



# Addressable Re-configurable Technology (ART) Tetrahedral Robotics at the NASA Goddard Space Flight Center

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# ART Development Team

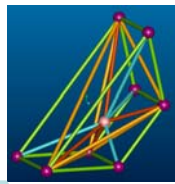


- **Goddard Space Flight Center**
  - **Solar System Exploration Division (Dr. Steve Curtis, PI)**
  - **Mechanical Systems Division**
  - **Instrument Systems and Technology Division**
  - **Electrical Engineering Division**
  - **Information Systems Division**
  - **Mission Engineering and Systems Analysis Division**
- **Ames & Langley Research Center**
- **Applied Research Laboratory**
- **Honeywell**
- **University of California, Berkeley, Center Of Integrated Nanomechanical Systems (COINS)**
- **Hope College and Mercer University**





# What is ART?



ART stands for Addressable Reconfigurable Technology(NASA GSFC Patent):

- ART is a class of system architecture.
- ART systems use a minimum of differentiated components.
- The differentiated components of an ART system are addressable.
- ART systems architecture supports “self-healing”.
- ART systems are inherently modular and redundant.
- ART development is evolutionary; can exploit and absorb new revolutionary technologies. A strategic approach.
- ART is the same architecture at different scales.
- ART is a *path* for the development of robotics



1st Generation: 30 in



2nd Generation: 9 ft



Fully Compressed

3rd Generation: 4 ft







X Generation: 1 cm  
UC Berkeley Micro-insect  
shown for scale





# What do ART Robots look like?

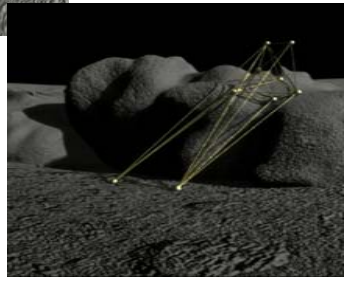
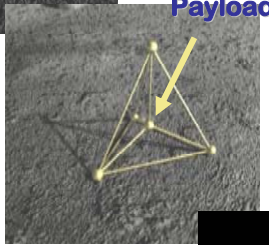
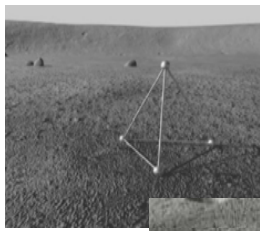
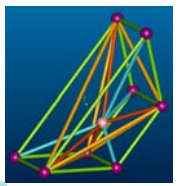


- Individually addressable “struts” and “nodes”.
- Arranged into tetrahedral forms.
- Scale from huge to nanoscale
- Increase degrees-of-freedom by increasing the number of reconfigurable elements
  - 1-Tet, 
  - 4-Tet, 
  - 12-Tet, 
  - more than 200 Tets (Worms or Arms), 
  - swarms!
- Evolvable Neural Interface - NASA Patent
- Addressable Reconfigurable Technology(ART) - NASA Patent

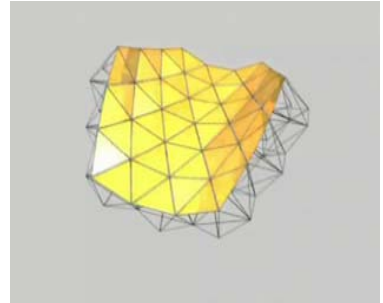




# Some ART Robotic Concepts



QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.



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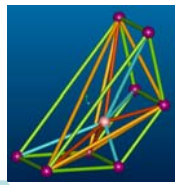
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- Increasingly complex ART-based structures are possible with advanced technologies



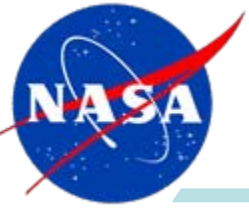


# Why ART technology?



- Ubiquitous” computing and robotics are the future.
- Evolutionary development path rather than “one-of” development.  
Efficient. Feasible.
- Complexity will make systems simple in the future.
- ART robotic systems can emulate or incorporate “traditional” technologies.
- Centralized or distributed control, with or without autonomy.
- High level “planning” AI interfaces to low level “autonomic” via a Evolvable Neural Interface(NASA GSFC Patent)
- ART is applicable over wide scales of size and distribution.





# What can ART do?



## Mars Animation

QuickTime™ and a  
Sorenson Video 3 decompressor  
are needed to see this picture.

Field test at “the crater”  
In September 2005

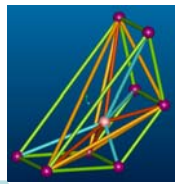
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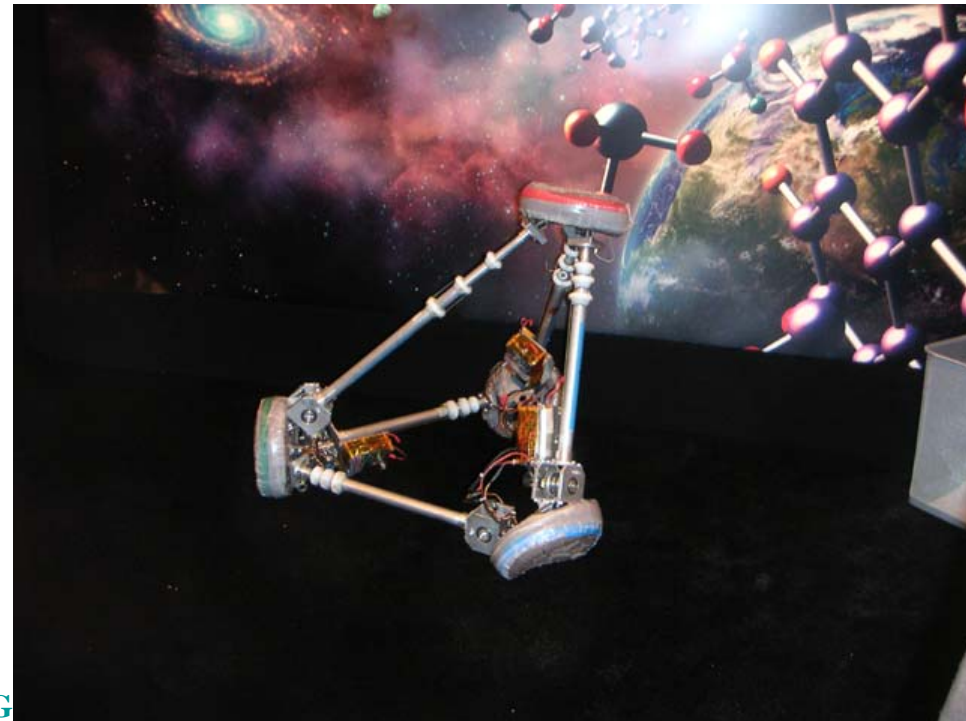
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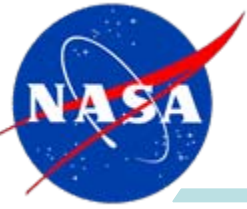


# 1<sup>st</sup> Build: The 1-TET

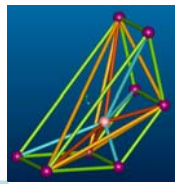


- 6 Struts forming single-cell mechanism with a flopping gait
- Nested aluminum tubes with nylon top & bottom pieces
- String-pulley actuation using kevlar fishing line
- Hobby shop motors with chopper wheel & opto-coupler for incremental encoder
- Universal joints on a plate surrounded by pipe foam for a node
- Struts had a net ~2:1 compression ratio
- COTS development kit electronics on proto-boards
- Programmed stepping sequence, performed open loop by rote
- Built the summer of 2004, the 1-TET has its difficulties, but has been successfully demonstrated world-wide since then

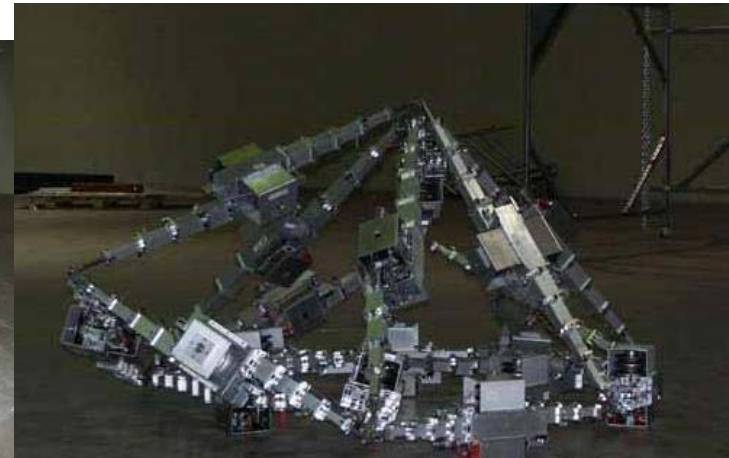
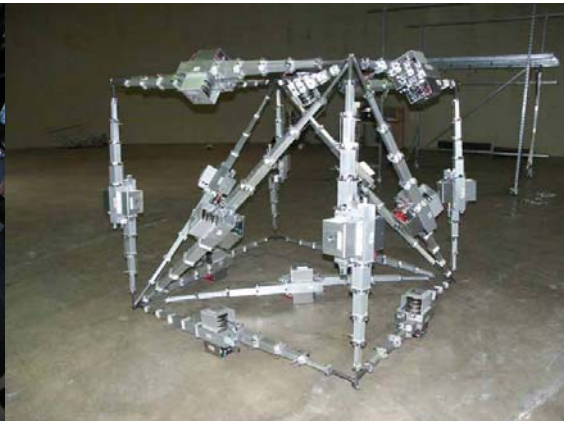
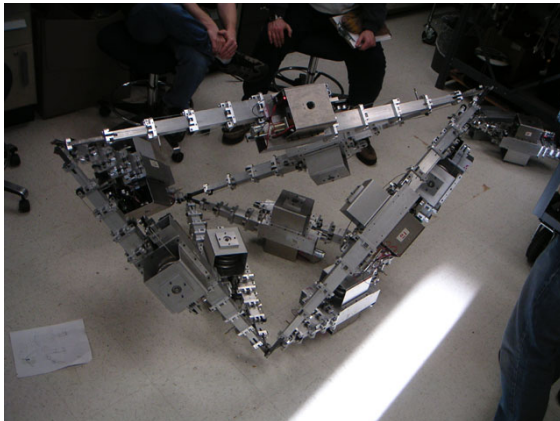
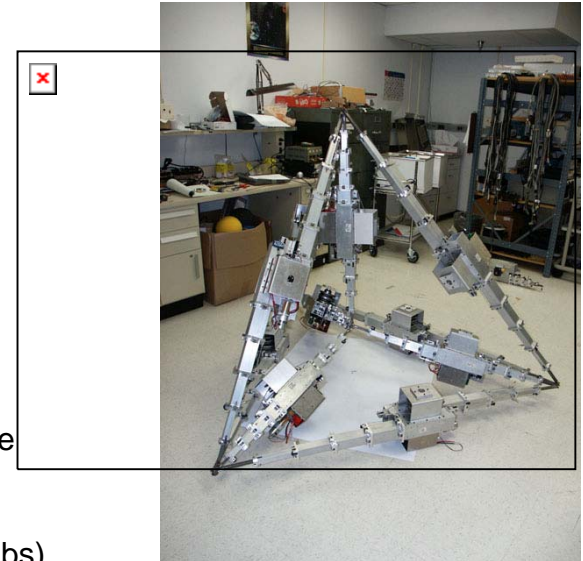




# 2<sup>nd</sup> Build: Large 12-TET

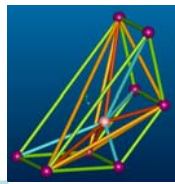


- 26 Struts forming a shape-shifting, walking cubic structure
- Nested aluminum square tubes with roller bearings
- String-pulley actuation using steel cable
- Powerful motor with planetary gearhead and worm gear
- Potentiometer to provide absolute measure of length by knowing pulley location
- Virtual nodes created by tying wire loops together in a tight cluster
- Struts designed for 5:1 achieved a net 4:1 compression ratio
- Custom electronics board on each strut created similar, addressable architecture
- Created a user-friendly computer interface with graphical representations
- Developed several intricate walking gaits – possible to walk without flopping
- However, struts were overly heavy and had difficulty supporting its weight (740 lbs)
- Uncertainty in length knowledge due to system “slop” made maneuvering difficult
- Built the summer of 2005, the TET struts, configurations, and shapes have been demonstrated widely





# 3<sup>rd</sup> Build: Lightweight 12-Tet



- 26 Struts forming a shape-shifting, walking cubic structure
- Completed fabrication and assembly of a 92-lb 12-TET that carries science payloads (~2 lb) in the central node.
- Other external nodes can also accommodate sensors and instruments .
- Struts use nested screws with exoskeleton for actuation (5.3:1 compression ratio).
- Developed dynamic simulations to choreograph TET motions.
- Cross directorate collaboration involving all divisions of AETD.
- 12 TET must take complex shapes and climb 40° slope
- Must be remotely controlled
- Each strut must maintain commandable length and provide enough telemetry for central computer to generate gait profiles
- Struts fully deploy or contract in less than 10 secs

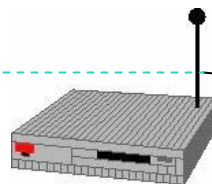
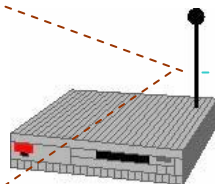
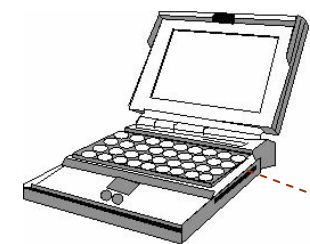
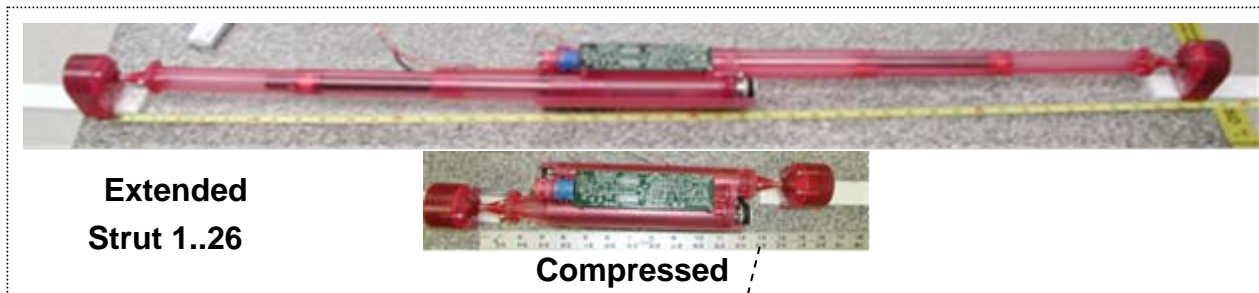




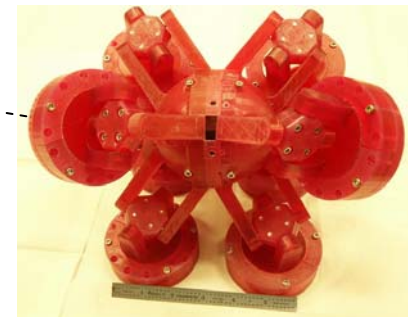
# ART in the Nutshell



**A revolutionary architecture for robotics...**



Zigbee  
IEEE  
802.15.4



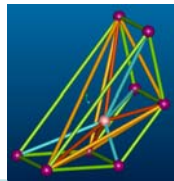
**A 3rd generation 12-Tet designed and fabricated in 2006!**



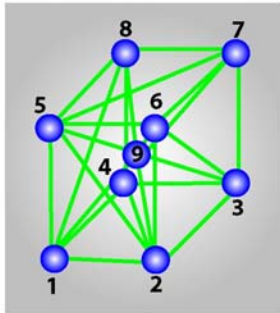
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# 12-TET Walker Geometry



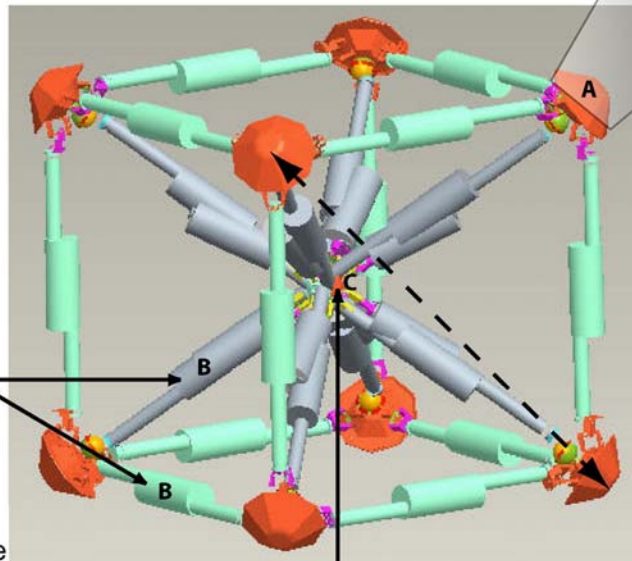
12-TET Schematic



Overall schematic of a 12-Tet. Note that the diagonal struts (dashed arrow) have been omitted for clarity in the center figure. **A:** Picture of the interior and exterior of an outer node. **B:** Picture of compressed third generation strut with motor. Each strut has its own battery and control electronics with Zigbee wireless control. **Lower right:** Pictures of the interior and exterior of the central node.



12 - TET



C: Picture of the interior and exterior of the central node.



Above is an example of a third generation strut. The cover is taken off to show battery and control electronics.

To the right is our central node. It will carry up to a one kilogram payload. The metal ruler measures six inches to scale.



Pictures of the first generation 1-Tet, and third generation 1 Tet. The first generation 1-Tet, constructed from hobby parts, is shown negotiating

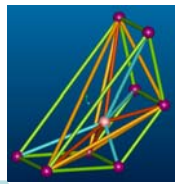
**First Generation 1-TET** a 15% grade at the Arizona meteor crater in September 2005, as part of the Jason expedition. An ([www.jason.org](http://www.jason.org)) educational project.



Third Generation 1-TET



# Mechanical Strut Design Strategy

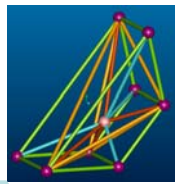


- Various trade studies performed, based on experience with previous builds
- Geometry: Double sided strut expanding in 2 directions
  - Improves compression ratio with fewer segments
  - Reduces crowding at the nodes to take complex shapes
- Actuation: Nested screws with exoskeleton
  - Screws resist backdrive, reduce play, are more robust than cables
  - Exoskeleton takes bending loads and protects from contamination
  - Others have tried screw-struts, but not achieved much more than 3:1
- Node: Cluster of 2-DOF and 3-DOF joints that TET walks on
  - Walking on nodes takes weight onus off of struts
  - Joint choices strike balance between node rigidity and node freedom
  - Provides rigid relation between points to improve knowledge & control

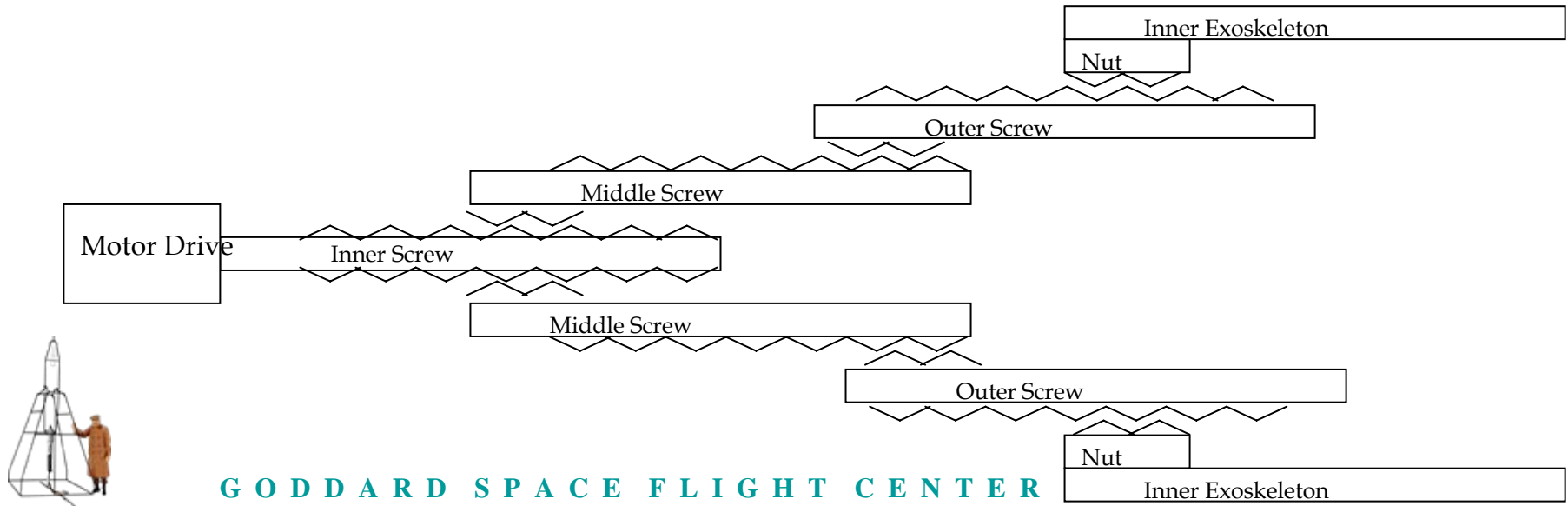




# Screw Design

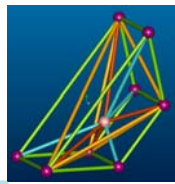


- Exoskeleton can not spin, which keeps the last nut from spinning, which makes the system progress linearly when the motor spins the inner screw
- Nominally available screw sizes of  $\frac{1}{4}$ " ,  $\frac{1}{2}$ " , and  $\frac{3}{4}$ " selected early on to get effort moving when finding custom screws proved very difficult, very expensive and very long lead time
- Aluminum screws chosen over steel: 65% less weight, plenty of strength
- McMaster Carr lubrication sprayed on all screws





# Exoskeleton Design

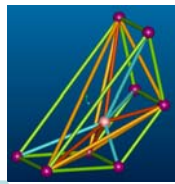


- Exoskeleton is three segments that extend from each side of main body and totally encase screws
  - Segments are keyed so they cannot turn
  - Stoppers & end caps keep segments from extending out of or falling into each other
  - Provides Contamination shielding
  - Protect struts during potential collision
  - Take bending loads to keep screws from binding
- SLA red material chosen over aluminum/composite tubes:
  - Relatively inexpensive to create and rapidly available
  - 57% lighter than aluminum
  - Relatively low friction (~.1)
  - Features can be built right in to minimize assembly
- Post-build sanding needed so that .002"-gap tubes slide smoothly within each other
  - Separate bearings rejected because incorporating them would have increased size, weight, cost, and complexity dramatically

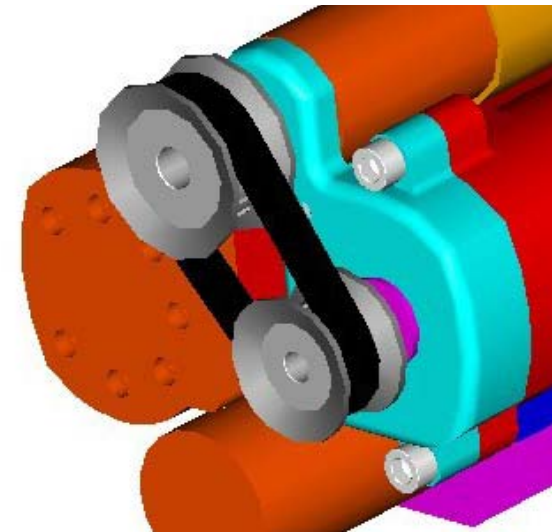




# Drive Train Design

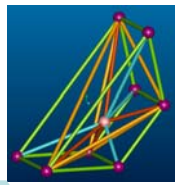


- Two motors selected versus one motor
  - Motor needed to be small  $<.97$ " diameter to fit within desired envelope, was easier w/  $\frac{1}{2}$  capability
  - Eliminates complicated drive train and beefy support for all mounts
  - Two motors allow flexibility to shift strut CG if that is desired for gaits
- Major challenge was preventing back-drive
  - Screws (4 threads per inch) do backdrive under heavy load
  - Worms gears and brakes were heavy, complicated, expensive, and had long lead time
  - Testing conducted on strut demo found that standard planetary gearboxes could resist more backdrive than our worst-case load resulted in
  
- Motor mounted coaxial with strut and on top of main "double" central housing
- Nook pulleys and  $\frac{1}{4}$ "-wide Nook belts mounted on motor shaft provide 1.30 : 1 mechanical advantage
- Light blue mount captures 2 ball bearings to hold screw and motor to housing





# Strut Packaging

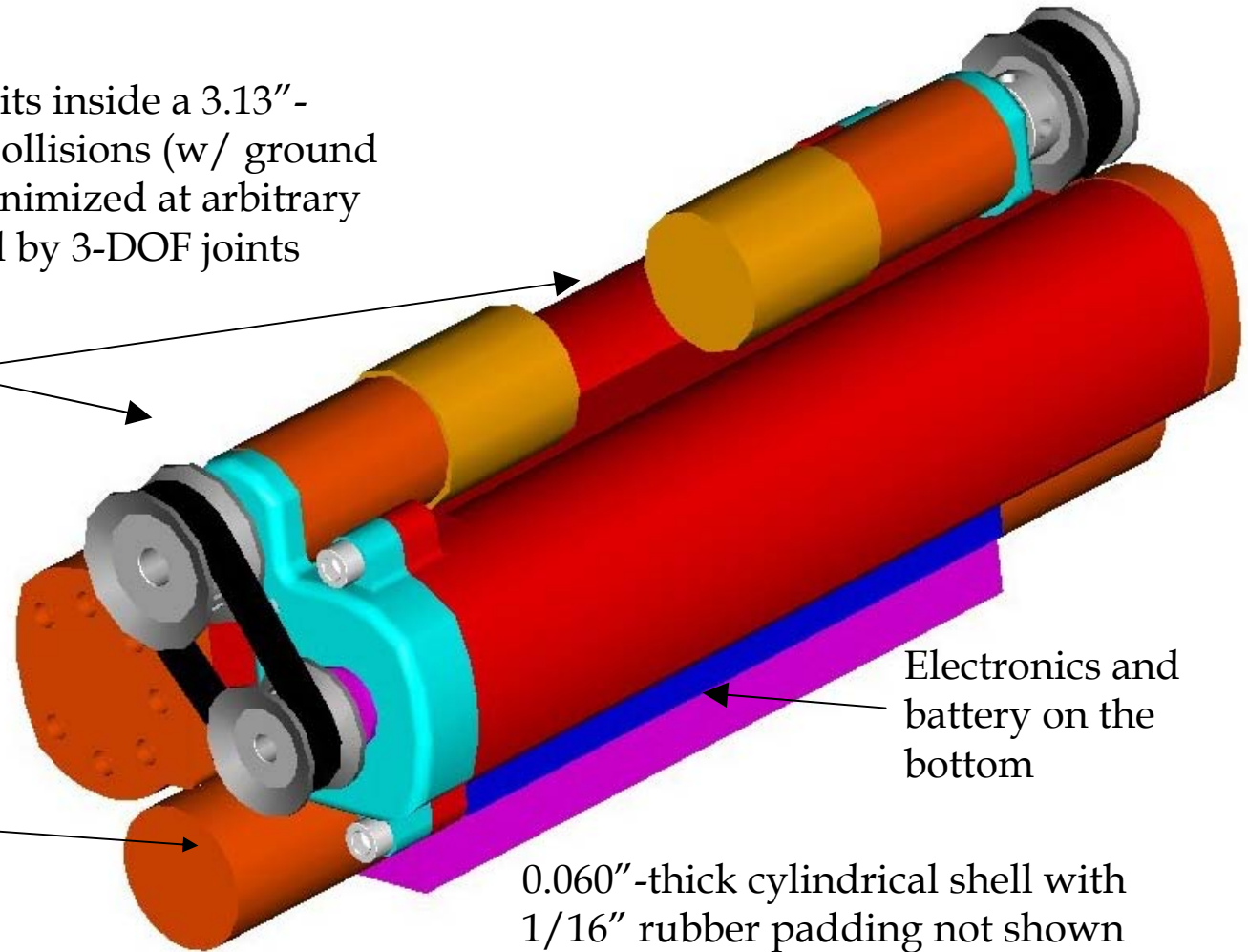


Entire strut packaging fits inside a 3.13"-diameter circle so that collisions (w/ ground and other struts) are minimized at arbitrary clocking angles allowed by 3-DOF joints

Two motors with gearboxes on the top

Two halves of strut are offset optimally to minimize compressed length

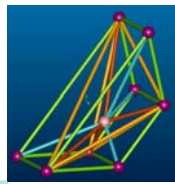
Have designed string pull-pots smaller (1" diameter, 1.5" long) than smallest pull pots commercially available



Electronics and battery on the bottom

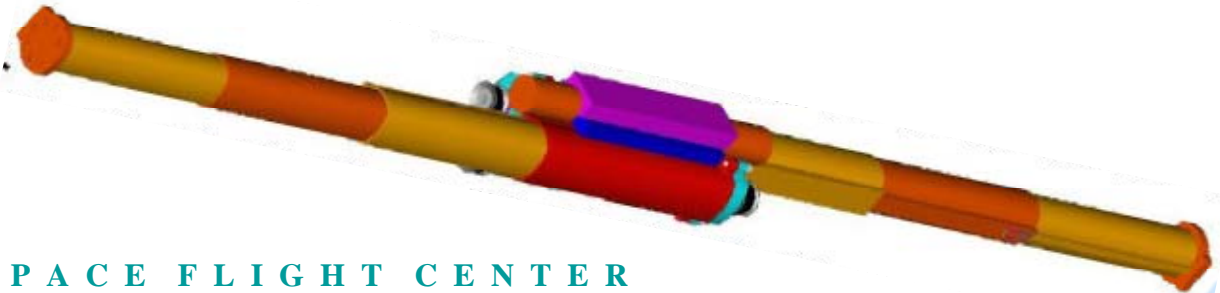
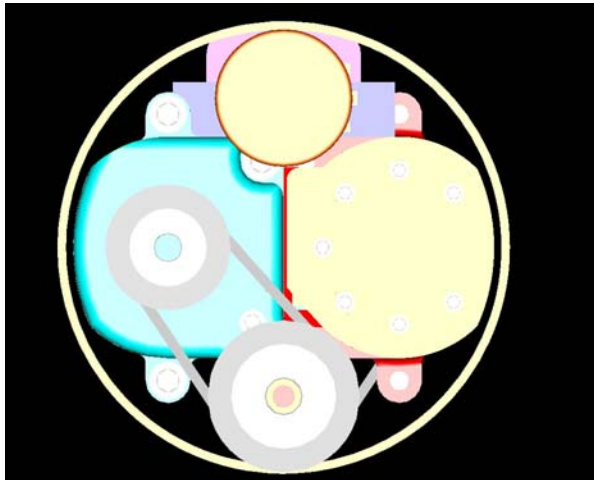
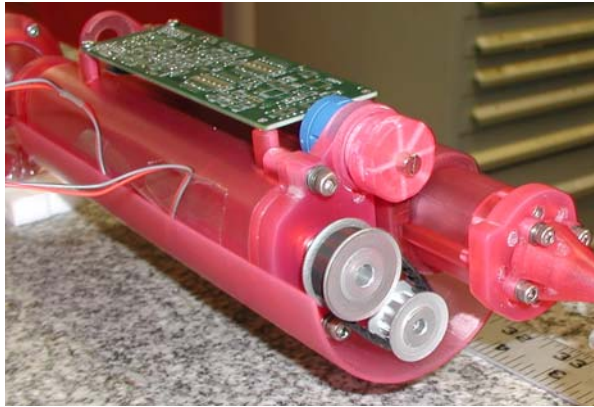
0.060"-thick cylindrical shell with 1/16" rubber padding not shown





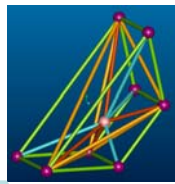
# As-Built Strut Characteristics

- Measurements on first complete strut:
  - Initial length = 8.36"
  - Extended length = 44.26" (Ratio is 5.29 : 1)
  - Diameter of strut = 3.25" (includes 1/8" rubber padding)
  - Mass of Strut = 2.62 lb
  - Vertical Deployment Speed and Strength Capability
    - Lifting Itself = 8s to go up, 8s to go down
    - Lifting itself + 7.5 lbs = 12s to go up, 8s to go down
    - Lifting itself + 11.3 lbs = 16s to go up, 12s to go down
    - Lifting itself + 14.0 lbs = 20s to go up, 12s to go down
    - Goal was to lift itself plus 4 struts (or  $2.62 \times 4 = 10.5$  lb)
  - Compression strength is at least 30 lb
  - Tensile strength is at least 18 lb
  - Battery Life for constant operation = 0.64 hr

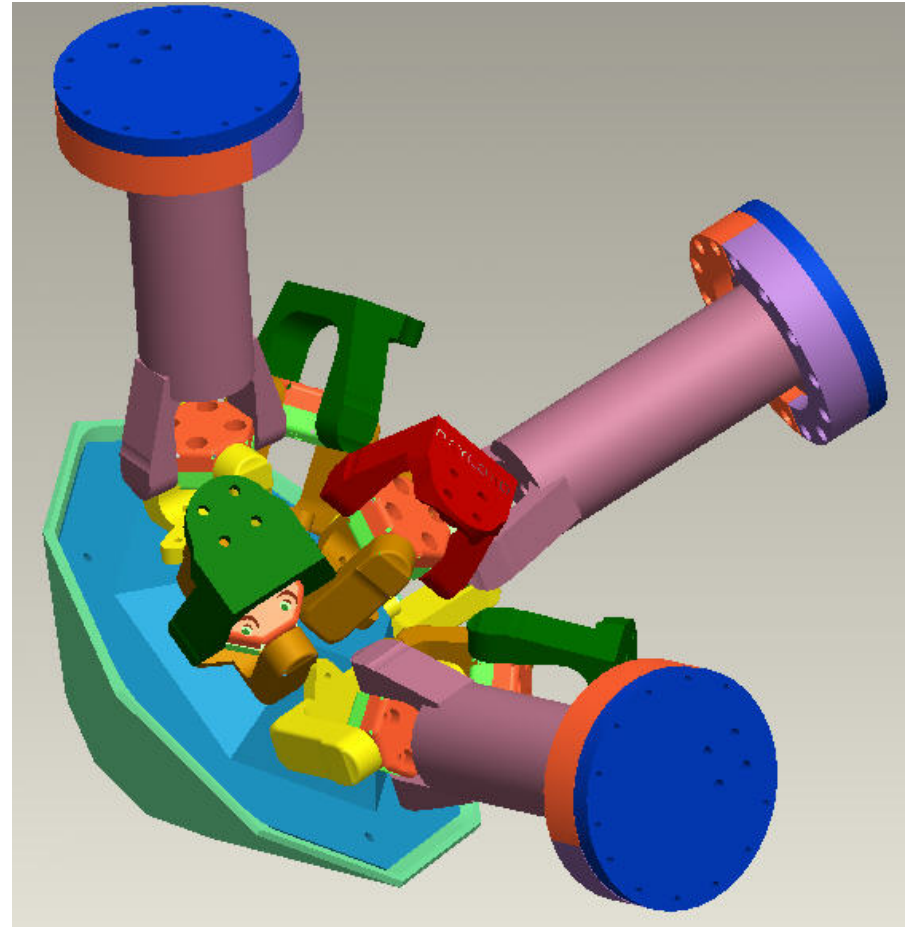




# Node Design

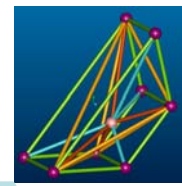


- Design Objectives
  - Provide feet for TET to walk on and assure struts stay off ground
  - Allow all struts to maneuver as much as possible (by providing large conical sweep and minimizing collisions)
  - Minimize TET mobility (or play in the nodes) when struts are not changing length
  - Maximize TET mobility when struts are changing length
  - Minimize node size to maximize effectiveness of strut expansion ratio and minimize overall size
  - Allow diagonal and side struts to be the same size (use extenders)
  - Had to determine if best to center end of offset strut, or offset it
  - Allow space in center for extra “payload” or future electronics

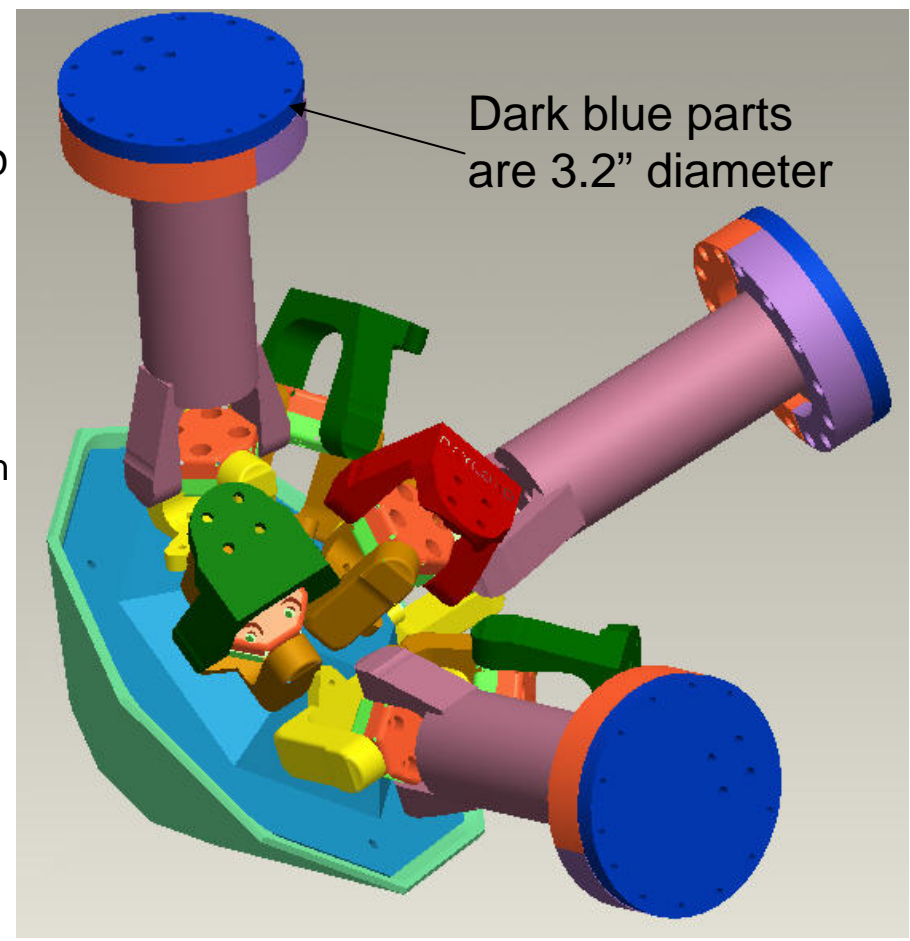




# Node Design

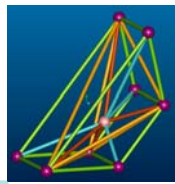


- Nodes on ground made stable by having them on 1 of 9 flat facets
  - Each facet coated with rubber for shock absorption and high friction
- With footprint rigid, could use Gruebler's 3-D Mobility Equation to determine mobility of 12-TET
  - Made all side struts have universal joints (2-DOF) on each side and all diagonal struts have universal-w/-clocking-revolute joints (3-DOF) on each side
  - This configuration eliminates play when struts fixed and allows full mobility when struts moving
- 10-degree angle allowed between neighboring 3.25"-diameter struts
- Joints can move > 74-deg cone
- Strut ground clearance is 0.3"
- Struts are colinearized at joint

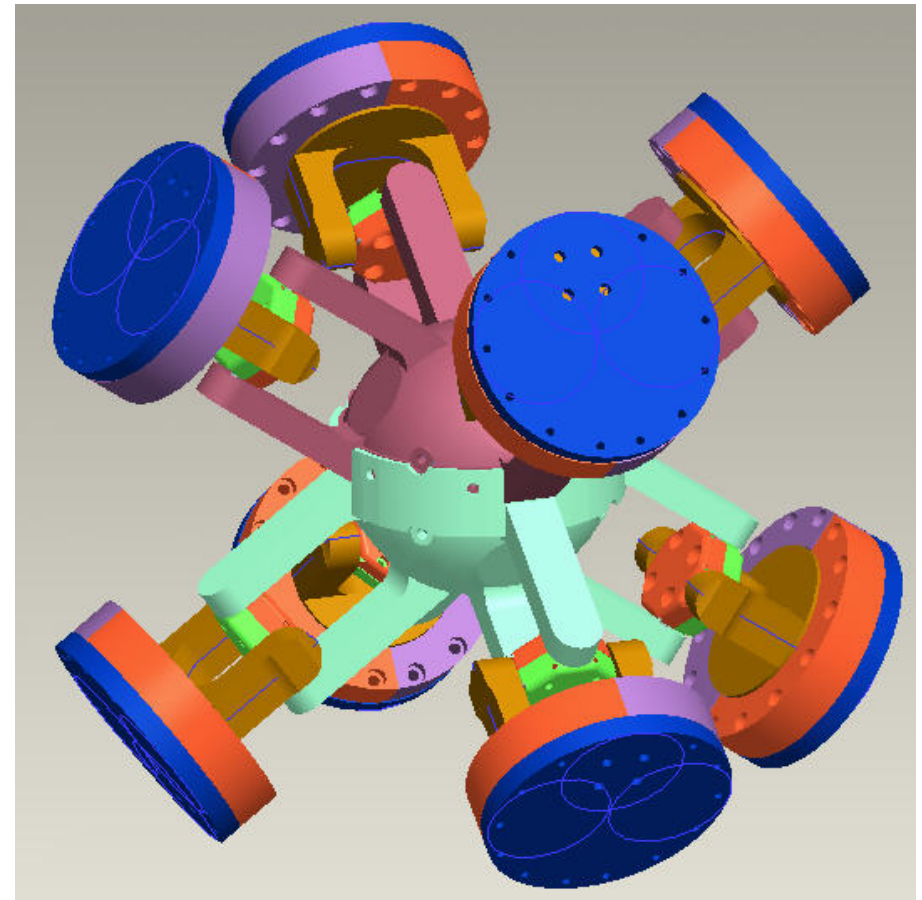




# Payload Design

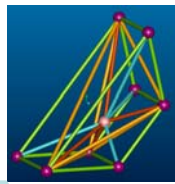


- Payload Design Objectives
  - Carry 1kg “science” payload
  - Allow payload struts to “wrap past” so all struts same size
  - Eliminate TET play when struts fixed and allow TET full mobility when struts moving
- Gruebler’s 3-D Mobility Equation showed four 2-DOF and four 3-DOF joints needed
  - Will use all short hybrid joints with option to pin revolute part in place when 2-DOF needed
- Made payload small enough so that 74-deg strut angle provided sufficient wrapping for all struts to be the same

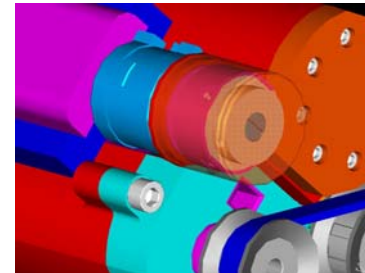




# Strut Design Strategy (Electrical)



- Central computer does all the “thinking” and commands strut lengths vs time then issues a universal “GO” command
- Working on fast strut-to-strut communications
- Microchip PIC 18LF6627 microcontroller with on board memory, A/D channels, PWM Channels, UART
- ZigBee communications in broadcast mode replaces Bluetooth multiple, synched 1-to-1 channels
- 2 motor drivers – can move both sides together or independently to shift c.g. of strut if necessary
- 3-Axis accelerometer to measure strut inclination
- String potentiometers for more absolute knowledge of the length of each side of the strut
- Battery level measurement & auto shutoff to save LiPo batteries
- 2 Force gauges to measure tension/compression forces
- Board temperature sensor to possibly update calibrations vs temperature





# Duty Cycle Estimate using Solar Arrays



Case

Battery Type	Battery Capacity	Voltage	Max. DOD	Max. Strut Dia.	Max. Strut Dia.	Length	Length	Cylinder Area	Mean Inc. Factor	Atmos. Factor	Solar Cell Type	Solar Insulation	Where ?	Solar Cell Eff. BOL	Solar Cell Eff. EOL	Single Strut Array Power (BOL)	12-Tet Array Power (BOL)	Single Strut Array Power (EOL)	12-Tet Array Power	Charge Time Estimate (BOL)	Charge Time Estimate (EOL)	12-Tet Operating Time	12-Tet Duty Cycle	
	mA-hr	Voltage	%	in	cm	in	cm	cm <sup>2</sup>	%	%		W/m <sup>2</sup>		%	%	W	W	W	W	hr	hr	hr	%	
Worst	LiPro	2200	7.4	25	3.13	7.95	6.98	17.7	348.67	35	80	GaAs	1358	Earth	12	5	1.59	41.4	0.66	17.2	9.303	22.33	2	8.958
Worst	LiPro	2200	7.4	25	3.13	9.67	6.98	17.7	424.09	35	80	GaAs	1358	Earth	12	5	1.94	50.3	0.81	21	7.648	18.36	2	10.9
Nominal	LiPro	2200	7.4	25	3.13	7.95	6.98	17.7	348.67	35	80	GaAs	1358	Earth	18	7	2.39	62	0.93	24.1	6.202	15.95	2	12.54
Nominal	LiPro	2200	7.4	25	3.13	9.67	6.98	17.7	424.09	35	80	GaAs	1358	Earth	18	7	2.9	75.5	1.13	29.3	5.099	13.11	2	15.25
Optimistic	LiPro	2200	7.4	25	3.13	7.95	6.98	17.7	348.67	35	80	GaAs	1358	Earth	26	10	3.45	89.6	1.33	34.5	4.294	11.16	2	17.92
Optimistic	LiPro	2200	7.4	25	3.13	9.67	6.98	17.7	424.09	35	80	GaAs	1358	Earth	26	10	4.19	109	1.61	41.9	3.53	9.178	2	21.79
Theoretical max	LiPro	2200	7.4	25	3.13	7.95	6.98	17.7	348.67	35	80	GaAs	1358	Earth	34	13	4.51	117	1.72	44.8	3.283	8.587	2	23.29
Theoretical max	LiPro	2200	7.4	25	3.13	9.67	6.98	17.7	424.09	35	80	GaAs	1358	Earth	34	13	5.48	143	2.1	54.5	2.699	7.06	2	28.33

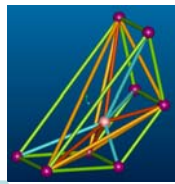
- About 2 A into a charger charges a 2200 mA-hr LiPro in one hour.  
Time in hours=(Battery Capacity)\*2\*Voltage/(2200\*(Single Strut Array Power))
- For a cylinder, power should have a pi/4 factor. Assume only half the struts are at pi/2 lengthwise at a time.  
79%/2=35%
- 2200 mA-hr buys 2 hr operating time.

On the moon, using GaAs flexible solar arrays, a duty cycle > 10% should be possible during the 27 earth-day lunar day. They are not practical for earth.



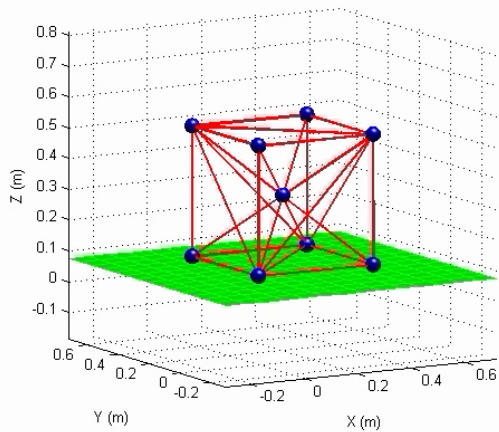


# 12-TET Simulation and Gait Development

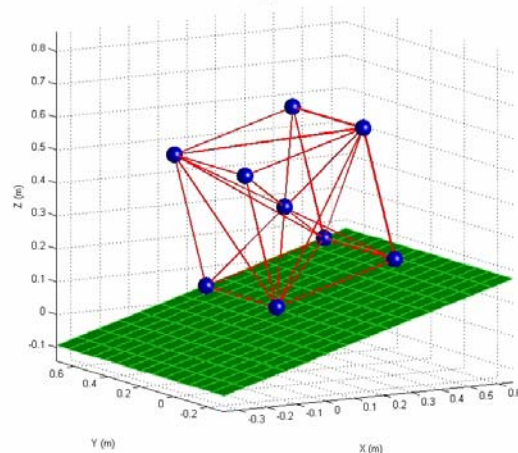


- Visiting professor, Dr. Miguel Abrahantes, and interns developed a detailed dynamic model of 12-TET using MATLAB/SimMechanics
- Incorporates strut mass, length control, correct number of segments, friction, gravity, and many other linear & nonlinear parameters
- Investigated and simulated various gaits with simplified control
- Will be a valuable tool as intelligent control algorithms progress

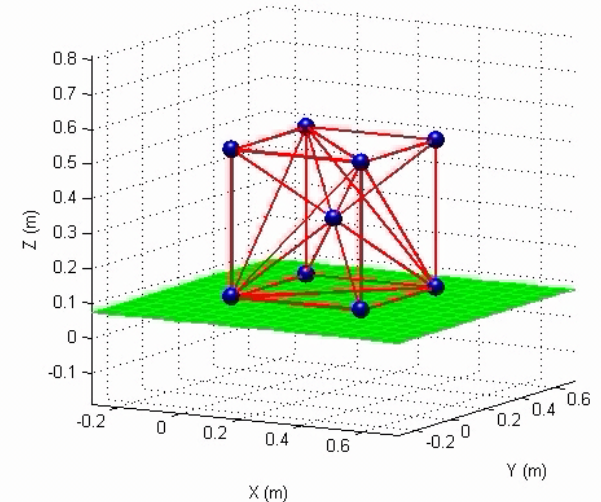
12 TET @ t = 0.00 sec



12 TET @ t = 0.00 sec

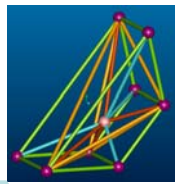


12 TET @ t = 0.00 sec





# Strut Control & Synchronization



- Visiting professor, Dr. Philip Olivier, and interns developed a Decentralized Adaptive Controller (DAC) for strut control.
  - Homyoun Seraji, “Decentralized Adaptive Control of Manipulators: Theory, Simulation, and experimentation”, IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, Vol. 5, No 2 April 1989.
  - Performed Lagrangian analysis to demonstrate that Tet Equations of Motion are consistent with application of DAC to struts.
  - Programmed DAC in C and performed resource analysis. DAC will consume about 13% of PIC processing and memory resources.
  - Worked with Dr. Abrahantes to develop and improve the 12-Tet tableau, and to develop simMechanics models of the 12-Tet.
  - Improved tracking performance under varying load without using computer processing and bandwidth intensive centralized robot dynamics.





# Technical Challenges

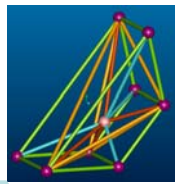


- Control System
  - Detailed motion simulations (simMechanics, Simulink)
  - Algorithm development (node location, motion planning)
  - Payload management
  - Autonomous operation, human interface and safety
  - Communications management
- Ruggedized components
  - Exoskeleton and node structure
  - Robustness with respect to impacts (rocks) and...
    - ...friction/wear due to grit
  - Mechanism reliability
- Power
  - Power management and control
  - Battery life and re-charge strategies (Solar cells)

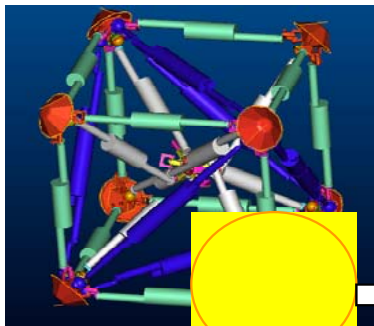




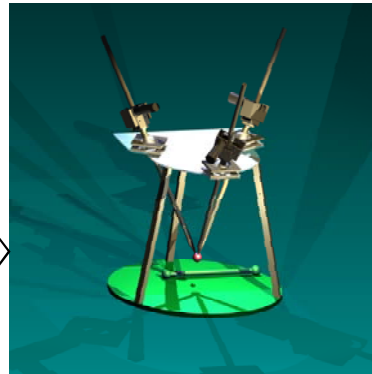
# Self-healing ART Structures



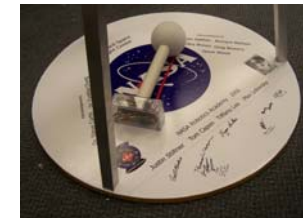
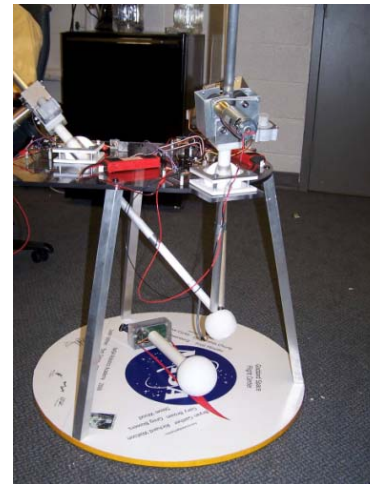
- Developed a hardware demonstration platform to show how a TET robot can search and find a loose strut using a 3-axis magnetometer.
- Successfully implemented closed-loop hardware control using Zigbee (IEEE 802.15.4) wireless communication protocol to synchronize strut actions in the search maneuvers.
- Collaborative effort between Robotics Academy interns, and 544 and 695 engineers.



Design

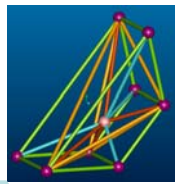


Self-Repair Demo Apparatus





# Worm Robots and Robot Arms



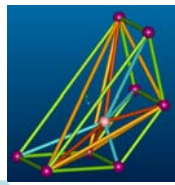
QuickTime™ and a  
H.264 decompressor  
are needed to see this picture.

QuickTime™ and a  
Sorenson Video 3 decompressor  
are needed to see this picture.





# Applications of ART: 2015-2020



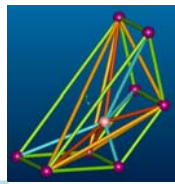
QuickTime™ and a  
Sorenson Video 3 decompressor  
are needed to see this picture.

- Swarms
- Spider class
- Mammalian class
- Large scale structures (solar sails)
- Reconfiguration





# Applications of ART beyond 2020



## Autonomous Nano Technology Swarm (ANTs) Mission

QuickTime™ and a  
Sorenson Video 3 decompressor  
are needed to see this picture.

## Lunar Amorphous Rover Antenna (LARA) Mission

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MPEG-4 Video decompressor  
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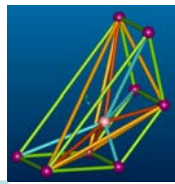




# High Accessibility Robotics

## Addressable Reconfigurable Technology (ART) Robotics

PI: Dr. Steven A. Curtis, Goddard Space Flight Center(GSFC)



### ART Robots are:

- made of nodes with struts that expand and contract,
- nodes and struts arranged in tetrahedrons, 1 to many,
- wirelessly controlled down to the component level,
- each component independently powered (no cables),
- able to move easily over rough terrain, climb boulders,
- able to climb up chimneys, span chasms,
- able to crawl through and under objects,
- inherently modular and redundant, self-healing,
- evolutionary, able to absorb emerging technology,
- implementable at all scales; nano- to 100's of meters,
- unary, or a swarm, all controlled from 1 central brain,
- best controlled using an *Synthetic Neural System*,
- a **class** of robotic system architecture,
- a path for future development of robotics.



< 1-Tet



< 12-Tet

High Mobility: Form follows Function		
Terrain	Operation	
Smooth, Low Relief	Roll	
Rugged, Low Relief	Climb over obstacles	
Cliff	Chimney up	
Crevasse	Bridge	
Opening	Flatten	
Repair	Strut Exchange	
Stow Grow	Change Size	

See mobility animations at <http://ants.gsfc.nasa.gov>

### Applications:

- access to areas inaccessible to other robot forms.
- swarms of robots for area reconnaissance.
- snake and more complex forms.
- payload carriers. Cameras and other sensors.
- Hitchhiker robots to supplement other systems.

URL: <http://ants.gsfc.nasa.gov>

### Collaborators:

Goddard Space Flight Center, Langley Research Center, JHU/Applied Physics Laboratory, Honeywell, University of California-Berkeley, Hope College, Mercer University

### Status:

- 1-Tet form designed, built and tested.
- 12-Tet form designed, built, and under test.
- MOU to be signed with UC Berkeley for 1cm tall 1-Tet > About the size of this insect mechanism by UC Berkeley
- *Synthetic Neural System* developed, to fly on ST-8 for in space test.



### Contact:

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[Cynthia.Y.Cheung@nasa.gov](mailto:Cynthia.Y.Cheung@nasa.gov)