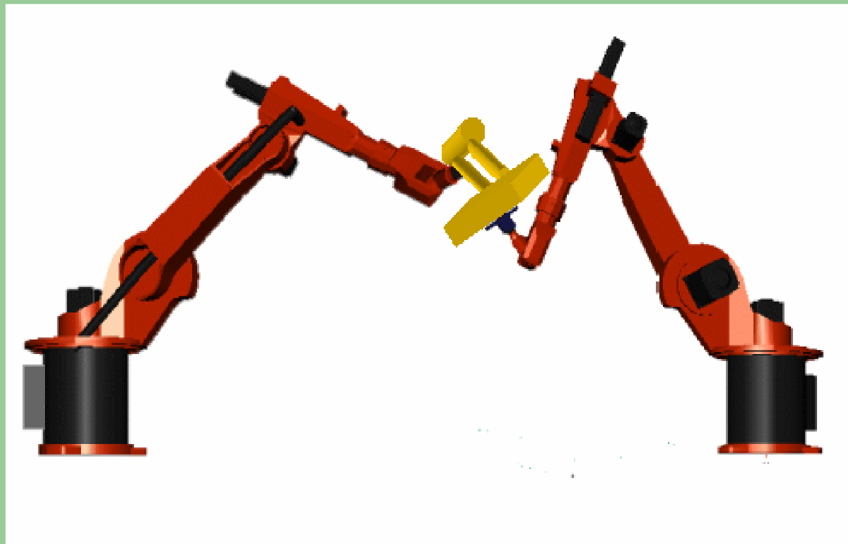


Autonomous Self-Extending Machines for Accelerating Space Exploration

NIAC CP 01-02 Phase I

Hod Lipson, Evan Malone
Cornell University

Computational Synthesis Lab

CORNELL

Computational
Synthesis Lab

CORNELL

Motivation

- Robotic exploration has a long cycle time
  - Better propulsion
- Mission goals are inflexible
  - Design more complex robot
- Failure is catastrophic
  - Make more stringent reliability testing

→Vicious circle of cost and complexity

Computational Synthesis Lab

CORNELL

Concept

- Remote autonomous fabrication of complete functional systems
  - Design after launch (shorter cycle)
  - Less commitment (more flexibility)
  - Task specific robots (less complex)
  - Repair and recycle (reliability less critical)

Computational Synthesis Lab

CORNELL

Prior concepts

- Self replicating lunar factories
  - It more efficient to send information in preference to matter
  - Ambitious future missions can be greatly shortened through remote factories
  - Self-extending facilities can have much more flexibility

Advanced Automation for Space Missions, Robert A. Freitas, Jr. and William P. Gilbreath, editors.

Computational
Synthesis Lab

CORNELL

Our concept

- Fabrication system that is
  - Compact
  - Fully autonomous
  - Can fabricate fully functional systems
  - Can build systems larger than itself
  - Can build repair / extend itself
- High gain fabrication system: SFF

SFF: Two architectures

- Comprehensive
  - Can make “anything”
  - Has every conceivable fabrication method
  - Catch: Shifts the cost and reliability to SFF
- Minimal
  - Has a minimal spanning base of materials
  - Cannot make all things, but can achieve any functionality
  - Catch: Requires re-parsing of design in terms of available capabilities

Example: A possible minimal architecture

- Articulated arm SFF
  - structure, actuation, sensing, power, control, recycling
  - Assembly
- Multiple identical arms cooperate
- Redundancy
- Self repair

Computational
Synthesis Lab

CORNELL

Summary of proposal

- Analyze missions requirements
- Consider a variety of destinations
- Survey available and foreseeable SFF technologies

1. Provide roadmap to alternative architectures
2. Evaluate architecture through limited implementation

Background on SFF

- Introduction to Solid Freeform Fabrication
- State of Solid Freeform Fabrication Today
  - Materials
  - Processes
  - Products
  - Markets
  - Developmental trends

Computational
Synthesis Lab

CORNELL

Commercial SFF Processes

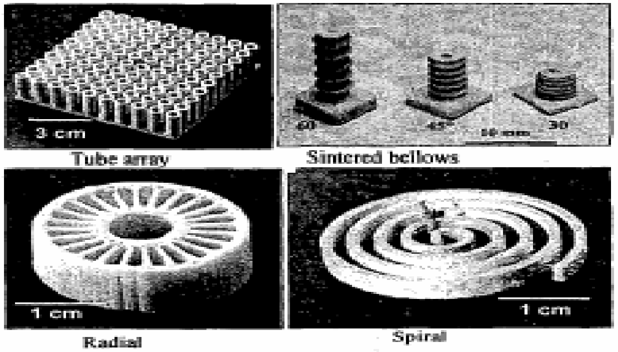
- Fused Deposition Modeling (FDM)
- Laminated Object Modeling (LOM)
- Stereo Lithography (SLA)
- Selective Laser Sintering (SLS)
- 3-D Printing / Multijet Modeling
- Laser Direct Metal Deposition (DMD / LENS)

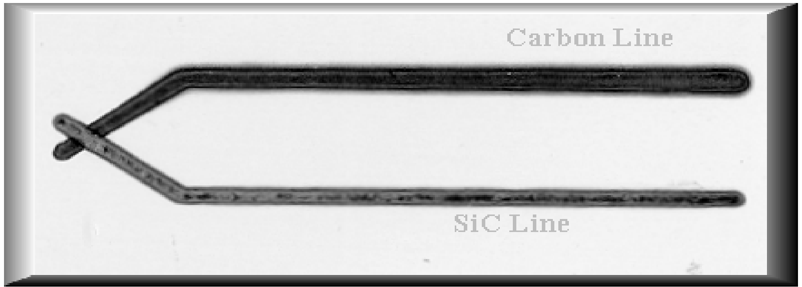
Computational Synthesis Lab

CORNELL

Research in SFF Processes

- Piezo actuators / sensors via LOM, SLS, FDC/FDMM, including electrodes (Rutgers)
- Fabrication of SiC / C thermocouples on Al_2O_3 ceramic, and "welding" (CVD) of ceramic via SALD (U.Conn.)
- Universality by CMU/Stanford SDM
- Passive circuit elements by laser processed sol-gel materials (Sciperio)
- DMD of on-demand spare parts in space
- FDM in zero-g (Vomit Comet)
- Focused Solar Sintering / OW
- Electron Beam SFF





SiC-Carbon Thermocouple on Alumina Substrate Fabricated with the SALD Technology

Computational Synthesis Lab

CORNELL

Future of SFF in Missions

- Near-term, near Earth:
  - Spares on demand / inventory reduction for ISS – *too easy (for NIAC!) and already underway*
- Mid-term, Moon, Mars:
  - Repair / extension of planetary landers / rovers,
  - Preparation of facilities / resources for manned mission
- Long-term, Outer planets, beyond:
  - Very distant scientific missions
  - Essential component of indefinite duration robotic mission / self-replicating robotic ecosystem

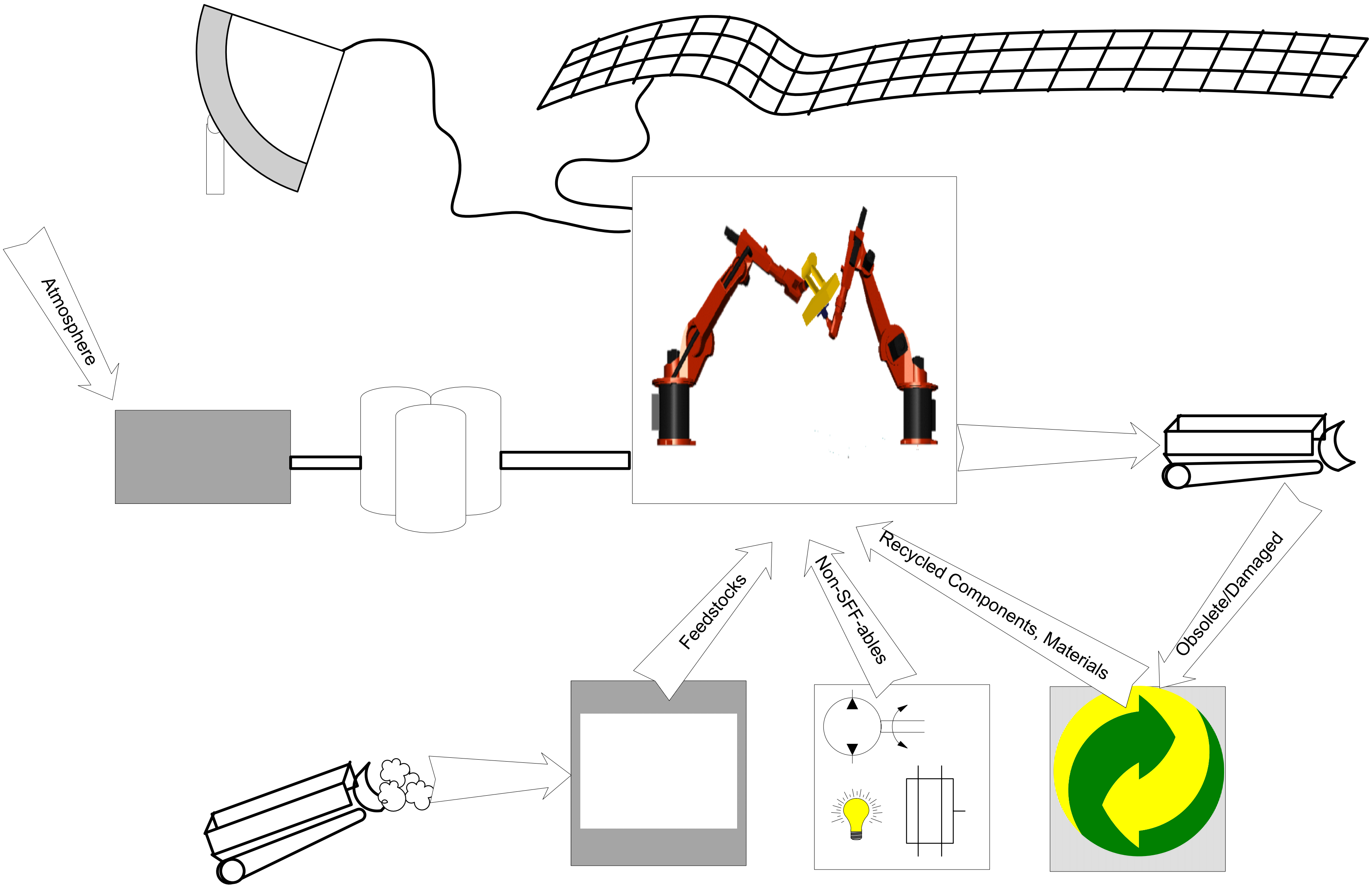
Computational Synthesis Lab

CORNELL

Mission Requirements

- What do these missions require of a fabrication system?
  - Produce Functional Components / Functional Systems
  - Compact size, low mass
  - Energy efficient
  - Large functional gain / small set of inputs
  - Simple, robust, and safe system
  - Tailored for use of *in situ* resources and products of ISRU and recycling
  - Fully automated, high yield process

Example: Architecture for MARS



Two thrusts of development

#1: Universality of the fabrication process

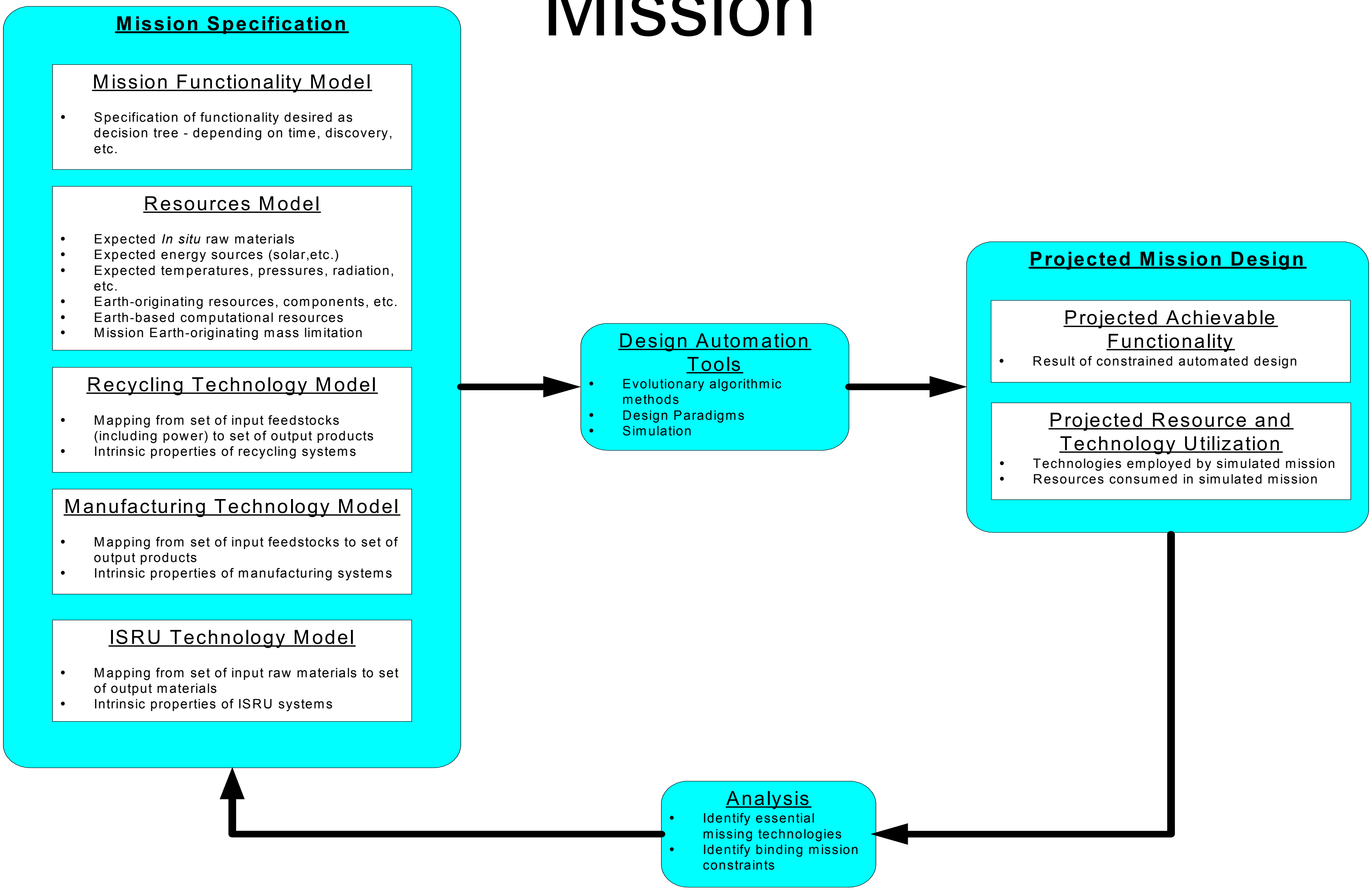
- Commercial development of SFF processes for "mass customization"
- What is not likely to be achieved by commercial efforts?
  - Process integration, compaction (too many proprietary, no motivation)
  - Basis sets of materials / ISRU focus
  - Production of fully functional systems in SFF style
  - 100% automation

Two Thrusts of Development

#2: New design paradigms: *“Design for …”*

- Solid freeform fabrication of fully functional systems (different “components”, multi-materials, wild geometry)
- Use of *In situ* resource feedstocks
- Highly constrained material selection
- Automated recycling / reuse
- Automated assembly / disassembly
- Automated extension / replication

Design Process for Fabricator Mission



Computational Synthesis Lab

CORNELL

Technology Evaluation Platform

- Small scale, 6 axis industrial robot arm
- Multiple tools
  - Linear motor driven hot extruder for thermoplastics (polypropylene)
  - Pneumatic dispenser for conductive grease, silicone RTV elastomer
  - Hot pneumatic dispenser for low-melt alloy
- Automatic part “slicing” and path planning software

Computational Synthesis Lab

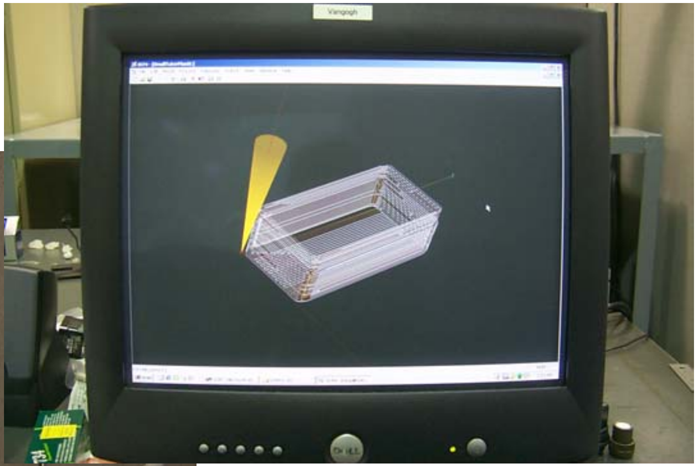
Cornell

Progress

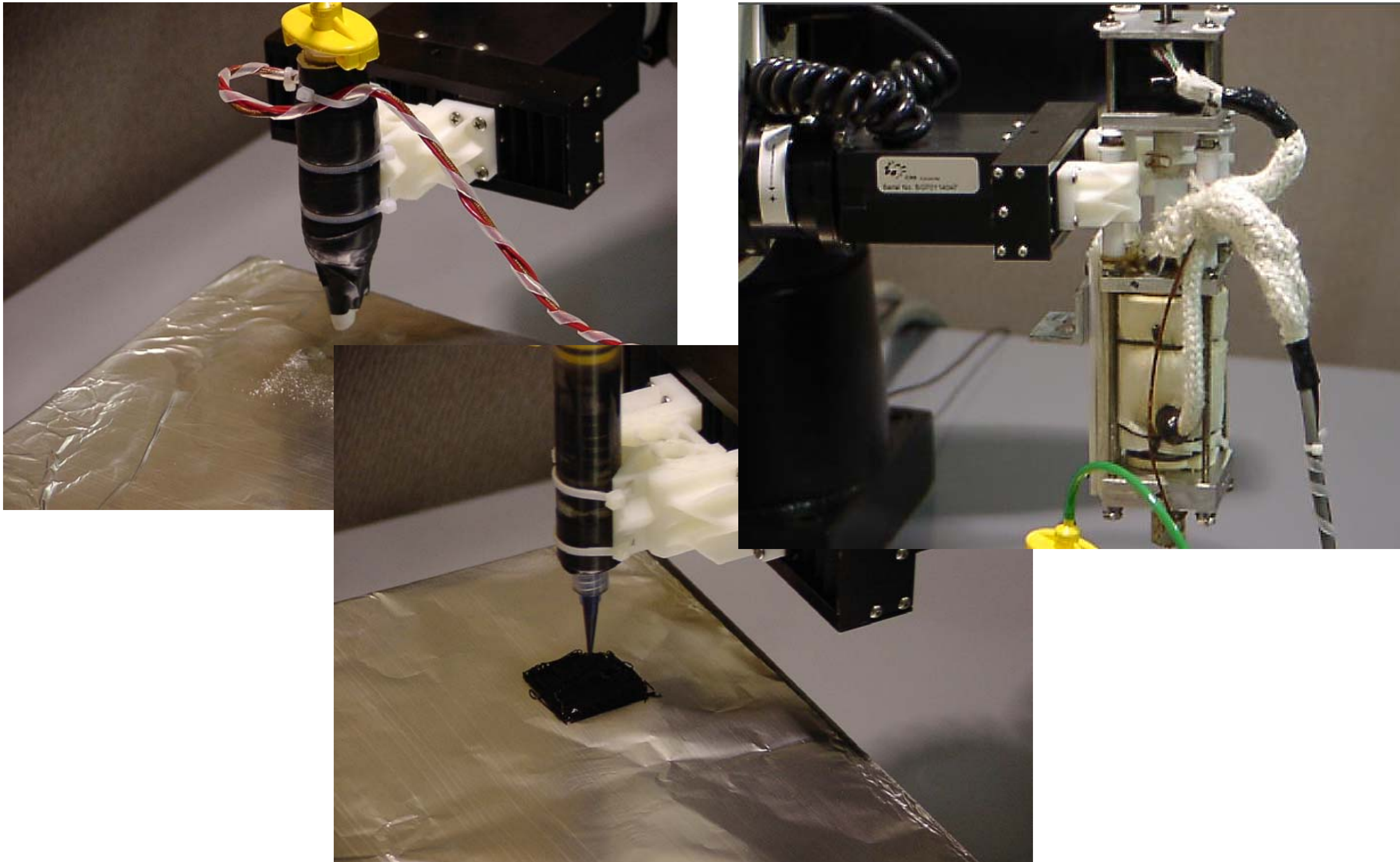
- Automatic tool changing
- Tool control
  - Multiple tools means many processes to refine and control
  - Using OOP to simplify interface
  - Hardware is very heterogeneous
- Path following: planar raster paths for now
- All the pieces are working together!

System


Key Justification[1]
It more efficient to send information in preference to matter
Ambitious future missions can be greatly shortened through remote factories
Self-extending facilities can have much more flexibility


Vangogh

Dispensers



Results

Computational
Synthesis Lab

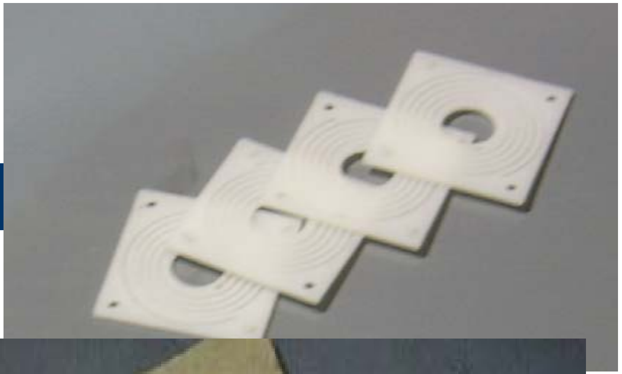
CORNELL

System in Action

Computational Synthesis Lab

CORNELL

Near Term Goals



- SFF Actuators
  - Electroactive Polymer Actuators
  - Extruded solenoid
- Power storage
  - Printable Zinc-air battery
- Controls / Electronics
  - Mechanical switches
  - Resistors
  - Capacitors
- Build minimal functional mobile robot!

Computational Synthesis Lab

CORNELL

Conclusion / Recommendation

- Solutions foreseeable for structures, articulation, actuation, conduction
- Key Challenges
  - Develop SFF power storage, control logic
  - Integrate basis set of processes into compact system
  - Develop design paradigms for SFF, complete functional systems
- Our role and plan
  - Seek functional universality
  - 100% automation
  - Fabricate entire functional robot