BEES for ANTS: Space Mission Applications for the Autonomous NanoTechnology Swarm

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The Autonomous NanoTechnology Swarm (ANTS) mission architecture is based on BEES (biologically inspired engineering for exploration system)autonomous, addressable, self-configuring components with a tetrahedral structural framework which form tethers, struts, or shells which can be reversibly deployed or stowed from nodes. The architecture is currently being implemented using ElectroMechanical Systems (EMS) as Addressable Reconfigurable Technology (ART). The design elements and issues are being finalized as a working prototype, a tetrahedral walker, is being built. Near-future ANTS Miniaturized ART (MART) systems using MEMS systems for the Lunar or Mars surface applications would involve a payload carrying multi-tetrahedral (12 or more tetrahedral elements) multi-functional lander/rover. In current simulations, this ANTS craft indicates a capability for 'flow' across highly fractal surfaces. Future ANTS NEMS-based or Super Miniaturized Reconfigurable Technology (SMART) for small body survey applications have been conceptualized. Such applications of ANTS architecture could be implemented in two decades, requiring only the anticipated incremental advances in nanotechnology.

Nomenclature

BEES = Biologically-inspired Engineering for Exploration Systems
ANTS = Autonomous NanoTechnology Swarm Space Architecture
ART = Autonomous Reconfigurable Technology (EMS)
MART = Miniaturized ART (MEMS)
SMART = Super Miniaturized ART (NEMS)
MEMS = Micro Electro Mechanical Systems
NEMS = Nano Electro Mechanical Systems
PAM = ANTS Prospecting Asteroid Mission Concept
LARA = ANTS Lander Amorphous Rover Antenna Mission Concept
SARA = ANTS Saturn Autonomous Ring Array Mission Concept
TetWalker = 1, 4, 12, or many tetrahedra system used as ANTS rover
Node&Strut= deployment mechanism for ANTS structures: nodes apices, struts sides of tetrahedra

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I. Introduction

THE Autonomous NanoTechnology Swarm (ANTS) is a mission architecture based on an ant colony analogue, as the name implies. [See official ANTS website http://ants.gsfc.nasa.gov.] Reconfigurable and transformable both individually and collectively, ANTS structures, mechanisms, and organization are designed to excel at survival and achievement of goals as discussed in references 1 and 2. As in living systems, major keys to success are the capabilities for mobility in a range of environments, in this case from space to rugged surface, and for effective gathering and management of energy and information resources in those environments. These capabilities are achieved by using autonomous, addressable, self-configuring nodes which form a reversibly deployable/stowable structural framework. The framework itself is the skeletal-muscular structure, consisting of tethers, struts, or shells. Individuals (systems or crafts) have common frameworks with common subsystems, as well as one of a small number of special function subsystems, such as a particular instrument, all deployed from nodes.

As in living systems, modularity, recapitulated at every organizational level, combined with the high degree of addressability and reversibility in each module, allow for operation and transformation of the structure in response to the movement or function required. Essentially, we have a biomechanical analogue[3,4].

The simple tetrahedral structures based on ANTS architecture are capable of reconfiguration and are thus dynamic. This attribute clearly depends on the capability for reversible deployment of several or more structural elements from individual nodes. As the number of nodes, and the number of elements deployed per node, increases, more complex, continuous behavior emerges to allow major shifts in functionality to meet environmental demands (space to surface to underground) or human needs. In addition, a robust response to injury or environmental change is achievable, as in a biological system, through the built-in reversible behavior mechanisms at the nodes, allowing adapting to the injury by 'limping' while stored replacement nodes migrate to damage site to replace 'broken' components.

Addressable nodes create the capability for both (1) standalone autonomic operation as called for by environmental feedback within a subsystem or system, and (2) team collaborative operation requested as a result of higher level decision making by the CPU-enhanced heuristics onboard or externally by a human agent. The use of bilevel intelligence should allow full functioning in both autonomous routine (decentralized) and heuristic decision based (centralized) behavior. The basis for this intelligence is described elsewhere[2,5-7].

In the sections which follow we will describe the ANTS-based conceptual design and its biological analogues for major components of the architecture: Tetrahedral Structure (Units and Networks), Structural Nodes and Struts, and Structural Layer (Surfaces). We will also look at prototypes and models for examples of simple, transitional, and complex structures. The range of applications of the ANTS paradigm considered span the continuum in terms of level of complexity and development time: 1) near-term mobile platforms for planetary surfaces, Lander Amorphous Rover Antenna (LARA) in reference 8, 2) future autonomous flyers for survey of dynamic deep space targets, Prospecting Asteroid Mission (PAM) in reference 9, and Saturn Autonomous Ring Array (SARA) in reference 10.

II. Tetrahedral Structure

Why use the tetrahedron as the basic structural unit in ANTS architecture?

The tetrahedron is a polyhedron with properties which make it optimally suited for stability and space filling [Fuller, 1975; Edmondson, 1986]. As illustrated in its comparison with the cube and sphere in Table 1, it has a minimal structure (the fewest edges and least volume per surface area) as discussed by Fuller (1975) in reference 11 and Edmondson (1986) in reference 12. Its triangulated structure gives it the great mechanical stability of triangles. Just as triangular facets can be used multiply to express the area of all surfaces, tetrahedra can be used multiply to express the volume of all 3D systems. Irregular or beveled edge[11] tetrahedra, or tetrahedra in combination with octahedral 'holes'[12] can be used to fill space. In ANTS space-filling architecture, the basic structural unit is the irregular tetrahedron.

Due to its distinctive properties, the tetrahedron is ubiquitous in nature. The utility of the tetrahedron is well demonstrated (e.g., Mason and Berry, 1968)[15] by the role of silicate (silicon surrounded by 4 oxygens) as building blocks for non-organic solid material (rock) (Figure 1). Silicate tetrahedra occur singly (nesosilicates with Si:O of 1:4), as pairs sharing one oxygen 'corner' (sorosilicates with Si:O of 2:7), as ring structures where two oxygens

Table 1 Comparison of Regular Polyhedral Forms with Tetrahedron

Polyhedron	Edge: Greatest Dimension (a)	Area:Volume
Sphere	0: a (diameter)	0.17 a^2: a^3 (Pi a^2: 6 pi a^3)
Cube	a:sqrt[3]a	6.0 a^2: a^3
Tetrahedron	a:a	14.7 a^2: a^3 (sqrt[3] a^2: sqrt[2]/12 a^3)

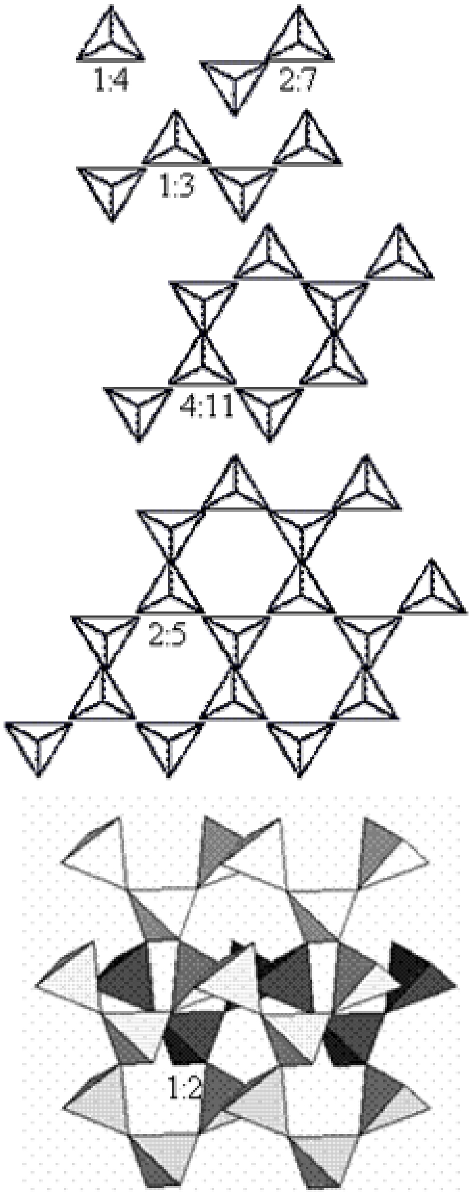

Figure 1 Arrangements of tetrahedra in silicates. In single, double, chain, layer, and 3D network configurations as described in text.

are shared (cyclosilicates with Si:O of 1:3), as single (Si:O of 1:3) or double (Si:O of 4:11) chain structures where two or more oxygens are shared (inosilicates), as sheets where three oxygens are shared (phyllosilicates with Si:O of 2:5), and three-dimensional networks where all oxygens are shared (tektosilicates with Si:O of 1:2). The greater the sharing of 'corners' to fill space, the greater the distortion in the Si-O-Si bond angle. In silicates, that variation is limited to angles between 180 to 90 degrees [e.g., Mason and Berry, 1968][15]. Cations can thus permanently fill 'spaces' between the tetrahedra pairs, rings, layers, or networks.

In complex ANTS structures, tetrahedra are formed between successive layers of nodes (Figure 2) Edges of tetrahedra, or struts, are connected in multiples of three at multi-faceted nodes, varying from 18 to a combination of 12 and 9 facets in alternate layers. Tetrahedral shapes aren't constrained as in rock forming materials and can be changed. The design of nodes allows the angle between sides to range from nearly 180 to nearly 0 degrees, a feature which provides a dynamic structure, capable of both changing shape and in fact locomotion.

As the number of the tetrahedra in a structure increase, so does its inherent complexity and capability for transformation. The sequence of images in Figure 3 illustrates the well defined steps taken as identifiable nodes deploy/stow struts within a simple tetrahedral 'walker'. As the number of tetrahedral increases and a more continuous structure is formed, more complex, continuous behavior of multi-node systems emerges to achieve the required functionality.

III. Nodes and Struts

All ANTS structures consist of interconnected nodes. Struts are deployed from nodes, which must have the capability of deploying several struts using an ElectroMechanical mechanism in simple architectures, and many struts (up to 18) using MEMS or NEMS mechanisms in more complex structures. In all cases, a major challenge is deploying individual struts independently over the widest possible range of angles.

Nodes are spherical enclosures in order to maximize volume for a given size, a solution often used to solve comparable problems in biological systems as discussed in reference 16. Nodes must be large enough for the permanent mounting and protection of deployment devices for each strut, along with required electronics, power and communication systems. Ideally, all of these are housed in the nodes to optimize weight distribution for ease of operation.

A variety of biologically inspired[16] strut deployment mechanisms are being considered for ANTS architecture. Mechanisms include combinations of telescoping appendages, angling (pulling or winding) line, constant force springs (coiling), or compression/extension springs, opening/closing surfaces, as in living systems. Biological mechanisms are a good place to look for inspiration in the design of efficient, robust, configurable mechanisms. The need to develop efficient mechanisms in nature is driven by the greater energy requirement for larger mass creatures on one side, and the greater energy per mass (due to greater surface area and thus heat loss per volume) for smaller mass creatures on the other.

A. Telescoping

The telescoping movement, pulling or pushing apart of overlapping otherwise identical segments of progressively smaller size, is widely used in nature to perform a variety of functions, due to the relatively simple design and minimal energy consumption requirements[14].

A ubiquitous mechanism among invertebrates, especially insects, is the telescoping of specialized organs of the lower extremity. Ants themselves have been observed to respirate through telescoping the segments of the gaster, rapidly contracting and slowly relaxing lower abdominal segments to release carbon dioxide[17]. The females of many of the larger insect species use telescoping ovipositors to deposit eggs within a plant or animal host[18] In addition, aquatic insects use telescoping gills for respiration[19] Figure 4 illustrates the range of these biological mechanisms.

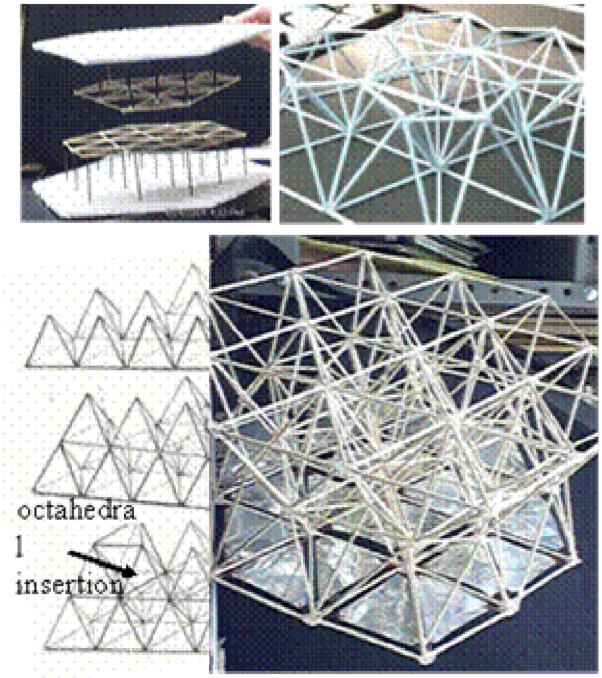

Figure 2 ANTS Tetrahedral Structure Models. Top left shows the two alternating layers in the structure, top right the two layers joined by struts, bottom left space filling with regular tetrahedra with octahedral insertions and bottom right space filling (three layer structure) with irregular tetrahedra alone.

A more complex mechanism, still based on the telescoping principle applied in more than one dimension, is employed by vertebrates for movement of external appendages. Striated muscle fibers (Figure 4) used for external movement consist of a three dimensional network of interleaving bundles, which increase in the degree of overlap to decrease the size and length of tissue expanse when the muscle is contracted and decrease in the degree of overlap to increase the size and length of tissue expanse when the muscle is extended. Lengthening of muscle achievable through this telescoping action varies from typical factors of greater than one to two for internal muscle, but is greater for external muscles with specialized function. Salamander and chameleon tongue used in prey capture deploys to six times greater than its stowed size as discussed in by Deban in references 20 and 21. In terms of strength, animal muscle is normally capable of, because designed conservatively to, 'carry its own weight'.

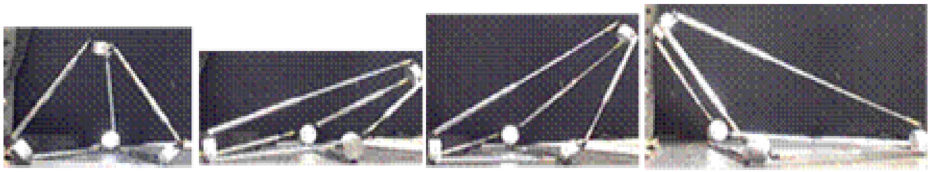

Figure 3 Model of Tetrahedron with edges as struts deployable from nodes at apices. One 'flip' is being performed as described in text.

In our current prototype, we are using telescoping legs, with a minimum to maximum size ratio of 2.5. Our requirement is to design a system which will 'carry its own weight' plus a small payload, which constrains the thickness and weight of materials used in the struts. Telescoping struts (Figure 5), consisting of either PCV pipe or COTS thin wall brass tubes, and are in three segments ranging from just under half an inch to 2 inches in diameter and from 12 to 18 inches in length. Deployment mechanisms under consideration (Figure 5) include a motorized string pulley system, discussed in section B, a motorized cable connected to compression spring system, discussed in section C, or pneumatic or hydraulic systems.

Figure 4 Biological Telescoping Mechanisms. From left to right gills of aquatic insect, gaster of ant, ovipositor of dragon fly, and vertebrate striated muscle, from respective websites in order:
http://trog.cs.umb.edu/streams/streamsKey/thm/Taeniopteryx_02_thm.jpg
http://www.agr.state.ga.us/assets/images/Fire_ant.png for fire ant
http://rbcm1.rbcm.gov.bc.ca/nh_papers/img_nhpapers/dfly019s.jpg
http://www.udel.edu/Biology/Wags/histopage/empage/em/em.htm

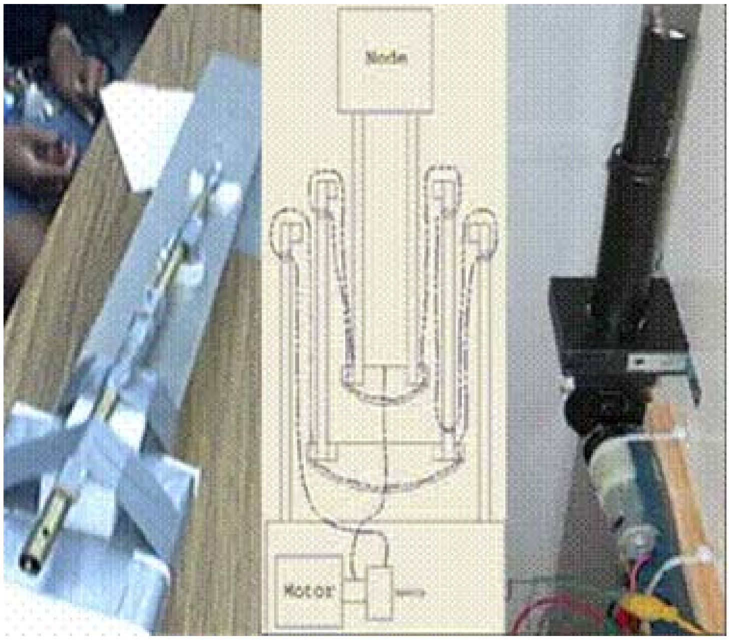

Figure 5 Strut and Deployment Mechanisms for Current Model. On left is thin wall brass strut and diagram of string pulley mechanism in the middle. On right is PVC pipe strut with spring on cable mechanism.

B. Angling (Pulley and String)

In the biological world, the ultimate 'angler', albeit a passive one, is the jellyfish, which uses barbed, detachable, sticky stinging cells (nematocysts) to paralyze and attach itself to any living thing coming in contact with its tentacles. Those tentacles wrap around the victim as the jellyfish swims, acting as line, as the jellyfish attempts to move its prey right up to its interior oral feeding tube as discussed in reference 22. Figure 6 illustrates the ubiquitous jellyfish, one the notoriously venomous box jelly from the tropics [http://www.ucmp.berkeley.edu /cnidaria/C_sivickisi.html], and the other an unidentified jellyfish from the temperate mid-ocean deeps [http://oceanexplorer.noaa.gov/ explorations/02sab/logs/aug19/media/jelly_600.jpg]. Tentacles vary in length, but are generally comparable or shorter in length than the body diameter. Longer tentacles mean greater likelihood for entangling prey, a strategy used by some species such as Man of War, but more work getting the food inside.

The prototype ANTS walker currently under development uses a motorized string pulley mechanism for deployment of struts (Figure 5). The length of the string is initially wrapped around the telescoping tubes, and the strut is stowed. This system is lightweight, compact and has the mechanical advantage of a pulley, minimizing the power requirement. This mechanism has limitations in weight-bearing, and payload carrying, capability, and thus is considered a near term solution.

C. Compressional/Extensional Springs

An exemplary biological analogue for compressional/extensional springs is found in the extremely efficient and effective dolphin swimming mechanism as discussed in reference 23 and illustrated in Figure 7. The up and down motion of the broad fluke on the narrow tail causes forward motion in the water, or swimming. It isn't performed by the muscle contraction mechanism just discussed, but by a pair of passive internal compressional spring-like tissue, which generate a 'pogo stick' motion. This tissue combines connective tissue and fat with 3D structure which make it especially stiff. It includes the subdermal sheath, helically wound around the tail and attached to the skeletal frame, combined with wedges of stiff dolphin collagen-rich blubber attached to the top and bottom of the tail. This mechanism is so efficient that the dolphin's metabolic rate does not increase as their tails beat and they swim faster. up to 20 miles an hour, over long distances. A kangaroo hops in an analogous manner.

A mechanism under consideration for the next version of the ANTS walker uses compressional spring (Figure 5), compressed to stow the strut as needed and store up energy for strut deployment. A motorized steel cable pulls a compression string embedded in the struts. The initial position for the strut is thus fully extended. A major limitation is the power required to maintain a strut in any other position. Thus, this design is seen as evolving into a pneumatic or hydraulic design.

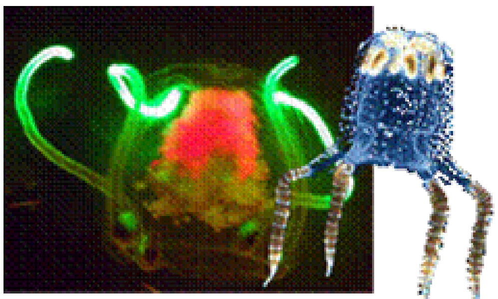

Figure 6 Biological anglers. Illustrated here are a box jelly from the tropics and unknown jelly from deep ocean from respective websites: http://oceanexplorer.noaa.gov/explorations/ 02sab/logs/aug19/media/jelly_600.jpg and http://www.ucmp.berkeley.edu/cnidaria/ C_sivickisi.html

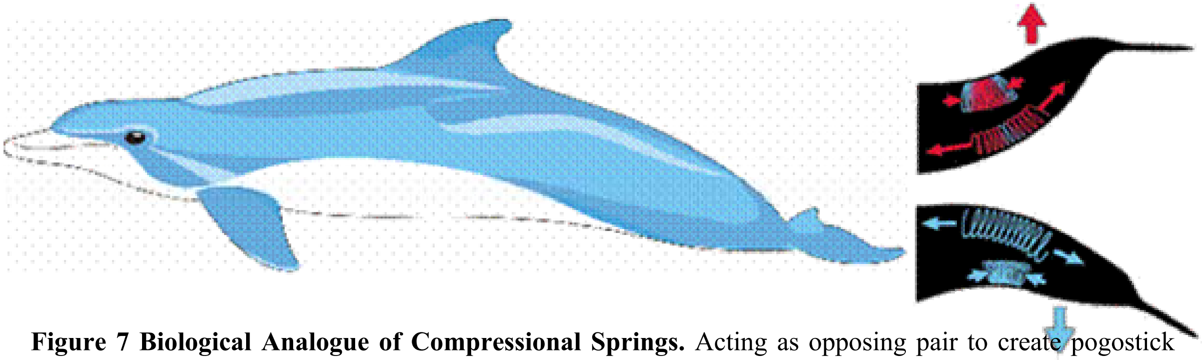

Figure 7 Biological Analogue of Compressional Springs. Acting as opposing pair to create pogostick like motion for swimming with little energy expenditure in dolphin. Dolphin from http://biology.usgs.gov/features/kidscorner/games/ocnscramb_ans.html, mechanism illustration from http://biomechanics.bio.uci.edu/_html/nh_biomech/dolphin_spring/dolphin.htm.

D. Constant Force Spring (Coiling)

The formation of a coil acting as a constant force spring, albeit a passive or very low resistance one in many cases, is a frequent strategy of living systems. Such coiling is done to efficiently store and minimize exposed area and exposure to potential loss or attack. Figure 8 presents several examples of this strategy. Recently, DNA has been observed to form flat, helical tori in 'storage' locations[24]. Early invertebrates, gastropods, used a flat helical shell [http://www.museum.vic.gov.au/collections/sciences/natfoss.asp], later adapted to an elongated form for more efficient swimming[25]. Many animals with elongated body morphology, vertebrates such as salamanders and invertebrates such as millipedes, coil to minimize exposure as a defense mechanism[26].

Future ANTS structures will be designed with opposing pairs of constant force springs (Figure 8) for strut deployment, evolving from the telescoping and compression spring mechanism. The deployment device will consist of oppositely wound tapes, carbon based in later versions, combined by zippering of notches or a spring spiral. Such a mechanism is compact and efficient and offers a major mechanical advantage of complete strut stowing. The key to success will be the design for the mechanism for locking the oppositely curved tapes. This essentially becomes a combined mechanism.

E. Combined Mechanisms

Biological organisms frequently combine mechanisms to perform more complex functions. One such example, also an effective dual spring mechanism, is the tongue of salamanders and chameleons discussed in references 20, 21 (briefly mentioned above), 27, and 28 (Figure 9). Extremely interleaved muscle fibers wrap around a bone in the center of the tongue, acting as an unleashed compression spring and telescoping outward with a force of 50g, expending its length by a factor of 6. In addition, telescoping layers of protein fibers wrap around the tongue, also attached to the bone at its base, and act as a tensional spring, slipping off the tongue bone but pulling the tongue back as it reaches its maximum extent. This retraction creates suction at the end of the tongue, which keeps the prey in place as the chameleon flips it into its mouth.

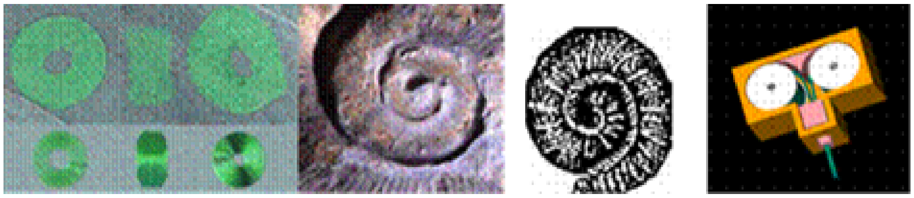

Figure 8 Coiling/Constant Force Spring Mechanisms. From left to right, the coiling of DNA for 'storage', toroidal coiling of paleogastropod shell, defensive coiling of millipede, and the opposing tape device with zipper proposed for future ANTS system nodes. The left three from websites in order:
http://www.museum.vic.gov.au/collections/sciences/natfoss.asp
http://www-vis.lbl.gov/Vignettes/KDowning-DNA/
http://www.sardi.sa.gov.au/pages/entomolo/pdf/milliped_bailey.pdf

F. Surfaces

For deployment of layers, sheets of material with a variety of functions, the plant kingdom offers simple, efficient analogues. Plants deploy layers, known as foliage. Movement of foliage is controlled through electro chemical mechanisms, analogous to those in animal muscle.

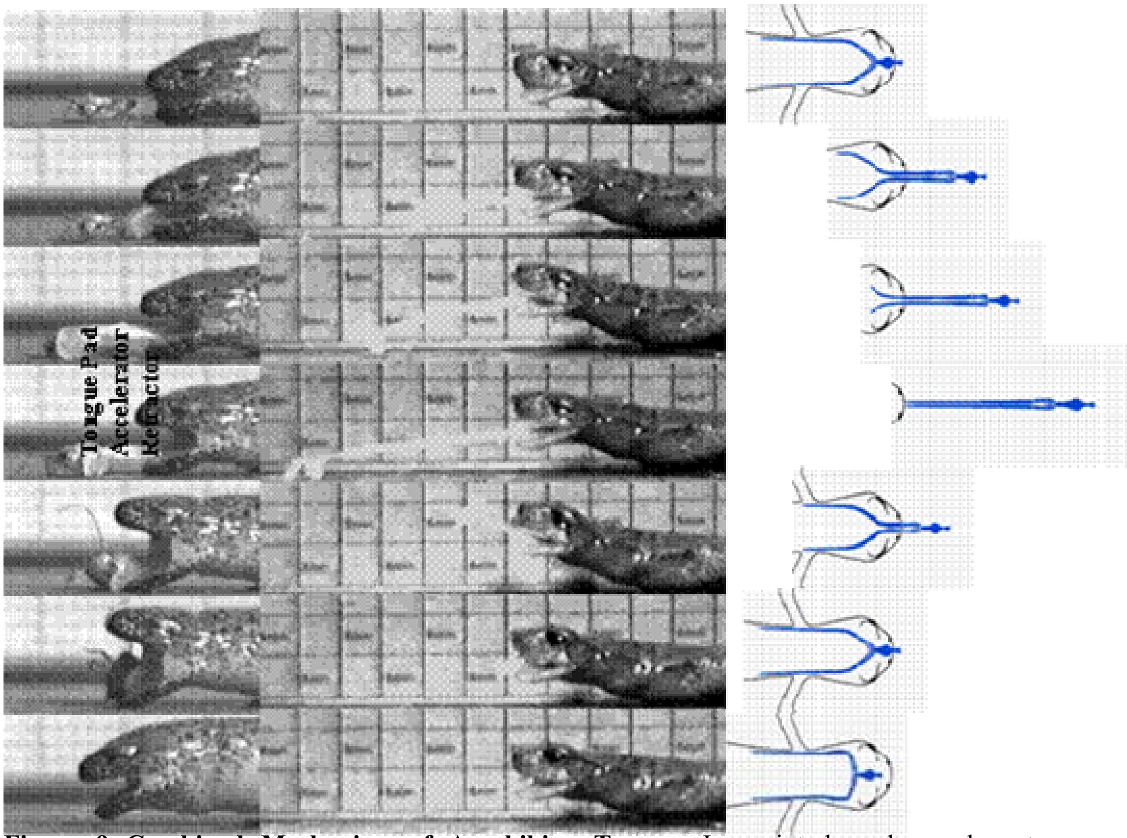

Figure 9 Combined Mechanism of Amphibian Tongue. Inner interleaved muscle acts as compressional spring connected to bone (accelerator). When reaches full extension, spirally wrapped muscle acts as extensional spring and pulls back (retractor), creating suction to hold prey at end of tongue (pad). From http://autodex.net, work of Deban[20,21].

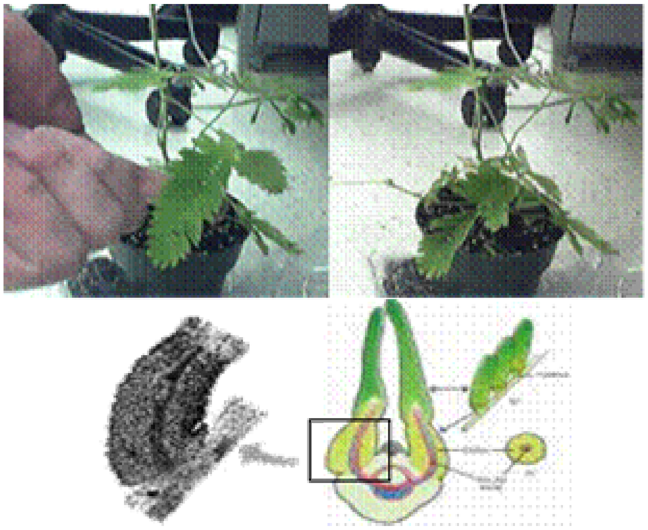

Figure 10 Mechanism in Sensitive Plant. Top frames show sensitive plant before and after touching. Below diagram of pulvinus motor organ attached to fronds with expanded view from the side from: http://scidiv.bcc.ctc.edu/rkr/Biology203/lectures/EnvControl/EnvReg.html

Mimosa pudica (MP), otherwise known as Sensitive Plant, has been singled out for discussion and study because it is one of a handful of plants which displays a comprehensive foliage closure mechanism in response to minimal mechanical stimulation and does so easily, reversibly, rapidly, and, because it is not carnivorous, it has no unusual energy requirements [29,30] (Figure 10). Thus, MP is a potential analogue for ANTS surface deployment and stowing mechanism.

This leaf closure response, a defense mechanism for protecting foliage from predators, occurs as a result of reduction in cell turgor, or osmotic water pressure, and thus is a form of wilting[29,30]. How does this ‘plant hydraulic’ reaction occur? In MP, this reversible response (nastic movement) can result not only from touch (thigmonastic), but also from movement (seismonastic) and light reduction (nyctinastic). These responses are caused by electrochemical changes in the leaves. Studies have indicated that mechanically stimulated parts of the plant exhibit

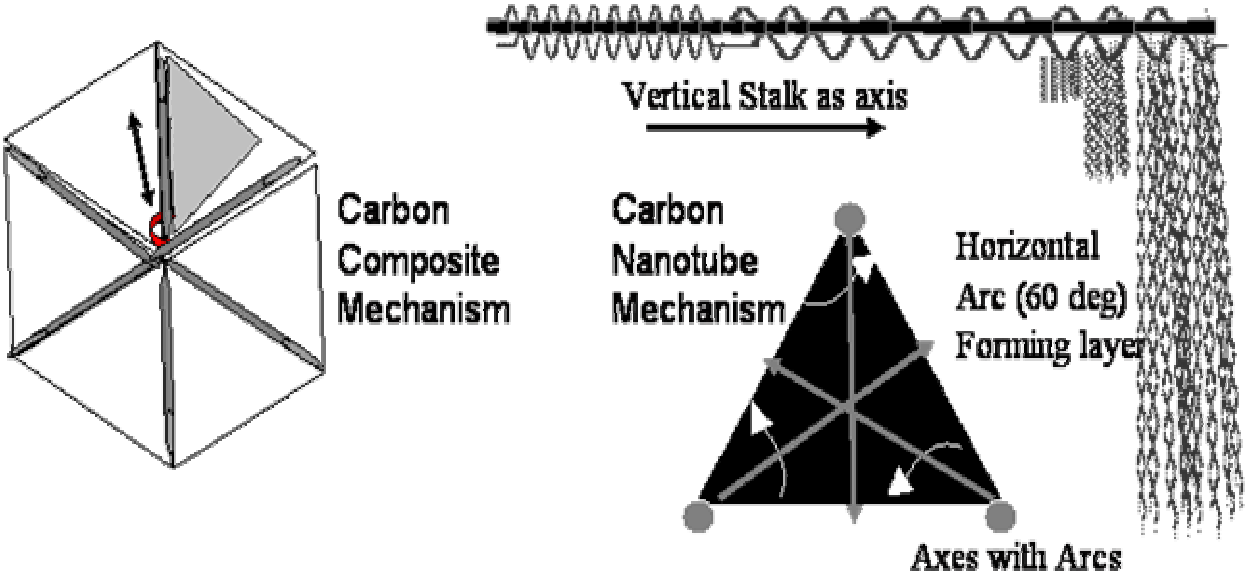

Figure 11 Solar Sail Surface Proposed Deployment Mechanisms. On right, NEMS level design using Carbon Nanotubules directly. Springs deployed as vertical stalks under compression wrapped with tensional coils. Dendrites with similar structure deployed in 60 degree arcs toward opposite side. Density and order of dendrites determines reflectivity and strength. On left, MEMS level design using Carbon Fiber Composites. Compressed carbon memory fabric wrapped on shade-like connector attached to oppositely wound spring. Deployment along arc and in direction opposite spring.

flaccid cells, correlated with lowering of osmotic water pressure, and lower potassium ion levels, whereas unstimulated areas contain turgid cells, correlated with increase in osmotic water pressure, and high potassium ion levels [31,32]. Typically, outflow of water follows outflow of potassium ions, in an attempt to maintain equilibrium in ionic concentrations. Studies have also found high abundances of turgidity controlling substances called turgorins in MP leaves[31,32]. A motor organ at the base of the leaves, called a pulvinus (vascular core surrounded by a two regions, extensor and tensor, of thin-walled cell cortex[29,30], controls whole leaf motion (Figure 11). Apparently, the permeability of cells in the pulvini increase in response to rise in sucrose accompanying mechanical stimulation, allowing rapid flow of ions, including calcium and potassium. Outflow on stimulated

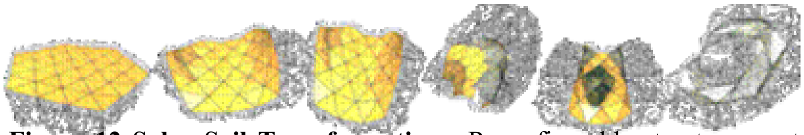

Figure 12 Solar Sail Transformations. Reconfigurable structure created from two layers of nodes with fabric deployed from special nodes as discussed above from one layer of nodes.

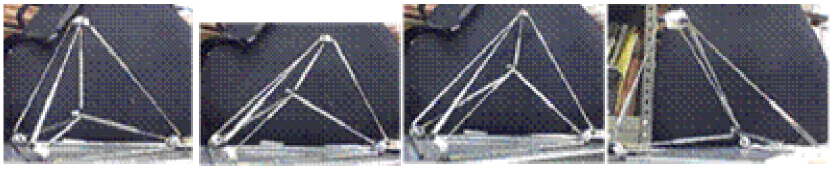

Figure 13 4Tetrahedron Walker Model. As in Tetrahedron in Figure 2.4, one flip is being performed. In this case additional node helps to accomplish required change in center of mass more easily.

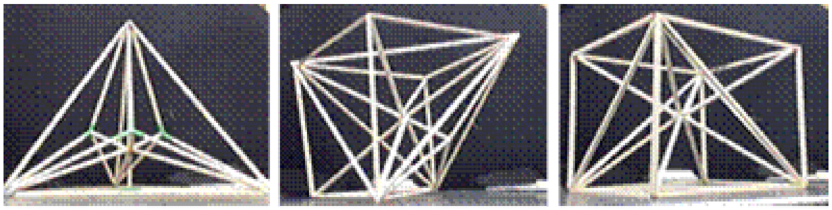

Figure 14 12Tetrahedron Stationary Model. As discussed in text, note complete transformation from tetrahedron highly angular for tipping to nearly spherical easily for movement to cubic stable for standing.

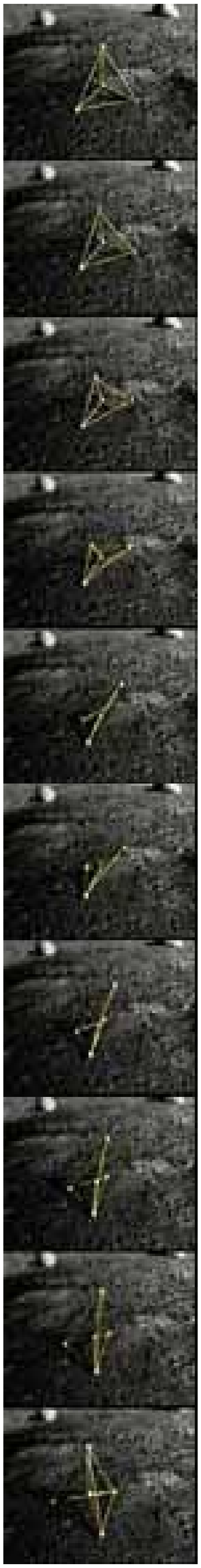

Figure 15 The 4Tet Movie.

side is accompanied by decreased turgor and contraction, while inflow on the other side is accompanied by increased turgor and expansion. In this way, a leaf can be 'turned'. As the electrochemical shifts occur in a stimulated area, the response can be transmitted to adjoining areas as well. The electrochemical 'signal' is transmitted rapidly (1 cm/sec) and accompanied with a measurable electric response (galvanometric negativity)[33-35].

Behaviors and requirements for deployment for future ANTS components, including surfaces and hydraulic struts, are in many ways similar to those described for MP. Such deployment would require efficient (low power @ <1 Watt and low mass @ <<1 kg for power generation system), rapid, reversible movement in response to a minimal electrical signal, ideally caused by flow of charge through the nodes, analogous to pulvini.

ANTS surface deployment mechanisms will be implementable at the MEMS level[36]. Several mechanisms have been proposed for deployment, depending on the extent to which carbon nanotubule technology is developed as discussed in references 37-39 (Figure 11). For near future application, carbon fiber composite MEMS nodes could be used to deploy the relatively low aerial density (5g/cm2) [see http://www.esli.com and http://www.meetingsmanagement.com/pdf/PF-2004.pdf] carbon fiber composite sheets with 'shape memory' in the full deployment position. The 2D spooling mechanism could be a shade-like roll up device progressively released or stowed by an opposing force carbon-based spring. As CNT technology advances and continuous CNTs [http://www.ipt.arc.nasa.gov/], with properties approaching individual nanotubes become available[40], mechanisms using only the nanotubes themselves could be utilized, thus reducing aerial density and power requirements. As in the salamander tongue, the core would consist of interior interleaved multiwalled CNTs acting as compressional springs under compression to provide the releasing force. Wrapped around the interior would be helical carbon nanotubes acting as tensional springs, to provide the stowing force. Attached to the core would be telescoping helically wrapped dendritic nanotube branches, to create a multi-layer capability. The more branches and the higher the order of branching, the greater the effective surface area would be. Carbon-based material carries charge; thus, as in MP, induced changes in electrical potential could by used to activate the open or close side of the node, and thus regulate the amount of surface material deployed.

Such nodes would be used form the PAM concept for the proposed 10,000 facet 100 sq meter solar sail supported by a 3D truss structure consisting of two layers of interconnected nodes illustrated in Figure 12[9,36]. Very effective attitude control could potentially be achieved by using such reversibly deployable components for surface and struts to control amount and distribution of sail area (and thus center of pressure) as well as shape. [See Sail Animations at official ANTS website, http://ants.gsfc.nasas.gov]. Even if control of individual facets was minimal, with only fully deployed or fully stowed positions available, deploying as few as 3 or 4 facets properly distributed, would lower sail area by more than a factor of 1000 (the nominal requirement) while controlling the attitude. By changing the effective shape and size of the 3D truss structure, the direction of momentum vectors, and thus direction and speed, could be dramatically modified.

IV. Models of ANTS Systems Based on BEES

Detailed models, for near term applications of ANTS architecture, based on the mechanisms outlined above, are already being constructed. A prototype for the single tetrahedron walker is currently being constructed. Under consideration here are models for the single tetrahedron walker (Figure 3), for which a prototype is currently being constructed, the 4Tetrahedron version of the walker with a central payload carrying node, or 4Tet, for which detailed engineering and field testing plans are being developed, the 12Tet, a rover exhibiting behaviors of greater continuity and complexity, for which models are being developed.

Shown in Figure 13 is a series of images of the four-tetrahedral walker through one 'flip'. As in the prototype, struts can move freely over almost 180 degrees of motion and can be changed in size by a factor 3 to 4. Forward flipping occurs when the center of mass is pushed far enough off center by extending above ground struts. Struts can then be trimmed every few steps as needed to maintain the step size appropriate for the terrain. The interior 'payload node of the 4Tet can be used to advantage in changing the center of mass so that a forward ‘flip’ occurs.

Shown in Figure 14 are stationary models of the 12Tet. Notice the capability for transformation from the stable tetrahedron, transition through less stable more spherical form for locomotion, or to less stable cube (2 tetrahedral bases per face) more easily tipped, with just 12 tetrahedra!

Figure 15 shows a sequence illustrating the 4Tet locomotion in a lunar surface environment. The interior node is designed to be used for a payload as well as to adjust the center of mass.

Figure 16 shows two sequences from an animation clip of the 12Tet, showing stowing for storage (decreasing in size) in bottom five frames, and complex transformations to climb up and over an object in top five frames. For comparison, transformations of a many-Tet system, from flyer, to rover, to antenna, are shown in Figure 17, as the system shifts from landing (aerodynamically stable and flattened), to surface mobility (amoeba-like, high degree of freedom) to communication (convex curves on stable base). Animations of all of these structures may be seen at http://ants.gsfc.nasa.gov.

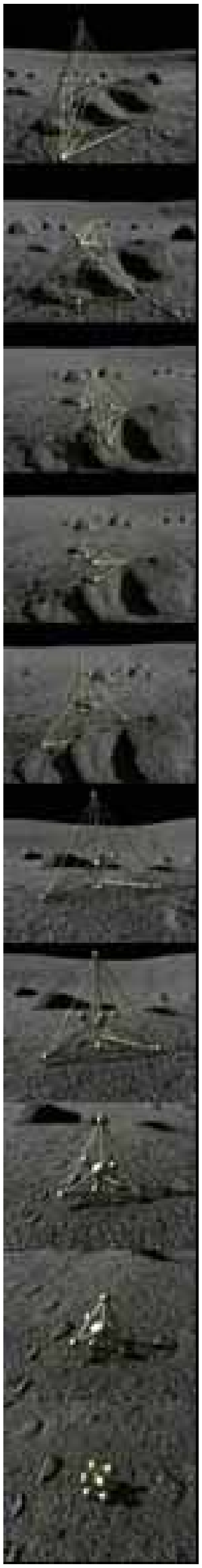

Figure 16 12Tet Movie Clips.

V. Summary

Table 2 shows compares mechanisms in ANTS systems to their biological analogues, their requirements, optimal applications, strengths, and weaknesses. An important issue for biological systems as well as for ANTS architecture is power consumption. Biological systems use combined (opposing force) mechanisms to minimize organism fuel requirements, meaning access to food and time spent eating, during prolonged activity. This observation is particularly true when movement is required. ANTS system development is already moving in that direction.

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Figure 17 ANTS Continuous structure proposed for LARA. Transformations from flattened form to snakelike and rolling forms and finally to antenna and beacon forms.

Table 2 Comparison of Biological and ANTS ART Mechanisms

Morphology/Mechanism	**Natural Analogue**	**ANTS**
Tetrahedral Structure	Basis of Si and C bonding (4 coordination) Basis of Non-organic Solids (Si)	One or more tetrahedra with nodes at apices which deploy struts as sides form basis of all structures, from simple walkers to continuous surfaces. Great variety of structures and behaviors possible.
Node and Strut: Telescoping	Used extensively in biological systems. For special appendages in invertebrates; for muscle tissue in higher phyla.	Strut extension mechanism for early walker. Combines well with other mechanisms, as in biomechanics.
Node and Strut: Pulley	Used in invertebrates such as jellyfish to capture and hold prey in buoyant environment with minimal energy requirement.	Very efficient String Mechanism for connecting winding motor to strut in early walker but with minimal strength.
Node and Strut: Compressional/Tensional Springs	Pairs used for pogo-stick like efficient locomotion in higher phyla, including mammals, e.g., dolphins, kangaroos.	Powerful Spring and Cable deployment mechanism for early walker but with greater power requirement.
Node and Strut: Constant Force Springs	Used extensively for coiling to minimize surfaces from loss or destruction in biological systems, from DNA to worms to amphibians.	Opposing wound tapes in metal allow or carbon based material for next generation ANTS systems.
Combined Mechanisms	Used in higher phyla for survival edge complex mechanisms, e.g., amphibians tongues, with telescoping interleaved muscle fibers for deployment and striking prey circumscribed by radially wound muscles acting as tensional spring for retrieving prey and stowing.	For early walkers, telescoping and Springs. At MEMS/NEMS level, to minimize energy requirement for surface deployment, telescoping or compression spring-like network for deployment wrapped with tensional springs for stowing for CNTs.
Surfaces	In plant kingdom, mechanisms using pulvini for opening and closing leaves, electrochemically controlled hydraulic mechanism operating under a variety of circumstances, especially developed in Sensitive Plant.	For near future surface deployment, Carbon fiber compressive Sheets for protective, reflective, or absorptive surfaces deployed from special nodes using pneumatic, hydraulic, or constant force spring mechanisms.