume a moderate market share increase and production of spare parts, then the initial investment of $4M - $7M in development is recovered 7-10 years after the project is initiated – including the initial years of development. This is not a high-risk, venture capital type investment because it will not yield a 300%-1000% return on investment in 3-5 years, but it will still yield a decent profit in the 10-year timeframe. It also makes sense for helicopter companies because the competitive edge gained is often worth more than the dollar amount of profit from a particular technology. Thus, partnerships with a helicopter manufacturing company or a large purchaser or helicopters (e.g. U.S. government) are reasonable strategies.

4.4 Barriers to Market

Both technological and business barriers exist in going to market. On the business side, there is no reason to believe that intercalation compound devices should draw more skepticism than any other device based on a new material, thus the concentration should be placed on the technical issues. On the technical side, low rates and the dependence of device response on history due to viscoelastic behavior are the two foremost hurdles.

Currently, the largest barrier to market is finding a material with both optimal mechanical and rate properties. This isn't to say that "brand new" materials are required; some existing ones have the required stiffness and others have the required bandwidths. A material with a combination of the two, or a combination of several materials for a compromise of properties must be developed. The other major barrier to market is the lack of prior use of intercalation compounds as actuators. Depending on many, difficult-to-predict variables, application of the technology on an aircraft may meet resistance by the FAA or other regulatory agencies.

On the device and even down to the material level, most intercalation compounds on the market today were designed for use as electrodes in batteries. As such, polymeric and other low-modulus materials are often a major component in the compounds, contributing to the viscoelastic behavior and the reduced performance as actuators discussed in section 2. A more rigid device expands the design space, allowing greater force outputs and/or use of levers or other additions to magnify strains. Efficiency can be significantly increased by substituting ceramic separators for polymeric ones and using stiffer binders in the electrode. Although these are not extreme changes in the active material or device, they are also not trivial.

In the specific business model discussed earlier, aircraft part fatigue lifetimes, which are dependent on stress levels determined by weight of components, should also be considered. Despite the increase in aircraft performance, there may still be resistance to implementation because of reduced lifetimes of complementary parts, such as the rotor hub, shaft, etc. On the other hand, the decrease in lifetimes may be more than justified by if an aircraft becomes capable of flight missions that were not previously possible. For example, if the capacity of a light helicopter that would not normally be able to carry all the equipment and personnel required to fly a search and rescue (SAR) mission was increased to a point of being capable of a SAR mission, then parts' cost and lifetime analyses no longer carry the same significance. However, these analyses are always up for interpretation, and what may seem a strong business case to one person may seem weak to another. The technology being rejected after significant investment in research and development is always a risk.

4.5 An Alternative Business Model

As discussed in section 4.0, the business plan proposed and analyzed here was chosen out of expedience from experience and research already completed. However, using helicopter rotor blades as the application for market entrance also has two major drawbacks: its narrow market and its technological complexity. There is some risk that the technology is abandoned by the rotorcraft industry, leaving few options if other applications are not pursued in parallel. However, the risk can be considered small if a major helicopter manufacturer or military organization is partnered with and vested in the research. Despite the amount of work already performed on applying intercalation compound materials in this field, a substantial technological burden remains before the first aircraft flight, as discussed in section 4.3 and 4.4.

Consequently, other potential applications and routes to market should not be discounted, especially if a simple application is found that has a large and immediate market. For example, if the active material can be developed to actuate on a shorter time scale and to move a lens, it can be used to enable auto-focus in cameras on cellular phones. As discussed in section 3.2.2, all photographs appear sharp as long as the object is several feet away and the resolution is low. As the resolution of these cell phone cameras increases, a focusing device becomes necessary. With over one billion cellular phones sold in the year 2006 and a growing proportion of these featuring cameras, a very large market is available [31]. Solid-state actuation eliminates complex moving parts, and perhaps even more importantly, generates a low power consumption device. Production of such a device would also be relatively simple, with most of the technology developed for the camera and the active material simply replacing the actuating component.

A variation of the sort of plug discussed in section 3.2.1 is another possibility for a practical application for market entry, as would a number of other devices, as discussed in the next two sections.

4.5.1 Alternative Cost Model

In general, any simple application with a large market and few or no similar technologies that can fit the necessary requirements – both technical and cost – would be a good one to pursue. This section will discuss a cost model for such an application. No specific product is defined. Instead, the cost of producing a "widget" is attempted in order to gain insight into a production scheme more in line with a simple, high-volume device.

For the greatest understanding of this business model, instead of delving into detail of this cost model, the key differences between it and the one discussed in section 4.2 will be discussed. The full cost model can be seen in Appendix B.

The largest logistical change would be a shift in location of the plant to China due to change in production rate. A larger factory is required, but real estate unit costs are assumed to drop by a factor of two – a very conservative estimate considering both that real estate is generally less expensive in China and that the factory no longer has to be in an industrial area since the product will be need to be shipped anyway. The labor rates drop from an average of $20/hr to $1/hr [30]. However, the scrap rate would likely increase, especially during the initial time period when unskilled workers are being trained.

In addition, factory hours would change from a single shift to three shifts, and extended to include weekends. More machining would be performed in-house, or out-sourced to local suppliers, dropping the cost of components. Assuming the product is a smaller-scale device than one for rotor blades, the lower active material volume requirement would further reduce material cost.

Also, annual production rates would go from single thousands to hundreds of thousands. A five-hundred-thousand actuator annual capacity plant is built, with half of the capacity used initially. Shipping costs are also added to the device. See Table 5 for a summary of differences between this cost model and the one from the rotor blade business model.

Table 5: Summary of differences between the two cost models.

	Rotor Blade Model		High-Volume Model
Production Rate	3,360 actuators per year	→	250,000 actuators per year
Production Capacity	20,000 actuators per year	→	500,000 actuators per year
Location	Industrial Section of U.S.	→	China
Real Estate Cost	$600 per sq. yard	→	$300 per sq. yard
Real Estate Req'd	200 sq. yards	→	3000 sq. yards
Labor Cost	$20 per hour	→	$1 per hour
Scrap Rate	5%	→	10%
Factory Hours	40 hours per week	→	154 hours per weeks
Material Cost	$200 per actuator	→	$17 per actuator
Shipping Cost	None	→	$2 per actuator

In creating this cost model, a representative, but specific, option was selected when a number of generally equivalent choices were available. For example several countries with similar work force and economic conditions were identified. However, China was chosen for the sake of clarity and ease of identifying economic statistics.

While geographic proximity to customers was a large benefit in producing relatively small quantities of targeted products in the earlier business model, in this case, the benefit is outweighed by economic costs because large volumes are desired. The monetary losses associated with a higher scrap rate and a shipping requirement are also easily outweighed by the lower labor and real estate rates associated with having the manufacturing plant in China.

4.5.2 Discussion of Alternative Business Model

This "large-volume production" cost model shows $7.2M annual cost for producing 250,000 actuators. This equates to approximately $30 per actuator. Thus, to be reasonably profitable, the selling prices must be on the order of $40 to $45 – for a profit margin of 33% to 50%. These types of prices could be reasonable for high-end devices. If the plant were operating at its full capacity of 500,000 actuators per year, the cost drops to approximately $23 per actuator, allowing for either higher profit margins or a larger application space. However, these relatively high prices do not allow for implementation into most commodity products.

This is not to say that a commodity product cannot be made from intercalation compound-based active materials. Several factors could reduce the device cost enough to allow for such use. Reduction of intercalation compound material price may be expected once development is complete and larger quantities are required. Although small-scale devices would be unlikely to provide enough material demand to lower prices significantly, larger-scale devices may. Cost of other components in the actuator assembly may also drop when larger quantities are purchased. A very simple device would also not require as much labor. Even with the lower wages, labor still contributes a significant amount to the final price.

These factors could reduce the cost of a completed actuator device by 30-40%, for an approximate $15 cost and a $20 to $25 selling price at full-capacity production. While still expensive when compared to, say, an electric motor in a remote controlled toy, these prices are within reason for many high-end product applications. At these selling prices, a company manufacturing 500,000 parts a year would have $10M - $12.5M of annual revenue with $2.5 - $5.0M in profit. However, the risk associated with such a venture is also significantly higher than that associated with the rotor blades venture.

It should be made very clear that these numbers were chosen to be representative of a specific "widget." Production of other devices could possibly have very different material, equipment, labor, and other requirements. Thus a much different cost model may need to be considered if a specific product is identified and a business is pursued. It should also be noted that this second cost model has ignored one of the primary reasons for entering the market with rotor blades: the fact that development is still required before this material can be used in a practical device. That cost is ignored in the elementary analysis presented here.

5.0 Conclusions

Recent research in intercalation compound materials has enabled actuation of large-scale structures. From more efficient helicopter rotor blades to wine bottle corks, many manufacturing opportunities exist to exploit the technology, and a strong patent position is held. A combination of cost analysis and market analysis show that business opportunities are present for at least one business model.

The rotor blades business model chosen does not offer a high reward at first. However, entering the market in rotors serves as a proof of concept that these devices work. It isn't a disruptive technology in this field; though the next generation of devices can potentially cause a paradigm shift, displacing all airplanes with bird-like aircraft and boats with fish-like vessels.

However, obstacles are also present, including materials selection and development and the potential need for FAA approval. These obstacles are balanced by the promising material properties available – relatively large, 2-3%, strains possible using small voltages, 5V, and the potential of a very high energy density.

Entrance into the market with a high-volume product has a higher risk, but also higher potential rewards. Reducing the cost of manufacturing the device to an acceptable level for commodity products would be difficult, but not impossible for high-end products. If a specific device is identified for manufacture, cost and schedule of developing the technology should also be major factors to consider.

After careful analysis, it is recommended that this technology, as it is today, be pursued as an embryonic technology at a seed stage of development. It will likely require on the order of 10 years before true gains are reaped.

However, it must be kept in mind that other potential applications, very different than those discussed in this paper, remain undiscovered for intercalation compound materials. Auto-focus of cell phone cameras is just one example. Finding the appropriate product – one with high demand and proper pricing – is a key aspect of a successful startup business. Although there are no obvious applications of this technology that fit this as of yet, that is not to say that such an application will not be found. If this occurs, then a new business model, perhaps one with much different risk and return potentials would be appropriate. However, this must also be tempered by the fact that, unless the design is inherently simple, would require a certain amount of development, lead time, and capital.

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Appendix A – Cost Model: Rotor Blade Business Model

Exogenous Data		
Annual Production Volume	336	Rotor Blade kits
Annual Production Capacity	2000	Rotor Blade kits
# Actuators/Rotor Blade Kit	10	actuators/kit
Working Hours/Day	8	hrs
Working Days/Yr	240	days
Cost/Manhour	$20	
Scrap Rate	0.05	
Accounting Life of Machine	15	yrs

*assumes made in U.S.A.

Process Calculations		
Daily Production Volume	8	actuators/day
Hourly Production Volume	1	actuator/hr

Material Input		
Intercalation Compound	$50	/lb
Amount required per actuator	1	lb
Actuator Assembly (includes casing, load transfer components, hinges, fasteners, etc.)	$150	/actuator
Rotor Blade Kits Produced	336	/year
# Actuators/Rotor Blade Kit	10	actuators
Total Material Cost	$672,000	/year

Equipment	Price per Machine	Workers/ machine	# Machines	Electricity	
Assembly tools (presses, drills, etc.)	$50,000	1	6	10	kWh/hr
Quality tools (calipers, micrometers, etc.)	$5,000	0.5	4		

Building and Land		
Cost/Square Yard	$600	/year
Space Required	200	sq yards
Total Space Cost	$120,000	/year

Manpower		
Cost	$20	/hr
Total daily Man hours	64	hrs/day
Working Days/Yr	240	days
Total Manpower Cost	$307,200	/year

Utilities		
Electricity	$0.05	/kWh
Required Electricity/Hr	10	kWh/hr
Working Hours/Day	8	hrs/day
Working Days/Year	240	days/yr
Total Utility Cost	$960	/year

Cost Analysis		
Materials	$672,000	/year
Manpower	$307,200	/year
Utilities	$960	/year
Total Variable Cost per Year	$1,029,168	/year
Total Variable Cost per Blade	$3,063	/blade
Total Variable Cost per Actuator	$306	/actuator
Equipment	$21,333	/year
Building and Land	$120,000	/year
Total Fixed Cost per Year	$141,333	/year
Total Fixed Cost per Blade	$421	/blade
Total Fixed Cost per Actuator	$42	/actuator
Total Cost per Year	**$1,170,501**	**/year**
Total Cost per Blade	**$3,484**	**/blade**
Total Cost per Actuator	**$348**	**/actuator**

Appendix B – Second Cost Model: Simple, High-Volume Device

Exogenous Data		
Annual Production Volume	250000	actuators
Annual Production Capacity	500000	actuators
Working Hours/Day	22	hrs
Working Days/Yr	360	days
Cost/Manhour	$1	
Scrap Rate	0.1	
Accounting Life of Machine	15	yrs

*assumes made in China

Process Calculations		
Daily Production Volume	694.44	actuators/day
Hourly Production Volume	31.57	actuator/hr

Material Input		
Intercalation Compound	$50	/lb
Amount required per actuator	0.1	lb
Actuator Assembly (includes casing, load transfer components, hinges, fasteners, etc.)	$10	/actuator
Shipping	$2	/actuator
Annual Production	250000	/year
Total Material Cost	$3,750,000	/year

Equipment					
	Price per Machine	Workers/ machine	# Machines	Elec-tricity	
Assembly tools (presses, drills, etc.)	$50,000	3	60	10	kWh/hr
Quality tools (calipers, micrometers, etc.)	$5,000	1	40		

Building and Land		
Cost/Square Yard	$300	/year
Space Required	3000	sq yards
Total Space Cost	$900,000	/year

Manpower		
Cost	$1	/hr
Total daily Man-hours	4840	hrs/day
Working Days/Yr	360	days
Total Manpower Cost	$1,742,400	/year

Utilities		
Electricity	$0.05	/kWh
Required Electricity/Hr	10	kWh/hr
Working Hours/Day	22	hrs/day
Working Days/Year	360	days/year
Total Utility Cost	$3,960	/year

Cost Analysis		
Materials	$3,750,000	/year
Manpower	$1,742,400	/year
Utilities	$3,960	/year
Total Variable Cost per Year	$6,045,996	/year
Total Variable Cost per actuator	$24	/actuator
Equipment	$213,333	/year
Building and Land	$900,000	/year
Total Fixed Cost per Year	$1,113,333	/year
Total Fixed Cost per Actuator	$4	/actuator
Total Cost per Year	**$7,159,329**	**/year**
Total Cost per Actuator	**$29**	**/actuator**