Tetrahedral Robotics for Space Exploration

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ABSTRACT

A reconfigurable space filling robotic architecture has a wide range of possible applications. One of the more intriguing possibilities is mobility in very irregular and otherwise impassable terrain. NASA Goddard Space Flight Center is developing the third generation of its Addressable Reconfigurable Technology (ART) Tetrahedral Robotics Architecture. An ART-based variable geometry truss consisting of 12 tetrahedral elements made from 26 smart struts on a wireless network has been developed. The primary goal of this development is the demonstration of a new kind of robotic mobility that can provide access and articulation that complement existing capabilities. An initial set of gaits and other behaviors are being tested, and accommodations for payloads such as sensor and telemetry packages are being studied. Herein, we describe our experience with the ART Tetrahedral Robotics Architecture and the improvements implemented in the third generation of this technology. Applications of these robots to space exploration and the tradeoffs involved with this architecture will be discussed.

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INTRODUCTION

Irregular and unknown environments pose critical problems for space exploration. Mission goals may lead to requirements for access to areas or spaces that are difficult to reach and hard, or impossible a priori, to characterize. Such goals can involve obtaining data pertaining to scientific questions and can also involve providing access to irregular, undeveloped environments in contingent situations; for example, involving search and rescue or forensic analysis. Developing systems with extra degrees of freedom that allow systems to adapt to and move around in complicated environments would provide an important new capability providing access to currently inaccessible regions, see Figure 1.

Addressable Reconfigurable Technology (ART) is an approach to developing systems with multiple degrees of freedom that is being studied at the NASA Goddard Space Flight Center (GSFC). ART features multiple reconfigurable systems acting together to provide advanced capabilities. These advanced capabilities include improved packing factors for deployable structures, active control and increased redundancy for reliability, and new possibilities for structural reconfiguration enabling mobility, multiple use, or configuration optimization. Addressable means that the individual elements of these parallel systems can be accessed and commanded individually and do not require a high-degree of subsystem autonomy. This means that ART systems can be implemented with current and near-term technologies, see Figure 2. More advanced applications have been discussed elsewhere [1,2,3,4], including for example, systems with the Autonomous Nano-Technology Swarm (ANTS) architectures [5]. These include discussions of the use of adaptable overdetermined trusses for solar sails, radiowave reflectors, manipulators, and modular and monolithic deployable structures.

A cutting-edge technology is Tetrahedral Robotics (TR), which involves active trusses made up of extensible structural members (struts) and interconnections (nodes) arranged in a tetrahedral mesh [6, 7]. The number of tetrahedra, or TETs, is an indicator of the complexity of a TR robot and the behaviors and shapes it can take on, see Figures 1-5. Using an ART-based design philosophy, changing the lengths of the struts in concert allows the truss as a whole to reconfigure itself into a variety of different shapes. The concept is scalable, depending on the technologies used to provide actuation and control, including power, communication, and computation. In the longer-term there are exciting possibilities for MicroElectro-Mechanical Systems (MEMS)-based systems with large numbers of struts enabling an essentially continuous, reconfigurable material. In the near-term, a set of technologies must be developed to enable these active overdetermined structures to take on useful behaviors. The current work focuses on using ART/TR adaptive trusses for mobility and access in irregular and complex environments.

In such environments, especially in the context of exploration, mobility and access mean more than covering distance. They also mean transporting and deploying payloads through and into difficult, even vertical, terrain. For science missions, data relating to important questions usually require access to new and unfamiliar locations that require adaptation during the mission. Without such adaptation, scientific return can be greatly limited. With the increase in the human element of exploration systems, improved capabilities for mobility, access, and adaptability can provide important new capabilities, particularly contingencies where human lives may depend on the ability to adapt equipment for unforeseen and unplanned activities.

All mobility technologies have their limits, the technologies we have been studying aim to enable access to regions that are not accessible by wheeled vehicles. Wheeled vehicles and legged vehicles (and creatures) can adapt to a wide variety of terrain, yet irregular, vertical, subterranean, and similarly hazardous locales push the limits of these modes of locomotion. In the natural world, evolution has driven the development of species that “finesse” such difficulties, e.g., birds that fly to nests on cliffs. Evolution has also led to species that deal more intimately with irregular environments, e.g., snakes which by fine control of their shape can seek prey in tunnels or bury themselves by flexing their bodies. These natural examples have inspired research into a variety of mobility technologies. The reconfigurable trusses that are the subject of this work seek to use structural

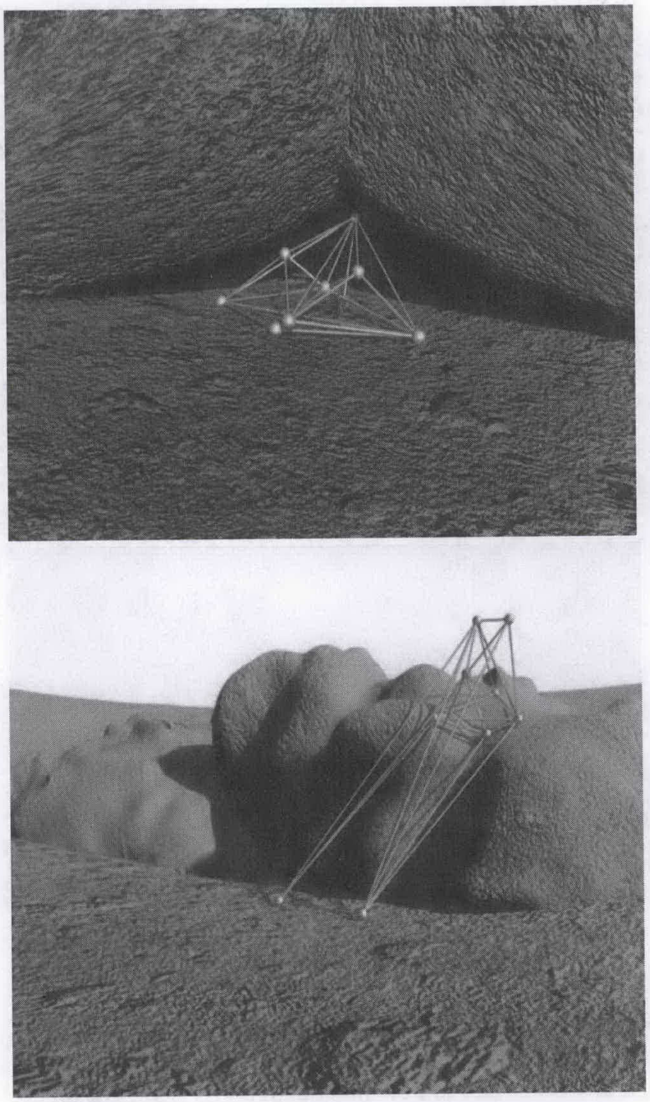

Fig. 1. Conceptual 12-TET Rovers with 26 large extension ratio struts integrated as 12 tetrahedra

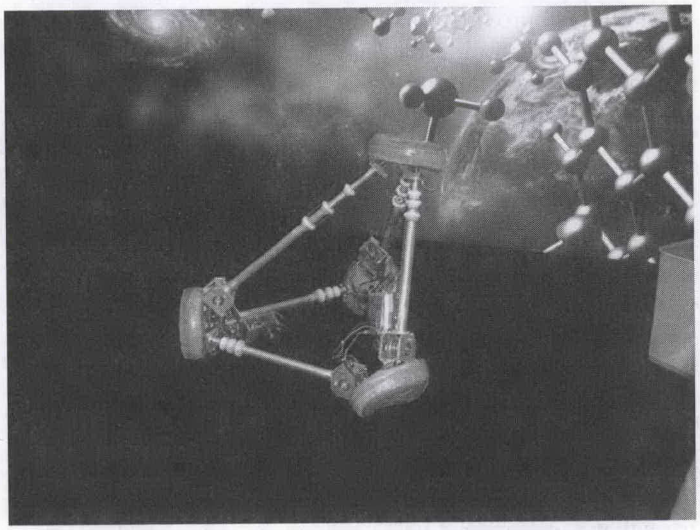

Fig. 2. First Generation 1-TET behavioral model

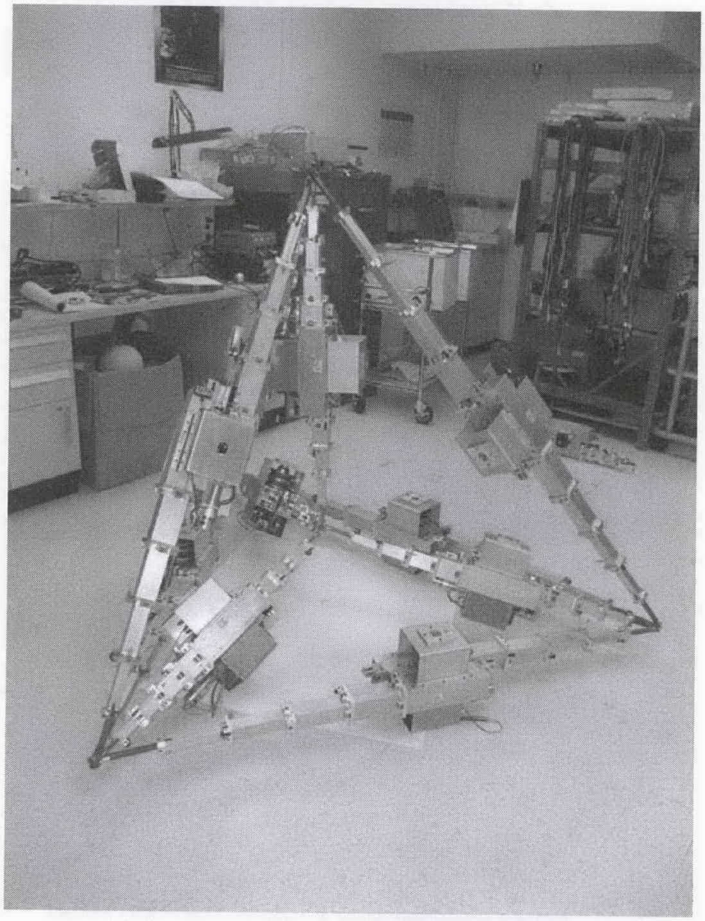

Fig. 3. Second Generation 4-TET

reconfiguration to reach for new levels of flexibility and adaptability.

It is worthwhile to note that adaptability need not focus only on the environment in which a mechanism is deployed. Our current focus is on bringing together control, communication, and actuation to enable tightly coupled parallel robotics and using these systems to adapt to external constraints to provide system mobility. This same capability is also applied inward, that is to constraints arising because of the mechanisms and subsystems constituting these tetrahedral robots. Should a strut fail; e.g., by seizing, there are sufficient degrees of freedom remaining to allow the rest of the system to continue to reconfigure and function. This does place novel demands on control algorithms, but a single failure will not cripple these parallel systems. In fact, it is clear that multiple struts may fail and as long as they do not form a pathological "substructure" within the structure, the structure as a whole will still be able to reconfigure and move albeit perhaps in a suboptimal way.

Previous work with Tetrahedral and adaptive trusses has been outlined in a previous paper [8]. The current line of work at GSFC on ART/TR began in 2004 with the development of the 1-TET, a one-tetrahedron reconfigurable truss that demonstrated basic movement and control of a determined system. The struts used in the 1-TET featured an

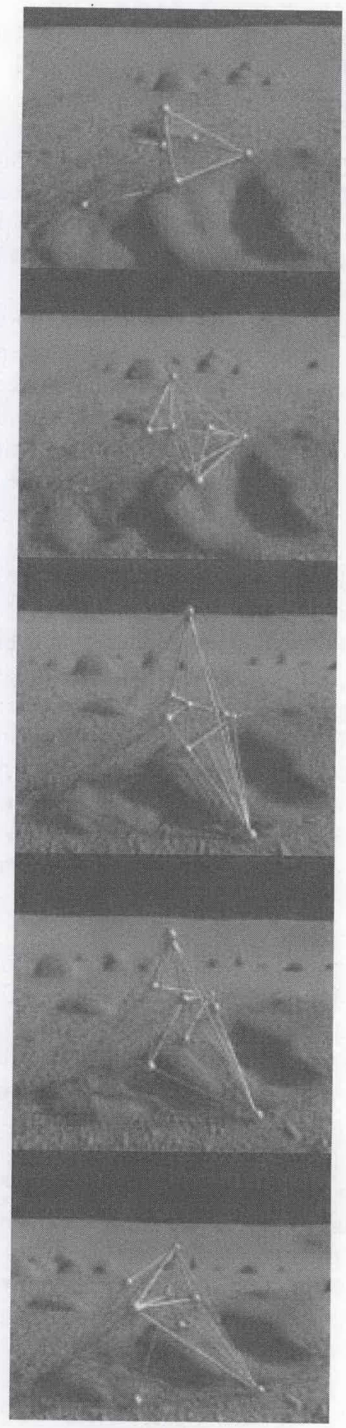

Fig. 4. 12-TET Amoeboid Motion: Moving Over a Rock; Long extension ratios provide flexibility and challenges for control

extension ratio of about 2:1, which was enough to allow the 1-TET to topple from place to place by moving its center of gravity. To provide more varied and useful locomotion, a follow-on effort sought to develop a 12-TET, a twelve-tetrahedron truss, with struts with a 5:1 extension ratio. Nicknamed "Arnold" because of its weight, this second-generation 12-TET was deficient in a number of

Table 1. Goals for the Third-Generation 12-TET

Requirement	Desired	Achieved (12/06)
Strut extension ratio (each)	5:1	5:1
12-TET Behavior	Complex shapes Climb a 40° Slope	Simple shapes First movements
Overall mass of 12-TET	< 60 lbs	~92 lbs
Control	Remote, open loop	Yes
Strut Length	Self-Maintained Individually Commandable	Yes
Strut Telemetry to Central Computer	Enough for monitoring and Generating Gaits	Yes
Strut Extension / Retraction Speed	Fully deploy in 10 sec.	Deploys in 6-10 sec.
Integrated and Tested	9/30/2006	~11/2006
Total Budget	$100 K	

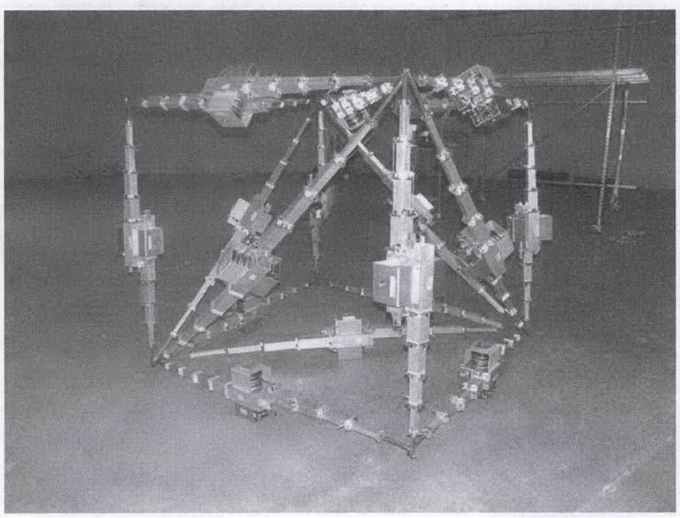

Fig. 5. Second Generation "Box Tet"
A 12-TET precursor lacking the central node.
Note the point-like connections or
nodes between the struts

ways; e.g., a 4:1 extension ratio was achieved, that we will discuss below. In this work, the third-generation ART/TR 12-TET is described which features a number of improvements over previous robots.

Each successive generation has taught us something about how to balance compliance, constraint, and configurability. We have chiefly focused on the structure itself, that is, on making a truss with active struts extensible, strong, and smart enough to be able to act in concert to reconfigure the overall shape of the truss. We have endeavored to develop a commandable system that can be used as a test bed to study control algorithms and different mobility strategies.

In this paper, we describe our experience with the second-generation 12-TET Arnold and its successor, the third-generation 12-TET. In the following sections, we briefly discuss Arnold's structure and performance. Arnold's successor features a complete redesign, which we will outline. In parallel with the prototyping efforts reported in this paper, we are studying technologies for adapting these structures for use on the lunar surface; for example, our electrostatic dust-mitigation research and its application to our prismatic joints will be discussed elsewhere [9].

PREVIOUS GENERATION TET ROBOTS

The first ART/TR was the 6-strut 1-TET which formed a single-cell mechanism with a flopping gait, see Figure 2. It featured nested, telescoping aluminum tubes with nylon top and bottom pieces, and changed their lengths by Kevlar fishing-line string-pulley actuation. As stated above, the ratio of these struts' fully extended to their fully compact length was about 2:1, which was enough to allow the simple structure to move its center of gravity out of its base, initiating a tumble. The electronics and motors were all Commercial-Off-The-Shelf (COTS). Kit development microcontroller prototyping boards were used with hobby

Table 2. Comparing the second and third generation struts

Second Generation "Arnold" (2005)	Third Generation (2006)
Bandolier, steel cable & pulley system	Nested screws with exoskeleton
One motor driving both "substruts"	Two motors for independent "substrut" actuation
Commercial stock aluminum square tubes	Custom stereo lithograhic fabrication
Virtual nodes from wire loop connections	Node cluster of ball & socket joints
Weight transferred to motor box	Weight transferred directly to ground
Motor box transfers weight to ground	
Photodiode and sector wheel for length sensing	String pull-potentiometers
Motor current monitoring and limiting	3-Axis accelerometer
Ground sensor	Battery level measurement and auto-shutoff
Low battery sensor	Motor current monitoring and limiting
	2 Force gauges for tension and compression
	Board temperature sensor
Central computer handles commands and telemetry	Central computer handles commands and telemetry
	Fast strut-to-strut communication is in development
BlueTooth with custom multiplexing	ZigBee using standard protocols
Mass 26 lb, Min/Max 28" / 116", Section: 28" × 18"	Mass 2.62 lb, Min/Max Length 8.4"/44.3", Dia. 3.1"

shop motors with incremental encoders implemented with chopper wheels and optical couplers to monitor strut lengths. The 1-TET onboard microcontrollers maintained a simple model of its orientation which it updated after performing a commanded action. Upon an external command executed a timed sequence of strut length changes calculated to cause a single step (or fall) in one direction immediately followed by a return to a similar, regular, initial state ready for another step. This simple procedure, open loop commanded and performed by rote, has allowed operators to direct the TET to maneuver about during many demonstrations around the world.

Though falling over is a feature and not a failure of 1-TET locomotion, finer control is desired for most scientifically motivated planetary operations. To move a step closer to a system that could carry and position a science instrument package more precisely, it was desired to have a system that could move about quasi-statically when desired and that could place an instrument package near or over interesting features such as cracks, crevices, or stones. To move to a quasi-static gait without (much) dynamic tumbling is realized by moving to more complicated TET robots with more tetrahedral cells, see Figure 3. One of the most exciting possibilities fitting within this paradigm is the possibility of putting together a 26-strut 12-TET ART/TR robot that is capable of a quasi-amoeboid motion, see Figure 4.

At this point we decided to redesign the ART/TR struts to account for the limitations of the 1-TET. To eliminate twisting and binding of the nested cylindrical tubing, nested square tubes were used. Friction of the Kevlar strings over the ends of the strut tube segments was deemed a problem, so for the new struts steel cable and pulleys were used. To lift itself and a science payload robustly a power electric motor with a planetary gearhead and worm gear were used. A potentiometer was used to keep track of strut extension. Excessive compliance and "flop" of the 1-TET's node end

Fig. 6. Third-generation strut fully retracted

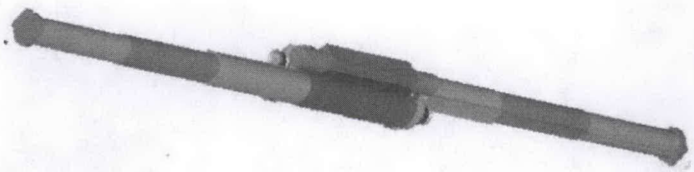

Fig. 7. Third-generation strut fully extended

plates was eliminated by creating a "virtual node," by tying wire loops together in a tight cluster. A custom electronics board on each strut created an ART addressable communications and control architecture. The struts could be queried and controlled by user-friendly interface software running on a laptop communicating with the struts via wireless links. To increase the variety of structural configurations the extension ratio of these new ART/TR struts was increased from 2:1 to 4:1, not quite reaching the goal of 5:1 but still sufficient to start exploring our gait concepts. A number of gaits and motions were designed to take advantage of these new capabilities, but the new strut did not meet our expectations.

Due to our limited resources, time budget, and our focus on using COTS wherever possible, the final weight of the struts greatly exceeded our initial estimates. Furthermore a small design change that greatly eased assembly of the struts turned out to have a dramatic effect on the mechanical behavior of the struts leading to the storage of a great deal of internal tension in the struts' actuation mechanism. In addition to this tension, the "bandolier" string-pulley system used in the 1st-generation and 2nd-geneeration ART/TR robots has an amount of "slop" in the length of the strut. For example, in the transition from compression to tension our robust struts would change length, sometimes significantly, perhaps 10%. Even in the face of these difficulties, the new strut design did allow us to examine strut communication, command, and control, and provided us with a look into how these ART/TR robots reconfigure themselves as their struts move around and reconfigure the trusses.

For example, we examined the simple augmentation of the 1-TET as a 4-TET in which a science package is held by 4 ATR/TR struts to the corner nodes of a 1-TET, see Figure 3. We used the 4-TET configuration to learn about the requirements for reconfiguring an over-constrained structure by moving the "central" science node around and outside of the tetrahedral volume. Such motions are an analogy for moving around any science package integrated with an ART/TR framework.

With the 2-TET ART/TR robot, we used the second-generation strut to take a few simple quasi-static test steps or reconfigurations. Most of our motion studies were with the 2-TET and 4-TET configurations. Because of the weight and tension we were careful not to perform, 1-TET style flopping gaits. A fully configured 26-strut 12-TET with the 2nd-generation struts (see Figure 5) weighs over 740 pounds! This presented a number of logistical problems in

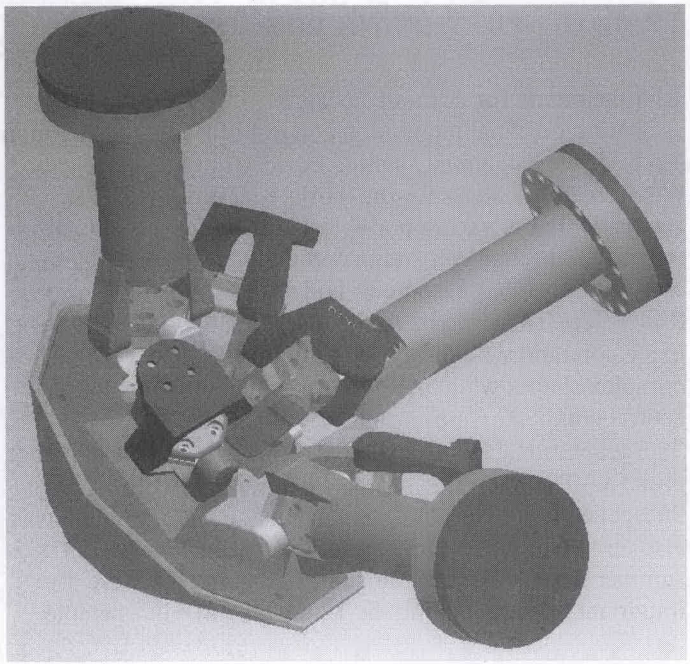

Fig. 8. Third generation node design

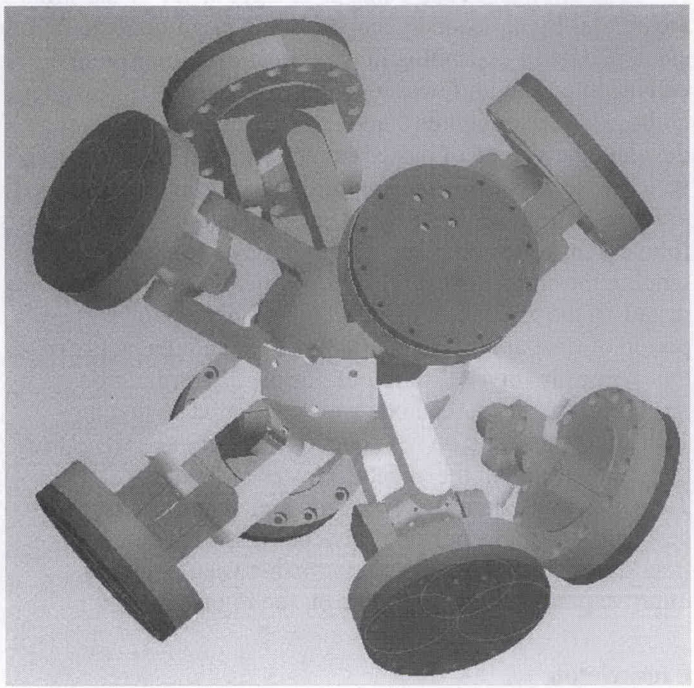

Fig. 9. Third Generation, Central Node, Science Payload Prototype

addition to the problems during test operations. At this point we stress that, so far, the ART/TR robots are to be considered behavioral models and technology demonstrators. These technologies are to be light-weighted and hardened for flight once the behaviors are demonstrated: we do keep in mind how to and maintain plans for a transition to flight-capability.

THIRD GENERATION TET ROBOTS

Requirements for a Small 12-TET

During our final integration and test of the 2nd-generation 12-TET, we had already started a trade study and requirements analysis for the third-generation ART/TR robots. Broadly, a more portable 12-TET that stressed the structural, mechanical, and material aspects of the system was desired. Again resources, budget, and time were also drivers, see Table 1. The basic goals of achieving a 5:1 strut extension ratio with the 12-TET structure able to take on complex shapes while in remote communication with a central computer were carried forward from the 2nd-generation TET. Constraints on weight and the ability to climb a 40 degree slope separate the 3rd- from the 2nd-generations. Speed of strut extension and retraction was also an important consideration. Finally, the availability of summer interns for parts finishing and assembly were also important for determining the 12-TET's overall timetable.

Mechanical Overview

Based on our experience from previous builds and on the trade studies, we decided to rework the node design for the 3rd-generation strut, see Table 2. The geometry of the struts are similar to the second generation, a back-to-back double sided geometry expanding in two directions, improving the extension ratio with fewer segments and reducing crowding at the nodes, see Figures 6 and 7. For actuation we have developed a system of nested screws within an exoskeleton, which has a greater extension ratio than we believe has previously been achieved. The 2nd-generation ART/TR robots transmitted the weight of the trusses to the ground by loading the ends (nodes) of a strut while its central pulley box rested on the ground. Anyone who has held a book for any period of time at arms length will understand the nature of the stresses involved. Therefore, for the 3rd-generation ART/TR structures, the node was redesigned so that the 12-TET would walk on the node, transmitting the weight to the ground through the node. A cluster of 2- and 3-degree-of-freedom (DOF) joints at each node were designed to strike a balance between rigidity and node freedom and provide a rigid relation between points to improve predictability and control, see Figure 8.

Exoskeleton

The exoskeleton with the nested screws is probably the major change in the 3rd-generation strut. The exoskeleton has three telescoping segments that extend and contract at the same time as the nested screws. The shape of the exoskeleton provides a brace against which the screws themselves turn, and the exoskeleton itself takes the bending loads of the structure to keep the screws from binding. For low-cost and rapid production of the exoskeleton, they were fabricated using stereo lithography, which allowed light and low-friction components with useful built-in features to be conveniently produced.

Fig. 10. Third generation 12-TET robot

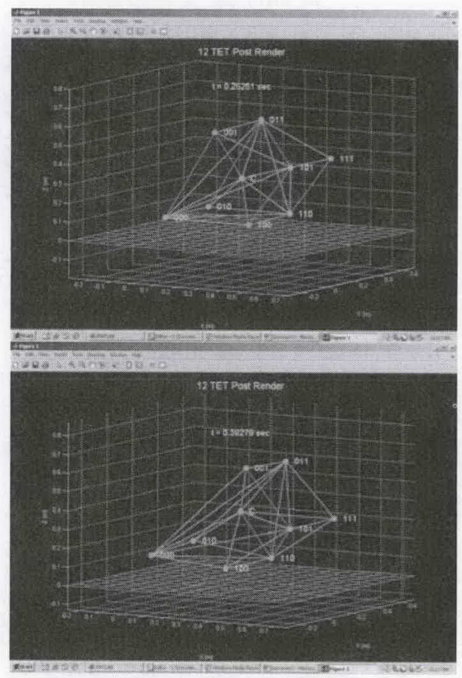

Fig. 11. A visualization from Matlab-based software used to model 12-TET dynamics and control

Actuation

These ART/TR struts feature two independent nested-screw/exoskeleton devices, that could work as one-side "substruts." Each substrut has its own motor which drives the screws via a pulleyshaft mechanism. Our gearbox/pulley mechanism provides sufficient resistance to backdrive to support the ART/TR mass and movement, and also provides some mechanical advantage, as well. Integrated pull-pots provide excellent strut-length sensing and the entire package fits within a 3.13 inch diameter by 8.4 inch-long cylinder, but can extend to 44.26 inches with a compression ratio of 5.29:1. A summary of strut characteristics, as built, are in Table 1.

Nodes

The ART/TR nodes also received a great deal of attention. The desire was to provide "feet" for the TET that would assure the struts would stay off of the ground while allowing as much maneuverability to the struts as possible. At the same time, however, we wished for the nodes to add as little as possible to our uncertainty in the configuration of the ART/TR 12-TET as a whole, i.e., to minimize sag and slop. We came up with a 9-faceted design involving 2- and 3-DOF joints that eliminates play when struts are fixed, yet allows full mobility when struts are moving, see Figure 8. This node design also provides space in which a payload may be placed.

Payload Node

A special payload-node was designed to carry a 1 kg "science" payload that allows the same ART/TR struts to be used for all 26 struts of a 12-TET, see Figure 9. Like the feet, the payload design eliminates play while struts are fixed, but allows full TET mobility while moving. The payload is small enough so that the wrapping angle for each strut about the payload is the same.

Command and Sensing

For the first moving behaviors of the 3rd-generation 12-TET, commands are transmitted from a central computer via ZigBee™ [1] wireless communication links to PIC microcontroller-based custom control electronics on each strut. The central computer, in our case an external laptop computer, sends a command sequence of strut lengths vs. times to each strut, and then broadcasts a universal "GO" command to the entire structure. Built-in sensors provide 3-axis accelerometry to measure strut inclination, string pull-potentiometers to provide strut length data, force gauges to measure tension and compression, as well as electronics board temperature. The battery level is also monitored and an automatic shut-off is implemented to save the Lithium Polymer batteries. The sensors and communication when coupled with the central computer provides a powerful framework for developing together a parallel computer that has a space-filling and behaviors for the 12-TET and other ART/TR structures. The integrated system can be seen in Figure 10.

Behaviors

The first behaviors to be developed will all be implemented via open-loop command sequences first tested in simulation. We have added a MATLAB-based simulation of the 12-TET to our existing kinematic and dynamic TET simulations, see Figure 11, [8]. These models incorporate a variety of strut parameters and provide a tool to investigate gaits and control algorithms. One such algorithm we have recently studied is the Decentralized Adaptive Controller, and we have found that DAC may provide an efficient means to control TET motions without depending on a centralized processor or burdening interstrut communication bandwidth.

CONCLUSION

In this work, we are exploring the synthesis of computation and actuation into integrated parallel systems that provide truly novel capabilities. Figure 12 gives an impression of the progress that we have made since the start of this work. We have learned a great deal about how to put together a physical mechanism capable of executing what amounts to a parallel computer program that has physical and geometrical implications. Note that components of the 3rd-generation struts have been fabricated by computer driven stereo lithography 3D plans constructed using Computer Aided Design software. Computer animations, stills from which are seen above in Figures 1, 4, and 12, show in a kinematic sense the motions that are possible, at least given their own level of detail and physical fidelity. The first of these two deals with constructing static structures and controlling that process via computer. The latter, the animations, controls the motions and geometries mostly kinematically, but as the technology goes forward with increasing fidelity and dynamics. We are working through the natural evolution of mechanical systems, adding computation and communication to operate many tightly coupled mechanical subsystems in parallel. In one sense, we are putting together a parallel computer that has a space-filling and reconfigurable geometry.

As of this writing, several ART/TR robots have been assembled from 3rd-generation struts, including most recently, a 12-TET, see Figure 10. All of the nonbehavioral requirements for a 3rd-generation 12-TET mentioned above have been met except for the 60 pound mass goal: the 12-TET as-built weighs in at just over 90 pounds. Full motion trials for the current generation 12-TET have begun, starting with simple reconfigurations that change the robots shape, but do not necessarily show mobility. In December 2006, we demonstrated mobility by a simple open-loop commanded step of the 12-TET.

We are being exceptionally careful during these trials with the 3rd-generation 12-TET, principally because the plastic parts generated via stereo lithography (SL) have proved more brittle than expected. This does not rule out SL for fabrication in the future, but does constrain material choice. Furthermore, we are learning that feedback adjustment of ART/TR behaviors is going to be very important for use in the field. The ART/TR structure tends to "settle" into configurations that differ from ideal "sticks & nodes" models from which kinematic commands are most easily generated. Incorporating sensor feedback into our ART/TR control is a natural next-step beyond kinematic open-loop commanding, and we believe that this will help the system deal with such non-ideal aspects. Though for flat or sloping terrain such feedback may not be necessary, it will certainly be required

[1] ZigBee™ is a trademark of the ZigBee Alliance, Inc.

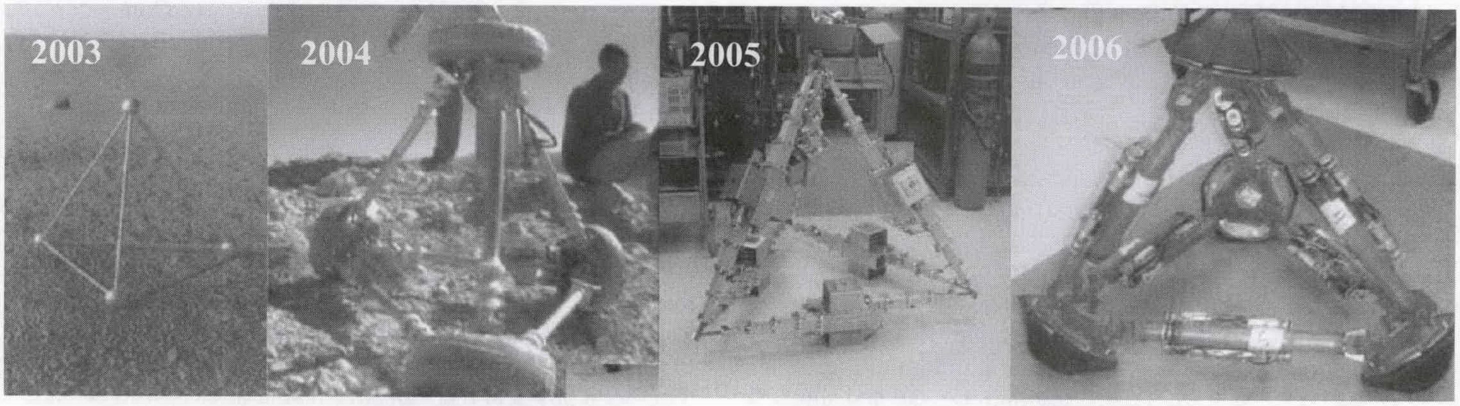

Fig. 12. The evolution of the most basic tetrahedral structure, the 1-TET, used for strut research and development. L to R: the notional concept, the first generation 1-TET in the field; Arnold, the 2nd-generation; the lighter 3rd-generation

to deal with more complicated terrains that require pressing against irregular features; for example, when climbing.

Currently we are working to close the control loop, to allow discrepancies between sensor data and that expected from the commands. This will allow the ART/TR robot to, for example, step on and go over a rock in its path by adjusting its gait. Such mobility is an important feature for the application of ART/TR in general and the 12-TET in particular to space exploration. We are studying ways to use the 12-TET as a vehicle to carry science instruments in crewed or un-crewed mission contexts. Even our current 3rd-generation 12-TET points out the possibility of providing mobile payload capacity at either central or corner nodes. The ART/TR architecture provides a unique capability to construct a wide variety of reconfigurable truss structures all constructed from the same fundamental strut and node elements, providing the possibility of a great deal of flexibility and functionality in an undifferentiated system.

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