Frontiers of Human & Machine Teamwork

Human-robot teams for unknown and uncertain environments

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Exploring Unknown and Uncertain Environments

Questions
• How to improve planning?
• How to reduce operational risk?
• How to increase human productivity?

Recon
• Gather data to reduce uncertainty
• Confirm objectives and priorities
• Reduce risk by evaluating hazards

Deployment
• Execute plan informed by recon
• Use recon data for situation awareness

Follow-up
• Informed by both recon and deployment
• Perform close-out or other tasks
Apollo Surface Operations

Harrison “Jack” Schmitt & Lunar Roving Vehicle
(Apollo 17 – December 1972)
What’s Changed Since Apollo?

- Kaguya
- Chandrayaan
- LRO
- 3D simulation
- Phoenix
- Zoë
- MER, Sojourner, Curiosity
- Dante II
- ATHLETE, K10, Chariot

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Exploration destinations

(one-way spacecraft travel times)

International Space Station (2 days)

Moon (3-7 days)

Lagrange Points and other stable lunar orbits (8-10 days)

Mars (6-9 months)

Near-Earth Asteroid (3-12 months)

Future missions will be longer, more complex, & require new technology

Robotics and Mobility
Deep Space Habitation
Advanced Spacesuits
Advanced Space Comm
Advanced Propulsion
Resource Utilization
Human-Robot Systems
Future Human Space Missions

Deep space (beyond Earth orbit)
- Long transit times
- Complex: many phases and critical events
- Small crews must be able to function independent of mission control

Use of “pre-deployment”
- Establish and maintain infrastructure prior to human arrival
- Prepare key mission elements before committing humans

Use of autonomy
- Enhance crew capabilities
- Supplement manual work
- Increase mission performance via in-flight maintenance and automated logistics
Space Mission Constraints

**Communications**
- Intermittent availability
- Variable and asymmetric bandwidth (bps to a few Mbps)
- Round-trip latency: 1 sec (LEO), 10-20 sec (Moon), 20-40 min (Mars)

**Space environment**
- Radiation, difficult illumination, electrical/magnetic fields
- Hard vacuum and temperature extremes
- Abrasive/toxic dust, micrometeoroids, rough terrain

**Limited advance knowledge**
- Remote sensing data limited in view angle, resolution, # of captures
- Little (if any) ground truth and discovery of the unknown

**Human limitations**
- Few people in space for limited periods of time
- Human manual performance limits, endurance,
Human-Robot Teaming

✓ Increase human productivity
✓ Improve mission planning & execution
✓ Perform tedious, repetitive tasks

Robots before humans
  • Reduce uncertainty (recon & prospect)
  • Site prep, deploy equipment, etc.

Robots in support of humans
  • Work in parallel / avoid slowing crew
  • Provide supplementary point of view
  • Carry equipment, take measurements

Robots after humans
  • Close-out work started by humans
  • Perform follow-up work (supplement)
Remote Operation of Space Robots

Operator on Ground
Robot in Space

Operator in Space
Robot on Ground

Operator on Ground
Robot on the Moon

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Robotic Recon Experiment

Objectives

• Test **robotic recon** ahead of crew
• Test **coordinated human-robot** field exploration
• Fold lessons learned into planetary surface science ops concepts

Results

• Captured **requirements** (instruments, comm, nav, etc.) for robotic recon
• Assessed **impact** of robotic recon on traverse planning & crew productivity
• Learned how to improve human productivity & science return

Why Is Recon Useful?

Landing Site

Shorty Crater (Station 4)
Field Experiment (2009)

**Planning**
- Mar 1 – June 1
  - Satellite images
  - Geologic map

**Robot Mission**
- June 14 – 26
  - K10 at BPLF
  - Ground control at NASA LSI

**Replanning**
- July 1 – Aug 15
  - Recon images
  - Terrain models

**Crew Mission**
- Aug 29 – Sep 3
  - LER at BPLF
  - Science backroom at BPLF

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Lunar Analog Site

Black Point Lava Flow (BPLF)

- 65 km N of Flagstaff, AZ
- Analog of the “Straight Wall” (Mare Nubrium / Rupes Recta)
- Basaltic volcanic rocks & unit contacts

![Map of Arizona with Black Point Lava Flow and Flagstaff marked](image1)

![Image of Lunar Surface](image2)

![Image of The “Straight Wall”](image3)
Collected Recon Data

8.5 GB data collected (52 hrs of robotic recon operations)
39 LIDAR scans, 75 GigaPan, and 95 terrain images
Orbital Data

Digital Globe QuickBird (60 cm/pixel)

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Surface Data

GigaPan panorama (180x60 deg, 1.6 Gpixels)

GigaPan panorama close-up

Terrain image (55 microns / pixel)

100% scale
Crew Mission (September 2009)

Space Exploration Vehicle (SEV)
- Prototype pressurized crew vehicle for lunar operations
- Two “suit ports” for rapid (15 min) egress and ingress
- 20 km/hr max, active suspension
- 3.5 x 5 m (wheelbase x length)

Crew A
- Mike Gernhardt & Brent Garry
- W1 (pre-recon) + N2 (post-recon) traverses

Crew B
- Andy Thomas & Jake Bleacher
- N1 (pre-recon) + W2 (post-recon) traverses
Crew Mission (September 2009)
“West” region

- Pre-recon plan was designed to be Apollo-like
  - Rapid area coverage (visit 5 geologic units)
  - Single visit
- Post-recon plan is **significantly different**
  - More flexible & adaptable
  - Recon data supports real-time replanning
- Impact of recon
  - **Reduced** science uncertainty
  - **Improved** target prioritization

An exploration problem

• Never enough time for field work
• “If only I could have…”
  ▪ More observations
  ▪ Additional sampling
  ▪ Complementary & supplementary work

The solution

• Use robots to “follow-up” after humans
• Augment human field work with subsequent robot activity
• Use robots for work that is tedious or unproductive for humans to do

Why is Follow-up Useful?

Landing Site

Shorty Crater

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Shackleton Crater at the South Pole of the Moon is 19 km in diameter and might present H$_2$O ice in surrounding shadowed zones. It is a prime candidate site for human exploration. Haughton Crater, also ~ 20 km in size, is by far the best preserved impact structure of its class on Earth and is located in a H$_2$O ground ice–rich rocky desert. Haughton Crater is an excellent scientific and operational analog for lunar craters such as Shackleton.
Crew Mission (July 2009)

Geologic Mapping
- Document geologic history, structural geometry & major units
- Example impact breccia & clasts
- Take photos & collect samples

Geophysical Survey
- Examine subsurface structure
- 3D distribution of buried ground ice in permafrost layer
- Ground-penetrating radar: manual deploy, 400/900 MHz
Geologic Mapping

- Stratified sediments
- Contact between carbonates
- View East into crater
- Gray carbonate breccia
Geophysical Survey

subsurface ice wedges
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Robot Mission (July 2010)
Robotic Follow-up Results

Geologic Mapping
- **Verified** and **amended** the geologic map in multiple locations
- In some places, robot data was ambiguous, or lacked sufficient detail to re-interpret the map

Geophysical Survey
- **Correlated** surface & subsurface features of “polygons”
- **Determined** average depth of buried ice layer

Conclusion

Many forms of human-robot teaming

- “Robot as tool” is only one model
- Humans and robots do not need to be just co-located or closely coupled
  ▶ Distributed teaming is also important

Concurrent, interdependent operations

- Human-robot interaction is still slow and mismatched (compared to human teams)
- Easy for robots to slow down the human
  ▶ Loosely-coupled teaming (in time and space) should also be employed

Distributed teams

- Require coordination and info exchange
- Require understanding of (and planning for) each teammate’s capabilities
Questions?

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