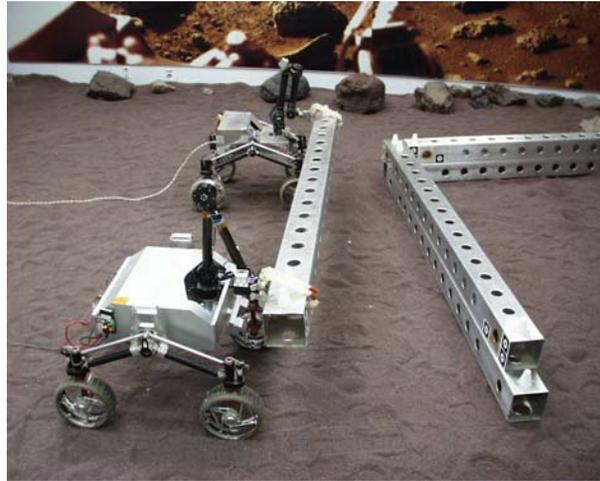


# Robotic Platforms for Implementation of Space Infrastructure



**Space Automation & Robotics Symposium**  
**30-31 March 2005**  
**Naval Research Laboratory**

Brett Kennedy, Ashley Stroupe, Terry Huntsberger,  
Avi Okon, Hrand Aghazarian

Jet Propulsion Laboratory,  
California Institute of Technology



# To-Do List

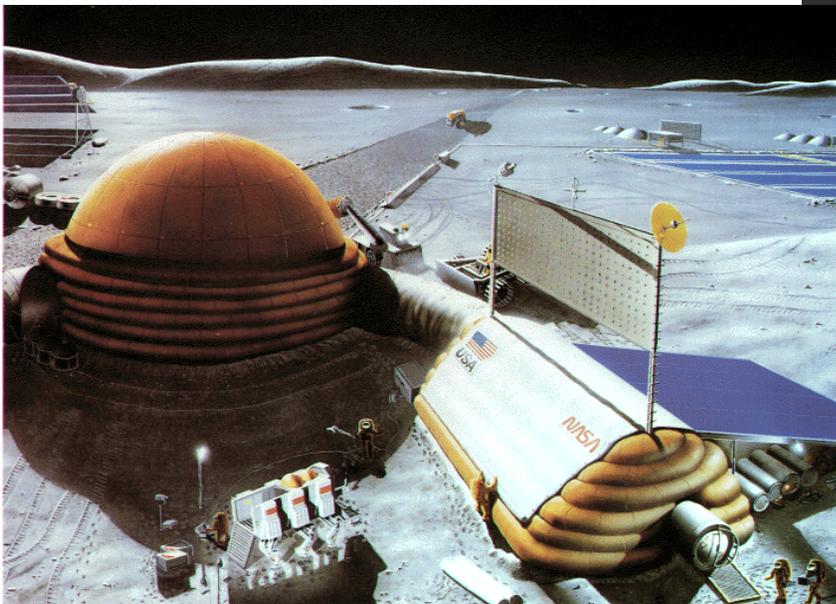
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- Motivation for space construction robots
- Philosophy of space construction robots
- Robotic Construction Crew (RCC) platforms
- Lemur II platform
- Common System Elements

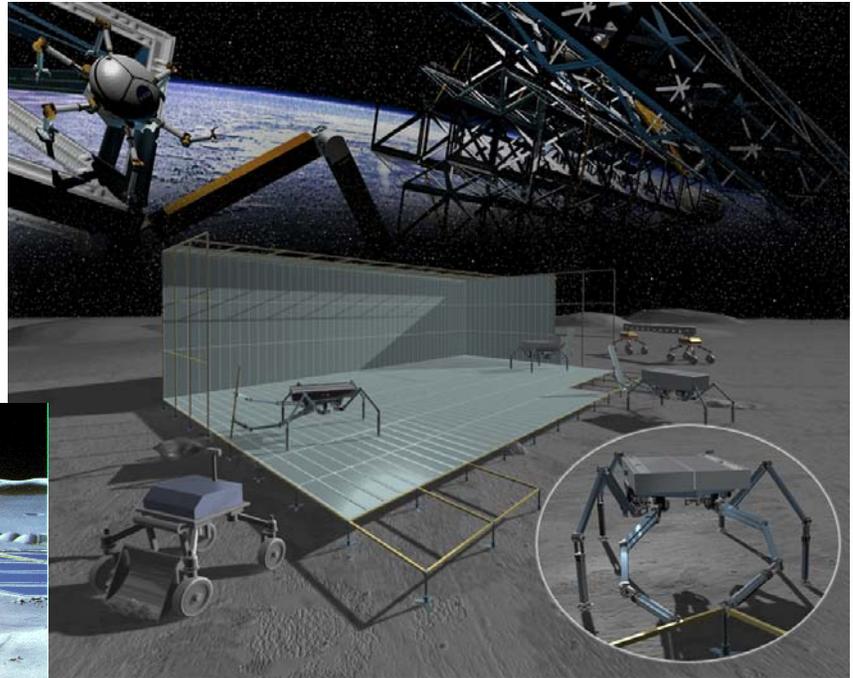
# Motivation: Surface Outpost Construction

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- Cooperative teams:
  - Large-scale
  - Many different tasks
  - Efficient and reliable



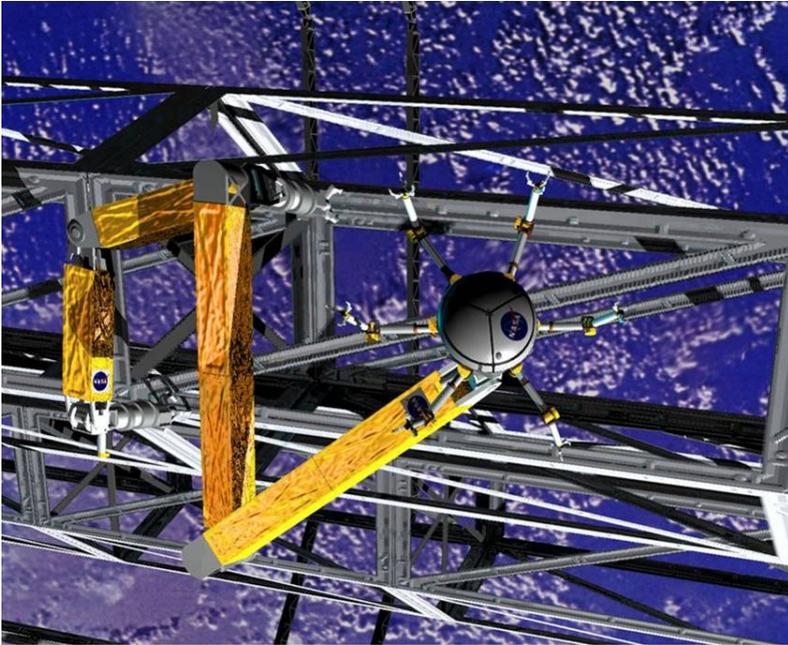
JSC Artist's conception of deployable lunar habitat



JPL Artist's conception of robotic construction

# Motivation: On-Orbit Construction

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Artist's conception of on-orbit construction

- Sustained operations:
  - Mobility on delicate structures
  - Manipulation on delicate structures
  - Many different tasks
  - Efficient and reliable

# Philosophy of Space-Construction Robots

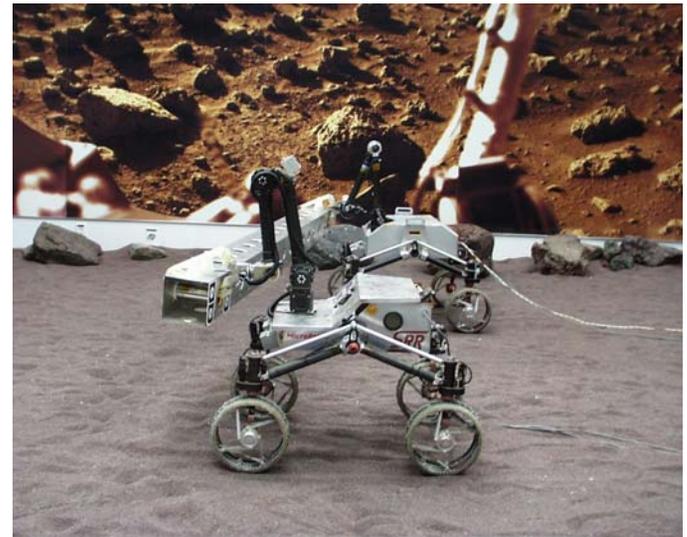
- Putting stuff up is expensive
- There are “un-preplannable” problems
  - micrometeorites make odd holes
- Ergo: Operational flexibility is important
  - smart (Ever gotten an ant to do something useful? Ever needed to build an ant hill?)
  - dexterous (don't maintain with cranes)
  - reconfigurable (unexpected jobs, bang-for-buck)
  - multi-purpose features



# Challenges

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- Maintaining rigid formations and performing precision motion in natural terrain or microgravity
- Moving and working in situations where force (both strong and weak) is important
- Fusing noisy and limited sensing (vision, motion, force-torque)
- Heterogeneous robots
- Limited processing



Robotic Construction Crew, JPL

# Robotic Construction Crew (RCC)

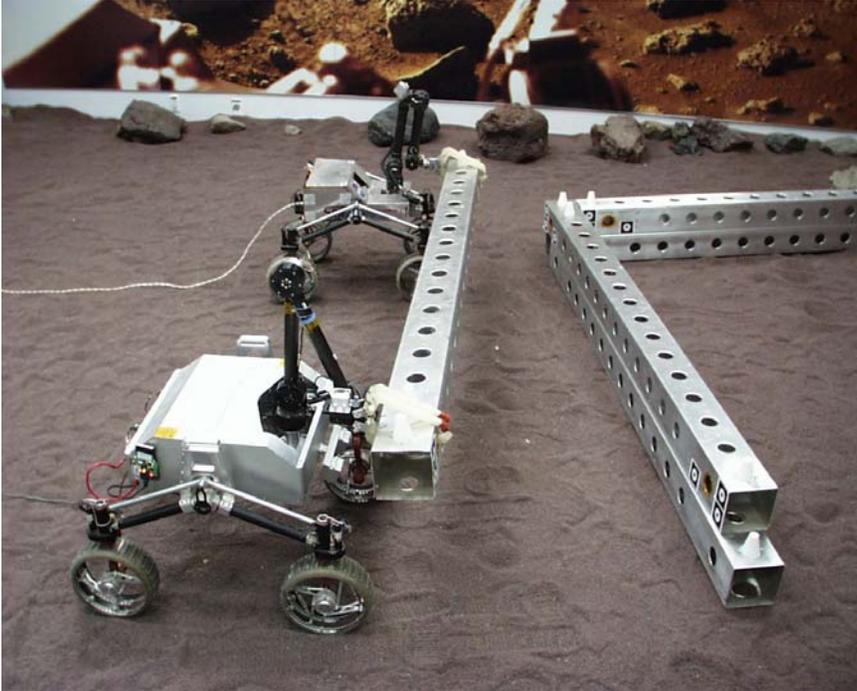
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Robotic Construction Crew approach  
a beam for pick-up

# Robotic Construction Crew

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RCC robots approach the structure for drop-off

- Force-torque feedback helps maintain formation and prevent catastrophic failures

- Leader-follower control ensures common actions and parallel execution



The RCC structure is representative of future surface infrastructure

# RCC Task Video

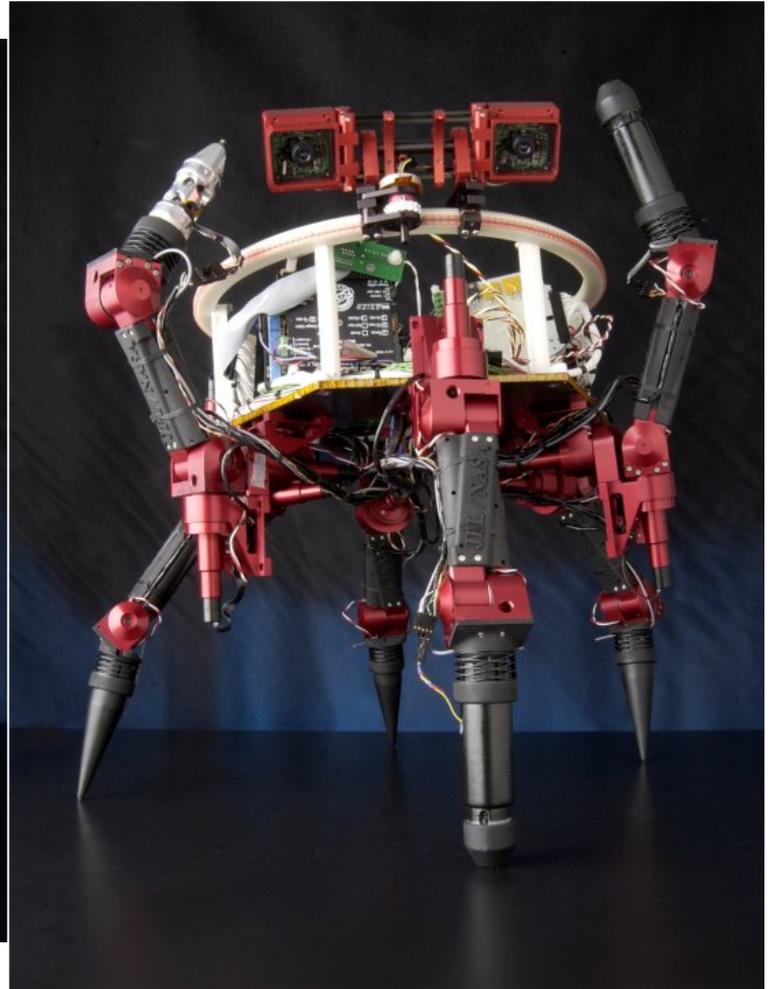
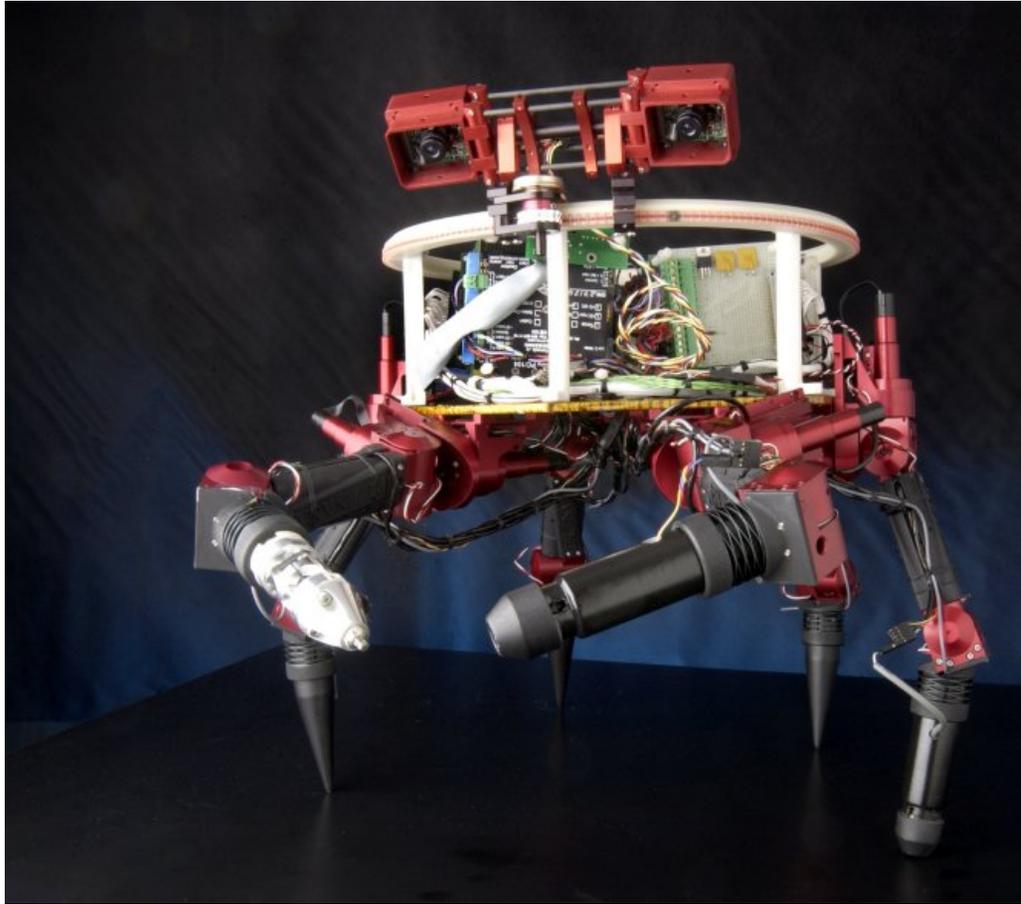
## Robotic Construction Crew



JPL

# Lemur II

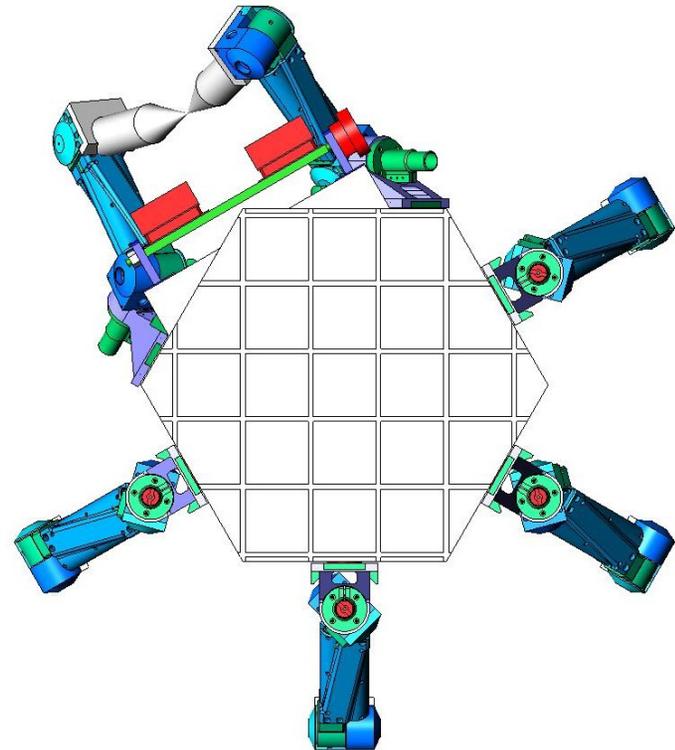
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# Platform Layout

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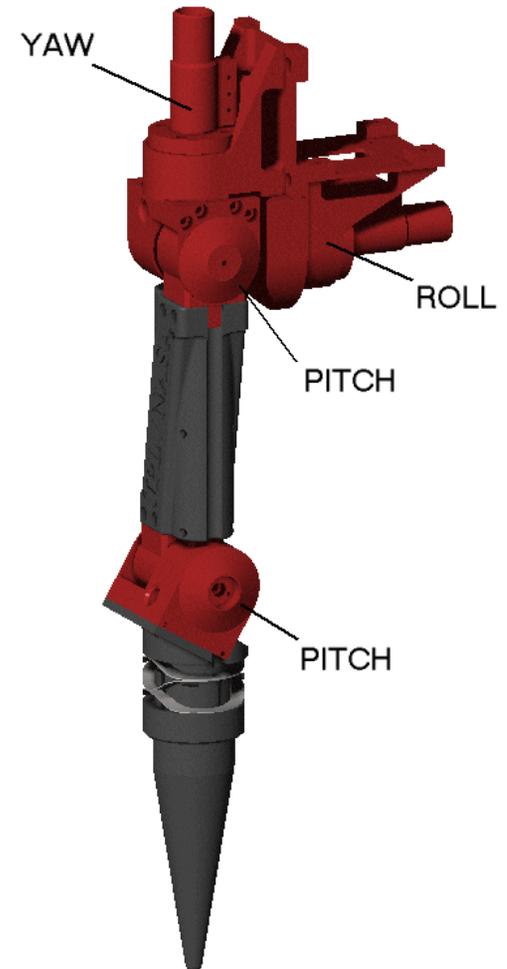
- Axisymmetric
  - Omni-directional mobility (in plane)
  - Omni-directional manipulation (in plane)
  - Omni-directional vision (in plane)
- 6 limbs
  - 2 minimum for manipulation
  - 3 minimum for zero-moment stance
  - 1 spare



# Limb Design

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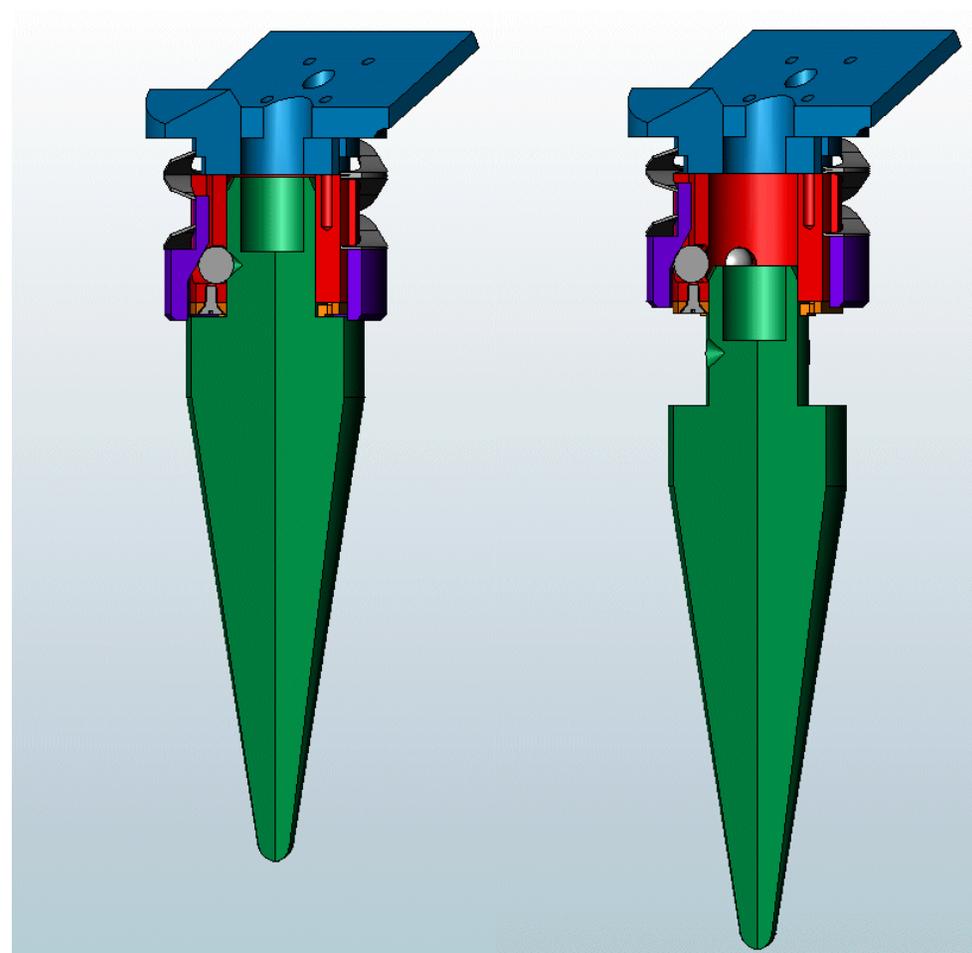
- 4 degrees-of-freedom
- Kinematically spherical shoulder plus knee
- 2 in-line joints
  - Shoulder roll and yaw
  - Infinite mechanical travel
- 2 right-angle drive joints
  - Shoulder pitch and knee
  - $\pm 90^\circ$  mechanical travel
- Tool changeout
- Force feedback
- Significant use of rapid prototyping



# Quick-Connect

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- Snap-in connection
- Inline load washer
  - Provides axial force feedback
- Inherent torque limiting
- Compatible with electrical connectors

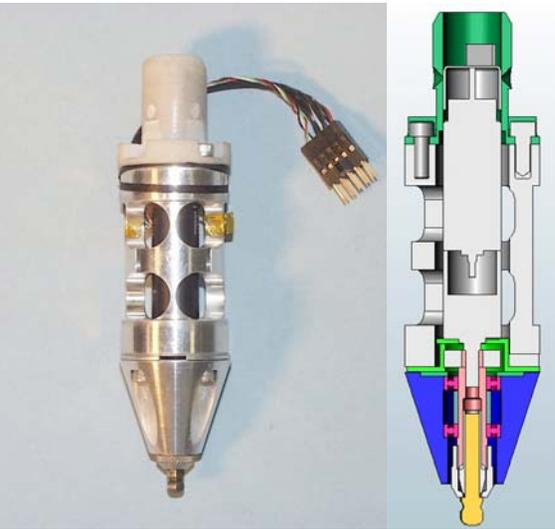


Engaged

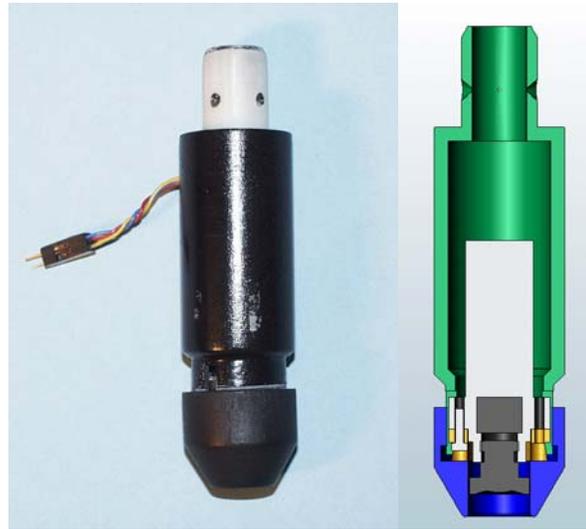
Released

# Tool Design

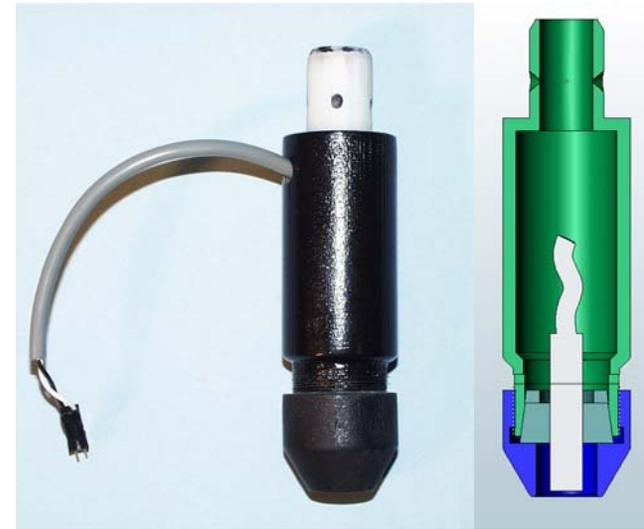
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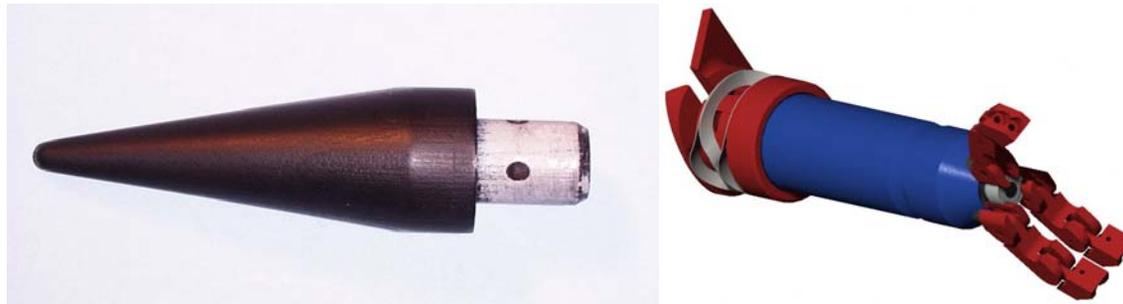
Rotary Driver



Palm-cam



Task Light



Basic Tool

# LEMUR's Big Picture

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**LEMUR IIa**

**January 24, 2005**

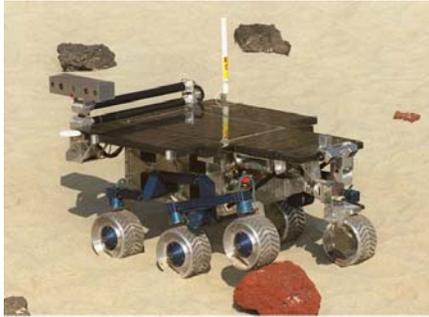
# Common System Elements

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*All or part of the following elements have been implemented on more than 14 robotic platforms*

- Avionics/Electronics
- Stereo Vision systems
- 3-Layer Software Architecture
- Application software (not an exhaustive list)
  - Low-level control
  - Machine Vision
  - Behavior-based planner

# Other Examples of Robot Platforms

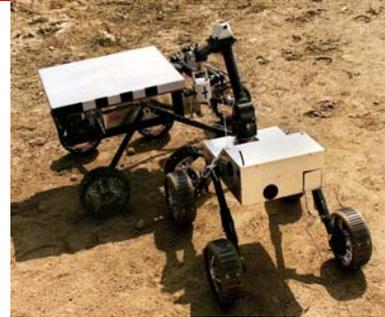


P-50243 ac FIDO Rover Robert M. Brown, JPL Photolab

### FIDO



### MER Egress Rover



### Sample Return Rover

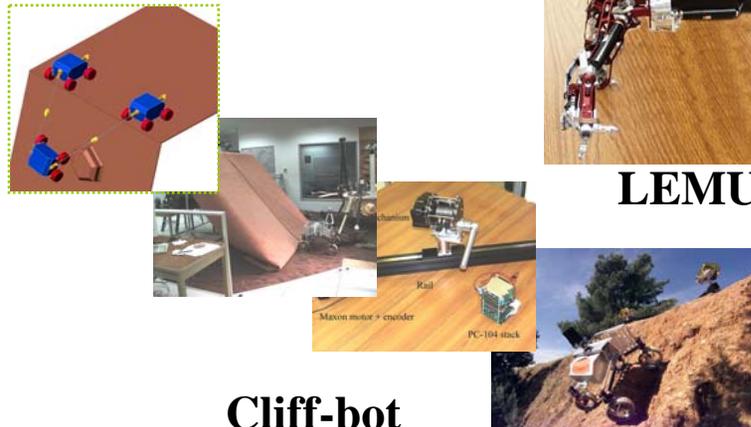


### Inflatable Rover

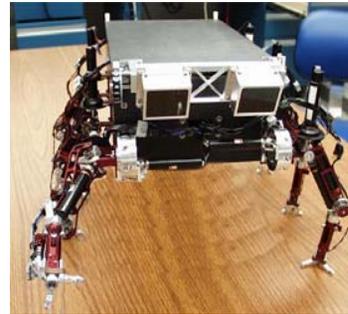


D2002\_1107\_B264 - MER Mobility Tests Robert M. Brown, JPL Photolab

### MER (testing)



### Cliff-bot System



### LEMUR I

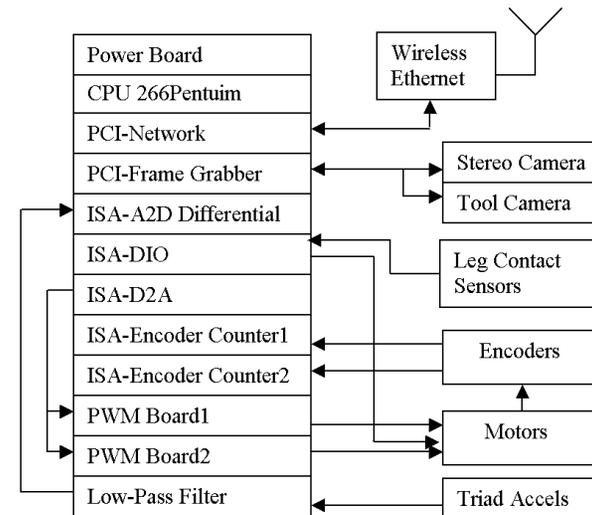


### All Terrain Rover

# Avionics/Electronic Hardware

- Qualified as Flight Electronic Ground Support Equipment
- PC-104 format stack
- Modular
  - Additional boards expand I/O, motor drivers, etc...
- Driver boards built around current-control chips

The stack in LEMUR I



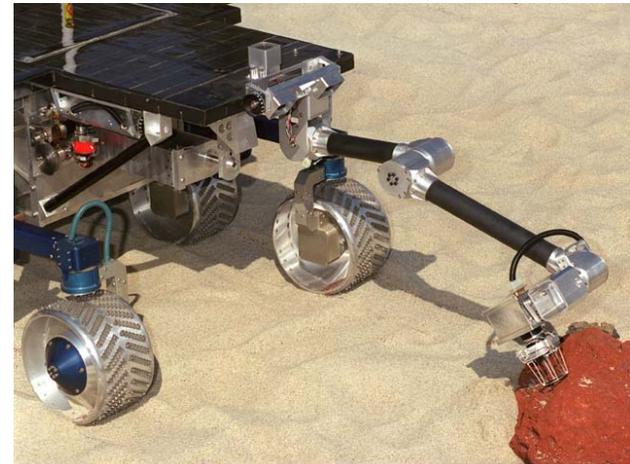
A functional layout of the stack

# Vision Systems

- Short-range stereo for hazard detection
- Long-range stereo planning
- Close-up monocular for Science & Inspection



The LEMUR stereo pair can travel along a circular track

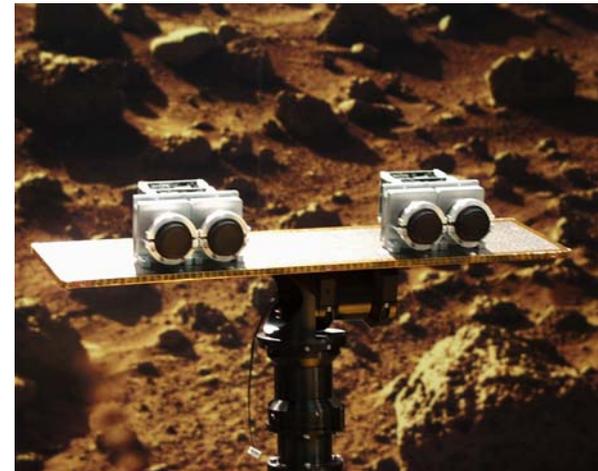


P-50243 dc

FIDO Rover

Robert M. Brown  
JPL PhotoLab

Arm-mounted cameras for inspection

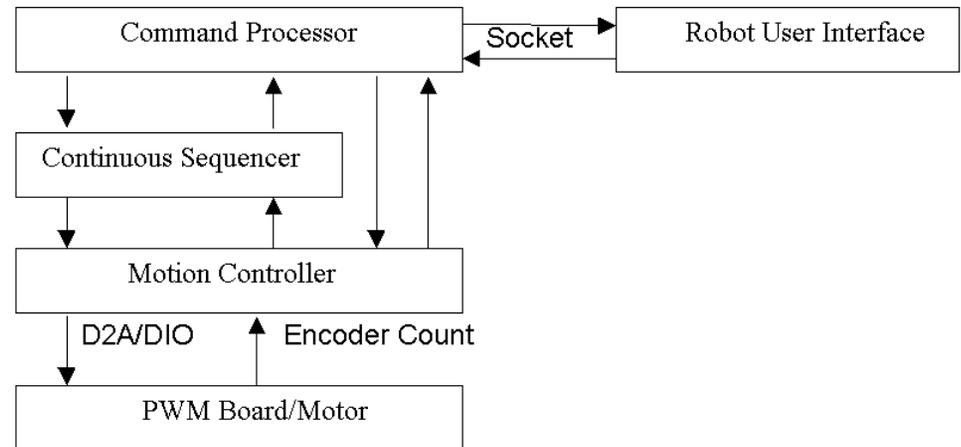
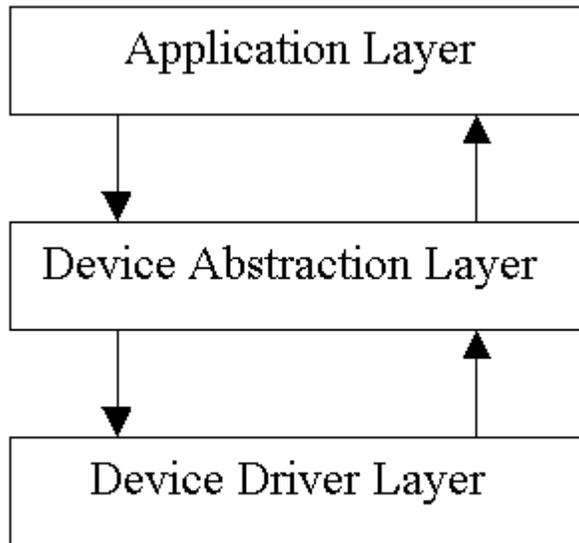


Mast-mounted cameras for navigation

# Software Architecture

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- Real-Time Operating System (VxWorks)
- Modular, 3-layer
- User-friendly (or at least user-tolerant)
- Deterministic

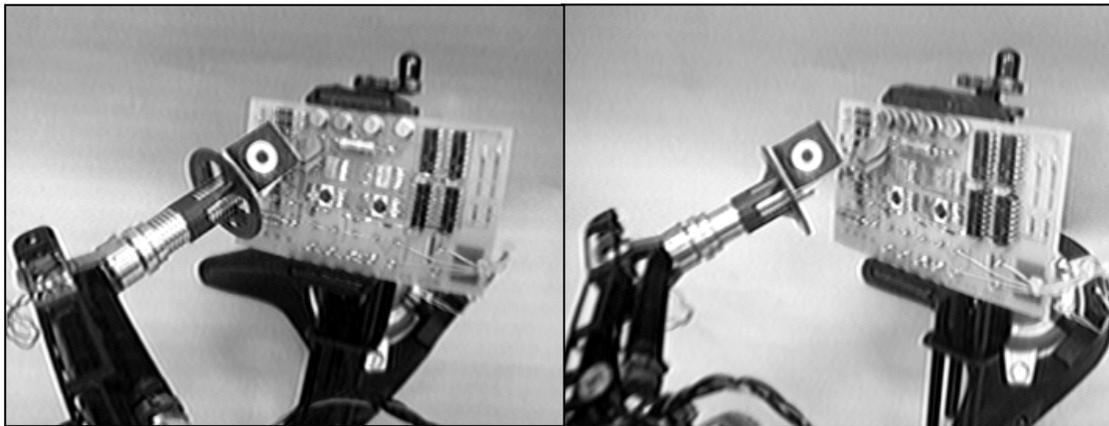


Information flow for motor control

# Application Software

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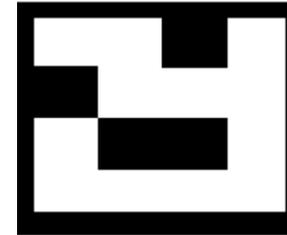
- Hybrid Image Plane Stereo (HIPS)
  - Dynamically updates mapping of camera model to joint-space
  - Allows for system non-linearity and graceful degradation



Left View

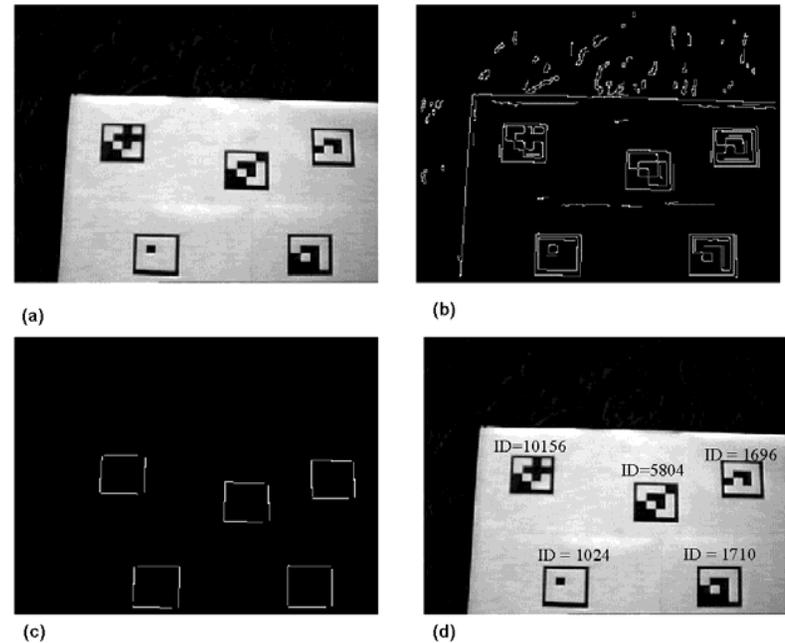
Right View

# Application Software (Cont.)



Sample 16-bit  
Barcode

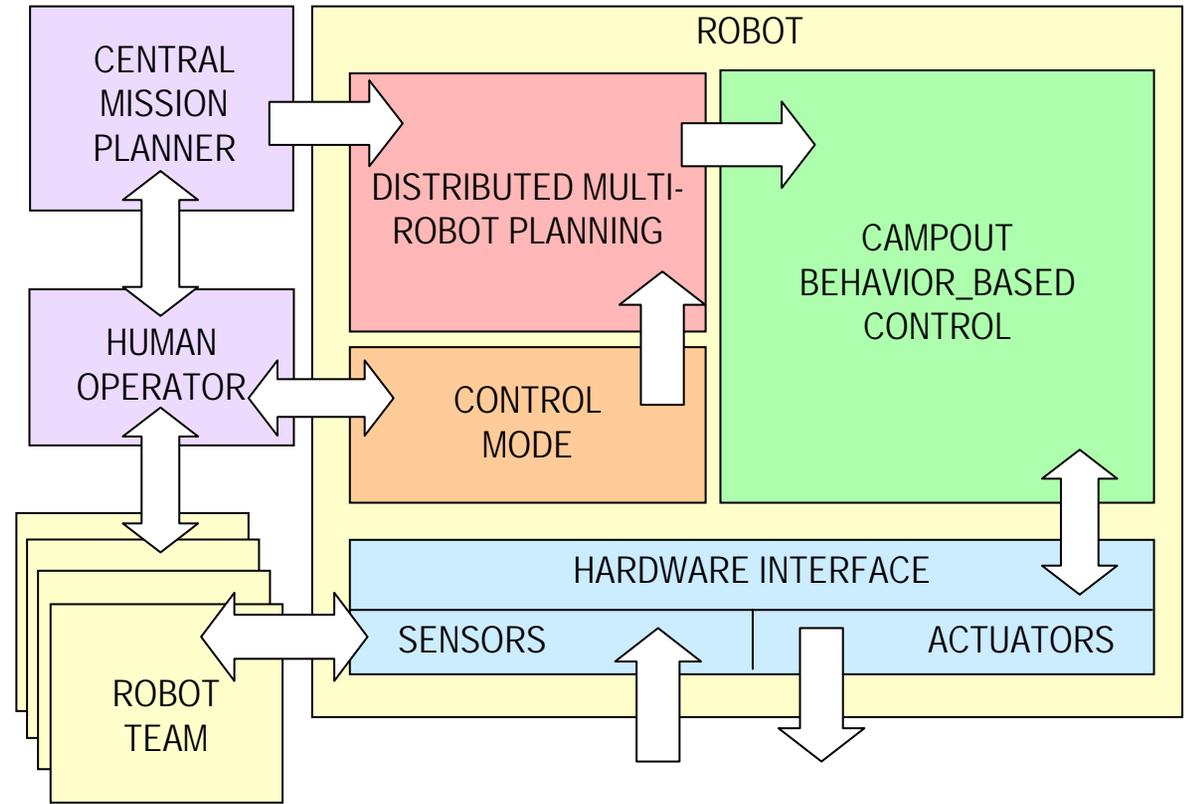
- Barcode data system
  - Passive
  - Non-volatile
  - Provides fiducial marks for orientation



Barcode Extraction  
Sequence

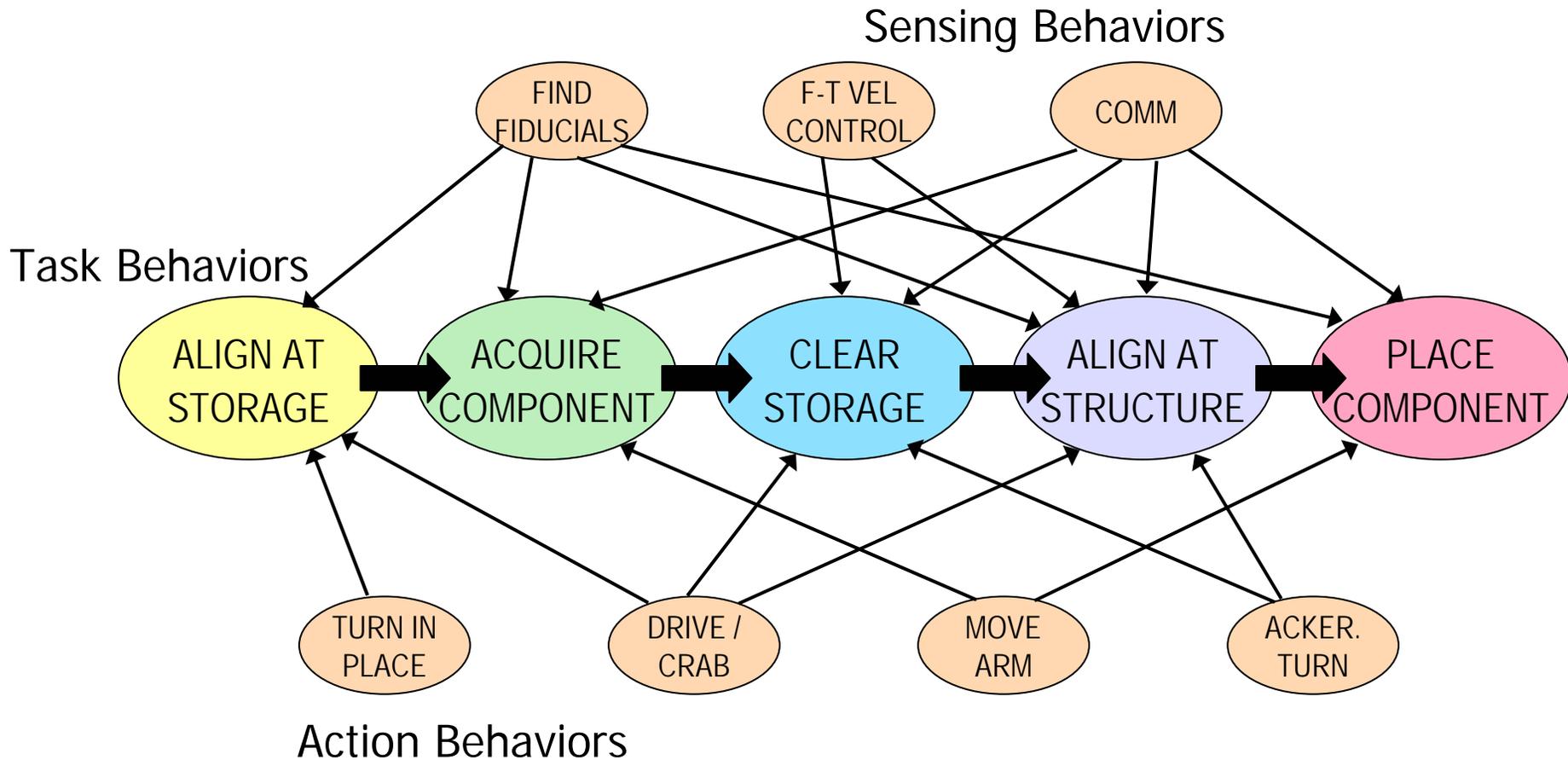
# CAMPOUT Behavior-Based Architecture

- Enables Cooperative and Coordinated operations of multiple agents
- Higher-level functionality is composed by coordination of more basic behaviors
- Decentralized planner
- Scalable



# Task Behavior Network for RCC

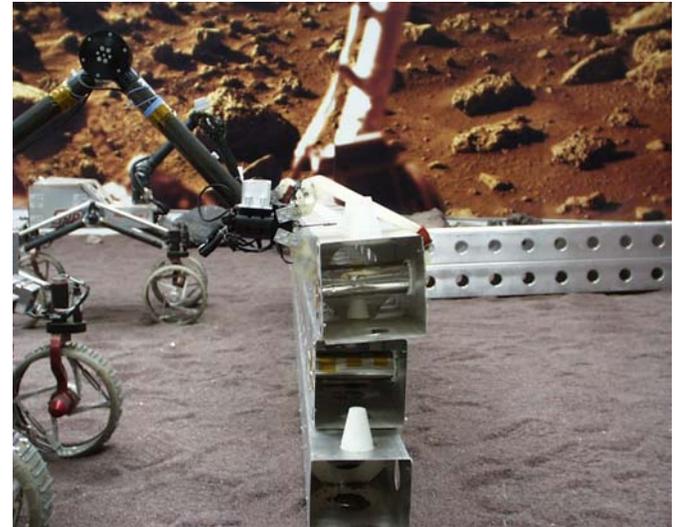
- Implemented in CAMPOUT architecture



# Robotic Construction Crew Summary

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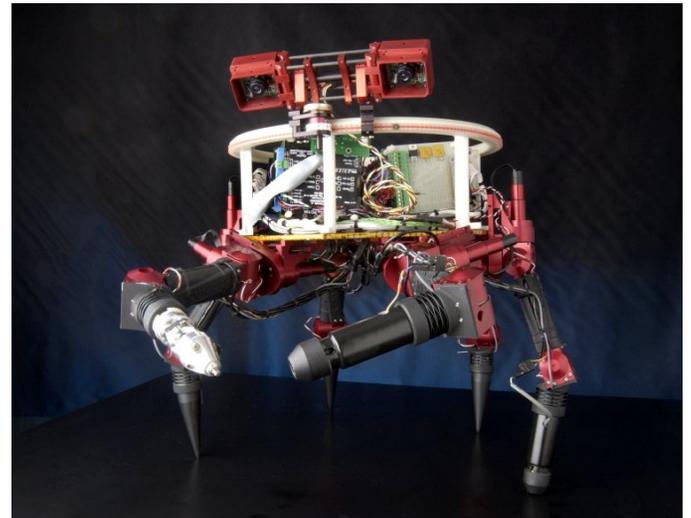
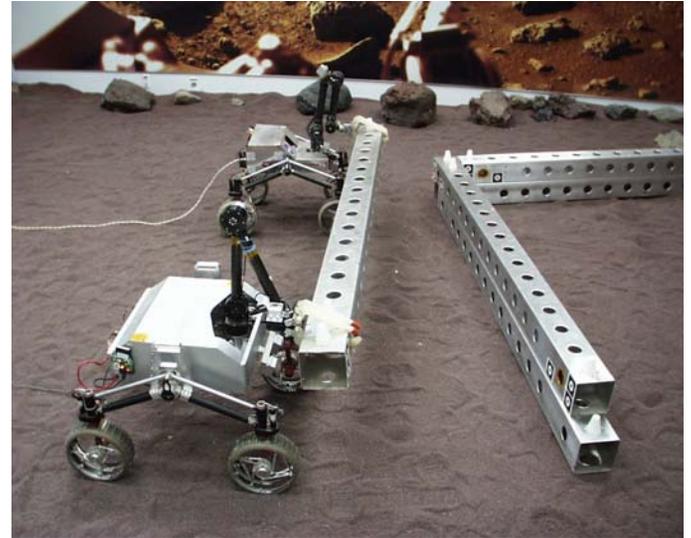
- Capabilities and Results
  - Force-torque feedback and velocity control for formations
  - Synchronization of motions with leader-follower control
  - Fusion of all available sensor data
  - Prevention of catastrophic failures
  - Low failure rate



# Take-Away Slide

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- JPL has a highly developed infrastructure geared toward space assembly and construction
- Guiding design philosophy is operational flexibility
  - Requires brains, joints, and a willingness to change (shape, tools, algorithms)



# Acknowledgements

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- Supporters and Contributors:
  - Paul Schenker, Neville Marzwell, Eric Baumgartner, Tony Ganino, Mike Garrett, Lee Magnone, Matt Robinson, Julie Townsend
  - NASA
  - Caltech

