Chapter 7.2 Biologically Inspired Robots

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7.2.1 INTRODUCTION

In a very real way, EAP and its related active polymer technologies such as McKibben actuators (and SMA to some extent) represent a sea change in humanity's technology. Since the beginning of the industrial age, our technology has been, by and large, a hard technology. The label "hard" is literally true from the standpoint of materials and systems. Structures tend to break rather than bend and systems tend to fail rather than degrade gracefully. Systems and structures tend to be divided physically and conceptually into discrete elements. EAP and its brethren, however, are undeniably "soft". Moreover, they are soft in terms of system control as much as in material properties.

As applied to robotics, the promise of EAP and "muscle-like" actuators lies on two major fronts. First, as the moniker "muscle-like" suggests, these actuators will make possible robotic systems that more closely resemble biological systems. This resemblance extends not only to the physical structure of the system, but also to the dynamics, control, programming, and, ultimately, use of these systems. As humans have much more varied goals than does Nature itself, the biological systems should also inspire designs that expand the use of muscle actuators beyond the applications to be found in Nature. Second, muscle actuator technology joins MEMS as a tool for the realization of so-called smart structures. One can easily conceive of robots for which structure, actuation, and sensing are so tightly interwoven as to be one system. With the progress in computing power, such smart structures could be the basis for robots that are flexible, both in form and function.

7.2.2 BIOLOGICALLY INSPIRED MECHANISMS AND ROBOTS

When we first contemplate the application of muscle actuators to robotics, our instinctive reaction is to visualize the creation of direct analogs of the creatures around us; home security is handled by a robotic dog, deep sea exploration is performed by robotic dolphins, and so on. Indeed, a humaniform robot is probably the most easily conceived form of robotics in popular thought. Such bio-mimicry (biomimetics) may have a place in some situations, notably entertainment robotics, but good scientists and engineers must be somewhat more careful in the application of Nature's designs. Three important points must be remembered when looking at Nature for instruction. One, Nature's technology is not yet our technology, nor its materials our materials, though muscle actuators have brought us closer. Two, Nature has a very different set of success criteria for its designs than we do for ours. Its creations have different jobs, different environments, and different cost functions to optimize. Third, *Nature is not perfect*. Though Darwin's paraphrased principal of "survival of the fittest" has borne itself out over the last century and a half, that "fittest" design is derived directly from an existing design and is only measured against other designs that have already been built. Human invention is only limited by our own vision and can be optimized relative to all potential designs. Those caveats stated, Nature remains an admirable teacher.

7.2.3 ASPECTS OF ROBOTIC DESIGN

The design of robotic systems is particularly challenging due to the breadth of engineering expertise required. In general, a robot may be represented schematically as shown in Figure 1. In brief, the "Outside Control" box refers to any off-board tele-operator, whether it is a computer or a human. Robots can be created without this component or the following "Communications" component, which represents whatever means the robot, has to pass and receive information. Communications can be as simple as a tether cable or as complex as NASA's Deep Space Network of large dish radio transmitters. Presiding over the control of the robot is "High-Level Control", which takes in objectives from the outside (if any) as well as internal objectives, compares those to the information provided by the sensors ("Sensors"), and then issues objectives to "Low-Level Control". Examples of high-level objectives are navigational imperatives, or data collection routines, or manipulation directives. The needs of these objectives are translated by high-level control into specific needs for individual actuators, primarily related to motion (position, speed, etc…). Low-level control represents the hardware and software directly responsible for producing the excitation signal (usually some form of energy from the "Power" source) to the system actuators ("Actuators"). Again, information from the sensors is compared to the desired goal, and the appropriate stimulus is fed to the actuators.

The actuators, in turn, act on the "Plant", which is a catchall name for the system, whose dynamics and statics the controllers seek to modify. In general, the "Plant" refers to the mechanical components of a robot. However, it could just as easily refer to a chemical solution, a magnetic field, or any other of a myriad of other physical systems. These components will be discussed in greater detail in the following sections.

7.2.3.1 Actuation: Designing Robots with Muscles

While the concept of EAP as muscle has been discussed in the abstract, it is useful to look what a "muscle" might mean to a design engineer. In essence, a muscle is a linear displacement actuator. The closest analogs in general use would be pneumatic or hydraulic cylinders. These actuators are the indisputable champions of high force applications (think Caterpillar equipment). The only other common solutions involve translating rotational displacement from a motor into linear motion through the use of cables and pulleys. However, if high force is not needed and simplicity is a requirement, muscle actuators may be an appropriate substitute. In fact, they offer several advantages over traditional actuation methods.

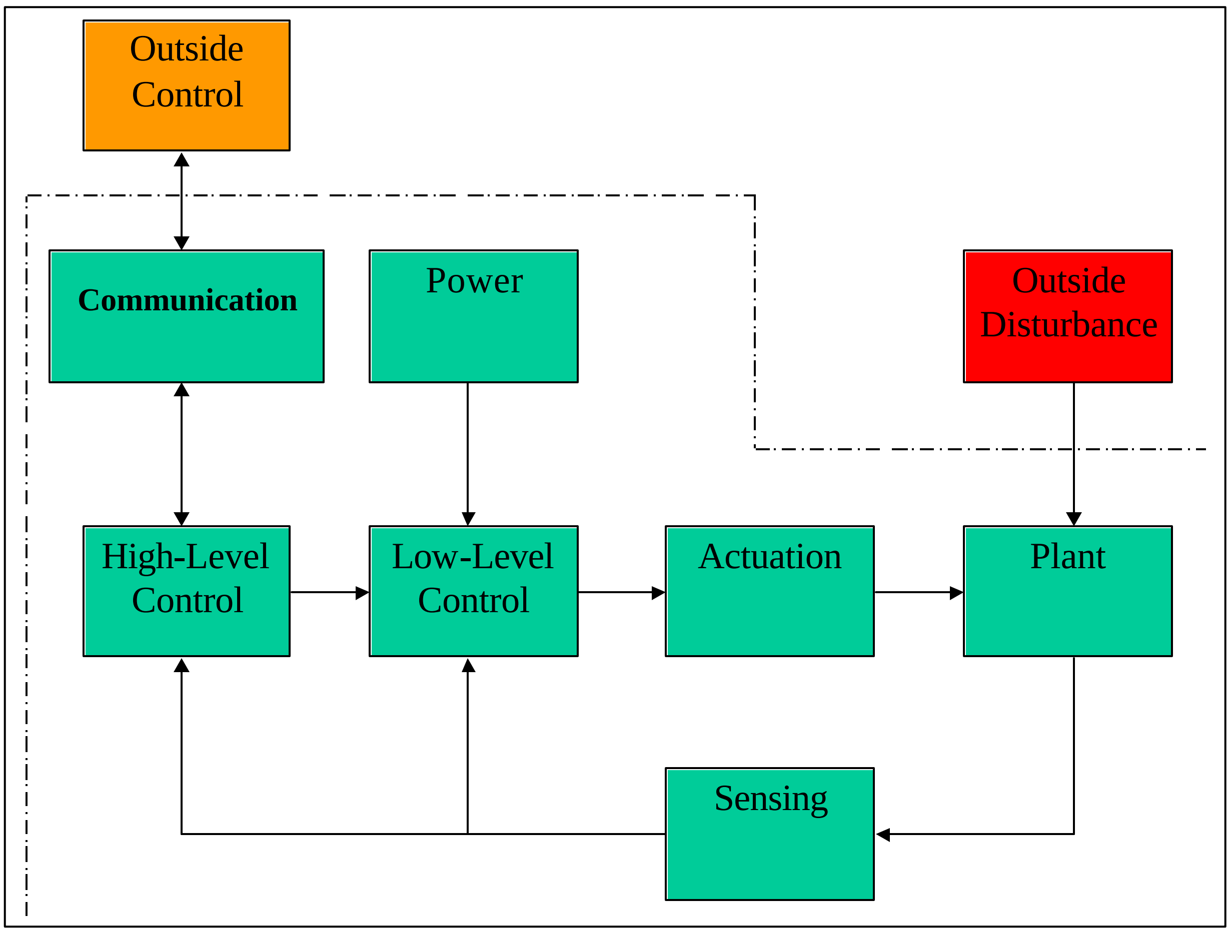


FIGURE 1: Schematic diagram of a generic control system showing information flow

As implied, the low moving-part count plays a significant role. Outdoing even the simplicity of a two-piece hydraulic actuator (piston and cylinder), one-piece muscle actuators have no surfaces that slide relative to one another. This attribute should correspond to an increase in reliability by reducing the potential for wear and binding. When measured against rotary-to-linear technologies, this aspect achieves a greater significance. Not only is wear reduced, but force loss due to friction (mechanical efficiency) is also reduced. Depending on actual design, there need not be any mechanical loss in a muscle actuator system, while mechanical loss is inherent in any actuator that relies on some type of transmission, as a rotary-to-linear actuator must.

More interestingly, and with a greater impact on the overall shape of the product, the displacement of the actuator does not have to occur along the same line of action as the part being actuated due to the flexible nature of the material. In other words, the main body of the actuator can be located around a corner from the part on which it acts (Figure 2). To jump ahead in the discussion, this characteristic can be seen in the muscles of the human forearm acting to control the flexion and extension of the fingers. That example also shows that when it becomes necessary to translate linear motion to rotary (muscle contraction to joint rotation), the mechanism need only be the attachment of the muscle to a lever arm about the joint. And, again, the actuator need not form a straight line from anchor to lever arm pivot.

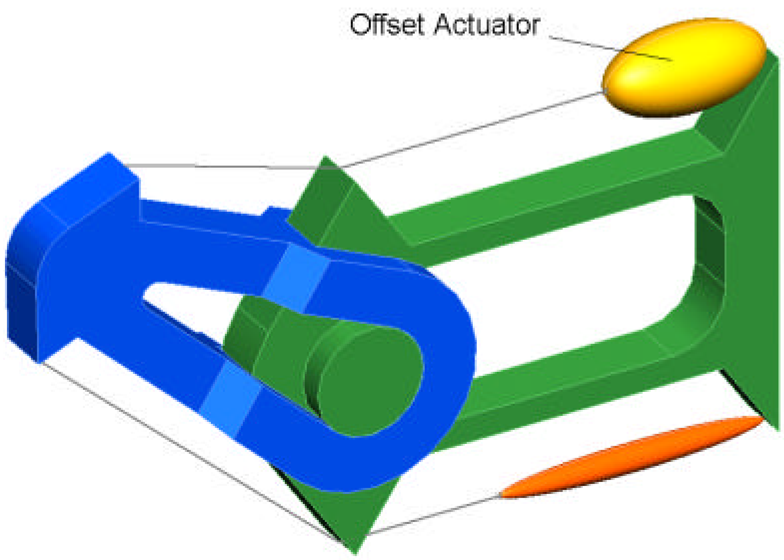


FIGURE 2: A schematic view of an arm driven by a pair of actuators emulating the operation of muscles.

One major difference between most common actuators and muscle-like actuators is that muscles have a preferred direction of actuation (i.e., contraction). Therefore, like in animals, joints in muscle-powered robots must have an antagonistic arrangement of actuators. This arrangement is shown in Figures 3. Simply, if a muscle (the agonist) moves a part, something (the antagonist), usually another muscle or a spring, must move that part back. In special cases, the force on the part imparted by gravity can also be used. Using a spring as the antagonist provides the simplest solution because only one actuator is needed. However, a spring-antagonist can be undesirable for power and mass considerations. The added demands are due to the fact that the actuator must work against the spring in addition to exerting the necessary on the environment. That extra force generation may require a larger actuator than otherwise necessary, with the attendant increase in power use. Of course, any restorative force inherent to the actuator can mitigate the design impact of the spring.

The muscle-antagonist requires the added complexity and mass of an entire actuator. However, the power requirements are lower due to the fact that only one of the actuators is activated at a time, providing only the force necessary to impart on the environment. Other advantages also come out of a muscle-muscle arrangement, and they will be discussed in the following section.

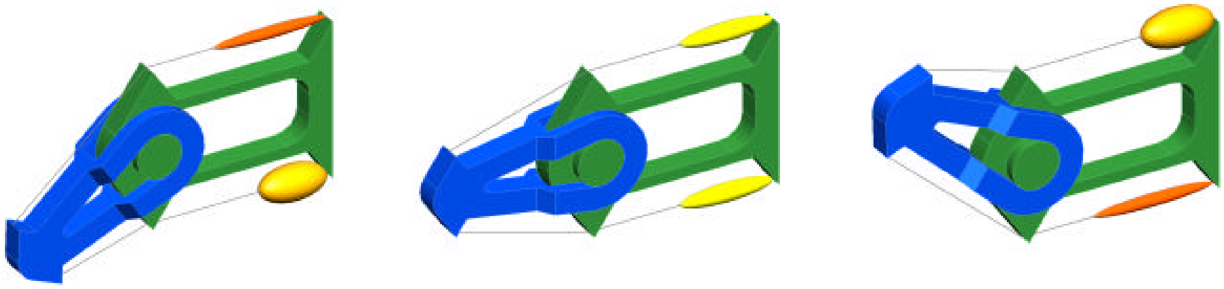


FIGURE 3: Schematic view of the articulation of an arm using a pair of muscles in an antagonistic arrangement.

7.2.3.2 Plant: The Effects of EAP on Dynamic System Response

Perhaps the least obvious influence of muscle actuators on systems design is how they affect the nature of dynamic control. In the Introduction, the system controls for active polymers were referred to as being potentially "soft". This assertion is based both on the actuator's mechanical material properties as well as the response of the materials to their particular actuation stimulus. Unlike the manner that dynamically "stiff" actuators are treated, muscle actuators' properties encourage their being treated as part of the structure.

Active polymers present an interesting material due to their combination of low spring rate relative to metals and their passive viscous (speed dependant) damping. In general, a controllable system must have some level of damping. Due to the low inherent damping of metal structures, classic systems will normally include a shock absorber to damp out unwanted motion or vibration imparted by the environment (think of your car). In the case of polymers, the shock absorber is built directly into the actuator (another reduction in part count!). In addition, the low spring rate allows the actuator to stretch in response to outside influences, storing energy that would have been otherwise imparted to the structure. In essence, active polymers can be thought of as a method of driving the wheels of your hypothetical car and providing the suspension as well, all in one package. If a computer is driving this car along a defined direction, it will have to react less often and less dramatically to the effect of potholes to keep the car going straight. This benefit in turn means that the computer doesn't have to think as fast (processor speed) or expend as much energy. If the example were instead a walking robot, its body would tend to move along a straight line despite the fact that its feet periodically stumbled on obstacles.

The springiness of polymers may provide another benefit. Animals have been shown to store energy in their actuation systems during certain phases of their motion, only to release it constructively in a later phase. In this way, energy that would have to be otherwise dissipated can be stored and then used to the benefit of the system, resulting in a greater overall efficiency. This concept is particularly well illustrated by the energy states of any running animal.

The materials from which polymer-based muscle actuators are made have another major mechanical difference from those of traditional technologies. They are inherently less dense than the generally metallic structures of what is commonly used. That aspect gives promise of radically lighter designs, leading to less inertia, which plays a significant role in the action of the control system. If the overall system is lighter, less energy is needed to change speed and direction, not to mention the decrease internal forces and stresses due to relatively smaller actuation forces.

Potentially one of the most innovative areas for system dynamics is the tailoring of system stiffness with the antagonistic muscle arrangement. The previous section indicated that activating only one actuator at a time could minimize power consumption. However, there are some significant advantages to having both muscles active at the same time. Some polymers have demonstrated a correlation between excitation signal and actuator stiffness. This would imply that the muscle actuators could be used as variable springs.

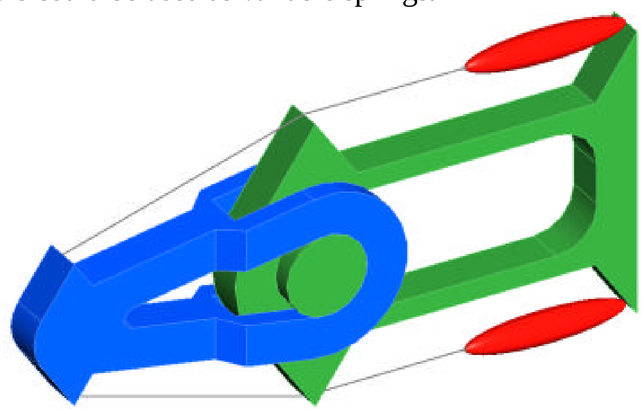


FIGURE 4: Schematic view of an arm in a rest position.

The schematic in Figure 5 provides an idealization of the antagonistic arrangement is shown in Figure 4.

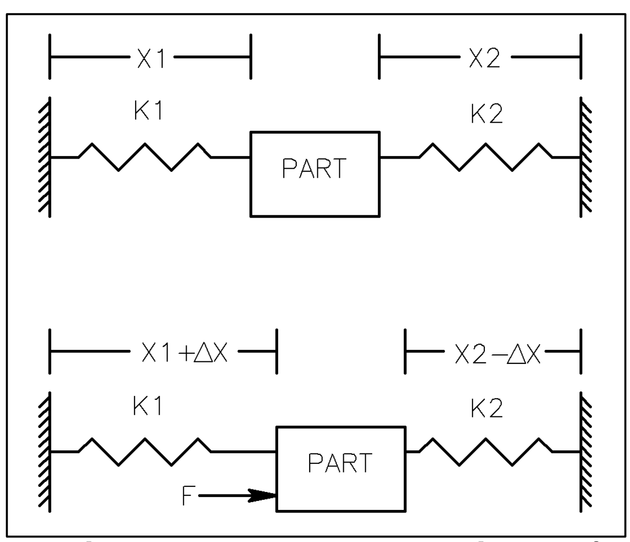


FIGURE 5: A mass with opposing springs representing the case of antagonistic muscle arrangement.

The upper view in Figure 5 represents the system at equilibrium without any outside force. Each actuator is symbolized by a tension spring element with stiffness ***K***. The lower view represents the same system that has been displaced *D**x*** due to an outside force ***F*.**

A force balance for the first case yields:

$$0 = K_1 \cdot x_1 - K_2 \cdot x_2$$

A force balance for the second case yields:

$$0 = K_1 \cdot (x_1 + \Delta x) - K_2 \cdot (x_2 - \Delta x) - F$$

Rearranging:

$$0 = (K_1 \cdot x_1 - K_2 \cdot x_2) + (K_1 + K_2) \cdot \Delta x - F$$

Given that the system was at equilibrium before force was applied,

$$\Delta x = \frac{F}{K_1 + K_2}$$

This equation supports the common sense notion that the stiffer the actuators, the more difficult it is for an outside force to disturb the system a given displacement. To illustrate the importance of this concept, think of the human arm. In its stiffened state, it provides an effective battering ram for a football player's "cold-arm shiver". However, with antagonistic pairs of muscles relaxed, the arm can clean delicate crystal glasses with a cloth. The concept of variable system stiffness can also be cast as a type of force control, which will be explored in the section on low-level control.

7.2.3.3 Sensors: The Information for Feedback Control

As is implied by the term "feedback control", sensing is extremely important to controlled systems. However, effective direct sensing may be more difficult for muscle-like actuators due to their more flexible morphologies. Most methods in common use are not applicable. Traditional motors and pistons are very convenient to monitor with encoders or potentiometers (to name two of the most common) because their areas and modes of motion are distinctly defined. For instance, rotary motors will have a shaft of some type to which a rotary encoder can be mounted. The amount of bend or extent of contraction/expansion in an active polymer is difficult to determine except for special cases. An example of such a case would be a contracting actuator that had a single line of action. It could be treated in the same way as a piston, the displacement determined with a linear encoder or potentiometer.

One possible direct measurement method would be the incorporation of strain gauges within the actuator. The effectiveness of such a system would be highly dependant on the material properties and the fixturing of the actuator because the strain in the vicinity of gauge must be a good indication of the strain throughout the actuator. Any large discontinuities in strain would create unacceptable errors in measurement.

The sensing for feedback control of active polymers may have to be taken from secondary sources that are more easily monitored accurately. This technique would require examining the entire actuated system for points that are amenable to current sensing methods. A case in point would be our hypothetical rotational joint from Figure 4. Rather than looking at the contraction of the actuators, the rotation of the joint could be measured with an encoder or potentiometer. Such a system of indirect measurement may prove a problem the less mechanically coupled the point of measurement is to the actuator. Lags in the response of the measured output from the actuator input may result in an unstable system.

When the desired feedback is force rather than displacement or its derivatives, the problem of output monitoring becomes somewhat less problematic. If normal methods of implementing force control are employed, the system need only strain gauges in the structure or load cells at the anchor points of the actuators. However, the antagonistic muscle arrangement mentioned above offers another path. Assuming that actuator stiffness is well correlated to excitation signal, a particular contact force profile could be maintained without any feedback. In fact, if polymer technology allows tailoring of stiffness response, it may be possible to create non-Hookian spring force responses, including constant force regardless of displacement.

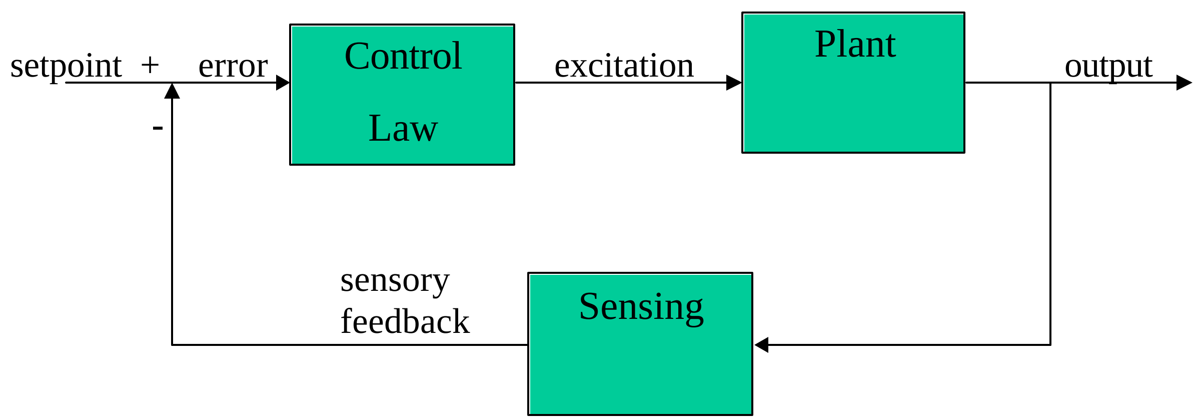


FIGURE 6: Schematic diagram of control system

7.2.3.4 Low-Level Control: Making Active Polymers Do what You Want

As the preliminary characterization experiments have shown (See Chapter 4.1), electroactive polymers tend to demonstrate a non-linear correlation between input and output. This condition causes complication in the techniques that can be used to accurately control these actuators. While no system that exists beyond the most primitive of experiments can be said to be strictly linear, those mechanisms that use common actuators can usually be approximated as a linear system. As a system moves away from linearity, classic control methods start to break down, and the system becomes inaccurate or unstable

A short primer on classic control may be useful at this point. Considering a system composed of only the actuator and using simple negative feedback control, the block diagram will look like Figure 6. Assuming that the system is being controlled for displacement, the set-point is the desired position, the excitation might be the voltage level applied to the actuator, the output is the true displacement, and the sensory feedback is the measured displacement. The error, on which the control law operates, is, not surprisingly, the difference between the set-point and the measured output. The Plant and Sensing have already been discussed, though it should be noted that this diagram differs from Figure 6 in that the Plant and Actuator blocks have been combined because the example system is limited to control of the actuator itself. The Control Law block represents the mathematical equation that relates the error to the excitation signal. Most commonly, (over 90% of installed industrial control systems) the equation used is the Proportional Integral Derivative equation. As the name suggests, the excitation signal is the sum of the multiple of the error, a multiple of the derivative of the error, and a multiple of the integral of the error.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

The "tuning" of this controller consists of determining values for the "gains" K_p, K_I, and K_d that satisfy stability and performance requirements. Although the PID control law is usually implemented as a software routine, it can actually be built as an analog circuit. For a much more complete and useful description of the PID controller, as well as most aspects of linear control, look to *The Art of Control Engineering* by Dutton *et al*.

As mentioned, however, active polymer actuators cannot be expected to be close to linear, and therefore the system cannot be expected to respond in a linear fashion even if a linear control law is implemented. Gains that work through one part of the system input envelope will cause inaccuracy or instability in another part. The next logical step, then, is to break the system response into regions that are themselves somewhat close to linear, and to linearize those regions. In practice, points in the input are chosen that correspond to expected operating points, and then the equation is linearized about those points. Formally speaking, a Taylor expansion is applied to the system response equation, and the linear terms of the expansion are used as the approximated system response for the region around the expansion point. In general, as the input moves further form the point of the expansion, the approximation will introduce larger errors into the system. The size of those errors versus the system design requirements will dictate the number of linearized regions necessary. For each of the regions a distinct set of gains is applied. The software monitoring the control of the system then switches between sets of gains depending on what region the system is currently operating within. This process is sometimes referred to as "gain scheduling". An example of the graph of a linearized response can be seen in Figure 7. It shows the equation $y(u)=u^3$ linearized about u=5 and u=10.

The method of linearization described assumes that a sufficient mathematical model exists to create a function. However, the general idea behind the creation of a piece-wise linear applies to statistical models as well. Instead of linearizing an equation, a linear fit can be created for regions of data, creating the same sort of approximated system model.

The type of non-linearity already discussed includes only continuously differentiable models. However, many of the most troublesome non-linearities fall under the heading of discontinuous. These complications include, saturation, deadzone, polarity (absolute value), quantization, switching, hysteresis, backlash, and friction. As there is no general closed-form solution to the dynamic equations governing systems with discontinuous non-linearities, there is no general approach to creating a control law for such systems. However, there are a few tools in the controls toolbox. One of the most common is "sliding control". In essence, sliding control uses a bang-bang (on-off) input, which is governed by a law that seeks to stabilize a function of the tracking error. This function is chosen to be linear in respect to the tracking error. A complete description of this method is beyond the scope of this book. However, a treatment of the subject can be found in *Applied Nonlinear Control* by Slotine and Li.

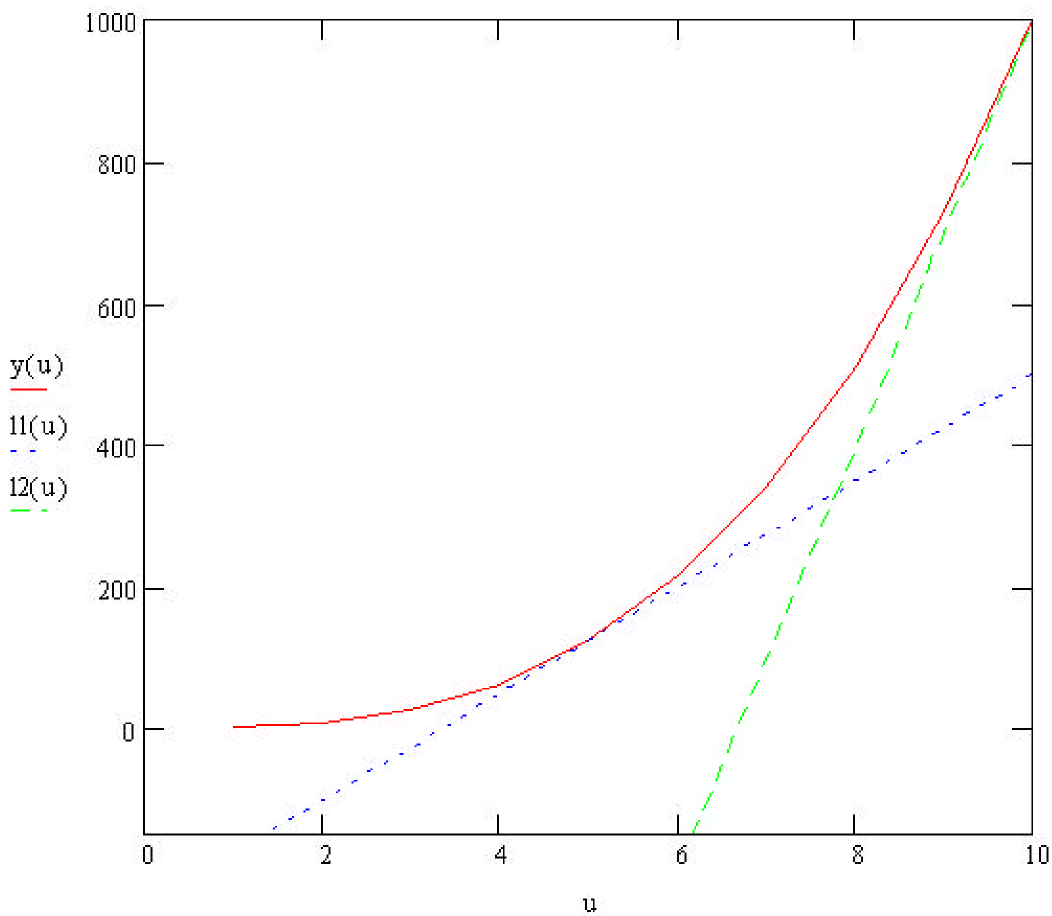


FIGURE 7: Example of linearization of the response of a system.

There is another interesting point to the control of active polymers. Just as they tend to damp disturbance forces, they should also damp input signals. Inherent input signal damping will protect a system from itself to some degree. Simple controllers tend to increase actuation input to saturation over a very short period of time, producing an internally driven shock to the system. Creating a controller that is more sophisticated as to how it applies actuation is more difficult and requires more powerful processors to implement. If the system automatically limits the rate in change of the input, system components will never see a self-produced shock load condition.

7.2.4 ACTIVE POLYMER ACTUATORS IN A TRADITIONAL ROBOTIC SYSTEM

A biologically inspired hexapod named LEMUR (**L**egged **E**xcursion **M**echanical **U**tility **R**obot) has been developed at the Jet Propulsion Laboratory as a step toward an on-orbit or extra-terrestrial maintenance robot. Despite its insectile appearance, it was conceived more as a six-legged primate (as the name suggests). Chief among its attributes is the ability to use its legs and feet as arms and hands. The current configuration, shown in Figure 8, is capable of walking on six legs or manipulating with two while stabilizing with the remaining four. The sections of the limbs below the knee/elbow have been designed to convert from feet to tools, as well as incorporating a quick-release mechanism allowing easy swapping of tool types.

Designing LEMUR using only standard electromechanical elements was quite tricky. As LEMUR is small (its body is only the size of a shoe box) for a robot with its level of articulation (20 independent joints with 2 actuated tools), incorporating a sufficient number of motors and drivetrains proved a challenge. In addition, the desire for a kinematically spherical shoulder joint for the front legs required a relatively complicated mechanism. Moreover, system demands required that the mobility system and structure comprise only about 50% of the overall 5kg mass budget. While the design problems were eventually solved, a robot in the same class as LEMUR could significantly benefit from using capable active polymer actuators in its design for many of the reasons discussed in the preceding sections.

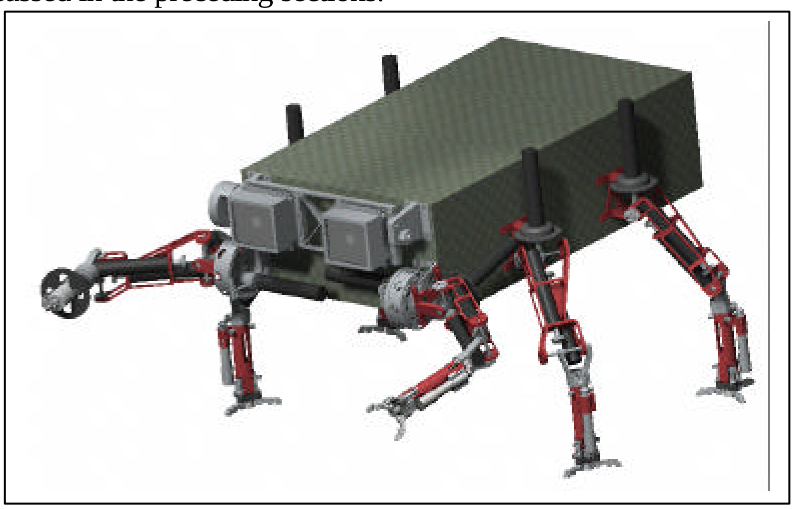


FIGURE 8: LEMUR can use its front limbs for mobility and manipulation

Immediately obvious are the benefits of designing biologically analogous limbs biologically analogous actuators. Two advantages are particularly applicable to LEMUR. First is the potential for a decreased mobility system mass. Given lighter actuators with less drivetrain structure, the overall system should be lighter as well. The second advantage is the simplification of the joint designs. As LEMUR's design doesn't use cable drives with remote actuators, the motors must be housed within the legs. This arrangement causes two problems. One is the placement of relatively massive components (the actuators) out on the end of links, increasing the rotational inertia of the system. Second is the difficulty of simply packaging the actuators. Mechanisms and parts become complicated and therefor less robust, heavier, and more expensive (in general). In contrast, we can look at the design of the spherical shoulder with muscle actuators. Rather than three distinct axes and actuators, one ball joint could be actuated using several artificial muscles. The exact number of muscles would depend on the particular agonist/antagonist scheme implemented. An example of such an arrangement can be seen in the Figure 9, which shows a human arm built by Blake Hannaford's lab at the University of Washington. It should be noted that the Washington lab is concerned with replicating a human arm. A limb designed for a LEMUR-class vehicle would probably be much simpler.

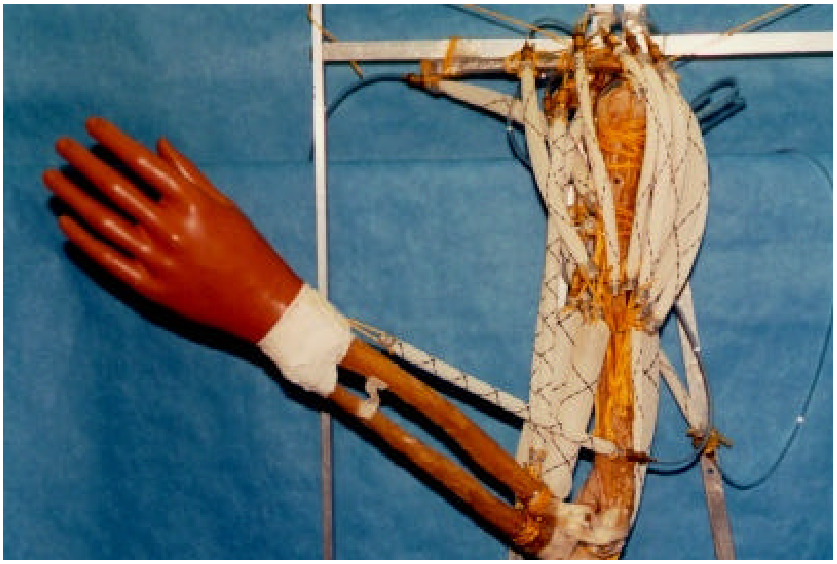


FIGURE 9. A high degree of freedom shoulder created using artificial muscles (Courtesy of B. Hannaford, University of Washington)

The modified LEMUR just described could provide a template for a first step in active polymer robots because it only substitutes muscles into the overall controlled system, leaving the computing and software architecture largely unaffected. This substitution is not trivial, of course. Other than the mechanical design aspects, allowances must be made for a different feedback system than is currently implemented (rotational encoders on the motor shafts), the actuator drive electronics must be radically modified, and a control method that takes the dynamics of the muscles into account must be devised. That said, an actuator substitution approach would provide a jumping-off point that would build on known techniques in software and computing. There are, of course, more radical approaches to design and control, which will be covered in the following sections.

7.2.5 USING RAPID PROTOTYPING METHODS FOR INTEGRATED DESIGN

Building robust robots is difficult – as any roboticist will tell you. However, in keeping with the design and manufacture of most artifacts most robot development follows a development cycle, which includes looping around the 'trial and error' phase. A great deal of time is often spent in cycling around this particular loop. Two techniques may be useful in the future to reduce the development time; rapid prototyping and artificial evolution. The embryonic technology of 3D printing may, in the future, allow us to 'print' out robot forms in EAP 'ink', which have been developed by artificial evolution in a simulated world. The following section takes a closer look at these ideas.

The steps involved in a rapid design and prototyping design loop have been already been touched on, but it may be useful to explore the tools that make fabrication possible in more depth. Probably the most important tool is a concept known as **S**hape **D**eposition **M**anufacturing (SDM), which is being explored as it pertains to robotics by the Dexterous Manipulation Laboratory at Stanford (directed by Mark Cutkosky). To borrow from a paper from the lab, SDM "is a technology in which mechanisms are simultaneously fabricated and assembled… [T]he basic SDM cycle consists of alternate deposition and shaping… of layers of part material and sacrificial support material" (Bailey *et al.*, 2000). The exact method of the deposition and shaping depends on the scale and application. In the case of the work being done by the DML, robots are fabricated by alternately molding polymeric parts then machining them with a CNC mill. Interspersed with these procedures is the incorporation of sensors and actuators. A finished part and its elements are shown in Figure 10. To date, SDM sequences are often *ad hoc*. However, a formalized methodology is under development by the Stanford Rapid Prototyping Lab in conjunction with the DML. This approach is explained in Michael Binnard in *Design by Composition for Rapid Prototyping* (1999).

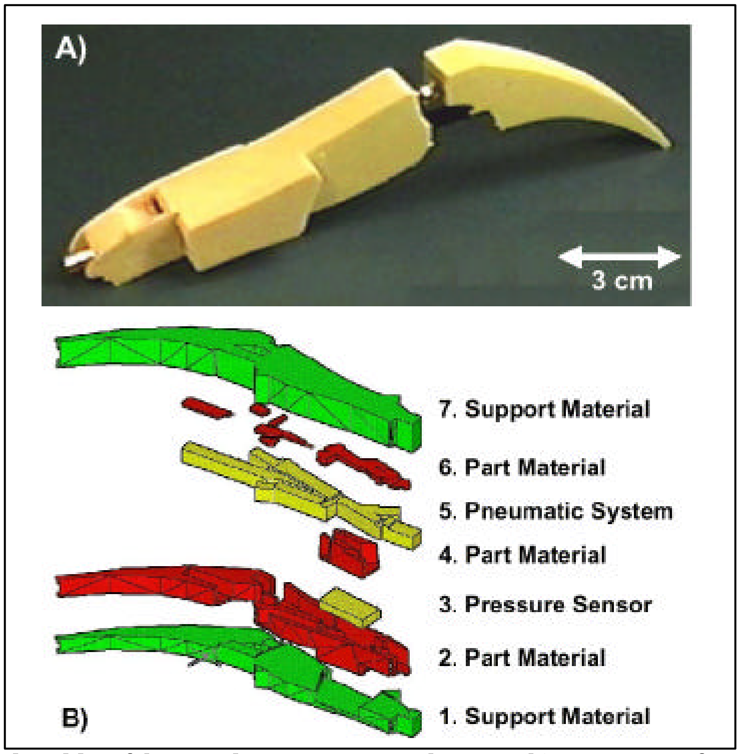


FIGURE 10: a) a completed leg fabricated using SDM techniques b) sequence of material layers and components (Bailey *et al.*, 2000 with permission)

However, several other part-forming technologies can be used in SDM processes, as well. Some of these are stereolithography (SLA), selective laser sintering (SLS), photolithography, and the aforementioned 3D printing. Of these, SLA and SLS have already been proven to be capable of building articulated structures down to a sub-inch scale (Mavroidis 2000). In the future, 3D printing may be useful for EAP robotics if it can be made to create heterogeneous material layers. With that advance, we could imagine laying down EAP or other active polymer at the same time as the polymeric structure. While current 3D printing lays down relatively thick beads of material, it may be possible to adapt ink jet printing to perform the same processes down to the micro-inch scale. In addition to the SDM techniques for mechanical elements, related techniques are applied in a concept called Molded Interconnect Devices (MID) for the manufacture of electrical circuits embedded in structures. In particular molding coupled with photolithography (or photoimaging) is used to create traces within polymer materials. Of course, at small enough scales, the fabrication looks much like that for typical IC chips. If already established practices from SDM and MID and/or IC manufacture are combined with the promise of active polymers, a truly integrated robotic system could be created.

7.2.6 EVOLUTIONARY DESIGN ALGORITHMS (GENETIC ALGORITHM DESIGN)

Once a robot is seen as a whole and each subsection as a variable that affects the response of the system, the impulse is to tweak those variables and simulate the response. One can imagine a design loop in which components are specified in the genotype of artificial creatures, the robot form and function is encoded, and the population of robots is then evolved over time through the implementation of pseudo-Darwinian selection for fitness. This selection process is sometimes referred to as genetic algorithm design. The best designed robots could be implemented in hardware and continue their evolution in the real world where they receive stringent testing and assessment. Some of them may return back to the simulated world and join their virtual fellows. Wonderful examples of such evolution supervised by humans can be found in the work of Hasslacher and Tilden (1995) concerning their physical populations of experimental machines. Here the intrinsic mechanics of robot evolution is based on the employment of minimalist electronics, reusability of components and utilisation of solar energy (BEAM, 1999). However, this process takes an inordinate amount of time due to the fact that fitness is measured by performance over time, and one is compelled to ask if there are techniques available that might speed the process. Is there any theoretical, or rather computer based, method that could offer us reliable techniques for fast evolution and easy prototyping of minimalist robotic devices? If rapid prototyping techniques such as stereolithography were used to produce real-world versions of the robots, the overall scheme of robot evolution would look like: (1) seed a primordial culture of robot components, (2) evolve population of robots, (3) select the best performers, (4) fabricate the robots using rapid prototyping techniques, (5) verify robots' performance in real world, (6) select best designs and inject their virtual copies back to the virtual robots' population, (7) go to the step (2).

Parts of such a design cycle have been explored by several researchers. Those working purely in hardware world are represented by Hasegawa and the gibbon-like robot *Brachiator*. It is built of several links, joints and pneumatic pistons. *Brachiator* moves from one branch of a tree to another by swinging its body as a pendulum (Hasegawa *et al*, 1999), as most monkeys do. The actuators of this “monkey” are controlled by artificial neural networks that learn and evolve themselves. In this case, no simulation is performed. The controller attempts to make a particular move using particular actuation profiles. A series of profiles are compared for effectiveness, and the best is retained and built on. Also in this vein of research is the reconstruction of an extinct swimming animal *Anomalocaris*, as described in Usami *et al*. (1998). The reconstructed creatures swim by the waving motions of 'fins'. Each creature is created by simple rules, where every rule gives rise to the action of a particular unit of the creature's body. Some genetic-inspired re-combinations of rule strings (the artificial 'genes') are employed to increase the morphological diversity that is directly linked to locomotion activity. By employing artificial evolution the better swimmers are selected.

Rather than emulating the design and function of existing animals, some researchers have started from the basic building blocks that nature itself uses. In the context of a simplistic design strategy a novel robotic creature must include endo- or exo-skeleton, muscles, sensors and primitive neuron-like control decision elements. It is quite convenient to consider the skeleton built from stiff cylinders or 'sticks' connected by joints. The muscles can be attached to the sticks as well as sensors and neurons. The most primitive virtual creatures with the minimalist design form a "clone" of Swimbots; swimmers that inhabit Ventrella's artificial ponds (Ventrella, 1998,1999). In this section, we will discuss in depth the creation of another construct, the virtual stick-based creatures, *Framsticks*, or Ulatowski-Komocinski machines. These are artificial creatures built from three basic components: rigid sticks, flexible muscles and primitive neurons (Ulatowski and Komocinski, 1998-2000).

Let us look briefly at the framsticks design. The body of a *framstick* is built from sticks. A stick is subdivided into a finite number of control points, which are affected by several forces: gravity, friction, elastic reaction, reaction with ground and many more. If framsticks collide with each other then some sticks may be destroyed. In addition to sticks the creatures also have muscles, neurons and receptors. They may also exhibit some kind of metabolism. Using specialised endings of the sticks, framsticks can assimilate energy from their environment and even ingest their dead fellows! A framstick starts its life with certain amount of energy. It dies when energy level is zero. The creatures dissipate their energy when idle; they also spend energy on static and dynamic muscular activity.

There are two types of muscles that join the sticks: bending muscles and rotating muscles. The muscles consume energy and are controlled by neurons. A framstick gets information about the environment via three types of receptors that can be attached to the sticks: G-receptor, T-receptor and S-receptor.

The G-receptor receptor is an analogue of an otolith, which can be found, in one form or another, in all real creatures from *Protozoa* to humans. The receptor signals if the position of the stick it is attached to is not perfectly horizontal. The T-receptor a receptor of pressure. The receptor generates constant negative value when it is free. Its value becomes close to null when it touches an object; it can go to a positive scale when pressure increases. The S-receptor is a receptor of a smell. It smells equally well presence of food and other framsticks; however the receptor does not discriminate between different stimuli. The receptors of smell and pressure are sufficient to guide a creature in its world. Theoretically we can avoid using the G-receptors; however, these receptors are quite useful when swimming creatures are concerned.

Framstick neurons are quite primitive. They are attached to sticks and take inputs from other neurons or receptors. They can bear self-inhibiting and self-exciting terminals as well. The neurons send their efferent terminals to the muscles. Being connected to rotation or bending muscles the neurons control rotation or bending of a stick relative to its neighbouring sticks. An excitation function of neurons is based on a weighted sum of input signals. Neuron reactivity can be tuned (via modification of genotype entries) by indicating how fast neuron updates its state toward weighted sum of its inputs and how long the current state persists. It is possible to achieve oscillatory mode combining the values of neuron reactivity.

The framsticks have simple hence powerful genetic system, which is instantiated in a separate program module. We could also mentioned that modifying framstick genotype one can change each stick's properties (e.g. rotation, twist, curvedness, length, weight, friction, muscle strength), topology of neural network and functions of receptors.

Genetic evolution is highly controllable. One can set up global intensities of mutations, parameters of genes reparation (which is a bit technical yet useful), features of crossover, mutation probabilities for genes coupled to all parts of framstick body, e.g. detailed mutation probabilities for neurons, muscles, and receptors. Mating preferences between the creatures are implicitly expressed via similarities of genotypes. User can also specify capacity of framstick world, or a maximal size of the population, rules for deleting genotypes (fitness-based selection, random deleting, or elimination of only worst types).

A selection of creatures is based on four basic characteristics: duration of life, velocity of movement, spanned distance, size of a creature. A fitness of any particular genotype (read individual) is calculated as a sum of weighted values of four selection characteristics. Sometimes energetic efficiency can also be employed to evaluate the fitness.

Two types of evolution process are implemented in **Framsticks**: directed evolution (selection) and "spontaneous" evolution. During straightforward selection one can specify parameters, which are used to evolve a best creature. That is we explicitly define optimisation criteria. Thus, for example, if we wish to produce the fastest lightweight crawlers we weight velocity parameter positively and structure size parameter negatively. Eventually we will get small and fast creatures. In a course of "spontaneous" evolution we may not define any explicit parameters of selection but just general rules of the evolution, such as outcomes of the collisions between the creatures, utilisation of dead creatures, ageing rate, specific of muscular work and so on. Neither of these parameters guides evolution: the only creatures with longest life benefit. A few examples of spontaneously evolved creatures are shown in Figure 11.

Let us look at a couple of examples of experiments made with the help of **Framsticks** software. Assume at first, we decided to breed some non-trivial swimming creature. In the artificial world we set up the water level above zero and put one-stick creature with no neurons, no receptors and no muscles in this bath. We adjusted simulation parameters to select creatures by both velocity and structure size. After several thousand generations of the creatures, during which we intervened in evolution and subjectively chose 'the best' examples. The final result was a creature consists of 20 sticks, 6 neurons, a couple of muscles and one G-receptor, responsible for a "sense of equilibrium". We call him *Back-swimmer* because he swims backwards: two branches of joint sticks form some kind of "legs" which move and 'grabs' water allowing the creature to move. As you can see in snapshot (Figure 11) of an artificial aquarium with *Back-swimmers*, several sticks of a creature float on the surface of the water thus keeping the rest of creature's body in medium layers of the water.

One lab that is attempting to use all the steps of the suggested design cycle is the DEMO lab at Brandeis University. The GOLEM project reported by Lipson and Pollack (2000) has resulted in physical models of robots designed through the use of genetic algorithms in simulation. The structure dictated by the algorithm was directly fabricated from a thermoplastic using a rapid prototyping technique known as 3D printing, and then the actuators were incorporated by hand. In essence, these robots represent a real-world instantiation of the framsticks, substituting electromagnetic actuators for theoretical muscles. The exciting next step for active polymer researchers would be to lay down the plastic muscles (and perhaps conductive plastic wires) at the same time as the plastic structure, allowing one-stop robot design and fabrication. This concept will be explored more in section 7.2.5.3.

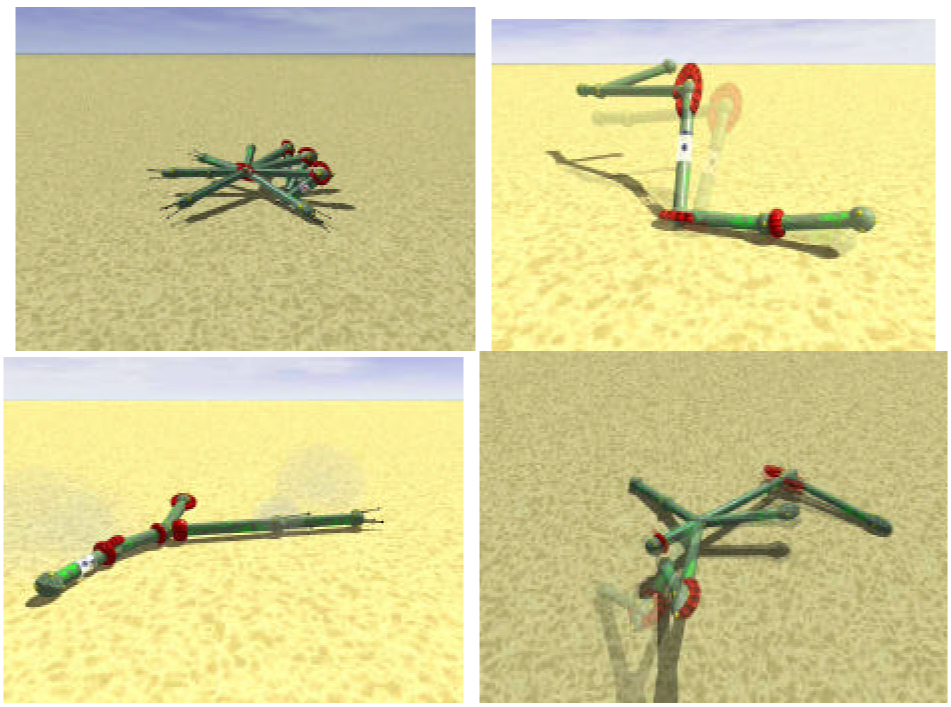


FIGURE 11: Examples of creatures evolved in the populations of framsticks in the dry and flat world. The images are taken from **Framsticks** official web site (http://www.frams.poznan.pl/) with kind permission of M. Komocinski.

7.2.7 EAP ACTUATORS IN HIGHLY INTEGRATED MICRO-ROBOTS DESIGN

The traditional model of a robot with discrete components may be joined by a new model in which the lines between controller, plant and feedback are less rigidly drawn. This new paradigm results in a much more tightly integrated system, which is enabled by up-and-coming technologies such as active polymers, rapid prototyping, and new simulation and design algorithms. The combination of these technologies promises important advances towards the engineering ideals of faster, cheaper, and more effective design cycles.

Although these techniques can be used to create systems of any physical size, they are particularly important, possibly indispensable, tools for the design and manufacture of tiny robots. These micro robots will have the advantages of being small (by definition), lightweight, and easily produced, therefore making them candidates for mass manufacture. As a somewhat whimsical example, consider a system of sub-inch robots equipped with a 'sticky' cilium or two composed of EAP that would enable them to move across small 'ceilings' and 'walls' inside a structure which is difficult for humans to access – perhaps the escalators in a subway. They may be able to power themselves using light, heat, ambient chemistry etc. or perhaps be built with a small on-board, gel-based battery system. With some judicious tinkering they are given two basic behaviors; a phototactic behavior in the presence of light and a default random walk in its absence. If these robots are 'injected' into the machinery, which is then optically sealed, the robots would then carry out a random walk and spread out through the machine. In doing so they may come across small items of grit and dirt, which could become attached to their bodies. After some appropriate time an intense light is shone into the machine from some 'exit' portal. The robots would then switch to their phototactic behavior and move toward the light source. In doing so the robots would bring out the small items of grit and dirt attached to themselves. Perhaps the robots would then be thrown away or even washed and re-used! This approach also has the advantage that broken robots themselves could be removed by their peers – but designers would also have to ensure that the robots didn't simply gum up the works!

7.2.7.1 Control of Micro-Robot Groups

Of course, the problem of controlling and coordinating the behaviour of very small robots must be considered. For the purposes of discussion let us focus on robots with volumes in the range of a cubic millimetre to a cubic centimetre. All we can expect to be able to build in this domain over the next few years are really quite dumb and simple robots, with rudimentary sensing, communication, locomotion and computation abilities. These robots will experience considerable limitations. As with all autonomous systems, not only will power provision be problematic, the very capacity of a single tiny robot to achieve anything or even to survive for any length of time will be in doubt; an individual is limited and vulnerable and so it is likely that only collective actions will succeed. On the face of it the prospects look bleak for an engineer required to build such a system. However, studies of evolved natural systems, particularly the social insects, provide us with an existence proof that collections of relatively 'simple', mostly reactive, creatures can achieve remarkable feats that are beyond the capacity of an individual; such organization is underpinned by decentralized mechanisms for decision making as well as for the control and coordination of task-achieving behavior. Although such studies engender optimism we should be cautious about the use of the word 'simple' sometimes applied to animals such as ants. The 'lowly' ant is a wonderful biological machine, which has been evolving for over 100 million years; a machine, which is capable, for example, of impressive feats of locomotion, power efficiency, navigation and strength. This form of decentralized system, which employs simple units, which appear to collectively solve problems traditionally tackled by a single smart individual, has sometimes been referred to as swarm intelligence. The task of control and co-ordination of a group or micro-robots might be encapsulated thus 'how do we get a lot of dumb robots to collectively do something smart?'

A number of researchers have contributed toward the definitions of swarm intelligence in the context of a distributed system with a large number of autonomous robots. Beni and Wang [1991] expressed the idea as *"the essence of the .... problem is to design a system that, while composed of unintelligent units, is capable as a group, to perform tasks requiring intelligence -- the so called Swarm Intelligence"*. Theraulaz *et al* [1990] define a swarm as *"a set of (mobile) agents which are liable to communicate directly of indirectly (by acting on their local environment) with each other and which collectively carry out a distributed problem solving"*. Such a swarm will exhibit functional self-organization [Aron *et al* 1990] as a consequence of the collective set of internal dynamics and interaction with the environment. Deneubourg & Goss [1989] neatly sum up the problem *"The key ... lies in remembering that at each moment the members of an animal group decide, act and interact, both amongst each other and with the environment, permanently changing the state of the group. Just as sociobiology, with its population genetics and games theory, shows the importance of dynamics and individual interactions in the evolution of social behavior we propose the analysis of these interactions as the straightest path to understanding the short term collective behavior of animal (read robot) groups.*"

The autonomous robots we currently build are mostly rudimentary, often unreliable, incapable of self-repair and problematic with respect to power budgets. Against this background we speculate that the construction of small robots in the future will necessarily have to incorporate advances in material science - including the incorporation of artificial 'biological material' such as muscle actuators, sensors, artificial metabolism as well as a firm understanding of principles underpinning the control and coordination strategies of social insects.

The minimalist approach has also been undertaken in other domains and the interested reader is directed to the following papers; kinesis, taxis and target following [Holland & Melhuish C. 1996a,1996b], secondary swarming [Holland O. & Melhuish C. 1996a, 1997a, Melhuish 1999b], formation of 'work gangs' [Holland & Melhuish C. 1997a, Melhuish *et al* 1998a, Melhuish *et al* 1999], collective behavior transition [Holland & Melhuish 1997a, 1997b]. A brief overview is given in [Melhuish 1999].

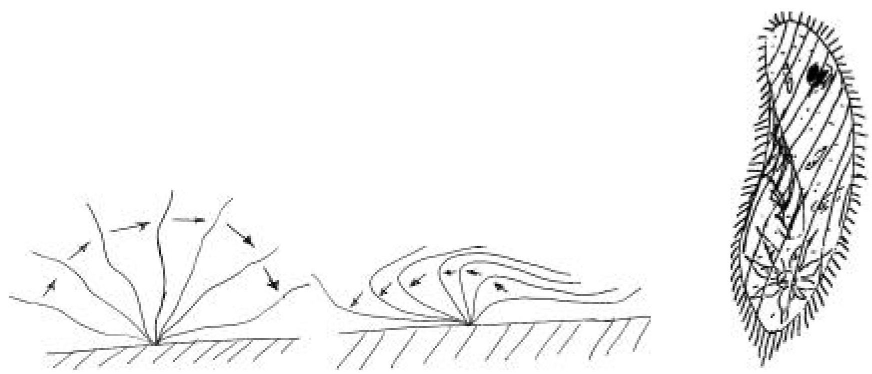
7.2.7.2 Unconventional Locomotion Controllers for Micro-Robots

When talking about sub-inch scale robots one would obviously turn to biological analogs. There are living prototypes of micro-robots who do not have centralized control, but who sense, decide, and act distributively. The *Protists* offer us ciliates and amoeboids examples.

The phylum *Ciliophora*, or ciliates, includes unicellular organisms, bodies of which are covered with cilia. One could refer to *Paramecium caudatum* as a typical example; see e.g. Melkonian, Anderson and Schnepf, 1991). Each cilium, attached to a membrane of a protist, sweeps with a power stroke in the direction opposite to intended direction of organism movement (Figure 12, A). The cilia are usually arranged in rows; this arrangement forms a longitudinal axis of beating

(Figure 12, B). Cilia beat coherently in waves and propel the individual forward. A physical integration of strokes of many cilia propel the protist in the direction opposite to the direction of beating.

Perhaps the control may be implemented by either information transfer via sub-membrane network of microtubules or coordinated contractions of the membrane travelling along the protist's body. In any case, we can speculate about direct analogies between wave of cilia beating, caused by excitation waves of the lattice, and waves of co-beating of cilia in protists, that move from front to rear parts of the organism. Working prototype of an artificial ciliate would be ideal. We are building it in the near future. However, in this chapter we will try to explore some idea of employing an excitable medium in the form of a molecular array of sensors and actuators to provide the controller for a micro-robot by exploiting decentralized computation.



A. B.

FIGURE 12: Ciliar mechanics in *Paramecium caudatum*. (A) Cilium beating, (B) Arrangements of cilia.

Whether we look at the conventional models such as sense-model-process-act or the behaviour-based architecture (Brooks, 1986), which stresses the tight coupling between sensors and actuators, three key design areas need to be addressed; sensing, actuation, and decision making. Implementation of sensory input devices is a non-trivial task. However, future research may show that such implementation can be either solved using conventional techniques and devices or the use of future smart materials, which conflate elements of sensing, actuation and 'processing'. Here we make a reference to 'unconventional' controllers. Conventional controllers might be considered to employ explicit control algorithms such as in digital computers and is often associated with an explicit symbol processing approach. In contrast unconventional controllers might employ implicit forms of computation as in the case of wave computation in which the 'result' of local micro-processes is some macroscopic phenomenon, which can be used, for example, as an indicator of some quality or quantity of state. A controller for robot navigation can be designed using several techniques, which are briefly discussed below.

We can, of course, couple sensory elements with motor units. This gives quite a wide range of complex robot behavior. These ideas are demonstrated by Braitenberg (Braitenberg 1984). By expeditious coupling of input with output, Braitenberg shows how interesting and seemingly directed behaviors (which he playfully refers to as love, fear, aggression etc) such as attraction and repulsion along with non-linear dependencies can result from simple input-output mappings.

An example of such an approach is the 'solarbot' shown in Figure 13. The solarbot consists of two wheels (made from small mobile phone vibrator motors) each coupled to a separate capacitor. Each of the capacitors is connected to a photocell 'wing' on opposite side of the body from the wheel. The robot can accomplish phototaxis by first storing the energy generated by each photocell on 'wing' in its associated capacitor and then releasing the stored energy to each wheel when sufficient power had been accumulated. In this way, the side of the robot which was nearer the light source would give its cross-couple motor more energy than the 'darker' side thus making the opposite wheel turn more. By judicious use of time constants to control the charge and release times the robot could then make its way toward a light source in a series of arcs.

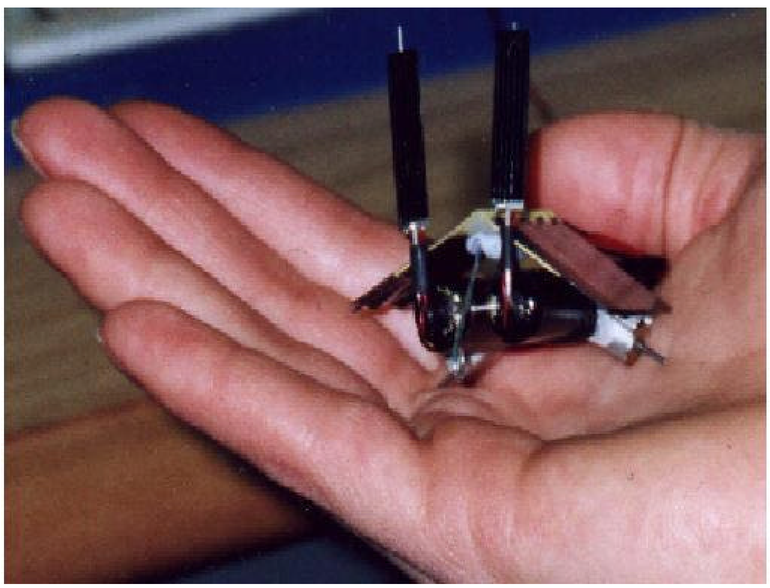


FIGURE 13: Solarbot made at IAS Laboratory at the University of the West of England

One might also be able to apply this simple 'Braitenberg Vehicle' style controller by judicious employment of linking input to output. One approach might be based on the dynamics of excitation in nonlinear media. This is a so-called wave based computing (Adamatzky, 2000). Two types of non-linear media, either discrete or continuous, are of particular interest: reaction-diffusion media and excitable media. Both of these types of media support waves, either phase waves or diffusion waves, in their evolution. The waves are generated by some external stimuli and travel through the medium. The waves interact with each other and form distinctive concentration profiles or dissipative structures as a consequence of their interactions. To implement computation in active wave media we could represent data by the distribution of elementary excitations or concentration profiles. The waves collide one with another, i.e. they implement 'computation' since the consequent dissipative structure or distributions of a precipitate can represent the 'results' of the computation (Adamatzky and Melhuish, 1999).

Let us discuss the wave based computing in an array of cilium-like actuators. Consider the idea of a micro-robot constructed as mobile array, which is required to demonstrate phototaxis. Let us first fabricate a two-dimensional molecular array in such a manner that every molecule of the array is associated with its eight closest neighboring molecules. After that we couple every element of the array with its own propulsive actuator as shown in Figure 13. We could perhaps choose molecules that are light sensitive, i.e. they are excited by photons. Let us assume, for simplicity, that the only molecules at the edges of the array are light sensitive. When such edge molecules are excited they transmit excitation (energy) to the internal molecules of the array. The excitation can be passed between one internal molecule to another internal molecule. Let us restrict the position of the actuators such that they can take up one of eight orientations. If the actuator positions itself away from the direction from which excitation arrives, then the actuator could produce a local propulsive force. The combined propulsive force of the array of actuators provides an overall propulsive vector toward external light source.

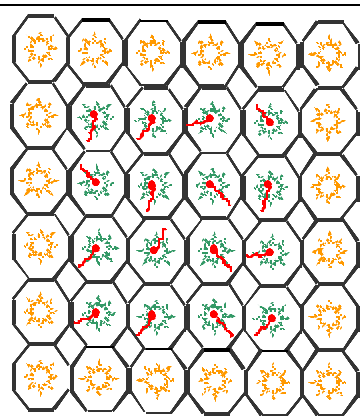


FIGURE 14: A sketch of excitable molecular array with incorporated actuators. Molecules are hexagonal. Cilia are shown explicitly.

All molecules of the array update their states in parallel; therefore we have parallel array of processing elements coupled with parallel array of actuators. In our model every molecule of the array connects with eight neighbouring molecules. Every molecule is excited if a number of its excited neighbours, amongst these eight neighbours, lies in the interval $[q_1,q_2]$, where q_1 lies in the range from 1 to 8 and q_2 lies in the range from q_1 to 8. This interval based parameterisation give us potentially 36 excitation rules. These rules determine various regimes of excitation dynamics on the molecular lattice: from chaotic dynamics to spiral waves to self-localised excitations.

Simulations have been conducted which employed a controller composed of an array of coupled sensors and actuators as described in the previous section. In computer experiments we place a robot at random in a virtual two-dimensional space with a light source. It was found that the robot demonstrated photactic behavior; typically the robot starts to wonder around, performs weird motions and then begins to move toward light source along some non-linear trajectory. This behavior of the robot moving through the two-dimensional space toward a light source can be explained by the following chain of events in the excitable medium of the controller. The edges molecules of the controller array are excited by the photons and patterns of excitation move inward the array. The movement of the excitation patterns modifies the local orientations of the actuators, attached to the internal molecules of the array. Local propulsive forces are generated by each actuator. The interaction between the local forces generated by each actuator and the environment implicitly create a form of 'vector integration' which then causes the rotation and translation motion in the robot. For each of 36 types of molecule sensitivity (due to the parameterization intervals of q_1 and q_2) we have recorded the robot trajectories and the space-time dynamic of excitation patterns. From observation of the form of trajectory we partitioned the parameter space into three main groups: Graceful, Pirouette and Cycloidal (Figure 15 and 16).

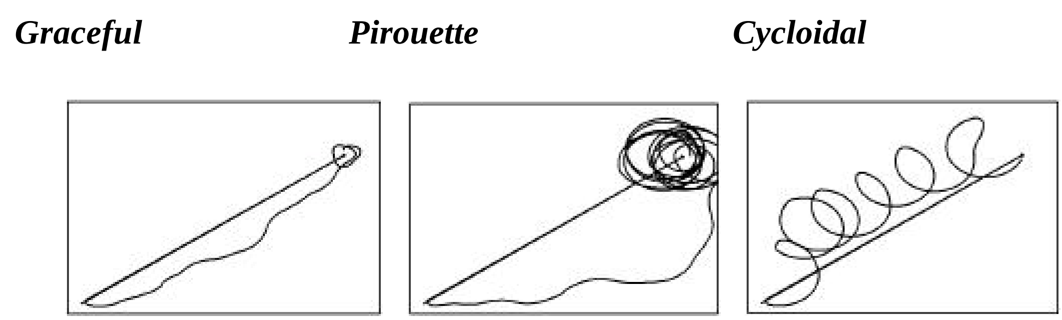


FIGURE 15: Example of robot trajectories for three main groups of robot locomotive behavior. The robot starts its journey at the left bottom corner of rectangular arena. The starting point is connected to the destination point (source of light) by a straight-line segment. The robot trajectories are curve lines.

To check whether these ideas work in real world experiments we installed a model of the excitable lattice controller in a mobile robot. The robot is about 23 cm diameter and shown in Figure 17. The excitable controller is simulated on the board processors, which is programmed in C. Ideally, every molecule of the controller must have its own actuator; as well as every edge molecule should be able to react on light. Unfortunately, the engineering realization of such set up would be very complicated and costly. Therefore we employed a realistic and pragmatic approach of employing a 'large' robot with two driving wheels and three light sensors (left front, right front and a rear sensor). The left and right sensors are coupled with left and right parts of the front edge of the molecular array. The rear sensor is coupled with the rear edge of the molecular array (Figure 17).

The model allowed the edge molecules to be excited with a probability proportional to the values on their corresponding macro-sensors. Orientation of global vector is transformed to the rotation angles of the robot (via spin speed of the motors) in a straightforward way. The following algorithm of robot behavior is implemented: evolve molecular array, calculate local vectors, calculate global vector, rotate robot, move robot at fixed distance, if light source is not reached go to first step, otherwise stop experiment.

Our robot performed inside a huge arena, which has an area 1760 times more than that of the robot. We placed a line of lights outside the arena. The behavior of the robot is recorded via a video camera, which is mounted 6 meters above the arena. At the beginning of every trial we put the robot near the edge of arena opposite to the light source. The robot is turned off when it reaches the light source. The highlighted trajectory of the robot is shown in Figure 17.

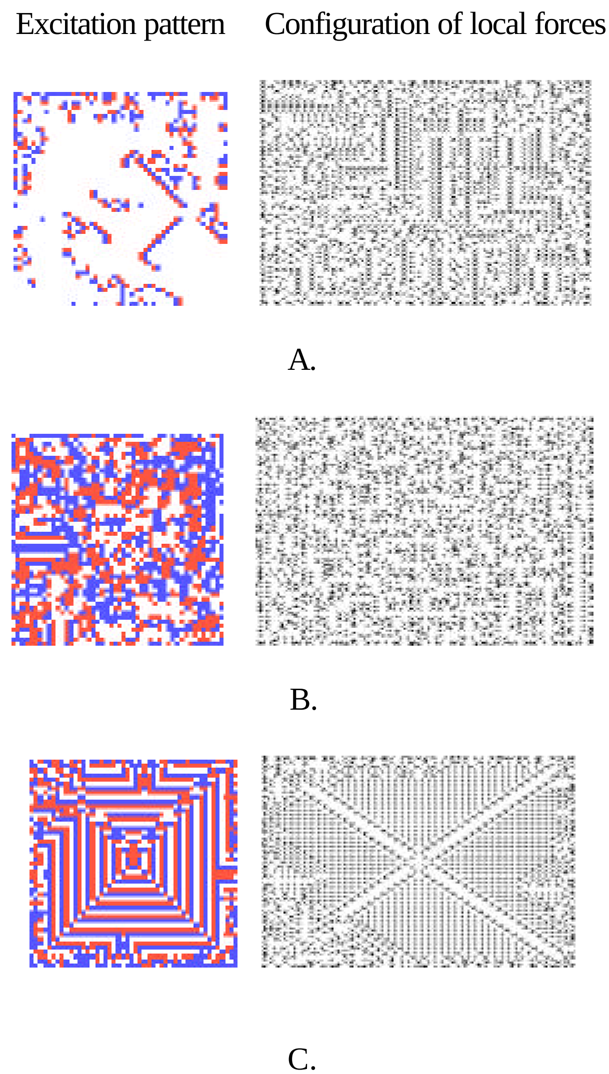


FIGURE 16: Excitation dynamics responsible for graceful (A), pirouette (B) and cycloidal (C) motions.

In the figure we noted that even light from a nearby corridor (two light spots at the top part of the arena) contributed to the noisy environment of the real world experiments. As we can see on the series of snapshots below the robot did not choose the right directions immediately. At the beginning the robot moved toward the incidental light spot. Then it 'realized' that this spot is not a source of light with maximal intensity. So, it implemented a U-turn and headed toward the light target. While approaching the target the robot changed its trajectory because of the second spot of light. However it recovered from this 'mistake' quite soon and eventually hit the light target.

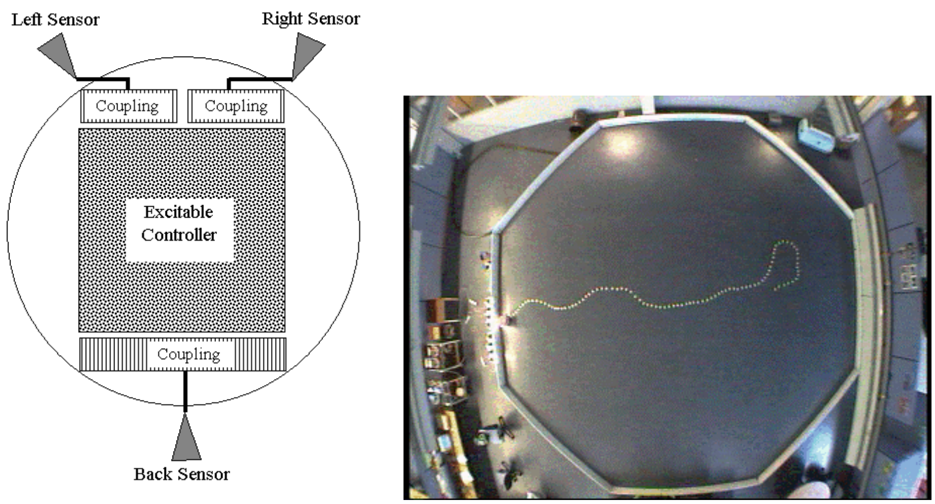


FIGURE 17: Conventional robot with ciliate-based controller. (A) Coupling of light sensors with simulated excitable lattice in real robot. (B) Trajectory of the robot, which searches for the source of light. The robot starts its journey at the far right part of the arena. The light source is positioned on the left.

Chemicals, as well as light, may serve as both a navigation driver and an actuator stimulus. A good example is the behavior of species of *Amoeba*. Amoebae move due to the effective separation of its cytoplasm into a sol and gel during the formation of it pseudopodium. When some parts of amoeba cytoplasm are transformed into sol, endoplasm starts to flow to this area. Resultantly, a membrane expands and the pseudopodium is extended forward. When sol-like cytoplasm reaches the end of the pseudopodium it is transformed into gel. This recurrent converting of sol into gel and back allows the organism to move purposefully. Two mechanisms, in general, may determine amoeba's motility: changes in intracellular pressure (Yanai *et a*l, 1995) and microtubule dependent development of pseudopodia (Ueda and Ogihara, 1994). The intracellular pressure is possible generated by contracting actomyosin resided in the cortical layer, whereas formation. Microtubules seem to be responsible for directional stabilization of pseudopodia, which enables amoeba to undertake reorientation steps (Ueda and Ogihara, 1994).

As mentioned, the sensing-actuating of amoebae is usually associated with chemotactic behavior. When an amoeba, let us talk about *Physarum polycephalum* at this stage, moves it usually has one linear pseudopodium, which is expanding during organism motion. If some attractive chemicals are presented in the substratum, then the linear pseudopodium is split into several lateral pseudopodia, which explore a space around the main linear tip. One of the lateral pseudopodia, usually positioned at the site of substrate with relatively higher concentration of chemicals, is stabilized and becomes responsible for linear motion. Thus a selection of concentration maximum is implemented by real amoeboids; see an example in the Figure 18. Quite similar ideas are already employed in the algorithm for shortest path computation by *Physarum polycephalum* in (Nakagaki, Yamada and Tóth, 2000). However, in this installment selection of leading pseudopodia is achieved not by its relative position at the site with higher concentration of chemicals but by the distance of the tip of the pseudopodium from the amoeba body's 'center'.

Perhaps the most obvious example of 'directed' behavior in amoeba is that of chemotaxis. However, it is interesting to enquire if we could also control the behavior of amoeboids by electro-activation? Quite possibly, it seems. There are examples of electrical sensitivity of both real (Korohoda *et al.*, 2000) and artificial amoeboids (Ishida *et al*., 2000; Hirai *et al*, 2000). It is reported that *Amoeba proteus* shows strong positive galvanotaxis. When put on the substrate influenced by a direct current field (Korohoda *et al.*, 2000) the amoeba moves toward the cathode.

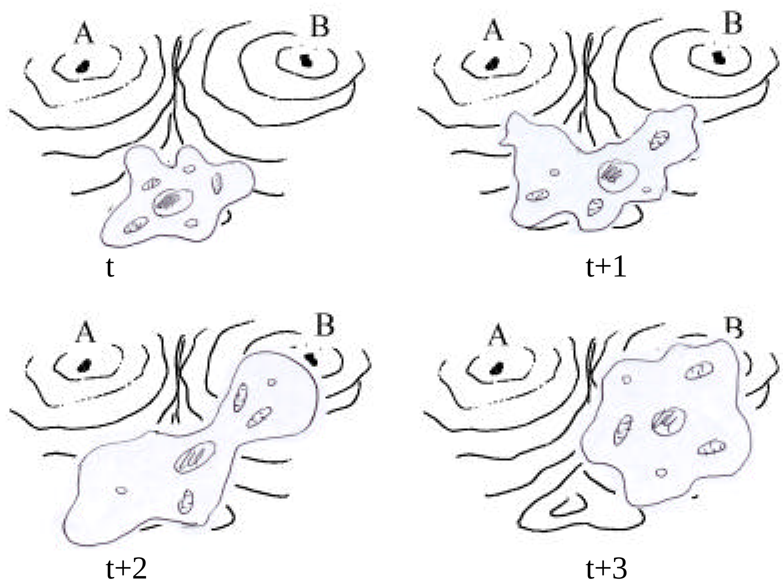


FIGURE 18: Chemotactic solution of a decision problem by amoeba. Concentration of attracting chemical, e.g. glucose, is higher at the site B than at the site A.

A beautiful example of artificial amoeboid like creature is offered in (Ishida *et al*., 2000). The liquid mobile robot, with no structure at all and easily changeable shapes, are realized there based on the paradigm of artificial amoeba developed earlier by Yokoi and Kakazu (1992). In the experiments the liquid metal robot is represented by mercury drops while its environment is a substrate with an array of electrodes, connected to external controller (Figure 19).

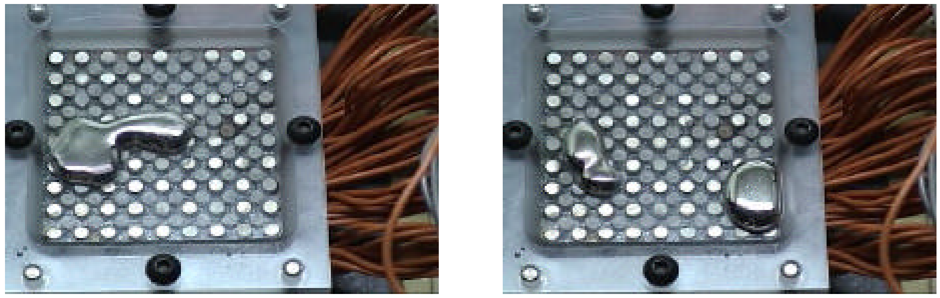


Figure 19: Liquid mobile robot. (Ishida et all, 2000); with kind permission of authors.

It is demonstrated in the experiments that by varying potential pattern of the electrode array one can easily guide the mercury drop, cause splitting of the drop into several daughter drops, their fusion and different types of motion (Figure 19). Galvano-motile polymers (Osada et al., 1992) and crystals (Hirai *et al*., 2000), may be promising non-metal substrates for artificial amoeboids.

7.2.7.3 Micro-EAP 'Integrated' Robot: A Case Study of a Phototactic System

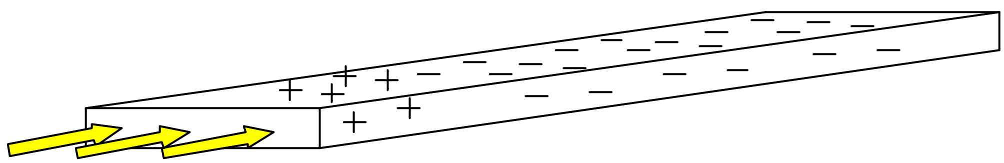
So, how might we go about creating micro-robots using EAP hybrid materials combined with some of the ideas of excitable media discussed above? It's interesting and fun to speculate how EAP could be combined with other smart materials to create micro-robot devices capable of phototaxis. Let's give our imagination some exercise.

First, let us look at the construction of a swimming 'pad' which could exploit an undulating motion of a plane polymer sheet. Suppose that a polymer material is made which has the characteristics of being able to propagate some wave of excitation – perhaps some ionic concentration. Figures 20a and b illustrate the idea. Light is allowed to enter the polymer at the end of the strip only (perhaps the rest of the polymer surfaces is covered in some light reflecting covering). The photonic energy alters the molecular state of polymer substrate, which, in turn alters the state of its neighboring molecules. In this way, given some appropriate refractory period for the molecules in the altered energy state, a wave of excitation could pass along the substrate. If the excitation layer could then be bonded to an actuation layer then it might be possible for an actuation wave to travel through the actuation layer (see Figure 20c). In this way the bonded laminate could ripple and execute some form of swimming behavior since the sheet of EAP is bent under the influence of electrical current spreading along the conductive sheet; repetitive generation of excitation waves, travelling along the pad cause undulating movement of the pad…. the pad swims therefore.

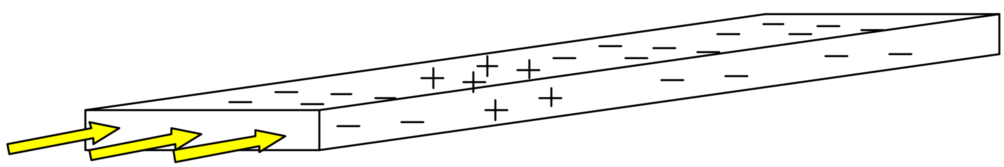
If the above arrangement in Figure 20c was duplicated, and the two units bonded back to back, we have the potential for differential locomotion. Like the 'solarbot' mentioned above, light on one side of the robot will excite its actuator layer more on its side than the other, which biases motion toward the light.

Perhaps we could take this one stage further and bond artificial cilli, constructed from laminar EAP, to an excitation layer. Figure 21 shows the principle. The excitation layer is bonded to artificial cilli constructed from laminar EAP tubules. When the excitation wave traverses an actuator it could deform appropriately. This gives the prospect for some form of crawling robot.

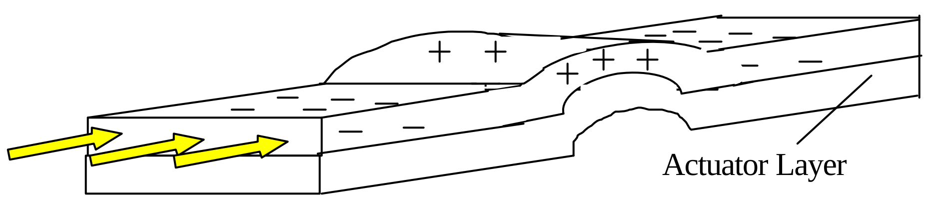
Let us speculate further. If we put together slabs of the units shown above in Figure 21 we could create a tubular construction as shown in Figure 22. The diagram illustrates one slab being activated more than the others. Waves of deformed EAP tubules are seen to be travelling backwards along the activated slab causing the robot to alter its direction. When the robot is lined up with the light source all slabs would become active. In this way such a tubular robot could therefore demonstrate phototactic behavior.



(a) Excitable media layer excited by light



(b) Excitable media layer propagating excitation wave



(c) Excitable media layer propagating actuation wave

FIGURE 20: Integrated system with sensing, computation, and actuation

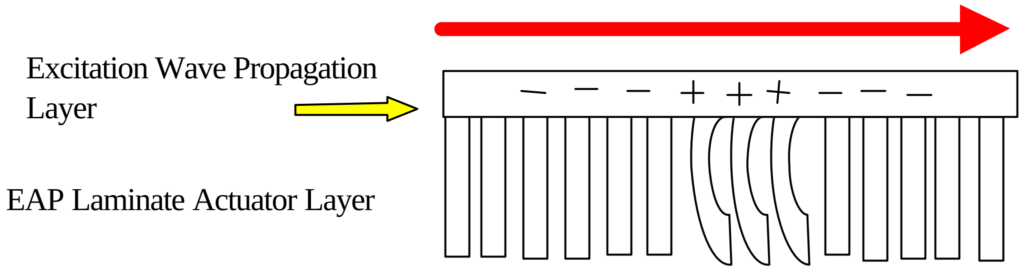


FIGURE 21: Traveling wave induced in the actuator layer of laminated cilia

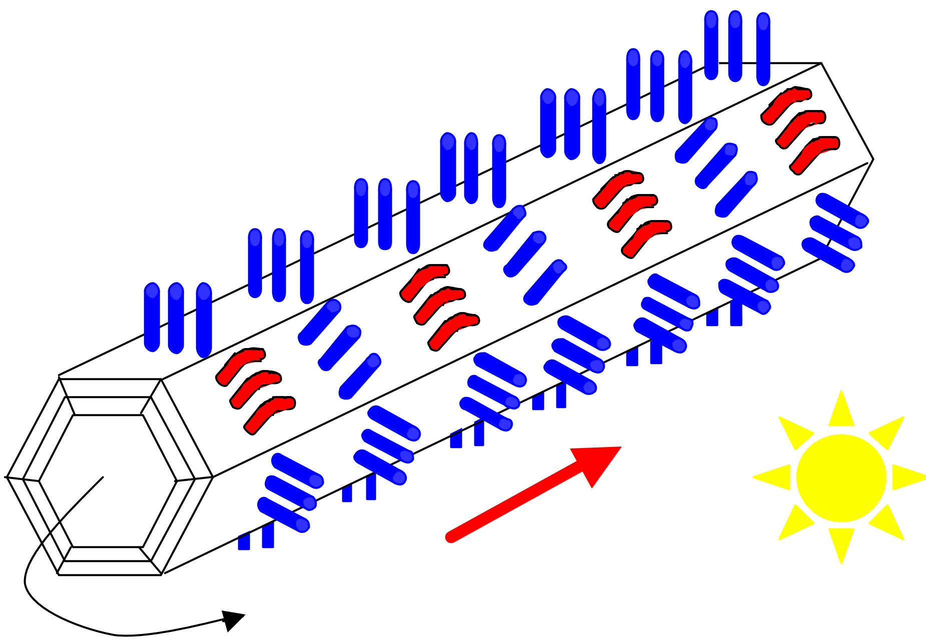
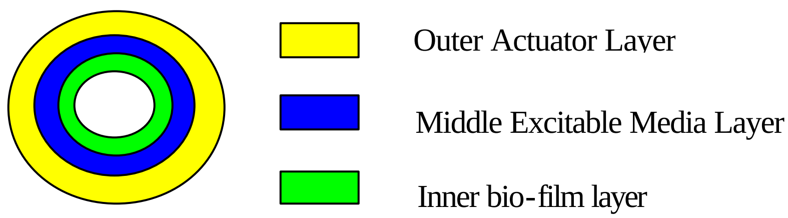


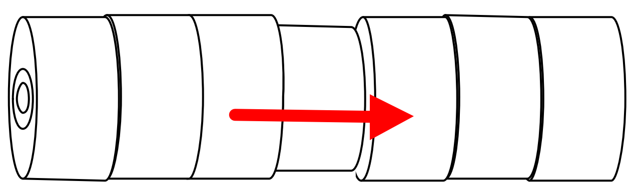
FIGURE 22. Travelling wave of actuators induced on one side producing phototactic behavior

7.2.8 SOLVING THE POWER PROBLEM – TOWARD ENERGETIC AUTONOMY

Of course, robots need energy to move and execute their behaviors. Conventional mobile robots usually employ on-board batteries, which either need replacing by humans or recharging stations (powered by generating devices). Very few, if indeed any, could be regarded as being energetically autonomous. Some researchers have recently started to look at this problem of how a robot can extract its energy from the environment. Researchers at the IAS laboratory at the University of the West of England (Kelly *et al.*, 2000) are building a robot capable of detecting and capturing slugs. It is envisaged that groups of robots could transport the captured bio-mass to a central digester, which could convert the bio-mass into methane thus providing the fuel for a fuel cell thus powering the robot. This collective idea is loosely modeled on the leaf cutter ant strategy. The University of Southern Florida (Wilkinson 2000) has employed a microbial fuel cell to convert sugar into the energy required to power a model train. The idea of a microbial fuel cell is also interesting. It is within the realms of possibility to employ a semi-permeable polymer substrate on which bacterial bio-film could exist. Perhaps, in the long term, one could imagine a tubular EAP based robot, existing in an aqueous environment, incorporating such a bio-film as illustrated in Figure 23a. Nutrients could be allowed into the tube either passively or forced by tubular actuators at the mouth. The mouth itself could be constructed from EAP actuator rings behaving in a manner analogous to a sphincter. Once the nutrient was inside the 'gut' it would be processed by the bio-film to produce energy in, say, the form of some energized molecule, or charge, which could diffuse through the inner membrane and power the excitation and actuator layers. The actuator layer could be comprised of a series of annular actuators. Waves of actuation along these 'muscle rings' could provide the peristaltic action (see Figure 23b) required by the nutrition system and possibly contribute toward locomotion as well.



(a) Cross section of concentric structure of 'worm' robot



(b) Peristaltic wave traveling along body axis

FIGURE 23: Robotic worm with artificial gut

7.2.9 THE FUTURE OF ACTIVE POLYMER ACTUATORS AND ROBOTS

Clearly the robotics field can benefit from actuator technologies associated with active polymers. While not applicable to all areas, even in advanced forms, artificial muscles may make robotic platforms possible that have up to now been the stuff of science fiction. At the most basic level, active polymers may be substituted for the existing electromagnetic actuators in otherwise classic system architectures, providing benefits in the physical layout, mass, and control of the robots. In particular, platforms that have been rough approximations of animals may reach new levels of realism and functionality. Perhaps most exciting, however, is the impact of active polymers on the way robots are designed and controlled when considering a "from-scratch" design mentality. Taking advantage of the "soft" characteristics of active polymers, entirely new robotic paradigms may be created. Through the use of genetic algorithms and rapid prototyping, the design cycle may be dramatically shortened and the effectiveness of the eventual product dramatically increased.

Moreover, with the advent of new micro-machining technologies including micro-sensing, micro-actuation, micro-electronics, micro-computation, it is reasonable to assume that very small mobile robots will be built in the future. Promising advances in EAP indicate that this material could be an enabling technology in the creation of small robots. EAP could be bonded with other polymers to create smart composites whose behavior can be 'programmed' by judicious mixtures of different layers. MEMS material might also be able to be bonded on or encased in EAP laminates, which gives the prospect for smart hybrid systems. The intriguing futuristic prospect of integrating bio-films within EAP to generate energy from 'food' in the environment has also been touched upon. The phototactic tube robot represents speculation on how EAP might be employed in the construction and control of individual micro-robots as well as the material characteristics of EAP that would be required. Mass production of robots of the same scale of size and complexity would also tend to follow. Current research, inspired by social insects, indicate how such machines might be controlled and how their activities can be coordinated. These systems could prove to be robust, inexpensive, and highly tailorable.

Despite the initial fears of the public and pundits concerning robots that weren't directly designed by humans, that exist in multitudes, and that are too small to see, the optimistic roboticist may look forward to a world in which mankind can manufacture polymeric systems to our benefit rather than detriment; and, moreover, we have the wisdom to differentiate. These robots can be simple and self-sufficient, perhaps even self-perpetuating (with the proper safeguards, of course). Suitable environments may range from the carpets of our homes to the pills from the pharmacy to the surface of other planets. As has been always true with robotics, we are only limited by our imaginations.

7.2.10 REFERENCES

Adamatzky A. (2000) Reaction-diffusion and excitable processors: a sense of the unconventional, *parallel and Distributed Computing Practices*, in print.

Adamatzky A. and Melhuish C. (2000) Parallel controllers for decentralised robots: toward nanodesign, *Kybernetes*.

Adamatzky A. and Melhuish C. (2000) Phototaxis of mobile excitable lattice, *Chaos, Solitons and Fractals*.

Aron S., Deneubourg J-L., Goss S. & Pasteels J.M. (1990). "Functional self-organization illustrated by inter-nest traffic in ants: the case of the Argentine ant." In: Alt W. & Hoffman G., Eds. Biological Motion, Lecture Notes in Biomathematics 89. Springer-Verlag: 533-547

Bailey, S. A., Cham J.G., Cutkosky, M. R., Full, R. J., "Biomimetic Robotic Mechanisms via Shape Deposition Manufacturing" 9th International Symposium of Robotics Research, Snowbird, Utah, October 9-12, 1999, p. 321-327.

BEAM (1999) http:\\www.solarbotics.com

Binnard, Michael, *Design by Composition for Rapid Prototyping.* Kluwer Academic Publishers, 1999.

Braitenberg V. (1984) Vehicles (MIT: Cambridge)

Brooks R. (1986) A Robust Layered Control System for Mobile Robot *IEEE Journal Robotics and Automation*, vol. 2, pp. 14-23.

Conrad J. M. and Mills J. W. (1997), *Stiquito: Advanced Experiments with A Simple and Inexpensive Robot*, IEEE Computer Science Press.

Conrad, M. (1990) Molecular computing *Advances in Computers* vol. 31, pp. 235-324.

Deneubourg J.L. & Goss S. (1989) "Collective Patterns and Decision Making." Proc. Int. Conf. on Ethology Ecology & Evolution vol. 1. Florence, Italy: 295-311.

Dutton, Ken, *et al*., *The Art of Control Engineering.* Addison-Wesley, 1997.

Ekeberg O. (1993) A combined neuronal and mechanical model of fish swimming, *Biological Cybernetics*, vol. 69, pp. 363 - 374.

Hasegawa Y., Ito Y. and Fukuda T. (1999) Behaviour adaptation on behaviour-based controller for brachiation robot, Lecture Notes in Artificial Intelligence, vol. 1674, pp. 295 - 303.

Hasslacher B. and Tilden M.W. (1995), Living Machines, *Robotics and Autonomous Systems*, vol. 15, pp. 143 - 169.

Hickey, Gregory and Brett Kennedy, "Six Legged Experimental Robot". NASA Tech Brief NPO-20897

Hirai H., Hasegawa M., Yagi T., Yamamoto Y., Nagashima K., Sakashita M., Aoki K. and Kikegawa Y. Methane hydrate, amoeba or a sponge made of water molecules *Chemical Physics Letters* 35 (2000) 490 - 498.

Holland O. and Melhuish C. (1996a) "Getting the most from the least: lessons for the nanoscale from minimal mobile agents", Artificial Life V, Nara, Japan: 59-66.

Holland O. and Melhuish C. (1996b) "Some adaptive movements of animats with single symmetrical sensors", 4th Conference on Simulation of Adaptive Behaviour, Cape Cod: 55-64.

Holland O. and Melhuish C. (1997a) "Chorusing and Controlled Clustering for Minimal Mobile Agents." European Conference on Artificial Life, Brighton, UK: 539-548.

Holland O. and Melhuish C. (1997b) An interactive method for controlling group size in multiple mobile robot systems. International Conference on Advanced Robotics, Monterey, USA: 201-206.

Ishida T., Iida T., Yokoi H. And Kakazu Y. Development of a liquid metal mobile object field (2000).

Kelly I., Melhuish C. & Holland O. (2000) "The Development and Energetics of SlugBot, a Robot Predator" EUREL: European Advanced Robotics Systems Masterclass and Conference, The University of Salford, Manchester Vol 2.

Kennedy, Brett, "Three-fingered Hand with Self-adjusting Grip". NASA Tech Brief NPO-20907

Korohoda W., Mycielska M., Janda E., and Madeja Z. (1991), "Immediate and long-term galvanotactic responses of Amoeba proteus to dc electric fields," *Cell Motility and the Cytoskeleton, Volume 45, Issue 1, 2000, Pages 10-26*

Leger, Chris, *Darwin2K: an Evolutionary Approach to Automated Design for Robotics.* Kluwer Academic Publishers, 2000.

Lipson, H. and J. B. Pollack (2000), "Automatic Design and Manufacture of Robotic Lifeforms", Nature 406, pp. 974-978

Mavroidis C., DeLaurentis K., Won J. and Alam M, "Fabrication of Non-Assembly Mechanisms and Robotic Systems Using Rapid Prototyping", Proceedings of the 2001 NSF Design, Manufacturing and Industrial Innovation Research Conference, Tampa, FL, January 7-10, 2001.

Melhuish C. (1999a) "Controlling and Coordinating Mobile Micro-Robots: Lessons from Nature" in Proceedings of the International Mechanical Engineering Congress and Exposition. IMECE'99. Nashville Tennessee.

Melhuish C. (1999b) "Employing Secondary Swarming with Small Scale Robots: A biologically Inspired Collective Approach". To be published in Proceeding of 2nd International Conference on Climbing and Walking Robots – CLAWAR. Portsmouth U.K. Professional Engineering Publishing Ltd.

Melhuish C., Holland O. and Hoddell S. (1998a) "Using Chorusing for the Formation of Travelling Groups of Minimal Agents" 5th International Conference on Intelligent Autonomous Systems, Sapporo, Japan.

Melhuish C., Holland O. and Hoddell S. (1999) "Convoying: Using Chorusing to form Travelling Groups of Minimal Agents" Journal of Robotics and Autonomous Systems Vol 28. pp. 207-216

Melkonian M., Anderson R.A. and Schnepf E. (1991) *The Cytoskeleton of Flagellate and Ciliate Protists* (Springer Verlag, 1991).

Menzel, Peter and Faith D'Aluisio, *Robo sapiens: Evolution of a New Species*. The MIT Press, 2000.

Nakagaki T., Yamada H. and Tóth Á. Intelligence: Maze-solving by an amoeboid organism, *Nature* 407 (2000).

Osada Y., Okuzaki H. and Hori H. A polymer gel with electrically driven motiliry *Nature* 355 (1992) 242-244.

Slotine, Jean-Jacques E., and Weiping Li, *Applied Nonlinear Control*. Prentice Hall, 1991.

Theraulaz G., Goss S., Gervet J. & Deneubourg J.L. (1990). "Task Differentiation in Polistes Wasp Colonies: A Model for Self-Organizing Groups of Robots." 1st International Conference on the Simulation of Adaptive Behavior. *From Animals to Animats*. MIT Press.

Ueda M. and Ogihara S. Microtubules are required in amoeba chemotaxis for preferential stabilization of appropriate pseudopods, *Journal of Cell Science* 107 (1994) 2071-2079

Usami Y., Saburo H., Inaba S. and Kitaoka M. (1998) Reconstruction of extinct animals in the computer. In: *Artificial Life VI: Proc. 6th Intern. Conf. Artificial Life* (A Bradford Book, The MIT Press), pp. 173 -- 186.

Ventrella J. (1999) http://www.ventrella.com

Vogel, Steven, *Cat's Paws and Catapults*. W.W. Norton & Company, 1998.

Vogel, Steven, *Life's Devices*. Princeton University Press, 1988.

Whittaker W., Urmson C., Staritz P., Kennedy B., and Ambrose R. "Robotics for Assembly, Inspection, and Maintenance of Space Macrofacilities" presented at AIAA Space 2000, Long Beach, CA. AIAA-2000-5288.

Wilkinson S. (2000) 'Gastrobots - Benefits and Challenges of Microbial Fuel Cells in Food Powered Robot Applications.' Journal of Autonomous Robots

Yanai M., Kenyon C.M., Butler J.P., Macklem P.T. and Kelly S.M. Intracellular pressure is a motive force for cell motion in *Amoeba proteus*, *Cell Motility and the Cytoskeleton* 33 (1995) 22-29.

Yokoi H. and Kakazu Y. Theories and applications of autonomic machines based on the vibrating potential method, In: *Proc. Int. Symp. Distributed Autonomous Robotics Systems* (1992) 31-38.

Ziegler J, Dittrich P and Banzhaf W (1997) "Towards a metabolic robot controller", *Information Processing in Cells and Tissues* (Plenum Press: New York), pp. 305-318