An Astronaut Bio-Suit System for Exploration Missions

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Dainese, Italy
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Research Partners & Advisors

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**Midé Technology Corporation** is a R&D company that develops, produces, and markets High Performance Piezo Actuators, Software, and Smart (Active) Materials Systems; primarily for the aerospace, automotive and manufacturing industries.
Bio-Suit Advanced EVA Research

• Astronaut EVA Performance
  - Human/Robotic database
  - Design Requirements & Spacesuit Modeling
  - Energetics and Biomechanics – Design Requirements
  - Mission Planning and Geological Traverse Analysis
  - EVA System Design for Flexibility and Uncertainty

• Advanced Spacesuit Design: Bio-Suit MCP System
  - Human Modeling & Requirements Definition
  - Space Suit Simulator – Exoskeleton Research
  - Bio-Suit Mechanical Counter Pressure (MCP)
    • Feasibility and Prototypes
  - International Design Collaboration: MIT, TAI, Dainese

• Educational Outreach
  • Bio-Suit & Knowledge Station
## Background and Contributions

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<th>Space Suit Mobility</th>
<th>Performance &amp; Modeling</th>
<th>Bio-Suit Concepts/Systems Engineering</th>
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<td>Tourbier <em>et al.</em>, 2001</td>
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<td>Korona, 2002</td>
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<td><em>Schmidt et al., 2001</em></td>
<td>Enhanced Performance</td>
<td><em>Pitts, Newman et al., 2001</em></td>
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<td><em>Carr, 2005</em></td>
<td><em>Blaya, Newman, Herr, 2003</em></td>
<td><em>Newman et al., 2004</em></td>
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<td><strong>Engineering Systems</strong></td>
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</table>
Human/Robotic Systems

- EMU, 27 kPa (4.3 psi)
- Human, robot, human suited, & robot suited
- 11 simple motions isolating individual joints
- 9 complex motions:
  - Multi-joint reaching
  - Locomotion
  - Step up 15 cm (6 in)

M. Tallchief
Robotic Space Suit Tester (RSST)

SARCOS Salt Lake City, Utah

Graph showing Elbow flexion angle (deg) vs. Elbow flexion torque (Nm)
Looking Back to Look Forward: Adaptation & Flexibility

• EMU: evolution from a contingency-only spacesuit to one that is capable of performing complex space station tasks

• Future EVA systems must be designed with change in mind otherwise we risk allowing the design to evolve in a suboptimal way.

• Want the design to be able to adapt to change in requirements:
  - within a single mission (change accommodation)
  - across multiple missions (flexibility)

Time, Uncertainty, and Flexibility: the three faces of the same coin

Extravehicular Mobility Unit and the Russian Orlan

Environment Change - Use Shuttle EMU Aboard ISS

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<th>Requirement Change</th>
<th>Design or Procedure Change</th>
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Environment Change - Physical Environment of ISS

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<th>Requirement Change</th>
<th>Design or Procedure Change</th>
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<tr>
<td>Minimum metabolic rate lowered</td>
<td>LCVG Bypass Designed</td>
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<td>Heated Gloves Designed</td>
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<tr>
<td></td>
<td>Thermal Mittens Designed</td>
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<tr>
<td>PNP must be &lt;0.995 over 10 years</td>
<td>Track Orbital Debris</td>
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<td></td>
<td>Define Allowable Penetrations</td>
</tr>
<tr>
<td>Different radiation exposure</td>
<td>Carefully plan all EVAs</td>
</tr>
<tr>
<td>Risk of propellant exposure</td>
<td>1-hr bake-out procedure</td>
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<td></td>
<td>Lengthen SCU</td>
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Environment Change - Technical Environment Advances

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<td>Advance in suit joint technology</td>
<td>Joint patterning and materials changed</td>
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<tr>
<td></td>
<td>Bearing design and materials changed</td>
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<tr>
<td>Need for delicate assembly tasks</td>
<td>Glove design and materials changed</td>
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<td>Increased EMU life</td>
<td>Battery redesign</td>
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<td>CCC upgrade to regenerable canister</td>
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<td></td>
<td>Carbon Dioxide sensor upgraded</td>
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<td></td>
<td>SAFER</td>
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<tr>
<td>Secondary system in case of crewmember separation</td>
<td>Coolant water bladder material change</td>
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Human EVA History
Creativity, Imagination, Innovation

Incredibly Creative & Innovative Designs
Revolutionary Design:

Bio-Suit System

Bio-Suit multiple components:
- Mechanical Counter Pressure (MCP) Bio-Suit
- A pressurized helmet
- Extremely mobile gloves and boots
- Armadillo-like articulated back structure
- A modular life support backpack

Systems Engineering: req’s., design life, model, interchangeable components

Idea: Custom-fit skin suit to an individual human/digital model

Space & Earth Applications: Mobility, Performance and Safety

\[ \Delta W = \Delta W_p + \Delta W_e \]
- \( \Delta W_p \) - Minimize through MCP design
- \( \Delta W_e \) - Bending (design) and Strain Energy (min. or max E)
• **Paint On, or Shrink Wrap, Second Skin**
  - *Electrospinlacing* seamless MCP layer.
    - Multi-filament fiber projected via electric charge onto grounded surface
    - Greatly improved tactile feedback
    - Custom, form fit
    - Seamless integration of wearable computing

• **Electroactive Materials**
  - MIT Field & Robotics Laboratory (Dubowsky)
  - MIT Institute Soldier Nanotechnology (ISN)

• **Electro-Mechanical assistance**
  - Augments astronaut’s capabilities
  - Countermeasure for microgravity deconditioning
  - Assisted locomotion 1G (AAFO) or Enhanced performance (Exoskeleton)

• **Shape Memory Alloys & Polymers**
  - De-couple donning/doffing
  - Large maximum strains (> 100%)
### Results → MCP Requirements

<table>
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<tr>
<th>MCP Tension</th>
<th>Knee Surface Area</th>
<th>Skin Strain Field Mapping</th>
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<tr>
<td>~2 kN/m</td>
<td>↓ 16%</td>
<td>Circumferential Strain</td>
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<tr>
<td>0.8 kN/m</td>
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</table>

- In knee region, when leg flexes from 0 to 90 degrees...

**Knee Volume**

- ↓ 18%
- In knee region, when leg flexes from 0 to 90 degrees...
Bio-Suit Skin Strain Model

(Circumferential Strain (Subject 1))

(Longitudinal Strain (Subject 1))

(MOU: Natick National Protection Center)
Augmented 1G Human Performance

Problem: Drop foot, pathology (Stroke, Cerebral Palsy (CP), Multiple Sclerosis (MS))

Solution: Creative design of an active ankle device

Contact 1: Adaptive biomimetic torsional spring - minimize slap
Contact 2: Minimized impedance
Swing: Adaptive torsional spring-damper to lift (propel) foot

Currently: Exoskeleton
- Harness, hip bearing, fiberglass members, ankle
- Fiberglass spring mechanism provides energy

Neuroengineering: Human/Robotic

False Platform Response

Knee Flexion Angle (degrees ± s.e.m.)

Time (sec)
Energetics & Biomechanics

- Apollo data as a baseline, first MCP suit (Webb)
  - Improve space suit design: minimize energy, max. mobility
Cost of Transport and Gravity

- Energetics of locomotion (walking and loping)?
- Moon: Stability, control
- If on Mars: Run (lope) don’t walk!
Space Suit Simulator – Exoskeleton

- Exoskeleton joint torques match EMU knee torques
- “Tuned space suit”
The Art of Engineering and Design
Results: MCP Initial Prototypes

Tibia Medial-Posterior Lateral

Tibia Medial-Posterior Lateral

Input: 29 kPa
≥31 kPa
26 kPa
24 kPa
21 kPa
Results: Minimum Energy Bio-Suit

- Maximizing mobility
- Minimizing energy
  - (Strain energy, stress and modulus)
Results: MCP Elastic Bindings

- Maximum mobility
- Active materials (de-couple donning/doffing)
- Shape memory polymers (large max. strain)

- Varying circumferential tension gives constant pressure as leg radius changes.
- Donning time ~5 minutes
- Knee flexion angle ~140°
Pressure Distribution Generated by the Elastic Bindings (Design Pressure ~27 kPa)

Prototype MCP generated on calf using Elastic Bindings

Front/Anterior

Back/Posterior
Successfully protected a human leg from the effects of external underpressure

ELASTIC BAND PROTOTYPES

Human MCP Garment Trials in Low-Pressure Chambers

Test duration* (minutes)

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<tr>
<th></th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
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<tr>
<td>Annis &amp; Webb (1971)</td>
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<td>Clapp (1983)</td>
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Note: * Excludes pressure ramp-down and ramp-up times
Exploration Path Planning

Objective functions:

\[ \theta = \theta_{\text{true}} - \theta_{\text{observer}} \quad \phi = \phi_{\text{true}} - \phi_{\text{observer}} \]

\[ SS = (\cos(2\theta) + 2)\cos(2\phi) = 2 \]

- Blue Path
- Red Path
- Greens Path
- Black Path: No Path

Start: (325, 230)  Goal: (183, 230)  Coordinates: (, )

- Distance: 1800 m
- Path Costs: 375

Altitude (m):
- Cone Crater
- Lunar Module

- Original planned route
- Deviation from original route on ATV
- Planned site
- Path deviation on foot
- Unexpected terrain problems
Digitally Designed: Bio-Suit Mockup

- From the human form – computer – fabrication.
- CAD models – human 3D scans and LoNE
- Automatic seams to positioning LoNE, primary and secondary
- 340 m
- 140,000 points (stitches)
- A novel closure system
- Custom spacesuit
2006 Bio-Suit Mockup
Explore Space!
The Knowledge Station is an educational portal where you can Explore, Interact, and Learn.

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**Interact** through the gestural interface to exercise on the ISS, explore Mars with Max in an advanced spacesuit, or teleoperate M. Tallchief (a robot) on Jupiter’s moon of Europa.

**Learn** about the world of NASA and NSBRI’s science and technology breakthroughs.

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References


Thank You – Questions?

NASA and NIAC
Back Up Slides

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