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.)

Today’s 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 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

- 2000: ROVERS
  Discrete Components

- 2010: STX
  Hybrid System

- 2040: CTX
  Continuous System
Self-Transforming Explorer/Worker Robot Concept (2010)

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

The STX c.2010
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 - $(10^2 \text{ and } 10^3)$
- Lightweight, simple and robust
- Fault-Tolerant

Digital Computer Analogy
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
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 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…..
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.
Find accessible area for a binary robot considering:
- Static stability
- Configurations are within the binary actuator ranges of motion and effort capabilities.
A Key Observation

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
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Miniature Rotary Joint

- Antagonistic pair of SMA wires
- Bistable elements sandwiched by flexure beams
- $\pm 25^\circ$ 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
Polypyrrole

Anions (PF$_6^-$)

- **Low Voltage** (0.5-10V)
- **High Force** (30 Mpa)
- **Inexpensive** ($1.50/kg)
Cantilever
Achieved Electro-static Polymer - gel

0.01 0.1 1 10 100 1000 kW/kg

Muscle - cardiac Muscle - skeletal

Piezo Polymer -conducting NiTi

Piezo Magnetostrictive

Polymer - Ceramic

SMA - Niti

Power to Mass
Active Strain

- Electro-magnetic
- Pneumatic
- Hydraulic
- Muscle-cardiac
- Polymer-gel
- Muscle-skeletal
- Electro-static
- SMA - NiTi
- Polymer-conducting
- Magneto-strictive
- Piezo-Polymer
- Piezo-Ceramic

( % )

0.01
0.1
1
10
100
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 $\infty$
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
Prototyping

Experimental Studies

SMA Based Actuator Experiments
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
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