Mechanism as Mind: What Tensegrities and Caterpillars Can Teach Us about Soft Robotics

John Rieffel[1] , Barry Trimmer[1] and Hod Lipson [2]

[1] Biomimetic Devices Laboratory, Tufts University, Medford MA
[2] Computational Synthesis Laboratory, Cornell University, Ithaca MA
john.rieffel@tufts.edu

Abstract

With recent advances in materials, interest is being applied to the idea of robots with few if any rigid parts, able to substantially deform themselves in order to flow around, and even through objects. In order to accomplish these goals in an efficient and affordable manner, space and power will be at a premium, and so soft robots will most likely be both under-actuated and under-controlled. One approach to actuation and control lies in embodying portions of both tasks within the structural dynamics of the robot itself. Such "morphological computation" is known to exist throughout the biological world, from the behavior of cellular cytoskeletons up to the tendinous network of the human hand. Here we present two examples of morphological computation - one from biology, the *manduca sexta* caterpillar, and one from engineering, a modular tensegrity tower - and explore how ideas from these realms can be applied toward locomotion and control of a highly articulate, under-controlled, soft robot.

Introduction

Imagine a robot that can squeeze through holes, climb up walls, and flow around obstacles. Once the domain of science fiction, thanks to modern advances in materials such as polymers (Huang et al., 2007), and nanocomposites (Capadona et al., 2008) such a "soft robot" is becoming an increasing possibility. This ability to significantly deform and alter shape, at a much higher level of detail than discrete "modular" robots (such as Yim's Polybot (2000) and Rus's Molecubes (1998)) makes accessable new and increasingly important environments such as mine fields and collapsed buildings.

However, this incredible flexibility and deformability brings with it considerable constraints in terms of actuation, power, and payload. Striving not to have any rigid or fully solid elements means that servo motors and batteries - the bread and butter, so to speak, of conventional robotics - are far from ideal. As a consequence, soft robots will in all likelihood be under-actuated, under-powered, and under-controlled. Therefore, the onus lies upon soft robotics researchers to discover ways of controlling these highly articulate systems.

Fortunately, nature itself has provided us with several quite viable prototypes, among them many of the large invertebrates such as the octopus, squid, and the *manduca sexta* caterpillar, the latter of which we will draw particular inspiration from in this work. As we discuss in detail below, the *manduca* is able to achieve incredible flexibility and control, despite having relatively few muscles and astonishingly few motoneurons in each of its segments. It is conjectured therefore that, in *manduca*, the interaction of hydrostatics, body wall tension, and muscles, all contribute to a degree of neuromechanics, or *morphological computation* (Trimmer, 2007). That is to say, a large amount of the work normally attributed to the neural system is instead "outsourced" and embodied directly into the mechanics of the structure. Similar types of morphological computation have been observed in other biological systems, such as the tendonous network of the human hand (Valero-Cuevas et al., 2007), wallabies Biewener et al. (2004), and cockroaches Ahn and R.J.Full (2002).

In this paper we review some details of *manduca*'s anatomy and locomotion as it pertains to morphological computation. We then present related work in which a highly complex mechanical system – a tensegrity structure – is able to achieve locomotion by exploiting the dynamical coupling between modules as an emergent data bus. Finally, we bring these aspects together when describing the design and control of a completely soft robot modeled loosely on the *manduca*. More broadly, we hope to present morphological computation – the use of mechanism as mind – as the best approach to solving the issues of actuation and control inherent in soft robotics.

The *Manduca Sexta* Caterpillar: a Model Species for Soft Robotics?

Caterpillars such as *manduca sexta* (**Figure 1**) are some of the most successful climbing herbivores in the world. They are incredibly flexible, with a large multi-dimensional workspace, are able to cantilever themselves over gaps up to 90% of their length, and perform a u-turn inside spaccesless than twice their body diameter(Trimmer, 2007). They are able to accomplish all of this because of, and at the same time despite of, the fact that they are completely soft-bodied and lack any rigid elements such as a skeloton. Unlike the beam-and-lever mechanics of vertebrates, *manduca* move through a complex dynamical interplay of hydraulics, body wall tension, and muscles.

Most remarkably, they are able to accomplish all of these complex behaviors despite a relatively simple anatomy. Most locomotion is performed by the co-ordination of their abdominal segments, each of which contains on the order of 70 muscles. Furthermore, each such segment contains relatively few motoneurons (one, or maximally two per muscle), and no inhibitory motor units (Trimmer, 2007). **Figure 2** contains an illustration of the major muscles within a single such segment. These muscles however, are in of themselves rather complex, exhibiting nonlinear and pseudo-elastic responses to load cycling (**Figure 3**) which are quite different than vertebrate muscles (Dorfmann et al., 2007).

All of these properties come into play when observing the crawling kinematics of the animal (**Figure 4**). Under normal locomotion, waves of motion pass from the rear segment of the animal

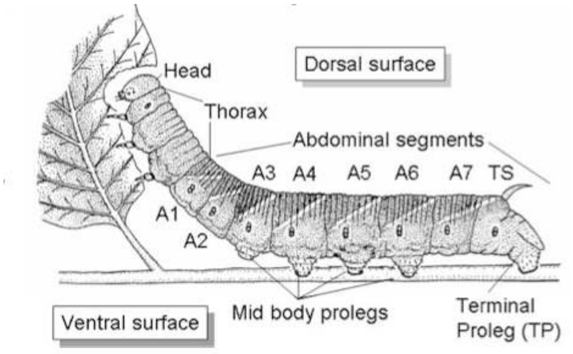

Figure 1: The external anatomy of the *manduca sexta* caterpillar. (adapted from Mezoff et al. (2004))

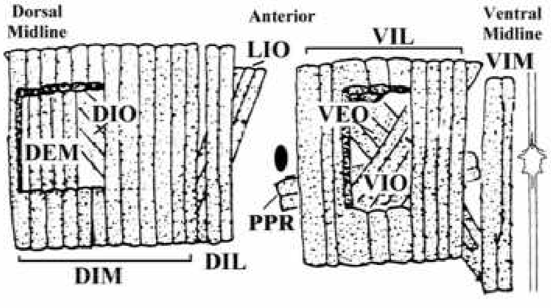

Figure 2: The major muscles from one side of an abdominal segment of manduca (from Levine and Truman (1985))

(TS) toward the head. As the wave propagates, each segment compresses then re-extends, with the dorsal and ventral parts remaining in phase. Somewhat puzzlingly, the length and radius of each segment co-vary - they narrow and shorten simultaneously . This suggests that fluid volume is not conserved during crawling - rather tissue and fluid are moved and compressed throughout the animal during locomotion (Trimmer and Issberner, 2007).

Combined, these complex mechanical properties, and the limited neural control, lead to the conclusion that the dynamics of the system is itself responsible for control tasks that would otherwise be attributed to neural circuitry. We explore and describe how a complex mechanical structure can exploit this kind of coupled dynamics in order to achieve co-ordinated motion in the following section.

Morphological Communication in Tensegrity Robots

Traditional engineering approaches strive to avoid, or actively suppress, the kind of nonlinear dynamic coupling among components exhibited in the anatomy of the *manduca*. Especially near resonant frequencies, these couplings tend to produce undesirable vibrations and oscillations that are difficult to predict and may sometimes be catastrophic. A variety of passive and active damping techniques have been developed to diminish these effect across many fields ranging from robotics to structural engineering.

Biological systems, by contrast, are often rife with complex dynamics. Beyond the examples from *manduca*, consider the principle of tensegrity, which can be found at many scales of life, ranging from the cellular cytoskeleton and the structure of proteins (Ingber,

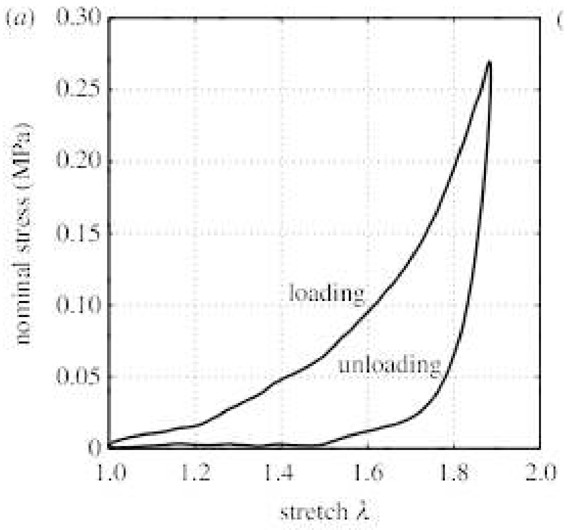

Figure 3: The pseudo-elastic response of a manduca muscle (from Dorfmann et al. (2007)). The muscle exhibits a large degree of non-linear pseudo-elasticity when subjected to load cycling.

.

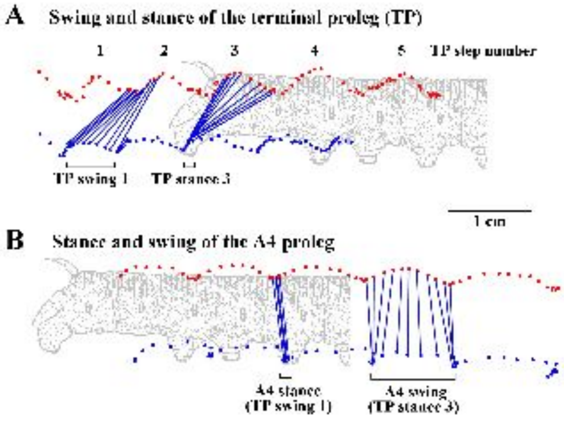

Figure 4: Movement of the *manduca* terminal and midbody segments during crawling (from Trimmer and Issberner (2007)).

1998) to the tendinous network of the human hand (Valero-Cuevas et al., 2007). At every scale, these systems contain the type of coupled mechanical and dynamical linkages which are so assiduously avoided in engineering design. Could there be in fact, an advantage to such high degrees of dynamical coupling?

The word tensegrity, a concatenation of tensile integrity was coined by Buckminster Fuller to describe structures first popularized by the sculptor Kenneth Snelson in 1948 (Fuller, 1975). Broadly speaking, a tensegrity structure is a set of disjoint rigid elements (rods) whose endpoints are connected by tensile elements (strings), and which maintains its shape due to the synergy between the compressive forces on its rods and the complementary forces in its cables. Such structures are pre-stress stable, in the sense that in equilibrium each rigid element is under pure compression and each tensile element is under pure tension. The structure therefore has a tendency to return to its stable configuration after subjected to any moderate temporary perturbation (Connelly and Back, 1998; Motro, 2003).

Unfortunately, these qualities which make tensegrities so attractive, largely pre-stress stability, carry with them complex nonlinear dynamics, even for relatively small tensegrity structures (Skelton et al., 2001), and as a result, active control is needed to dampen the vibrational modes of relatively modest structures. In almost all cases, deformation and control are achieved by changing the rest lengths of the tensile elements, for instance by attaching attaching strings to a reeled servo motor. In this manner, Skelton *et al.* have been able to demonstrate both active vibration damping (2004) and open-loop control of simple structures. Efforts such as these, however, seek to minimize and control the complex dynamics of tensegrity structures, and no effective model exists for the control of the complex dynamics of relatively large tensegrity structures. Rather than attempting to scale these control schemes to arbitrarily large and complex structures, our interest, by contrast, lies in harnessing and exploiting these dynamics in the same way that biological systems seem to.

Modular Tensegrity Robotics

Constructing robots from tensegrities is a double-edged sword. On one hand the homogeneity of the rigid elements allows for a high degree of modularity: each rod can contain identical sets of sensors and actuators – the parts of a 10-bar tensegrity are identical to those of a 3-bar one. On the other hand, any solution which relies upon centralized control of the robot faces a crucial problem: that of communication between modules. As the number of modules increases, the lines of communication (quite literally) increase, bringing both the challenge of coordination and the risk of tangles. Consider, for instance, the tensegrity shown in **Figure 6**. Even with a single sensor and actuator at each end of each bar, a centralized controller would need to synthesize, and co-ordinate the actions of thirty sensors and thirty controllers.

We implement a simpler alternative to the problem of control and locomotion by doing away with the notion of explicit intermodular communication completely. In our model we consider each rod of the tensegrity to be a simple module with a small controller capable only of sensing, and affecting the tension on a single string at each end. Each strut module consists of a rigid tube with a single servo motor mounted at each end. While, in principle, multiple strings could be actuated by multiple servos at each end, we have chosen to keep the design simple by limiting actuation on each end to a single string. **Figure 5** contains a photograph of a representative tensegrity robot which contains four strut modules

In order to add time sensitivity we use a variant of ANNs called spiking neural networks. Spiking neural networks (SNNs) were developed to model more continuous processes: input and outputs are both represented as single-value spikes (as opposed the sigmoid outputs of a conventional ANN) (Maass and Bishop, 1999). Instead of a sigmoid function, every SNN node contains a simple persistent counter, with adjustable offset and limit. At every time step, an SNN node sums its weighted inputs with the current counter value, and if the sum surpasses the limit the node fires a single "spike" to its output; otherwise the contents of the counter are decremented by a fixed decay rate, and persist until the next time step.

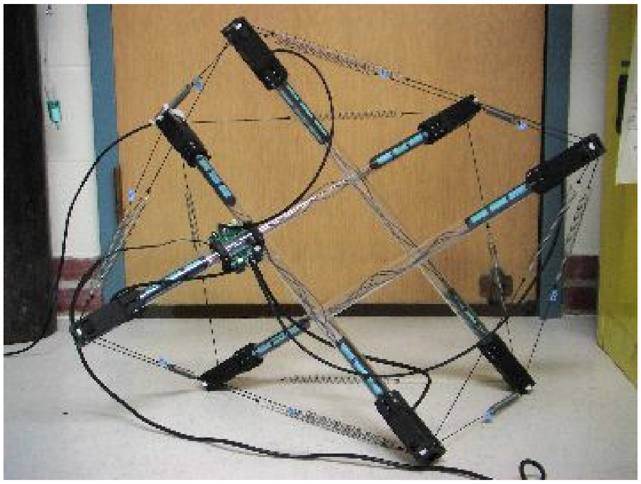
Figure 5: A tensegrity robot consisting of four strut modules and 16 strings

Each strut module in our tensegrity robot contains a single spiking neural network with two inputs, corresponding to the tension sensed at the single actuated string on each end, two hidden nodes, and two outputs. At every simulation time step, each module measures its inputs and feed them through the SNN. Output spikes are converted into string actuations by measuring the duty cycle of network spikes. Any spike rate above 30% over a 100 step period is considered "active", and the corresponding string is pulled by halving its rest length. Our choice of relatively simple binary actuation in this regard is an effort to simplify overall control, and to reduce the difficulty in translating simulated results into physical servo values.

Evolving Dynamic Gaits

In order to evolve gaits for tensegrity robots, the 15-bar tensegrity shown in **Figure 6** was reproduced within the Open Dynamics Engine (ODE) Simulation environment , the widely used open-source physics engine which provides high-performance simulations of 3D rigid body dynamics. Rigid elements were represented as solid capped cylinders of fixed length with a length-to-radius ratio of 24:1. Tensile elements were represented as spring-like forces acting upon the cylinder ends.

With only 30 actuators available (one at the end of each strut module), and a choice of 78 strings to actuate, we chose to evolve both the unique weights of the SNN within each strut module, and also which particular string at each end to actuate. Genotypes of individuals within the population therefore consisted of two subgenes. The first contained 180 floating point numbers corresponding to the collective weights of all 15 strut module controllers within the structure. The second consisted of a pairing of actuated strings with strut endpoints. A single point mutation could therefore either change a weight within the SNN or change which string was actuated at a particular endpoint.

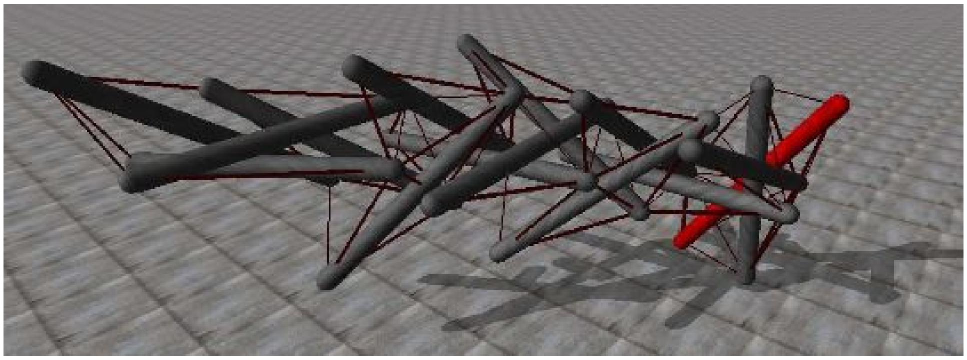

Figure 6: A complex and highly dynamically coupled fifteen-bar tensegrity structure

Using this framework, we were able to evolve the weights within the separate SNNs such that the structure as a whole was able to locomote. Each experiment consisted of a population of 150 individuals initialized with random SNN weights evolved over the course of 1000 generations. Individuals were evaluated within our simulated environment by measuring the travel of the center of mass over the course of 20,000 simulator time steps. Members of the population were then ranked by their fitness, and the bottom scoring half of the population culled. 75 new individuals were then created as offspring of the remaining population via fitness proportional selection, in which 30% of offspring were produced with two-parent crossover, and the remainder with single-point single-parent mutation.

Figure 9 shows the string activations of one successful evolved gait during a single gait cycle, and **Figure 7** contains snapshots of the movement of the ensuing locomotion. The path of the red sphere above the structure tracks the center of mass of the structure (vertically displaced for visualization). It is worth noting that this locomotion is accomplished despite the fact that the activity of the strings shown in Figure 9 is so low. The movement of the entire structure is, in fact, caused largely by the oscillation of just two of its 78 strings. This provides some indication of the extent to which the gait is exploiting the dynamics of the tensegrity itself, and its vibrational modes.

We can further qualitatively measure the coupling between evolved gait and system dynamics by observing the behavior of the structure when the speed of the evolved gait is adjusted while keeping the dynamics of the system unchanged. As shown in Figure 8 both the distance traveled *and the path traversed* vary significantly under varying speeds.

Toward A Soft Robot

Our aim is to create a completely soft, articulate and deformable robot modeled and inspired by the *manduca*. Like manduca (which grows 10000-fold without any changes in musculature or nervous system), we hope to arrive at a highly scalable solution - changing materials and actuators as necessary, while maintaining highly similar control schemes. The constraints any such system which strives to be fully soft means that space and power for actuation will be at a premium. It is clear that, much like the biological system, our soft robot must leverage every aspect of its morphology in order to offload what are normally considered computational tasks. The material proporties of the body wall and associated actuators will need to be, in effect, part body and part brain.

Figure 10 contains a photograph of a prototype of such a system. The main body of the robot is cast from a soft silocone elastomer and actuated using SMA wires. Our aim in this case is to attempt to mimic, albeit at coarser grain, the placement of muscles within *manduca*. Both the elastic properties of the silocone and the tension of the SMA springs can be tightly controlled, which will be vital for exploiting dynamics between them. It is no coincidence that the pseudo-elasticity demonstrated in the *manduca* muscles is very similar to that exhibited in rubber doped with carbon-black particles (Dorfmann et al., 2007).

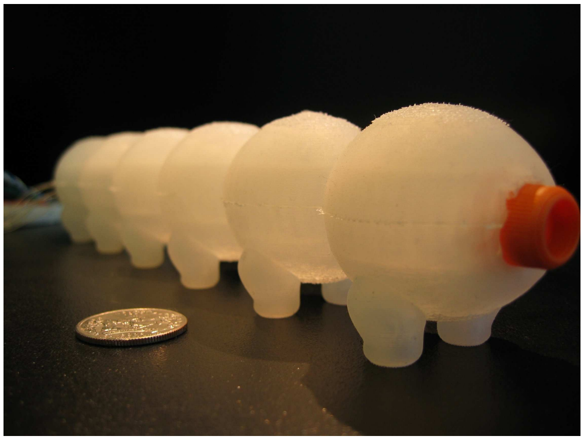

Figure 10: A prototype of the soft robot inspired by *manduca*.

Our results with tensegrities demonstrate that it is possible to model and evolve dynamically complex systems which are capable of exploiting effects such as mechanical coupling in order to achieve locomotion. These results do not directly translate to a soft robot however: the use of supple, deformable materials with such complex dynamics means that rigid body simulations, such as those provided by the commonly used Open Dynamics Engine (ODE) physics engine are insufficient. Instead, we will use the PhysX engine developed by Ageia Technologies, which is capable of providing realistic simulations of deformable soft bodies such as cloth and rubber. Within this system, we hope to be able to have tightly control over specific material properties at particular points of the body, such as stiffness, elasticity, without needing to resort to full Finite Element Analysis, which might be more accurate, but at the cost of significantly longer evaluation times.

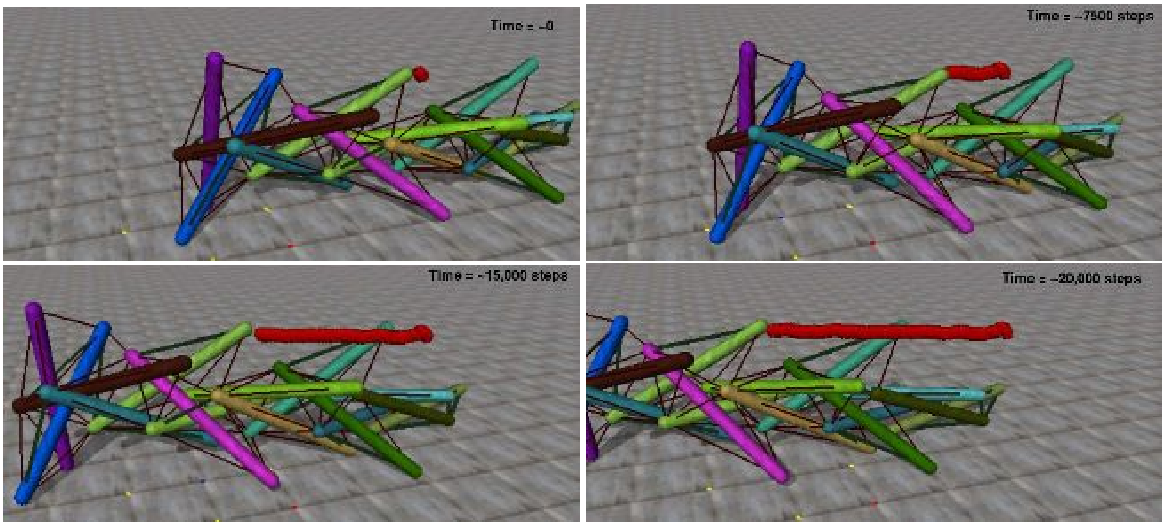

Figure 7: Snapshots of the motion of an evolved gait over 20,000 time steps

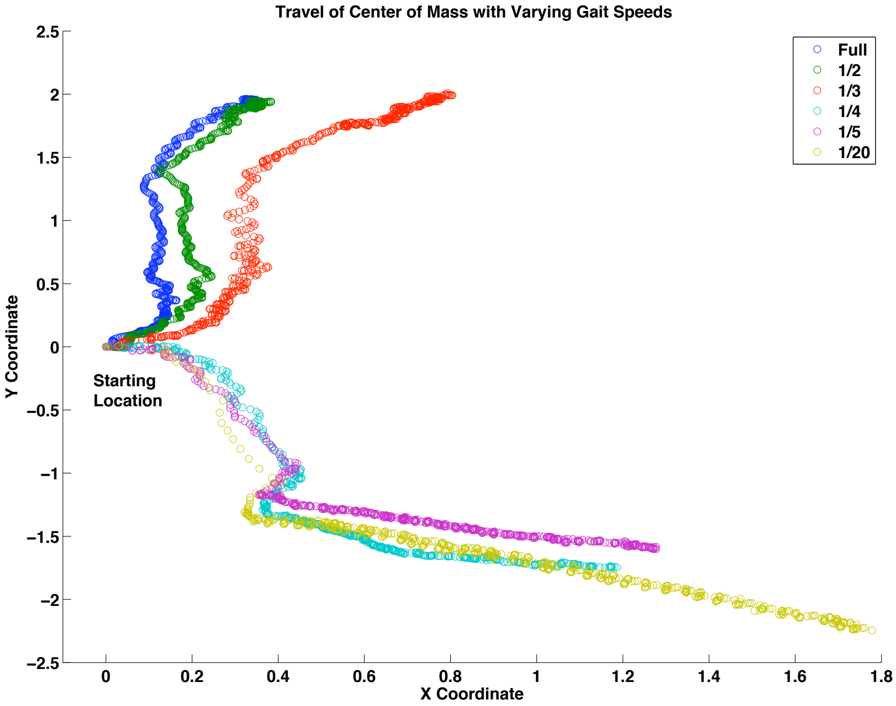

Figure 8: As the speed of the evolved gait is decreased both the distance traveled and the path traversed vary significantly.

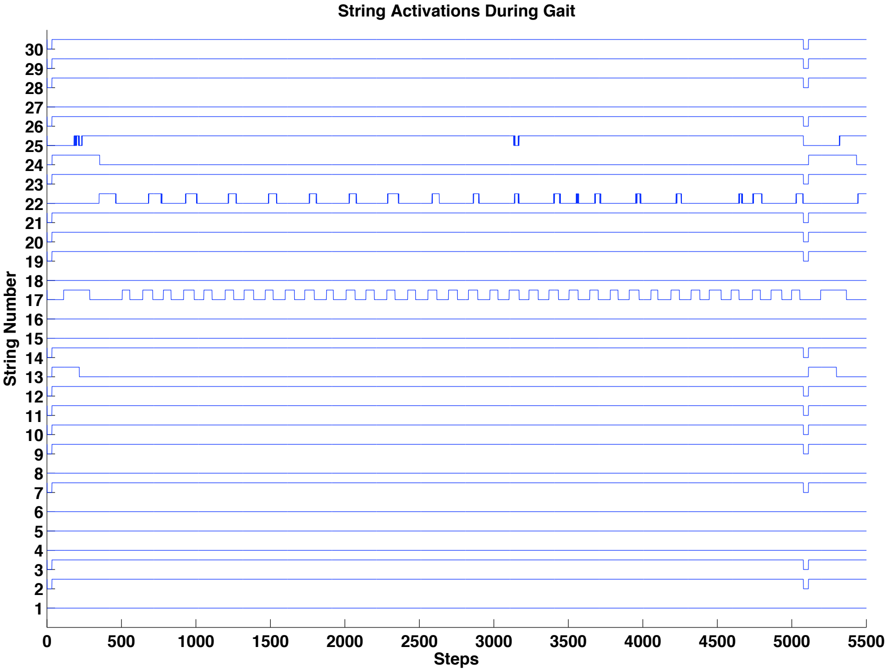

Figure 9: String activations of the evolved gait. Notice how very few of the strings are higly active. This indicates a high degree of efficiency in the gait, as the dynamic coupling between modules discributes the actuation throughout the structure.

Concluding Remarks

Advances in material science are bringing the promise of soft, flexible robots closer to reality. With the benifits of these new abilities and behaviors come new challenges in design and control. How can you actuate, much less control, a floppy amorphous structure that lacks any rigid elements? Fortunately a solution exists in the forms of biological invertebrates such as the octopus and the *manduca sexta* caterpillar. It is becoming clear that much of the ability of these animals lies in the particulars of their morphology – smart structures, in essence, which reduce the amount of neural computation required to perform complex tasks. Since we know it occurs in nature, we hope to reproduce simmilar effects in a soft robot. Here we have shown how one such form of *morphological computation* can arise in a complex mechanical system as well - in our case a large irregular tensegrity structure. With what we know, and what we hope to soon learn about *manduca*, and with the methodologies employed in making our modular tensegrity robots walk, we hope to shed light on how to build smart, resilient, and sophisticated soft robots. Regardless of the final appearance, it is clear that any successful soft robot's body will be at once both mechanism and mind.

References

Ahn, A. and R.J.Full (2002). A motor and a brake: two leg extensor muscles acting at the same joint manage energy differently in a running insect. *Journal of Experimental Biology*, 205.

Biewener, A., McGowan, C., Card, G., and Baudinette, R. (2004). Dynamics of leg muscle function in tammar wallabies (m. eugenii) during level versus incline hopping. *Journal of Experimental Biology*, 207.

Capadona, J., Shanmuganathan, K., Tyler, D. J., and Rowan, S. (2008). Stimuli-responsive polymer nanocomposites inspired by the sea cucumber dermis. *Science*, 319(7).

Chan, W. L., Arbelaez, D., Bossens, F., and Skelton, R. E. (2004). Active vibration control of a three-stage tensegrity structure. In *Proceedings of SPIE 11th Annual International Symposium on Smart Structures and Materials*.

Connelly, R. and Back, A. (1998). Mathematics and tensegrity. *American Scientist*, 86.

Dorfmann, A. L., Jr, W. A. W., and Trimmer, B. (2007). Muscle performance in a soft-bodied terrestrial crawler: constitutive modelling of strain-rate dependency. *Journal of the Royal Society Interface*.

Fuller, R. B. (1975). *Synergetics—Explorations in the Geometry of Thinking*. Macmillan Publishing Co.

Huang, J., Foo, C. W. P., and Kaplan, D. (2007). Biosynthesis and applications of silk-like and collagen-like proteins. *Polymer Reviews*.

Ingber, D. E. (1998). The architecture of life. *Scientific American*.

Kotay, K., Rus, D., Vona, M., and McGray, C. (1998). The self-reconfiguring robotic molecule. In *IEEE International Conference on Robotics and Automation*.

Levine, R. and Truman, J. W. (1985). Dendritic reorganization of abdominal motoneurons during metamorphosis of the moth, manduca sexta. *Journal of Neuroscience*, 5:2424–2431.

Maass, W. and Bishop, C. M. (1999). *Pulsed Neural Networks*. MIT Press.

Mezoff, S., Papastathis, N., Takesian, A., and Trimmer, B. A. (2004). The biomechanical and neural control of hydrostatic limb movements in manduca sexta. *J. Exp. Biol.*, 207(3043-53).

Motro, R. (2003). *Tensegrity: Structural Systems for the Future*. Kogan.

Skelton, R. E., Pinaud, J. P., and Mingori, D. (2001). Dynamics of the shell class of tensegrity structures. *Journal of the Franklin Institute*.

Trimmer, B. (2007). New challengees in biorobotics: incorporating soft tissue into control systems. In *IEEE International Conference on Robotics and Automation*.

Trimmer, B. and Issberner, J. (2007). Kinematics of soft-bodied, legged locomotion in manduca sexta larvae. *The Biological Bulletin*.

Valero-Cuevas, F., Yi, J., Brown, D., McNamara, R., Paul, C., and Lipson, H. (2007). The tendon network of the fingers performs anatomical computation at a macroscopic scale. *IEEE Trans Biomed Eng.*, 54:1161–6.

Yim, M., Duff, D., and Roufas, K. (2000). Polybot: a modular reconfigurable robot. In *IEEE International Conference on Robotics*.