2018 Workshop on Autonomy for Future NASA Science Missions

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DRM Breakout Report

Lunar Surface Exploration

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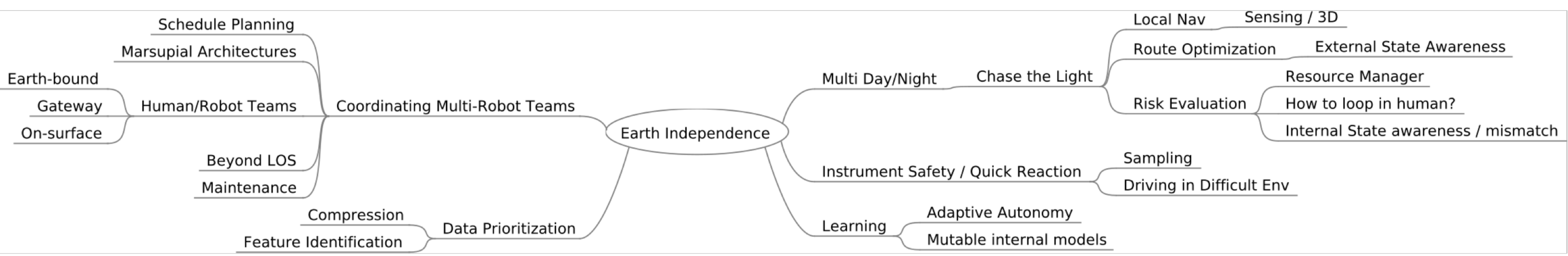
Determining Autonomy Needs

Assumptions:

- Focus on the near-term (late 2020s)
- Accurate landing capability (< 1 km^2)

DRMs:

- Wide Area Sampling
  - Multi-robot exploration
  - Missions with human interaction
- Polar Explorer



Autonomous Local Navigation

ITEM	Question	Response
A	Describe a specific Design Reference Mission objective or mission requirement to be addressed with autonomy.	- Long Duration / High Speed Rover (Could be a Sun-synchronous platform with limited communication to Earth during some periods) - Polar explorer (Some limited communication periods)
B	Describe an autonomous capability that could be used to accomplish (A).	- *Long-distance / multi-day autonomous surface navigation with a focus on hazard avoidance* - Explore new areas with interesting science where the terrain might be nontrivial topography
C	List the core autonomy technologies needed by (B). Refer to the Autonomous Systems Taxonomy table for technologies.	Sensing and perception (1.1), state estimation and monitoring (1.2), knowledge and model building (1.3), hazard assessment (1.4), mission planning and scheduling (2.1), activity and resource planning and scheduling (2.2), motion planning (2.3), execution and control (2.4)
D	List any other supporting technologies needed by (B), including assets from potential commercial partners.	*Lidar* *Stereo cameras* *IMU*
E	List any related/relevant R&D projects for (C) and (D). Include references (e.g. citation, URL, name of PI, name of org or private sector company performing the research).	*Anyone doing SLAM and other self driving technologies (lots of places)* *Avoiding pointing sensor at the Sun (AMES)*
F	Is (B) enabling or enhancing for (A)? Can this capability only be enabled with autonomous technology? Explain.	Enabling exploration of surface areas that have limited communication with Earth Enhancing autonomous navigation and increasing speeds and reducing times between commands Enhancing off-line decision making
G	Provide a rough estimate of the development costs for (B), and describe how (B) will increase (or decrease) overall mission cost (development or ops). Cost can be $, schedule, staffing, etc.	Leverage current technology and adapt to the lunar environment and requirements This may require a focused technology program to further develop the technology (increase TRL)
H	Describe how (B) will increase (or decrease) mission risk (development or ops). Risk can be performance, schedule, etc.	Reduce risk by selecting safe traverses (avoid slope and hazardous surface features when possible) Monitor rover health (e.g. solar) Reduce risk of mission failure due to limited operation time
I	Optionally list any comments, key points, questions, etc. not covered in the sections above.	Planning for sensor limitations (Sun in FOV/High Backscatter) Other sensor technology for detecting hazards

Multiple Robot / Assets Working in Coordination

ITEM	Question	Response
A	Describe a specific Design Reference Mission objective or mission requirement to be addressed with autonomy.	Wide area sampling (exhaustive SPAB) Comprehensive local site assessment (volatiles mapping) Simultaneous measurements (for transient/dynamic phenomena or for things that require measurements from multiple locations) Exploration into “comm denied” areas (into lunar pits/skylights/tubes)
B	Describe an autonomous capability that could be used to accomplish (A).	Multiple robots / assets (on surface, in orbit, in combination, possibly heterogeneous) all working in coordination to accomplish a joint objective / task.
C	List the core autonomy technologies needed by (B). Refer to the Autonomous Systems Taxonomy table for technologies.	2.1 Mission Planning and Scheduling 2.2 Activity and Resource Planning and Scheduling 2.5 Fault Diagnosis and Prognosis 3.1 Joint Knowledge and Understanding 3.2 Behavior and Intent Prediction 3.3 Goal and Task Negotiation 3.4 Operational Trust Building 4.1 Verification and Validation Assumption: focusing on teaming aspects (technology that enables autonomous teaming), rather than what is needed by individual robots
D	List any other supporting technologies needed by (B), including assets from potential commercial partners.	Might need: cross-link comm, team-level localization, cooperative power sharing/distribution (wired or beamed power transfer)
E	List any related/relevant R&D projects for (C) and (D). Include references (e.g. citation, URL, name of PI, name of org or private sector company performing the research).	Lots of R&D on multi-robot teams (e.g, robot soccer, DoD swarm projects such as DARPA OFFSET)
F	Is (B) enabling or enhancing for (A)? Can this capability <u>only</u> be enabled with autonomous technology? Explain.	Enabling, given the assumption that this has to be accomplished without Earth in the “ops loop”.
G	Provide a rough estimate of the development costs for (B), and describe how (B) will increase (or decrease) overall mission cost (development or ops). Cost can be $, schedule, staffing, etc.	Unknown at this time. Even for “build to print” missions (e.g., Mars 2020 as a “build to print” version of MSL) the cost “savings” may be limited. Overall question: Is the cost of building, deploying, and operating *N* robots = *N x cost ($)* of one robot? Or, is this more (greater complexity) or less (benefits of “scale”).
H	Describe how (B) will increase (or decrease) mission risk (development or ops). Risk can be performance, schedule, etc.	Depends on mission objectives: might reduce risk because the approach is more likely to either cover more locations (than a single robot), or be able to better reach an objective (get into a lava tube with comm), or to accomplish multiple objective simultaneously. BUT, this could increase risk because of potential n^2 interactions (and thus increased complexity over single system missions).
I	Optionally list any comments, key points, questions, etc. not covered in the sections above.	We assume that multiple robots are too costly to operate from Earth, or that it is more efficient or effective for the robots to work autonomously (rather than with humans in the loop). OR these robots have to operate when humans cannot be “in the ops loop” (e.g., no comms from the Moon to Earth, Gateway, etc). May need R&D on architecture – trade-off between distributed / centralized team control (particularly when the individual robots could be heterogeneous or when there are dynamic considerations)

Planning and Coordination in Multi-Robot Human-Robot Teams

ITEM	Question	Response
A	Describe a specific Design Reference Mission objective or mission requirement to be addressed with autonomy.	Wide-area / multi-site sampling in the Marius Hills volcanic crater region
B	Describe an autonomous capability that could be used to accomplish (A).	Planning and coordination in heterogeneous multi-robot human-robot teams to improve efficiency of sampling and avoid terrain hazards that could result in loss of instrument(s)
C	List the core autonomy technologies needed by (B). Refer to the Autonomous Systems Taxonomy table for technologies.	*Sensing and perception (1.1), state estimation and monitoring (1.2), knowledge and model building (1.3), mission planning / scheduling(2.1), Activity and resource planning / scheduling (2.2), Fault diagnosis and prognosis (2.5), Fault response (2.6), Learning and Adapting (2.7), Collaboration and Interaction (3.x), Test and Evaluation (4.2)*
D	List any other supporting technologies needed by (B), including assets from potential commercial partners.	Scheduling / planning in high-dimensional state spaces, with uncertain observations of environment and human performance, team actions, and shared beliefs.
E	List any related/relevant R&D projects for (C) and (D). Include references (e.g. citation, URL, name of PI, name of org or private sector company performing the research).	Contemporary research in belief space planning and human-robot teaming
F	Is (B) enabling or enhancing for (A)? Can this capability only be enabled with autonomous technology? Explain.	Enhancing – while the mission could be accomplished with a single robot, multi-robot operations with human interactions have the potential to reduce resource requirements
G	Provide a rough estimate of the development costs for (B), and describe how (B) will increase (or decrease) overall mission cost (development or ops). Cost can be $, schedule, staffing, etc.	Leverage current technology adapting to lunar environment and requirements through a focused technology program to increase the TRL.
H	Describe how (B) will increase (or decrease) mission risk (development or ops). Risk can be performance, schedule, etc.	Decrease risk due to better resource allocation strategies
I	Optionally list any comments, key points, questions, etc. not covered in the sections above.	May leverage contemporary work in natural language/understanding, psychology of human-robot teams, human state/performance estimation

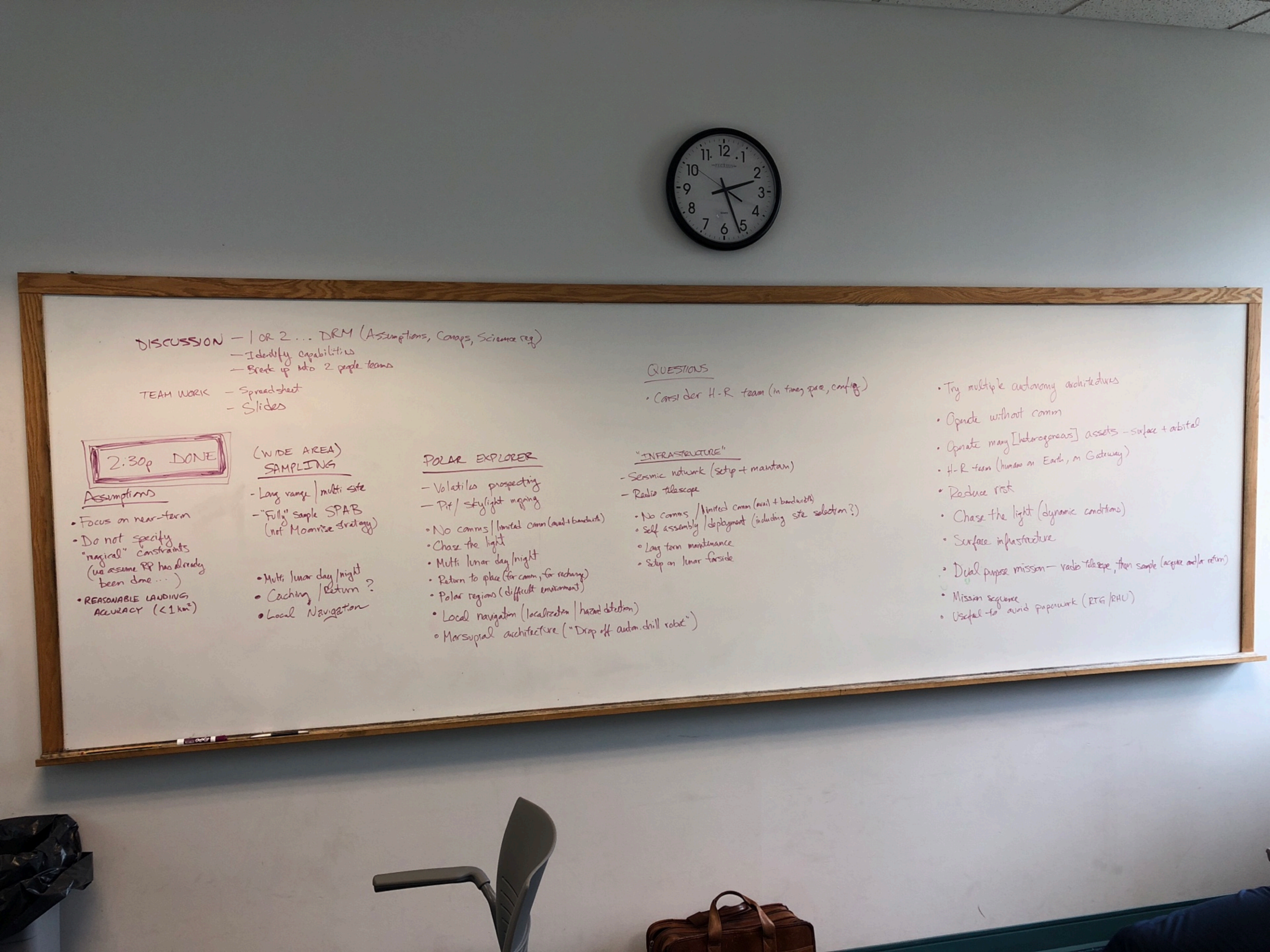
Adaptive Autonomy

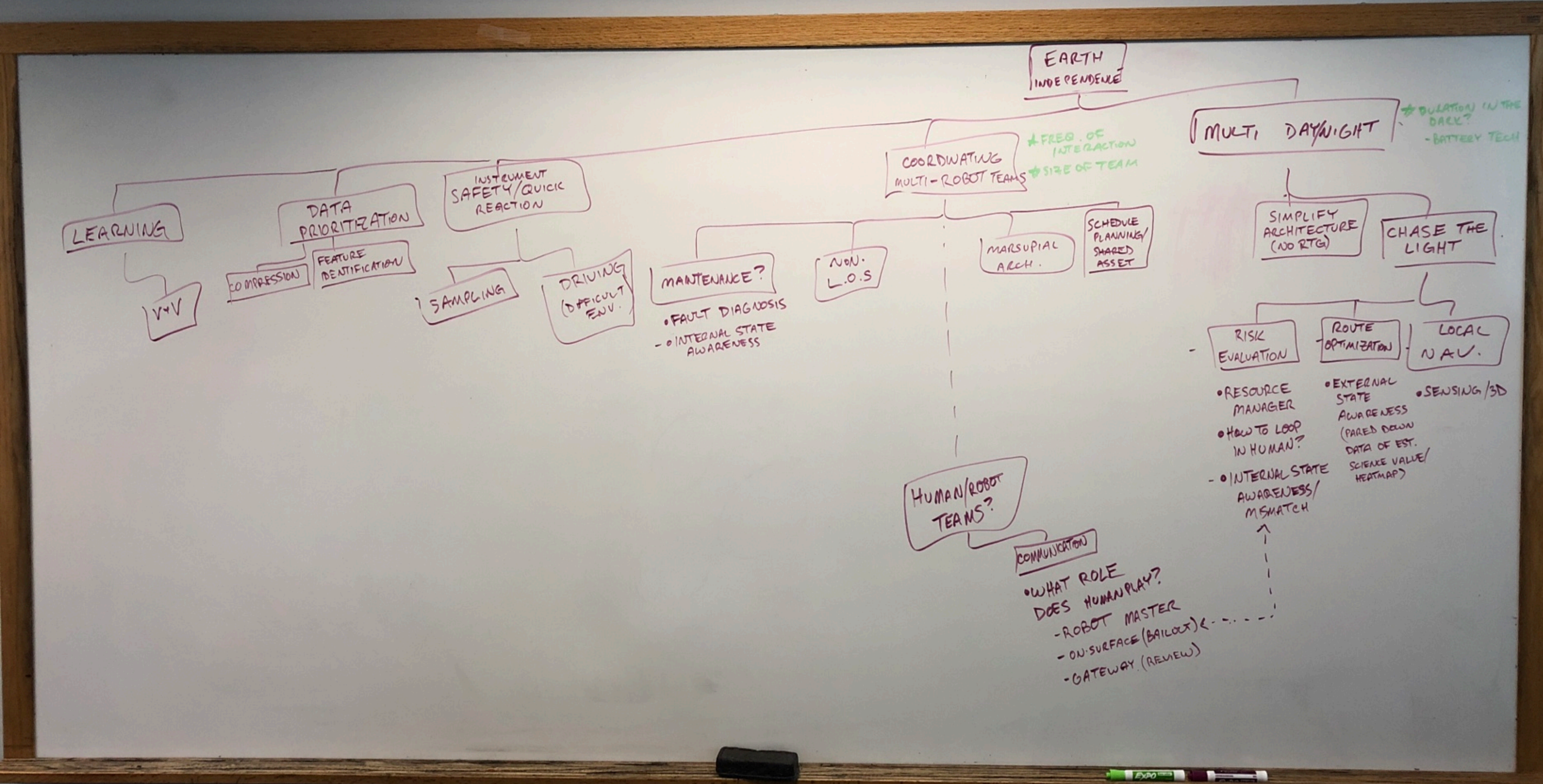
ITEM	Question	Response
A	Describe a specific Design Reference Mission objective or mission requirement to be addressed with autonomy.	- Long Duration/High Speed Rover (Could be a Sun-synchronous platform with limited communication to Earth during some periods) - Polar explorer (Some limited communication periods) - Any other mission with multi-site science, periods of autonomous operation, or long operational life
B	Describe an autonomous capability that could be used to accomplish (A).	Dynamic response based on experiential (reinforcement) learning. Internal/external state awareness. - Improve science site selection with pattern recognition - Improve out-of-comms navigation/fault recovery based on in-comms experience - Improve autonomous decision-making to better avoid risk - Model system performance and compare to baseline to track degradation over time
C	List the core autonomy technologies needed by (B). Refer to the Autonomous Systems Taxonomy table for technologies.	Sensing and perception (1.1), State estimation and monitoring (1.2), Knowledge and model building (1.3), event and trend identification (1.5), Anomaly detection (1.6), Execution and control (2.4), Fault diagnosis and prognosis (2.5), Fault response (2.6), **Learning and adapting (2.7)**, Modeling and simulation (4.4)
D	List any other supporting technologies needed by (B), including assets from potential commercial partners.	Lots of computing power Machine learning platforms/architectures
E	List any related/relevant R&D projects for (C) and (D). Include references (e.g. citation, URL, name of PI, name of org or private sector company performing the research).	Broad research efforts exist across both public and private communities.
F	Is (B) enabling or enhancing for (A)? Can this capability <u>only</u> be enabled with autonomous technology? Explain.	Enhancing – learned activities can improve likelihood of selecting interesting science sites, improve recovery operations based on successful past activities (including human interventions), allow more accurate assessment of system capabilities as degradation proceeds, and optimize performance over time (eliminate repeated mistakes).
G	Provide a rough estimate of the development costs for (B), and describe how (B) will increase (or decrease) overall mission cost (development or ops). Cost can be $, schedule, staffing, etc.	Leverage current technology and adapt to the lunar environment and requirements This may require a focused technology program to further develop the technology (increase the TRL)
H	Describe how (B) will increase (or decrease) mission risk (development or ops). Risk can be performance, schedule, etc.	Reduce risk by better characterizing/utilizing system capabilities Reduce risk by protecting assets more effectively Reduce risk of wasting science resources/mission life
I	Optionally list any comments, key points, questions, etc. not covered in the sections above.	

Candidate DRM White Papers

Propose one or more white papers that should be published in order to define and promote the key autonomy innovations identified by this working group.

- Autonomy for transformative exploration of the lunar surface
  - Autonomous Local Navigation
  - Multiple Robot / Assets Working in Coordination
  - Planning and Coordination in Multi-Robot Human-Robot Teams
  - Adaptive Autonomy


DISCUSSION — 1 OR 2 ... DRM (Assumptions, Conops, Science req)
— Identify capabilities
— Break up into 2 people teams
TEAM WORK — Spreadsheet
— Slides
2:30p DONE
Assumptions
• Focus on near-term
• Do not specify "magical" constraints (we assume RP has already been done ...)
• REASONABLE LANDING ACCURACY (< 1 km²)
(WIDE AREA) SAMPLING
- Long range | multi site
- "Fully" sample SPAB (not Moonrise strategy)
• Multi lunar day / night
• Caching / Return ?
• Local Navigation
POLAR EXPLORER
— Volatiles prospecting
— Pit / skylight mapping
• No comms | limited comm (avail + bandwidth)
• Chase the light
• Multi lunar day / night
• Return to place (for comm, for recharge)
• Polar regions (difficult environment)
• Local navigation (localization | hazard detection)
• Marsupial architecture ("Drop off auton. drill robot")
QUESTIONS
• Consider H-R team (in time, space, config)
"INFRASTRUCTURE"
- Seismic network (setup + maintain)
- Radio telescope
• No comms / limited comm (avail + bandwidth)
• Self assembly / deployment (including site selection?)
• Long term maintenance
• Setup on lunar farside
• Try multiple autonomy architectures
• Operate without comm
• Operate many [heterogeneous] assets - surface + orbital
• H-R team (humans on Earth, on Gateway)
• Reduce risk
• Chase the light (dynamic conditions)
• Surface infrastructure
• Dual purpose mission — radio telescope, then sample (acquire and/or return)
• Mission sequence
• Useful to avoid paperwork (RTG / RHU)


EARTH INDEPENDENCE
COORDINATING MULTI-ROBOT TEAMS
* FREQ. OF INTERACTION
* SIZE OF TEAM
MULTI DAY/NIGHT
* DURATION IN THE DARK?
- BATTERY TECH
LEARNING
V+V
DATA PRIORITIZATION
COMPRESSION
FEATURE IDENTIFICATION
INSTRUMENT SAFETY/QUICK REACTION
SAMPLING
DRIVING (DIFFICULT ENV.)
MAINTENANCE?
• FAULT DIAGNOSIS
- • INTERNAL STATE AWARENESS
NON. L.O.S
MARSUPIAL ARCH.
SCHEDULE PLANNING/ SHARED ASSET
HUMAN/ROBOT TEAMS?
COMMUNICATION
• WHAT ROLE DOES HUMAN PLAY?
- ROBOT MASTER
- ON-SURFACE (BAILOUT)
- GATEWAY (REVIEW)
SIMPLIFY ARCHITECTURE (NO RTG)
CHASE THE LIGHT
RISK EVALUATION
• RESOURCE MANAGER
• HOW TO LOOP IN HUMAN?
- • INTERNAL STATE AWARENESS/ MISMATCH
ROUTE OPTIMIZATION
• EXTERNAL STATE AWARENESS (PARED DOWN DATA OF EST. SCIENCE VALUE/ HEATMAP)
LOCAL NAV.
• SENSING/3D