Self-Transforming Robotic Planetary Explorers

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In the future, 10 to 40 Years, society will want robots to explore the planets, moons, asteroids and comets of the solar system, build robotic outposts and ultimately the infrastructure for human colonies.

Current Rovers-(2000 c.e.)

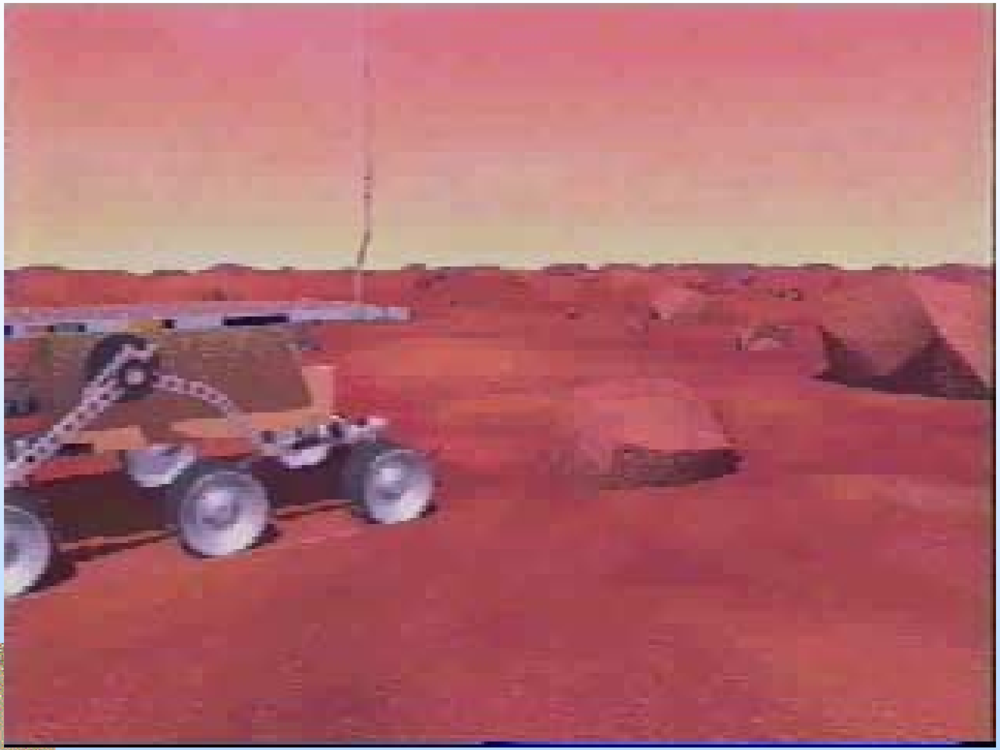
Todays Rovers Cannot:

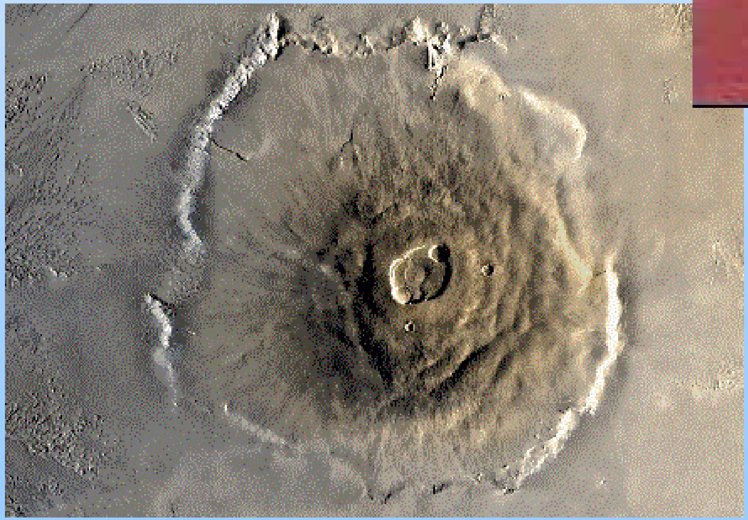
Traverse Varying Terrain Obstacles

Climb Steep Cliff Faces

Cross Wide Ravines and Canyons

Assemble Structures, For example: Fuel extraction as a precursor to HEDS missions



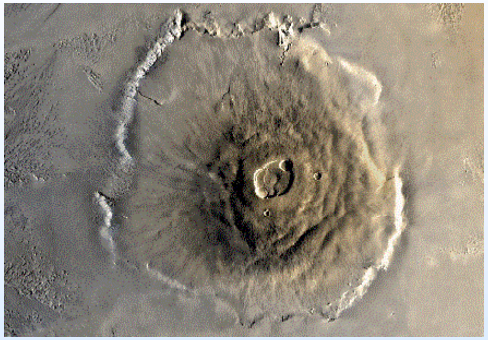


Peak Heights

Mars: Olympus Mons: 24,000 m

Earth: Mount Everest: $8,000^{+}$ m

The Future

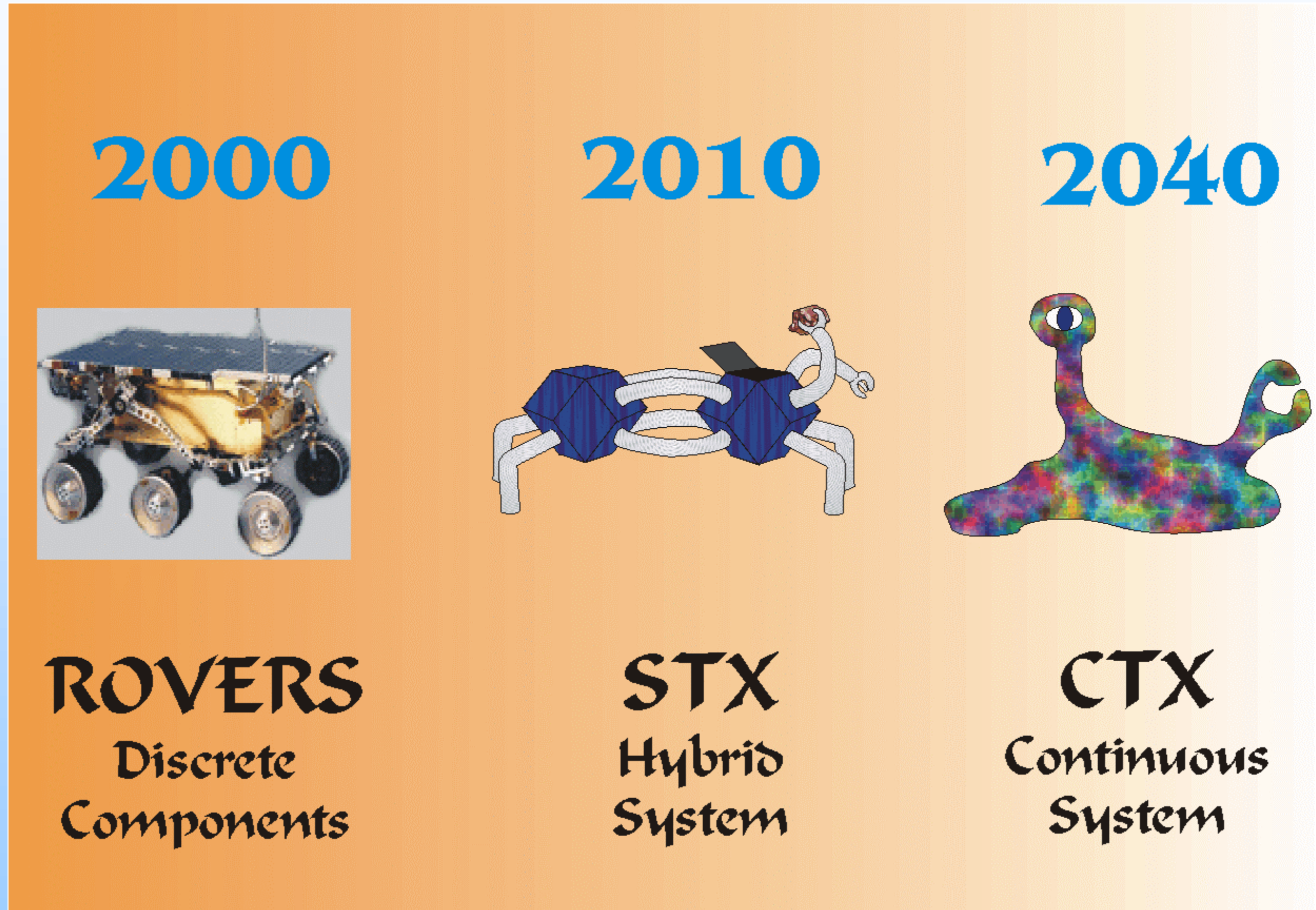


The current basic building blocks of robotic systems are not up to the challenges of the future.

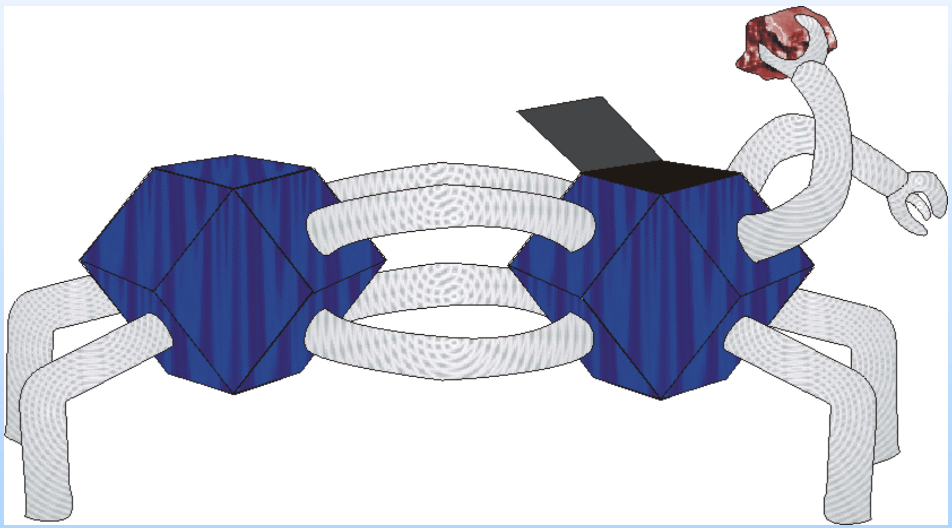
They are:			
	Unreliable	Expensive	Non-robust
	Complex	Heavy	Weak
	Inefficient	Etc...	

New Paradigms for the Design of Space Robotic Explorers and Workers are Needed.

Our Vision: A Progression of Self-Transforming Planetary Explorers and Workers



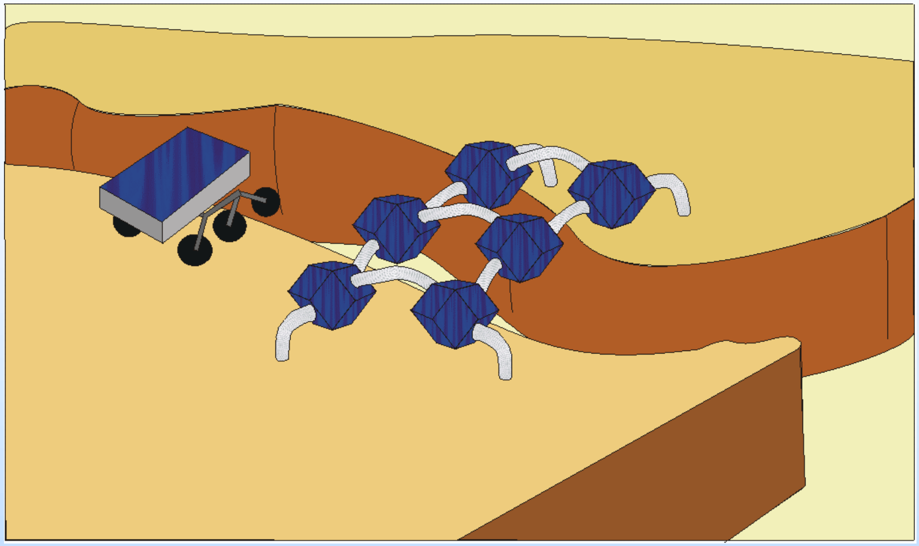
Self-Transforming Explorer/Worker Robot Concept (2010)

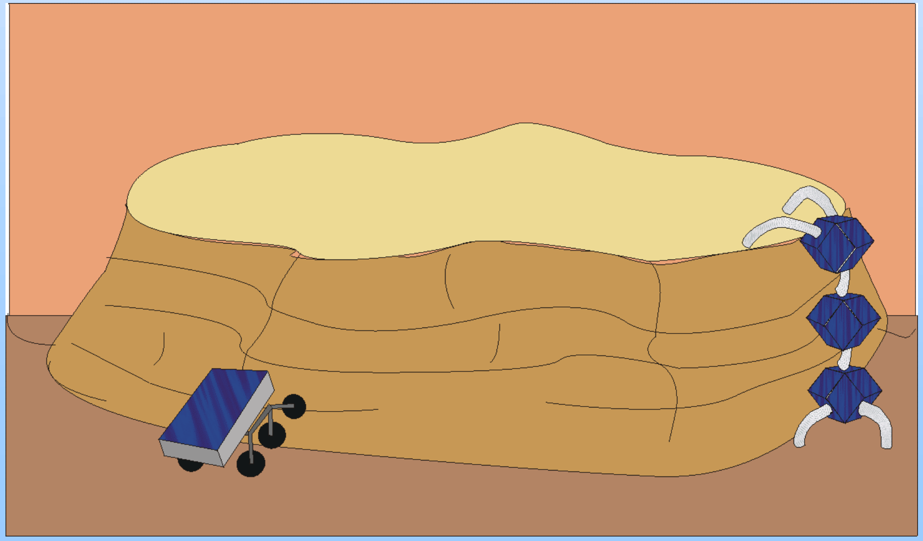


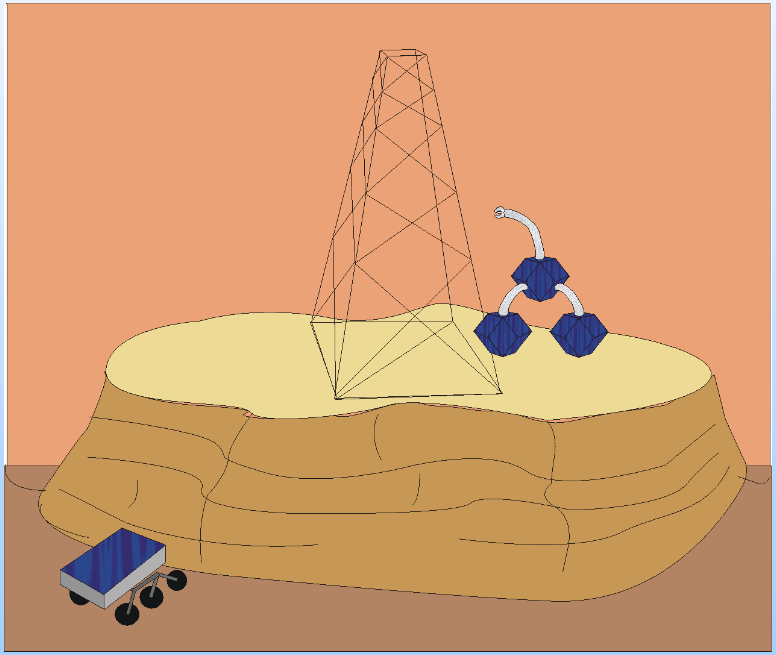
The STX c.2010

- Network of Node Elements
- Connected by Active Binary Elements (ABE's)

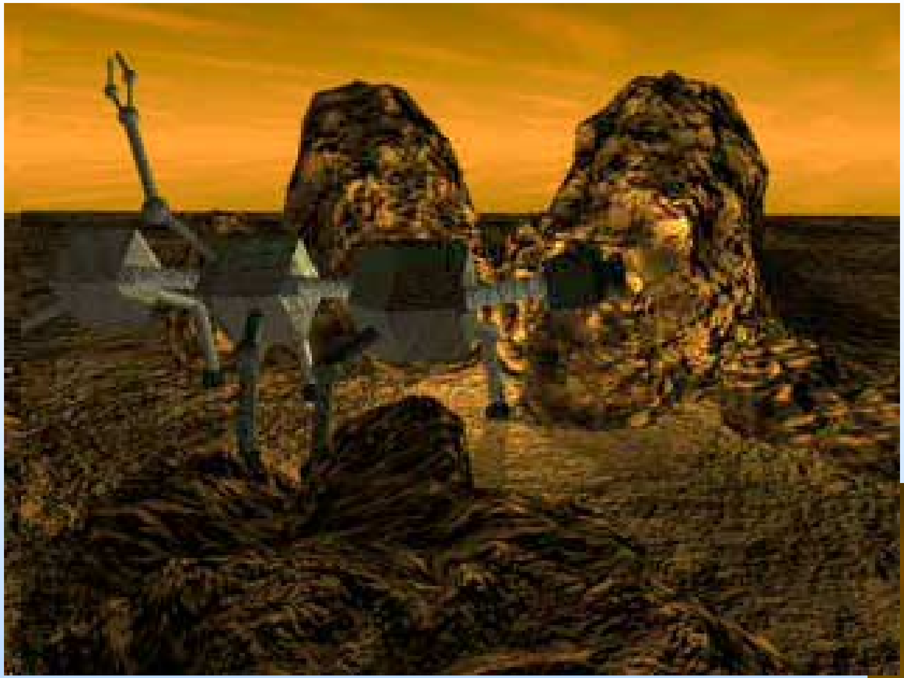
A Rover vs. The STX Self Transforming Explorer

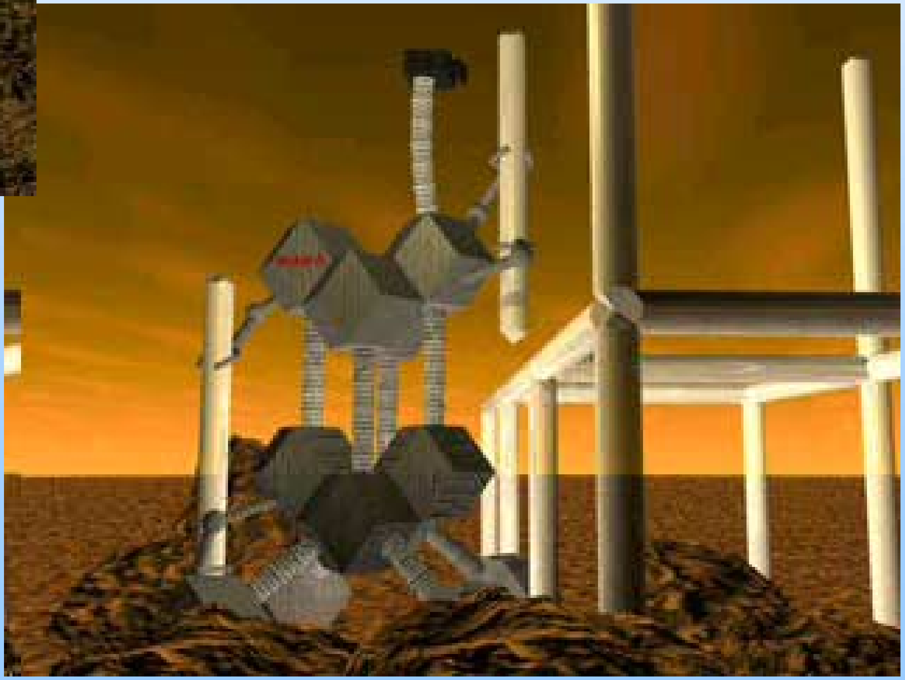






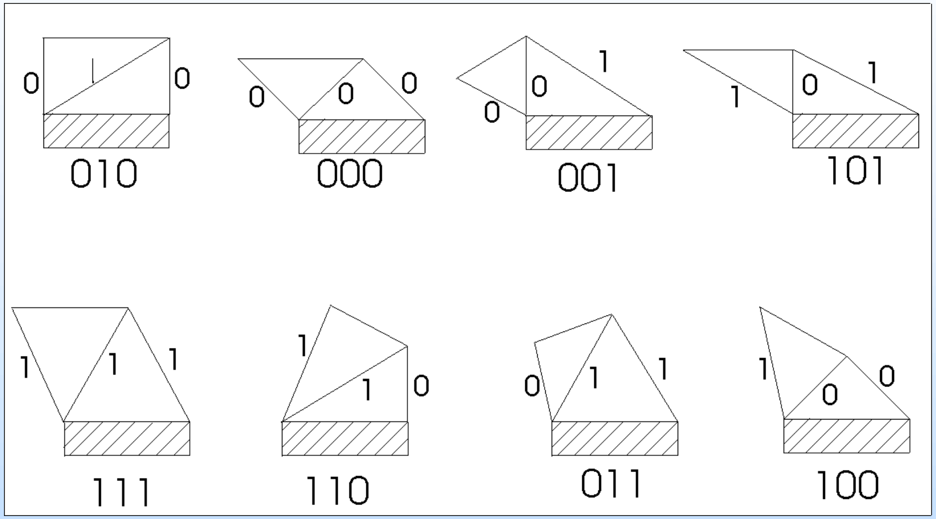
The STX Concept



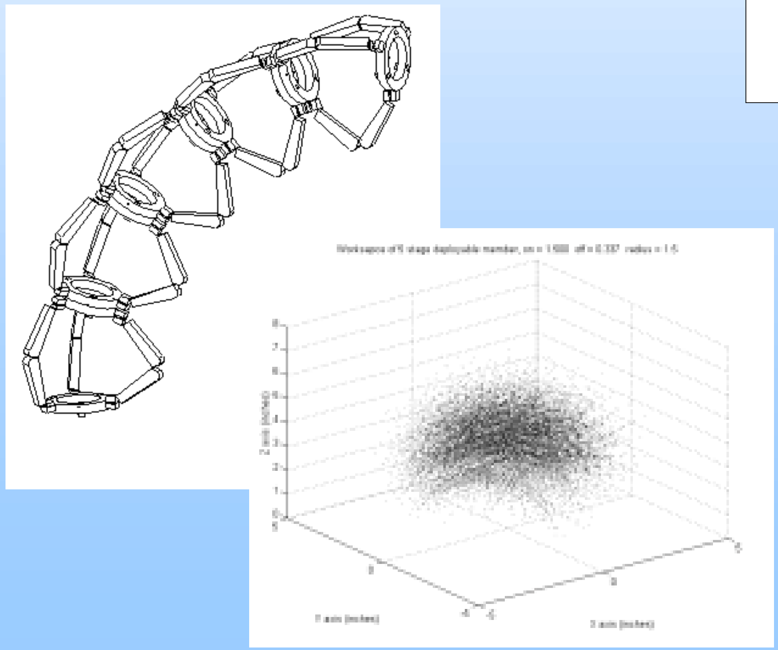


Binary or Digital Robotics -- A Key Element of STX

- Network of Flexible Members with Binary Embedded Actuators - (10^2 and $10^?$)
- Lightweight, simple and robust
- Fault-Tolerant



G. Chirikjian



Digital Computer Analogy

The NIAC Research Dilemma

The Dilemma:

NIAC research focuses on problems that may not have solutions for 10 to 40 years (2010 to 2040). It would not be expected for a NIAC project to demonstrate practical solutions now.

Our approach:

- In simulation, study the projected capabilities and limitations the system level concepts.
- By analysis and experiments bound the expected capabilities of the component technologies.

Phase II - Research Results
October 1999 to May 2000

Results Efforts and Results - Outline

- Simulation Studies
- Component Technologies
    - Binary Bi-Stable Devices for STX
    - Actuator Technologies-Conducting Polymers
    - Near Term Implementations of the Technology
    - Hyper-DOF Binary Devices - Step Toward CTX

Simulation Studies

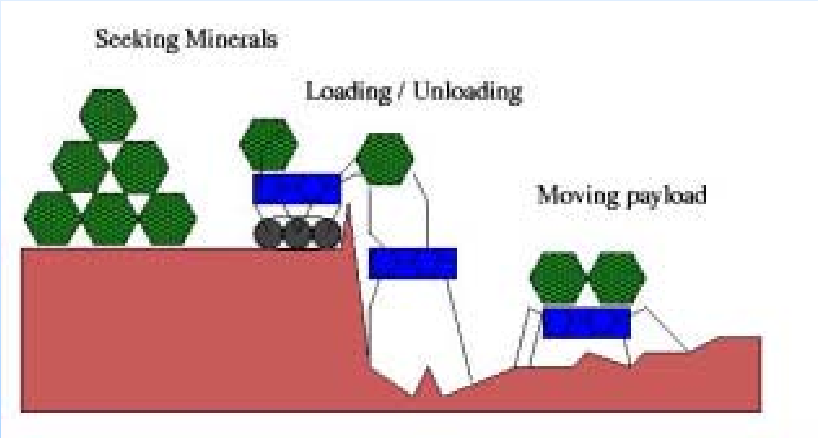
The “Dilemma” Makes Simulations a Key Element of Our Research.

Some Key Questions:

- Can binary systems perform useful task in complex planetary terrain?
- How many binary degrees-of-freedom are are required to achieve acceptable performance?
- How do you plan the behavior of these systems?

A Representative STX Robot Mission

Task: An Explorer re-configures into a Cooperative Robot Worker Crew to Construct a Resource Extraction Facility



Rough Terrain Explorer

Criteria: Accessibility
Speed
Power
Safety/Recovery, etc.

Material Transportation Worker

Criteria: Payload
Speed
Energy, etc.

Construction Worker

Criteria: Dexterity
Payload
Strength

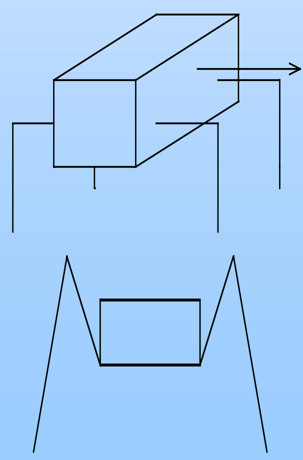
Etc…..

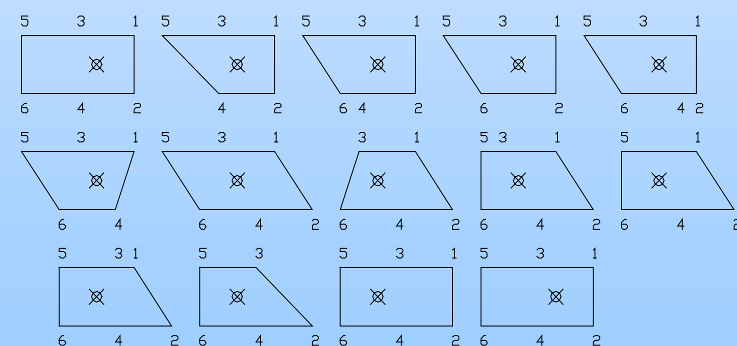
Initial Studies: Binary Gait (JHU)

JHU is studying

- Different configurations of simple legged binary robotic for mobility in benign terrain
- Methods to plan simple motions (walking, turning, etc) in benign terrain.

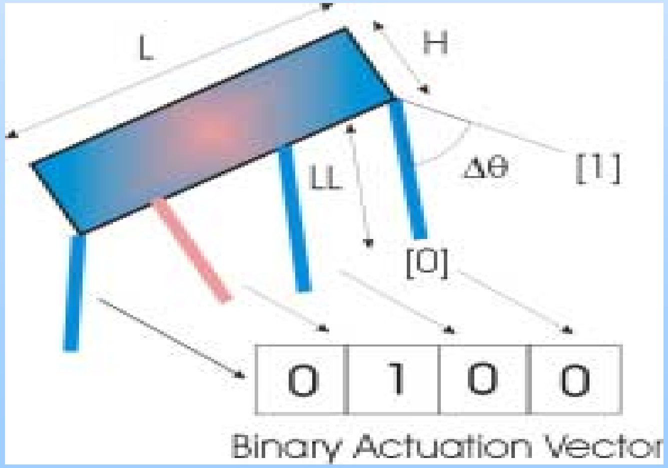
  - Gait
  - Kinematics
  - Statics
  - Etc.

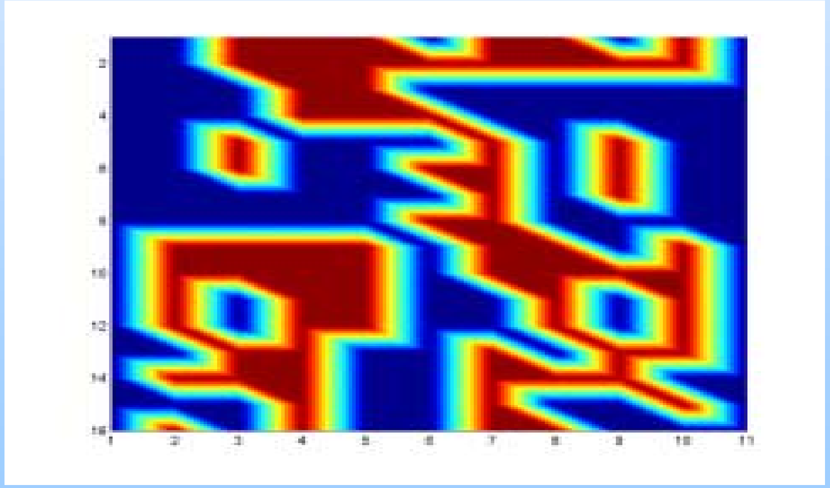




Initial Studies Rough Terrain Accessibility Studies-(MIT)

Find accessible area for a binary robot considering:
- Statically stablity
- Configurations are within the the binary actuator ranges of motion and effort capabilties.



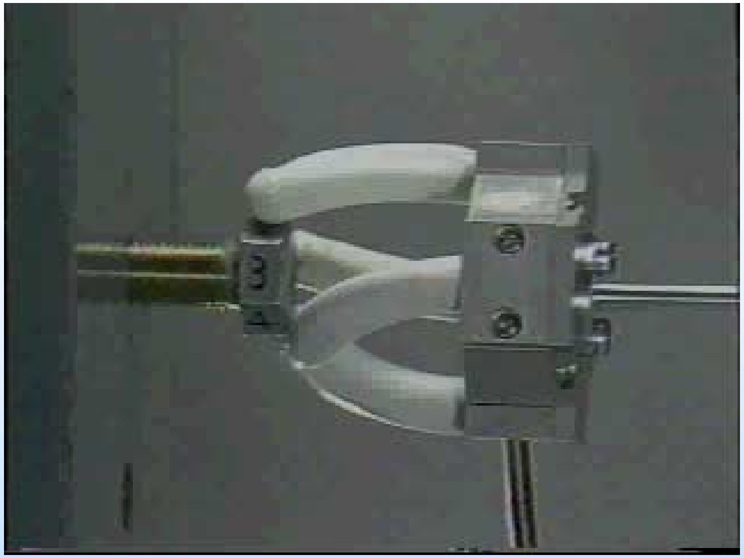


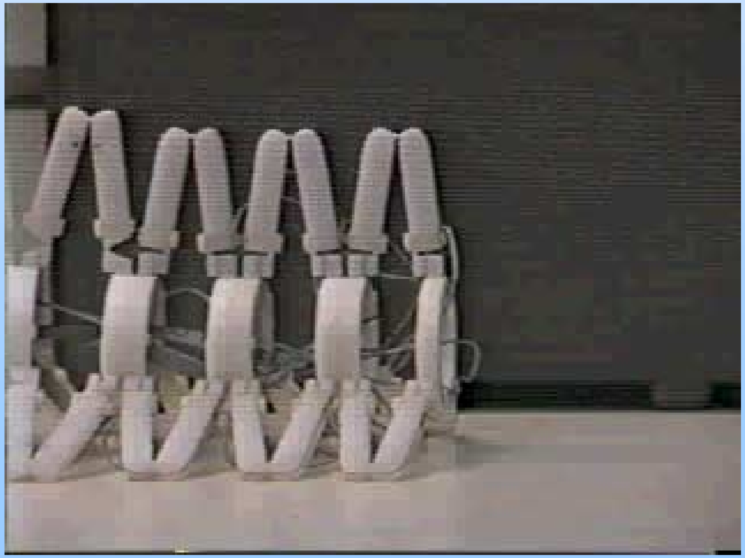
2-D Results

A Key Observation

Binary Systems with Component technologies having Large Numbers of Degrees-of Freedom Approach the Performance of Continuous Systems.

Component Technologies-Mechanisms





Compliant Mechanisms, Embedded Actuators and Sensors-ABEs

- Large Motions Without Motors, Bearings, Gears, etc.
- Greatly Reduced Number of Moving Parts
- Lightweight
- Binary Action
- Greatly Reduced Number of Sensors

Discrete Binary Actuated Bistable Elements

Conventional Technologies are Unable to Meet Demands for Future Planetary Systems:

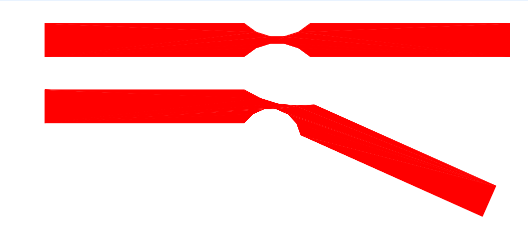
heavy
complex
failure-prone, etc.

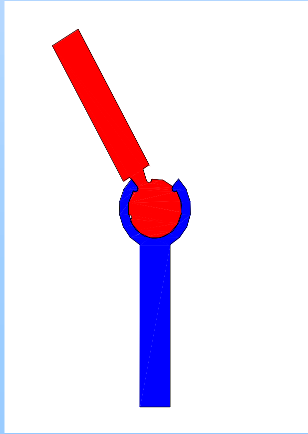
STX- Concept need large numbers of actuated bistable degrees-of-freedom. Our concept is to use:

Compliant elements

With embedded on/off actuators

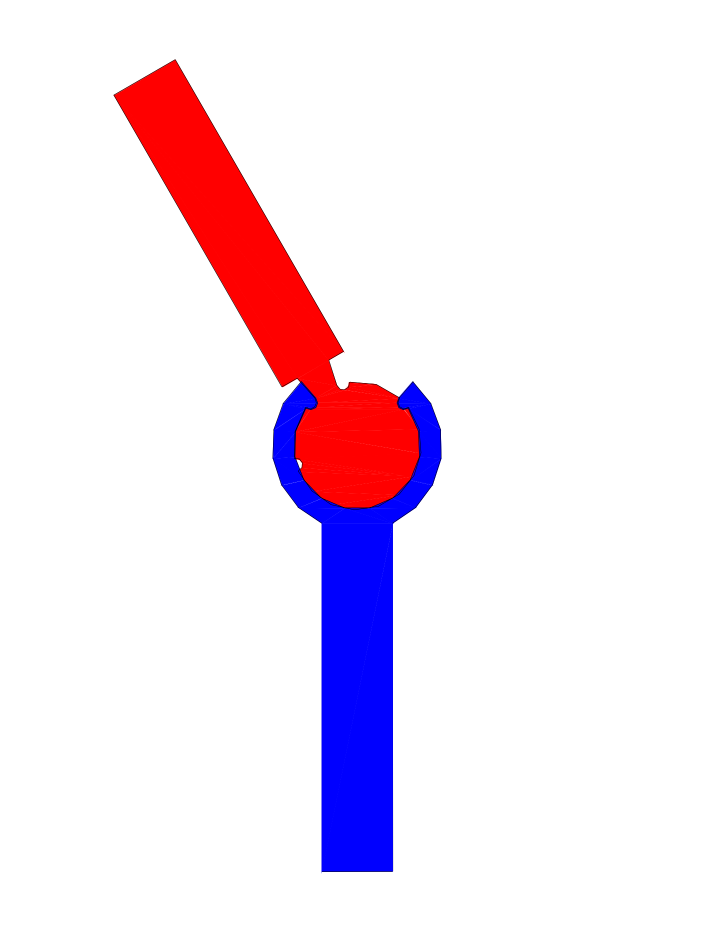
Internal detents:





The result would be a lightweight, simple, robust and fault-tolerant basic building block for STX.

Bistable Mechanisms



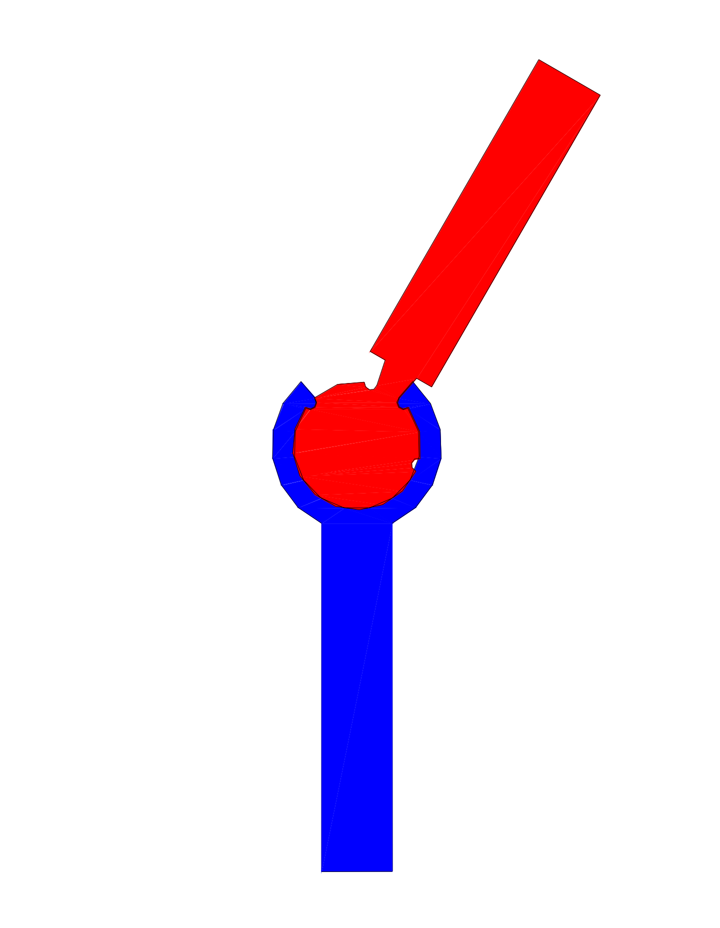
Eliminates the need for bearings, lubrication

Inherent spring characteristics provide bias forces, compliance

Internal detent structure latches into discrete states:

- eliminates need to keep actuators powered
- Improve disturbance rejection

Bistable Mechanisms



Eliminates the need for bearings, lubrication

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Internal detent structure latches into discrete states:

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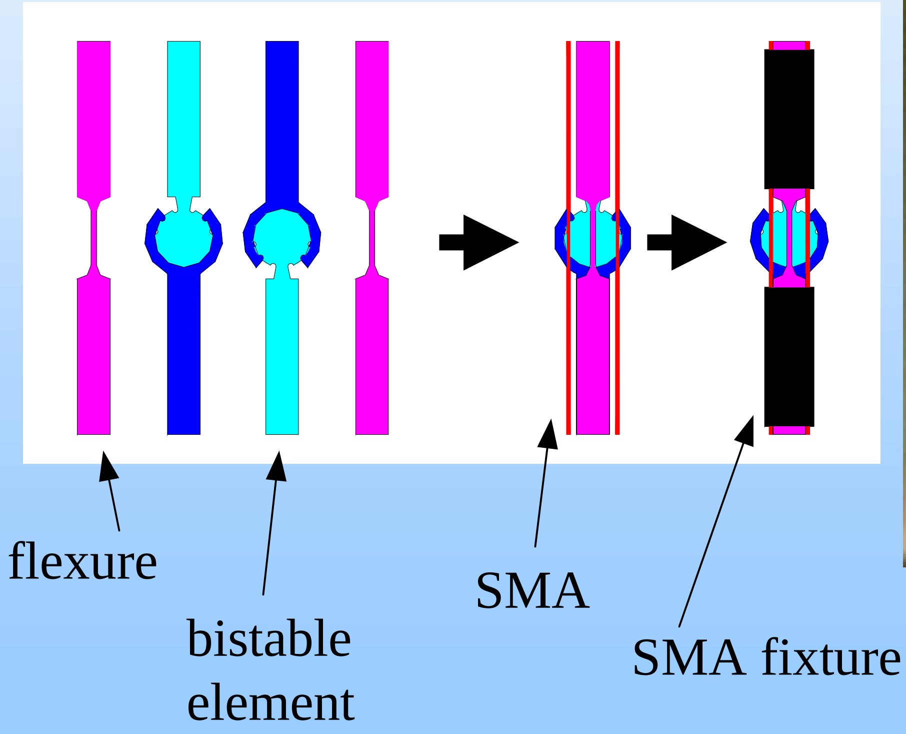
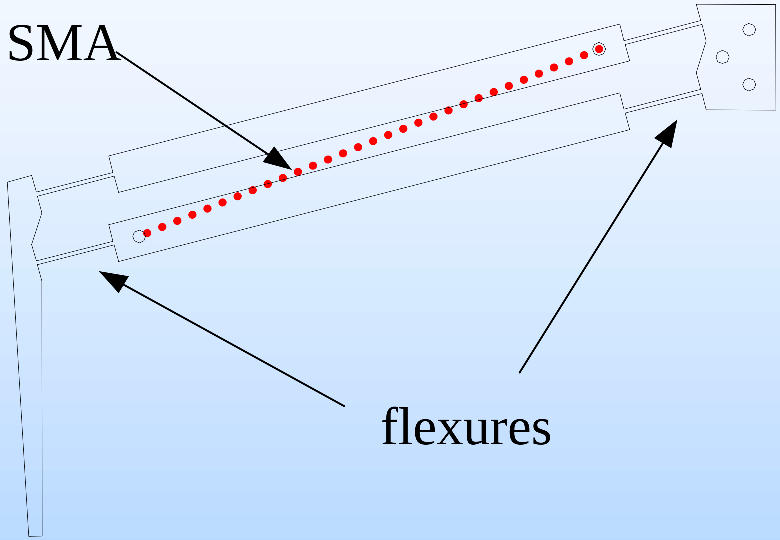
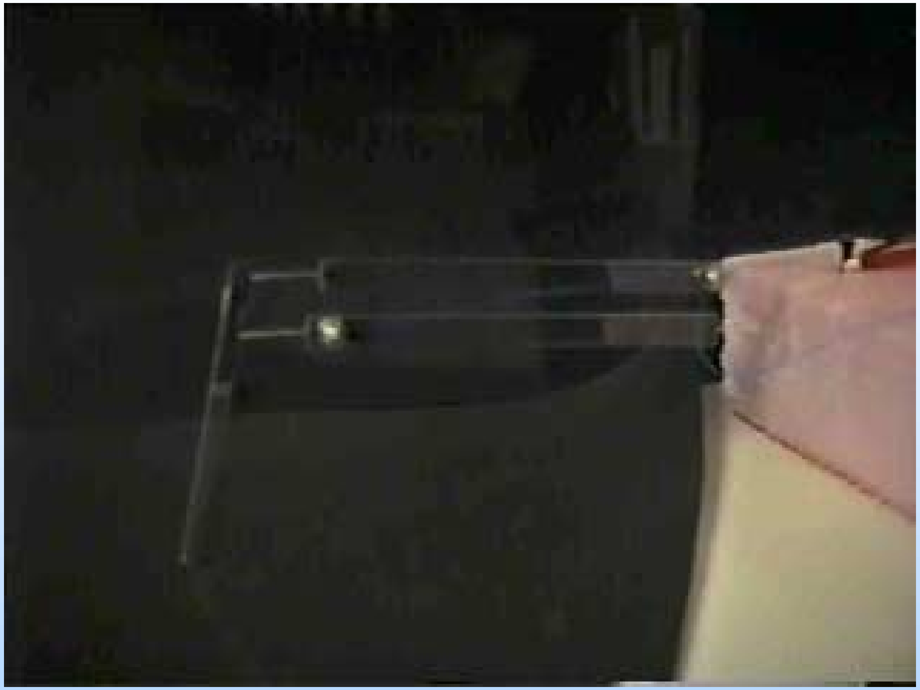
Miniature Rotary Joint

- Antagonistic pair of SMA wires
- Bistable elements sandwiched by flexure beams
- $\pm 25^{o}$ deflection



Pantograph Mechanism





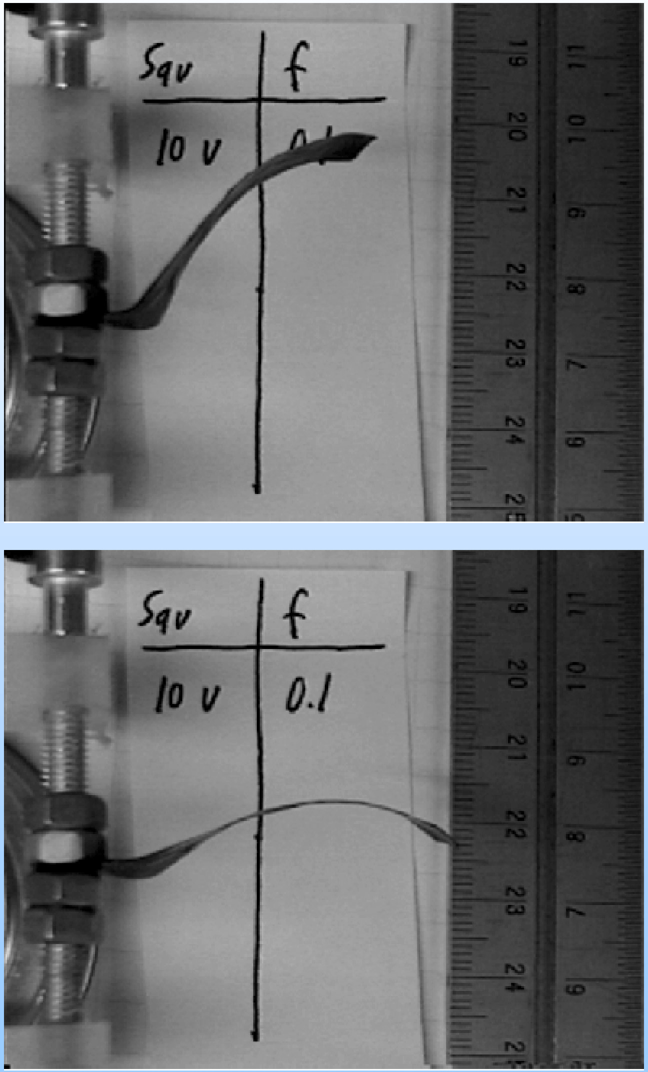
- Flexures replace bearings
- SMA actuated
- Considerable motion amplification

SMA are a Surrogate for Conducting Polymers

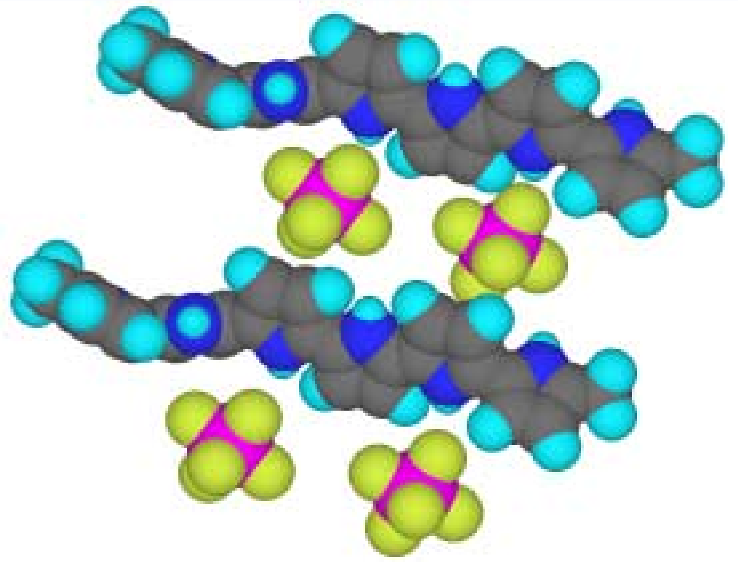
Component Technologies- Conducting Polymers

Conducting Polymers for:

- Embedded Muscles (Actuation)
- Sensing
- Signal Transmission
- Computation

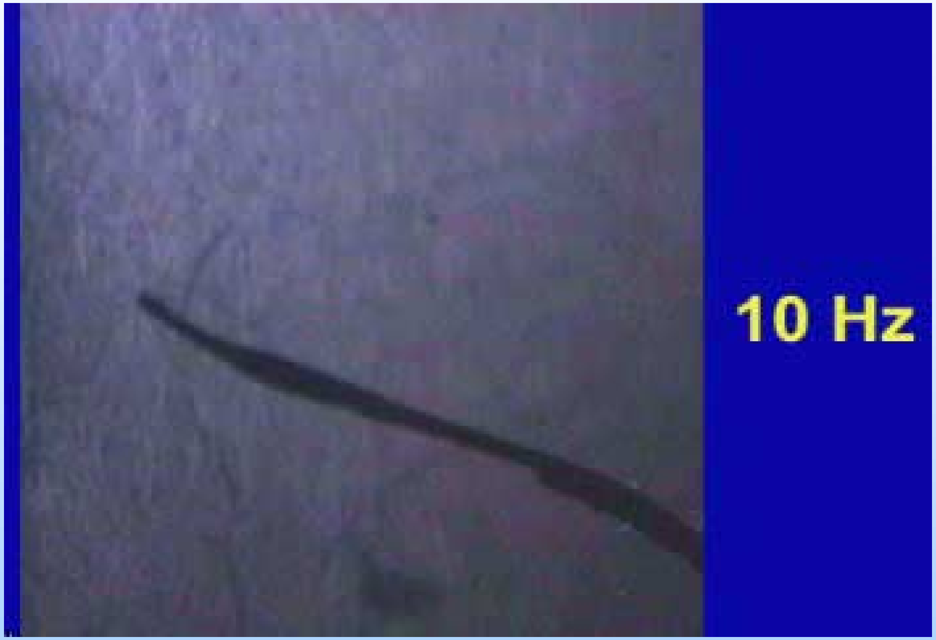


Conducting Polymers



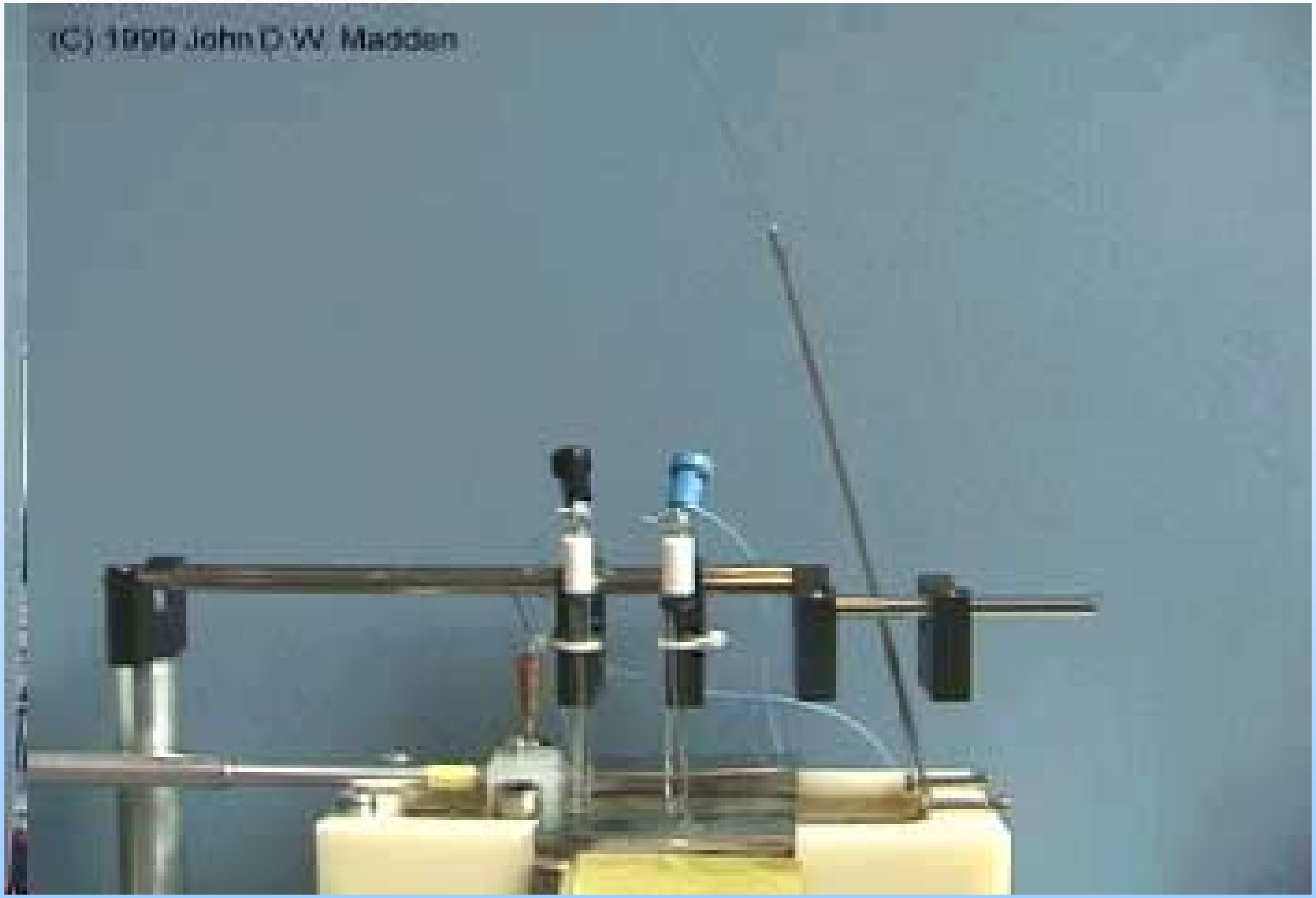
Anions (PF_6^-)

Polypyrrole

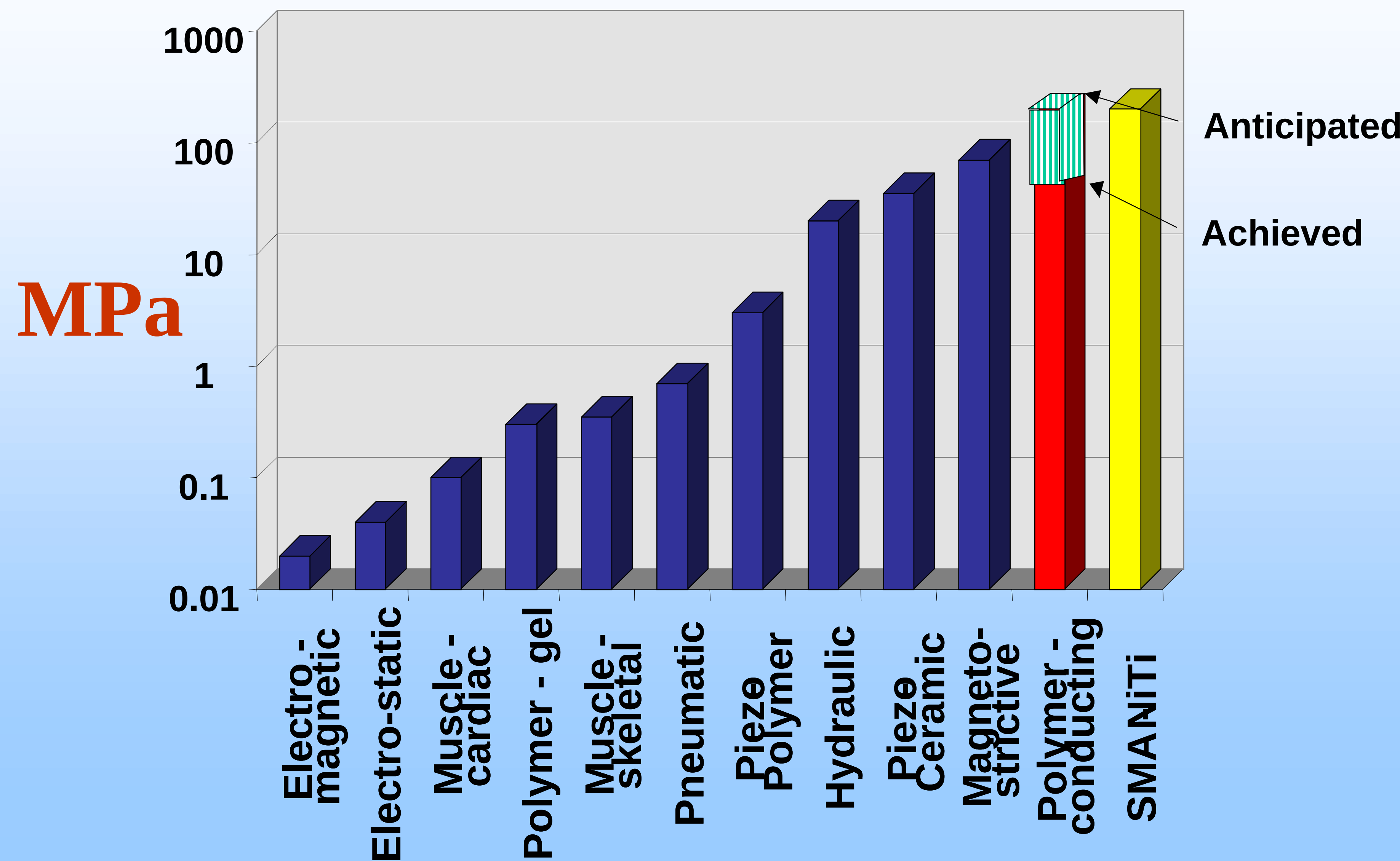


- **<u>Low Voltage (0.5-10V)</u>**
- **<u>High Force (30 Mpa)</u>**
- **<u>Inexpensive ($1.50/kg)</u>**

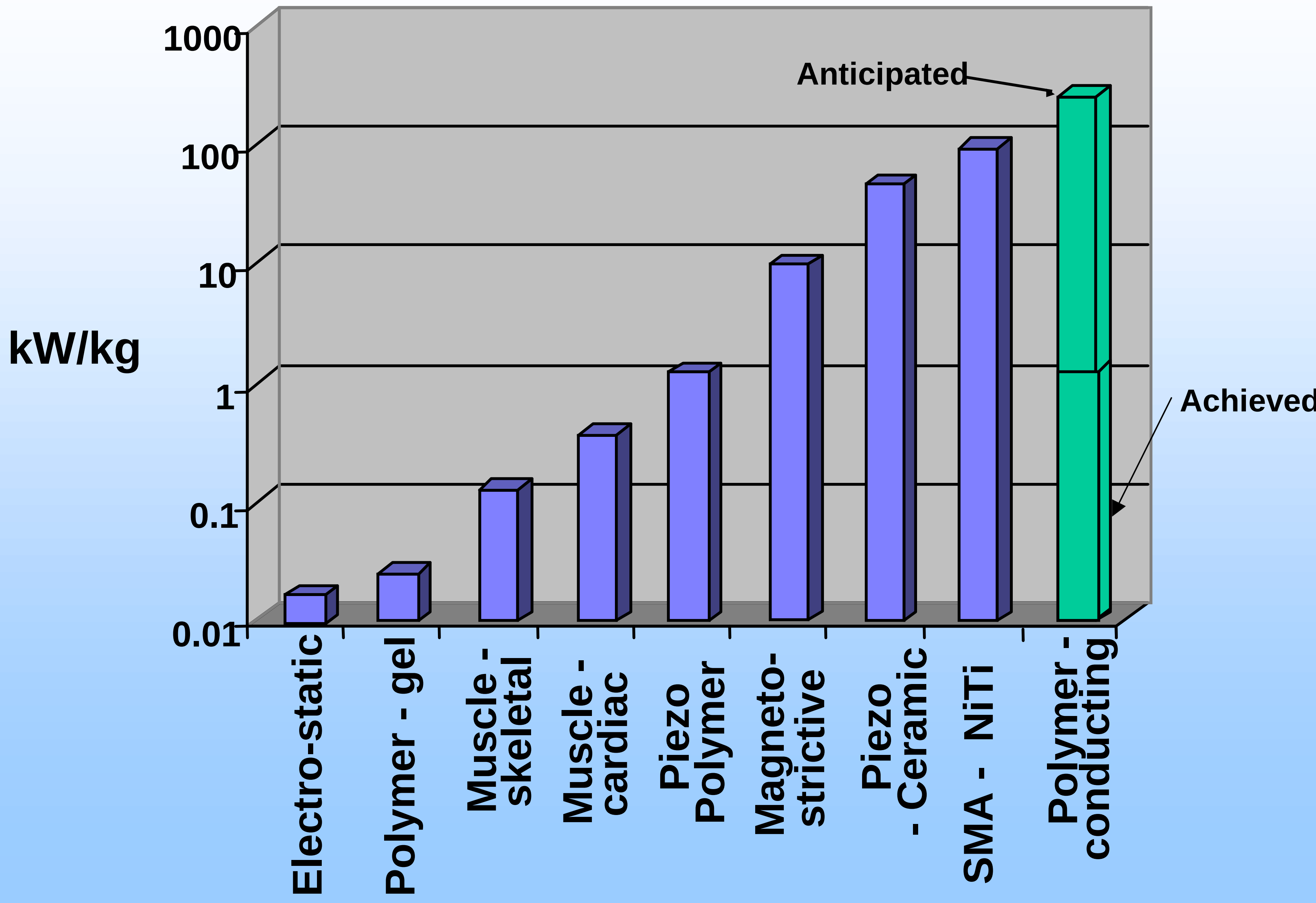
Cantilever



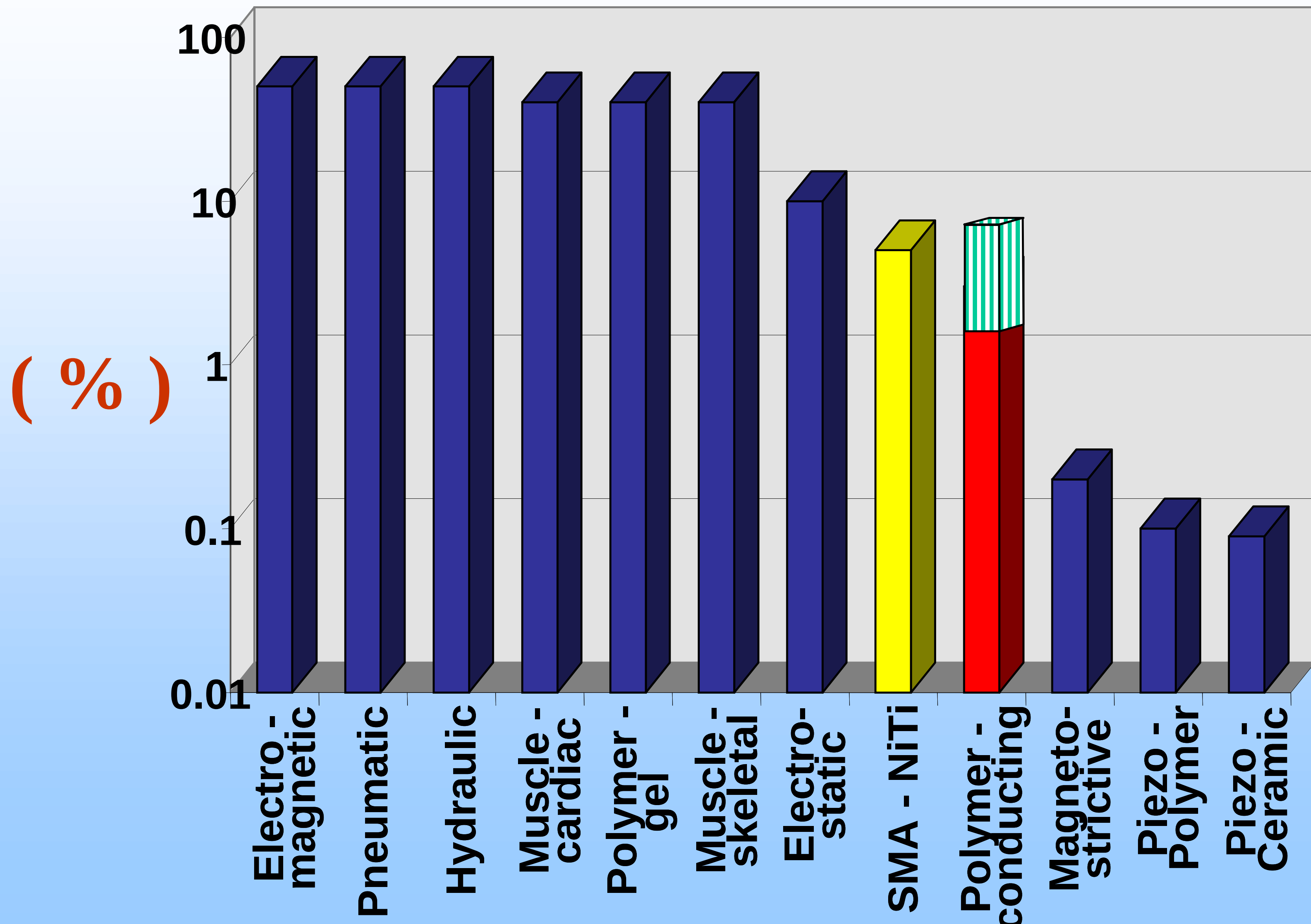
Active Stress



Power to Mass



Active Strain

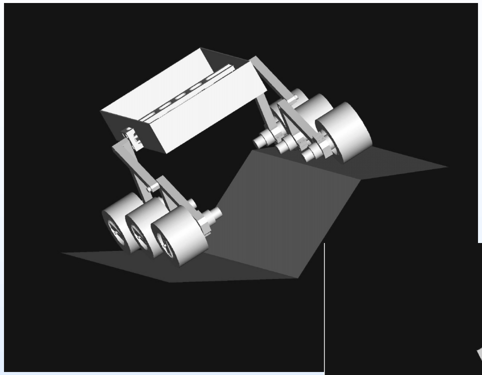


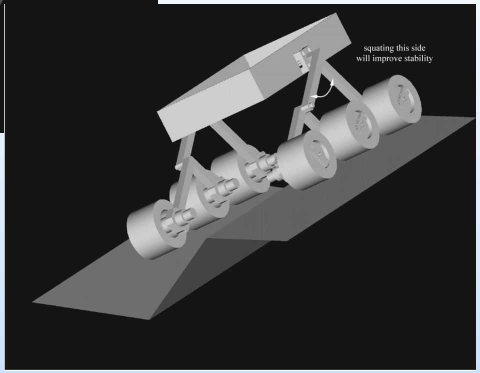
Conducting Polymers and The CTX Vision

- Actuators
- Wire (cf Cu)
- Transistors
- Sensors
- Batteries
- Super Capacitors
- Memory
- Light-emitting diodes
- Photodetectors & cells
- Electrochromic displays

While "engineering" problems remain to be solved, the results to date suggest the approach is feasible in the 10 and 10+ year time frame.

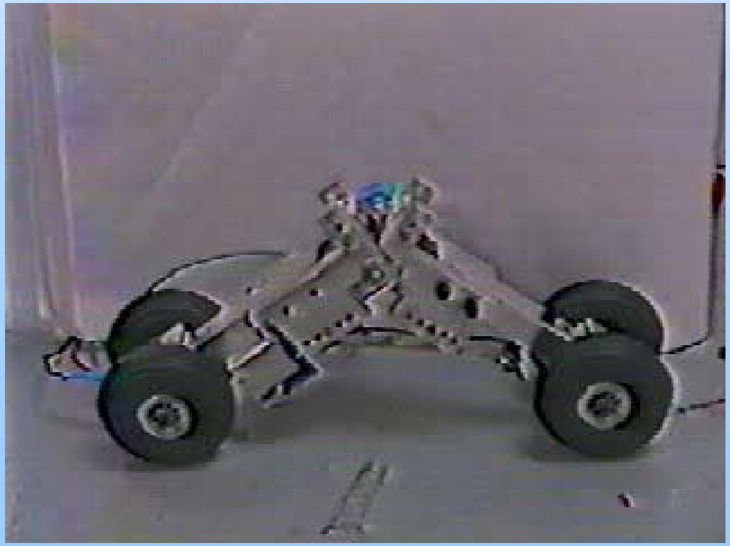
A Near Term Practical Implementation of Binary Mechanisms





A Reconfigurable Rover Rocker-Bogie Suspension (in cooperation with JPL)

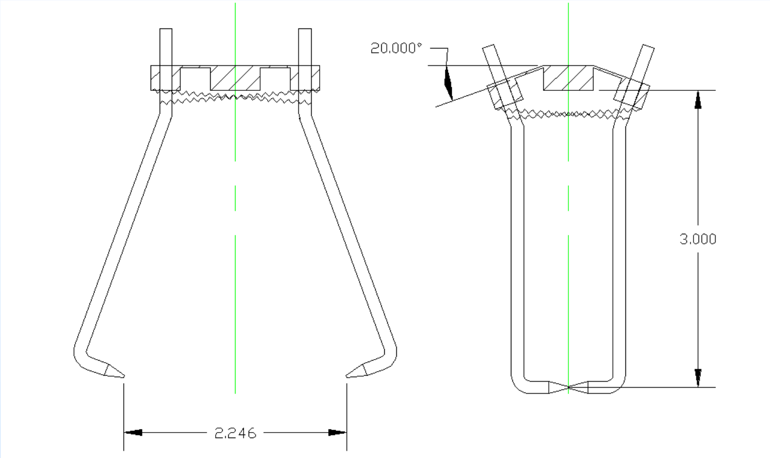
Objective: To adapt to difficult terrain and improve vehicle stability



Experimental system implemented with Shape Memory Alloys

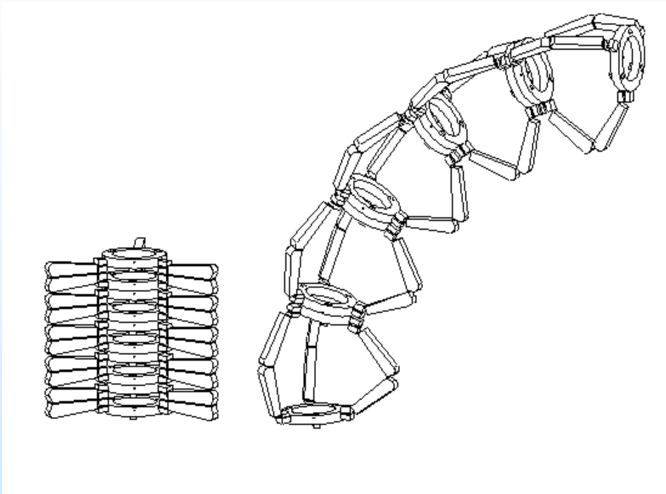
A Near Term Practical Implementation of Binary Mechanisms

A Binary Gripper

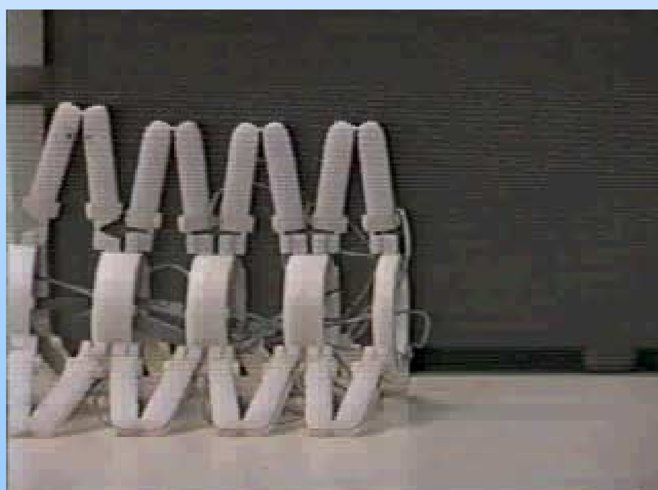


A Near Term Practical Implementation of Binary Mechanisms

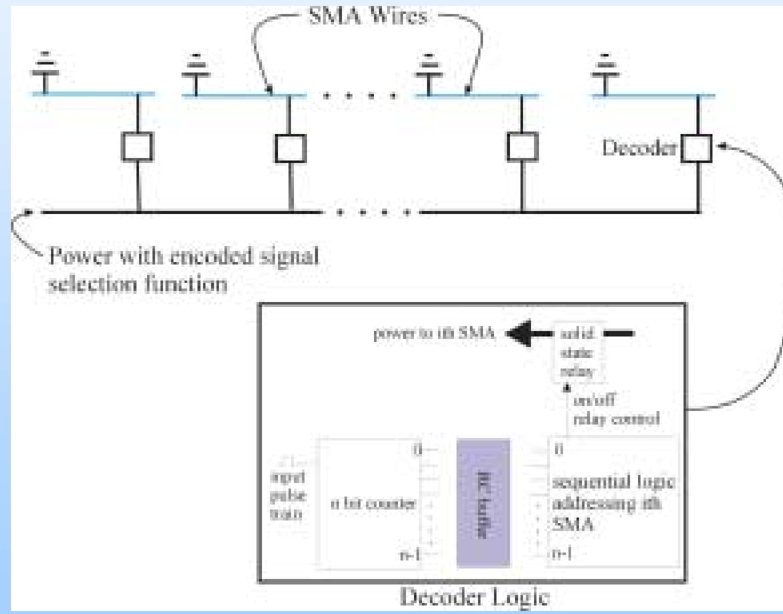
A Deployable Rover Camera Mount



Structure layout



Physical system



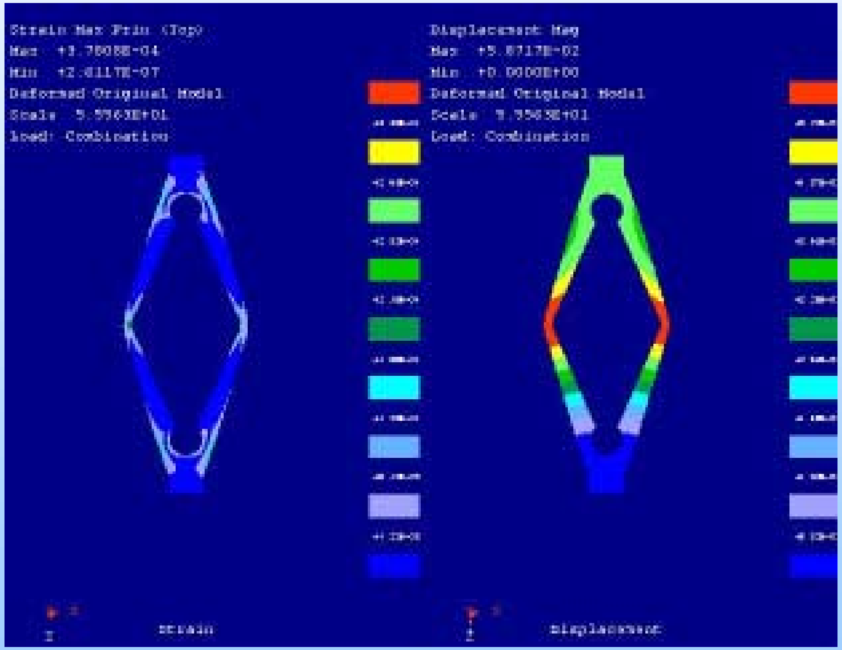
Minimum Channel Binary Controller:

Hyper-Degree of Freedom Binary Elements

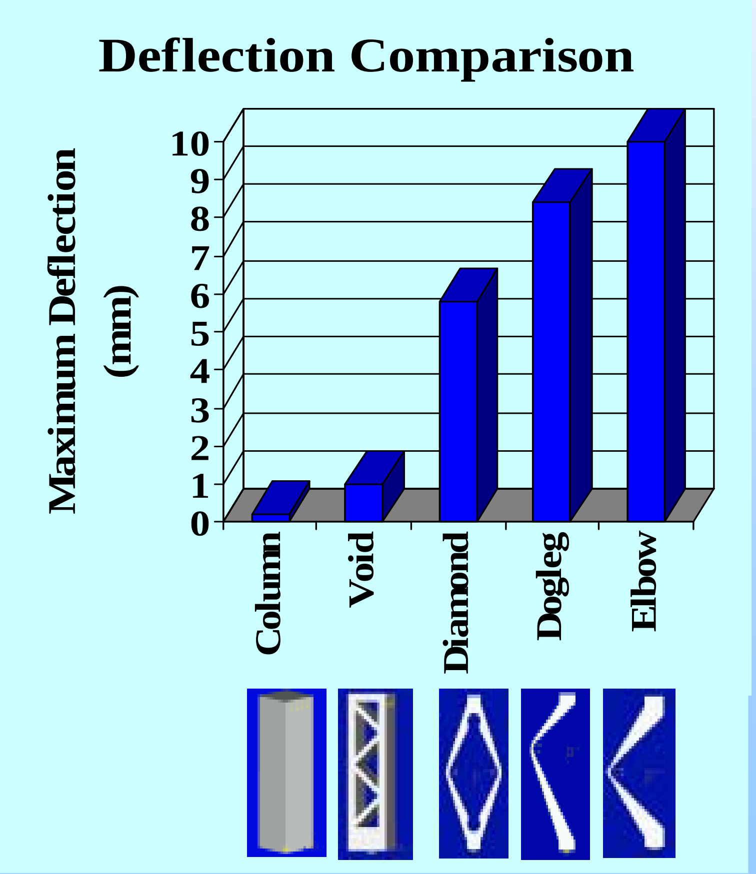
- Motivation: Provide the building blocks for the CTX Concept
- Distributed Flexibility to Achieve Large Motions
- Hyper-Binary DOF through Embedded Actuation and Sensing
- N approaches ∞

Analytical Questions:

- How to Shape Structures with Distributed Flexibility for large Deformations?
- How to Place Binary Actuators to Achieve Hyper DOF?
- Large Deformations = 100 Time Actuator Deformation.

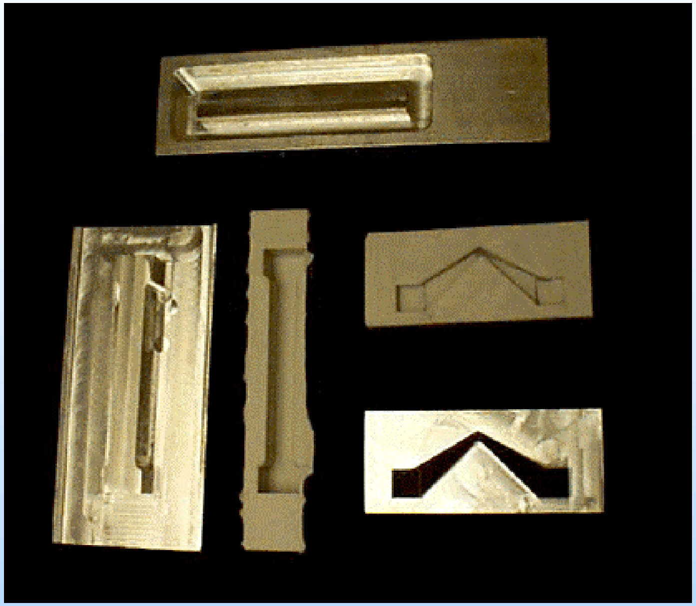


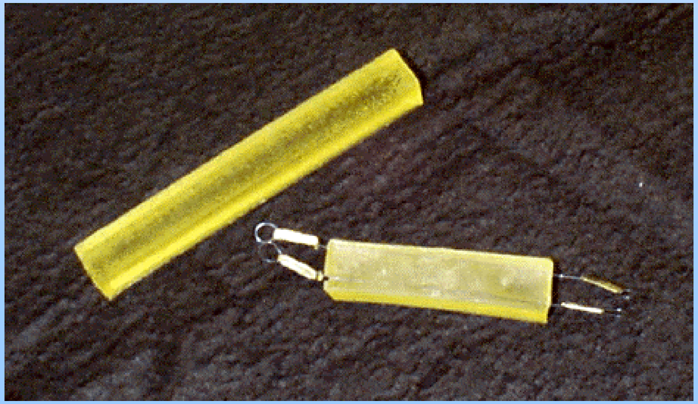
Finite Element and Optimization Studies



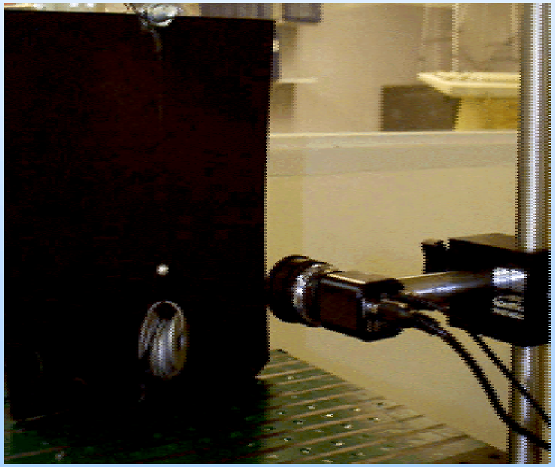
Experimental Studies

Prototyping





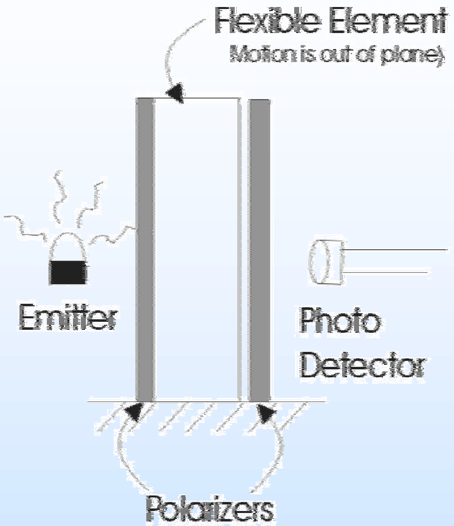
SMA Based Actuator Experiments



Embedded Sensing

Sensor Experiments

Polymer based Internal State Sensors for Control.



Adding Embedded Polymer Sensing to Embedded Binary Polymer Actuators in Elastic Polymer Members is a step toward to proof of concept of CTX Systems.

A New Paradigm for Planetary Robotic Explorers and Workers

NIAC
NASA Institute for Advanced Concepts

MIT

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