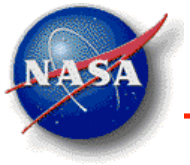
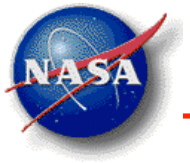


Collaborative Human-Robot Science Exploration on the Lunar Surface

LEAG Annual Meeting
October 1-5, 2007
"Enabling Exploration: The Lunar Outpost and Beyond"

Chuck Weisbin, Alberto Elfes, W Lincoln, Jeff H. Smith,
Hook Hua, Joe Mrozinski, Kacie Shelton

NASA Jet Propulsion Laboratory
Pasadena, CA



Overall Problem Statement

Given:

- A set of proposed LAT-2 missions and tasks to be accomplished
- A proposed set of agents, tools and resources, and their support structure

Compute:

- An appropriate allocation of tasks to agents with their associated resources so as to optimize a given figure of merit
    - Subject to given constraints

Result:

- A timeline showing what tasks are executed, when, and by which agent

Summary Description of Approach

1. Identify
   - **agents** : astronauts on the moon, robots operating autonomously or controlled from earth (i.e. not tying up astronaut time), etc.
   - **activities** (move, carry, deploy),
   - **resources** (tools, vehicles, power, time, etc.)
2. Identify **constraints** (ex: task A has to be done before task B, task C needs a human and a robot, EVA can only last N hours, etc.)
3. Define **figure of merit** to be optimized (ex: minimize EVA time dedicated to outpost construction and maximize science productivity of remaining time)
4. Define **starting configuration state S** (ex: astronauts in LSAM, UPR1 at HZ, etc.)
5. Define **goal configuration state G** (ex: power modules assembled and connected to habitat, etc.)
6. Search for **optimal allocation sequence of tasks** to available agents in parallel and/or sequential order.
   a. Starting from S, generate all the new possible configurations
   b. Evaluate each new configuration using FOM, select best alternative that does not violate any constraint
   c. Repeat until G is reached
   d. This process generates a tree; the optimal task allocation and associated information is given by the path between S and G

Description of the Problem 1

For Mission 5 (year 2021):

60 day mission – plan 1 day of Science tasks

Perform Six Science Tasks at each of Two Sites

(the first 5 km from the habitat, and the second 10 km)

- Rock samples
- Geological Context survey
- Rake sample
- Soil sample
- Drive-tube sample
- Core sample

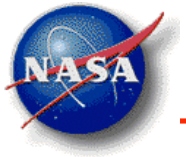
Agents and Resources

Agents available (Mission 5, from the May 2007 mission timeline):

- Astronauts 1 and 2
- MC 2 (tele-operated from Earth)

Resources available

- Pressurized Habitat, combined with MC1
- Hab Module 1
- Tools for the astronauts to conduct science tasks
- MC2 Science Package (coring tool, core storage containers)



Actions

- Actions are defined by the user
- Each action is described using:
  - **Name** of the action: DRIVE
  - **Arguments** to the action (what entities are involved in the action):

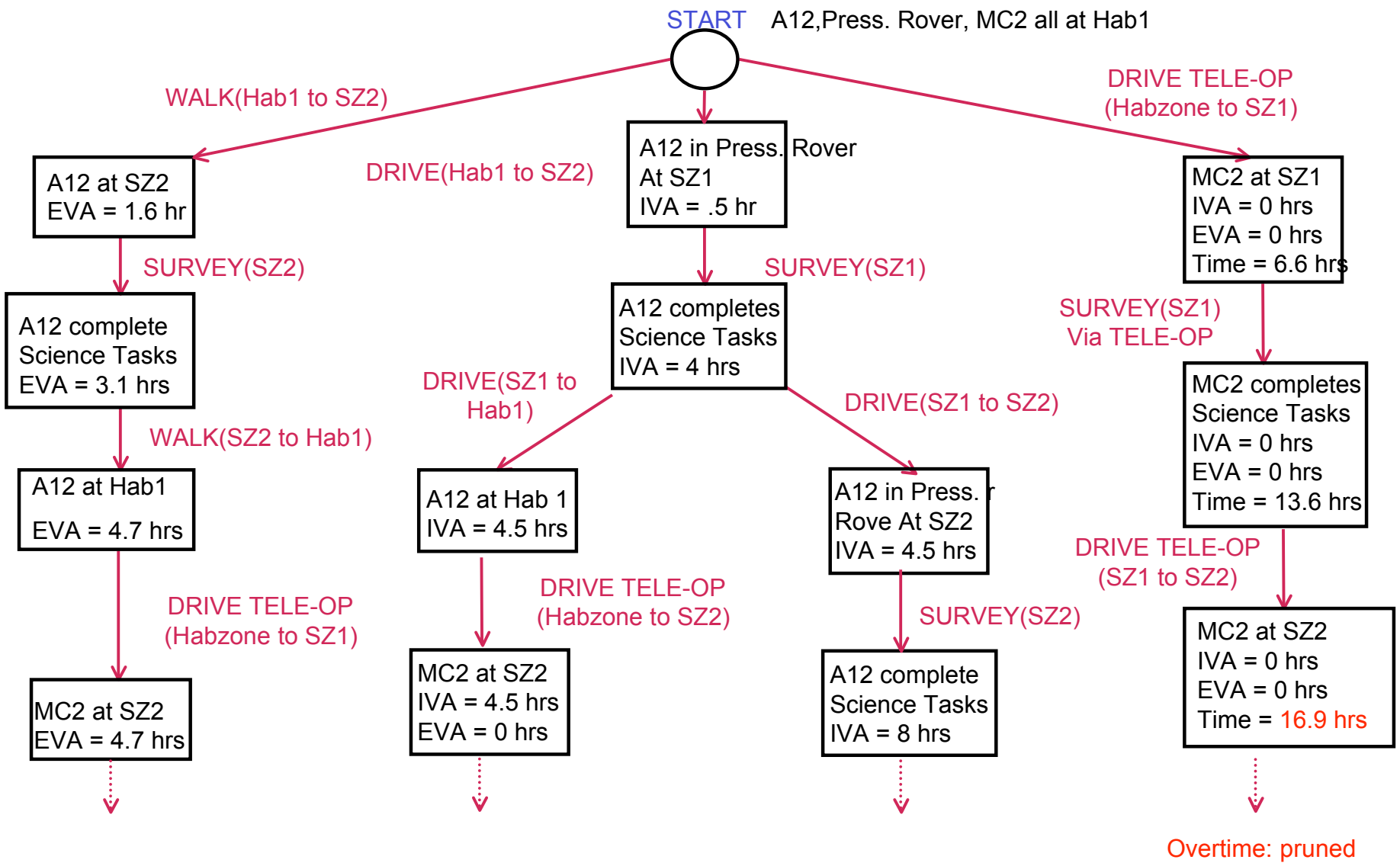
    DRIVE(astronaut A1, vehicle V1, location X, location Y)
  - **Preconditions** (what must hold for the action to be applicable):

    A1.location = V1.location = X
  - **Computational steps** that encode what the action does:

    A1.location := Y; V1.location := Y; A1.evatime = A1.evatime + delta;
  - **Post-conditions** (what must hold after the action was carried out):

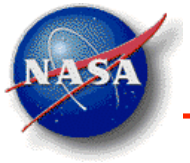
    A1.location = V1.location = Y

Survey Task: Partial Search Graph



Comparing Agent Times

Tasks	EVA Astronaut	IVA Astronaut (estimate)	Earth teleoperated MC2 (estimate)
Get Rocks	.25 hrs	.5 hrs	1 hr
Geological Context	.5 hrs	1 hr	2hrs
Rake Sample	.25 hrs	.5 hrs	1 hr
Soil Sample	.25 hrs	.5 hrs	1 hr
Drive-tube Sample	.25 hrs	.5 hrs	1 hr
Core Sample	1.75 hrs	3.5 hrs	7 hrs



Constraints

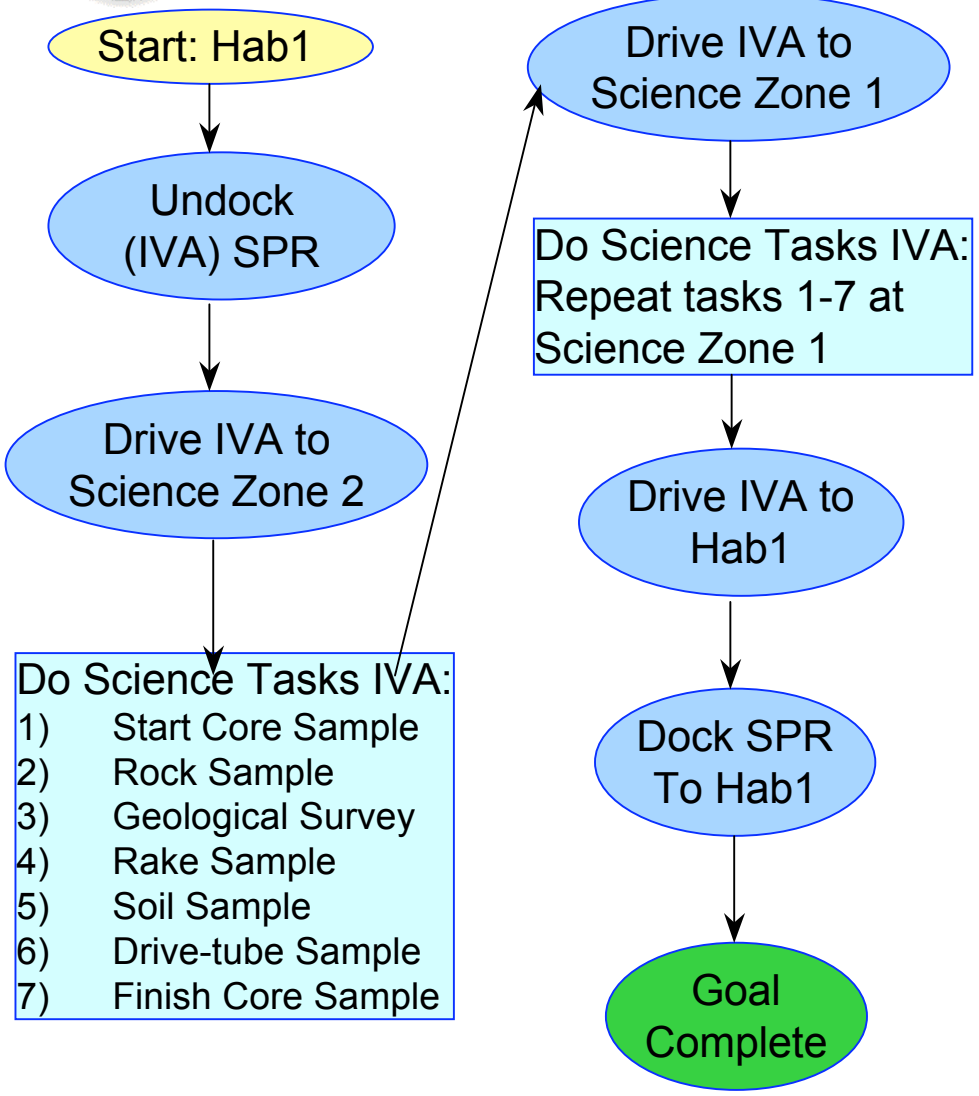
- The software allows the user to specify mission/system constraints

- Examples:
  - An astronaut can only perform up to 15 hours of IVA activities per day
  - An astronaut can only perform up to 8 hours of EVA activities per day
  - The EVA hours count against the possible 15 hours of IVA time
  - MC can only perform up to 16 hours before needing to recharge

Initial and Goal State Vector

State Vector Elements	Initial State Vector	Goal State Vector	Comments
Astronaut1.Suit	FALSE	FALSE	If astronaut 1 is suited for an EVA, TRUE, else FALSE
Astronaut2.Suit	FALSE	FALSE	If astronaut 2 is suited for an EVA, TRUE, else FALSE
Astronaut1.Loc	HM1	HM1	Astronaut 1's location. Can be an element or a location.
Astronaut2.Loc	HM1	HM1	Astronaut 2's location. Can be an element or a location.
FRED1.Loc	HM1	HM1	FRED1's location. Can be a location.
MC1.Loc	HM1	HM1	Mobile Chassis' location. Can be a location
Astronaut1.EVATime	0	minimize	Total EVA time for astronaut 1, starting at zero at the initial state
Astronaut2.EVATime	0	minimize	Total EVA time for astronaut 2, starting at zero at the initial state
Astronaut1.IVATime	0	minimize	Total IVA time for astronaut 1, starting at zero at the initial state
Astronaut2.IVATime	0	minimize	Total IVA time for astronaut 2, starting at zero at the initial state
Site1.GeoContext.Status	FALSE	TRUE	If the Geo Context science task at site 1 has been completed, TRUE, else FALSE
Site2.GeoContext.Status	FALSE	TRUE	If the Geo Context science task at site 2 has been completed, TRUE, else FALSE
Site1.RockSample.Status	FALSE	TRUE	If the Rock Sample science task at site 1 has been completed, TRUE, else FALSE
Site2.RockSample.Status	FALSE	TRUE	If the Rock Sample science task at site 2 has been completed, TRUE, else FALSE
Site1.SoilSample.Status	FALSE	TRUE	If the Soil Sample science task at site 1 has been completed, TRUE, else FALSE
Site2.SoilSample.Status	FALSE	TRUE	If the Soil Sample science task at site 2 has been completed, TRUE, else FALSE
Site1.RakeSample.Status	FALSE	TRUE	If the Rake Sample science task at site 1 has been completed, TRUE, else FALSE
Site2.RakeSample.Status	FALSE	TRUE	If the Rake Sample science task at site 2 has been completed, TRUE, else FALSE
Site1.DriveTube.Status	FALSE	TRUE	If the Drive Tube science task at site 1 has been completed, TRUE, else FALSE
Site2.DriveTube.Status	FALSE	TRUE	If the Drive Tube science task at site 2 has been completed, TRUE, else FALSE
Site1.CoreSample.Status	FALSE	TRUE	If the Core Sample science task at site 1 has been completed, TRUE, else FALSE
Site2.CoreSample.Status	FALSE	TRUE	If the Core Sample science task at site 2 has been completed, TRUE, else FALSE
DOCKED(FRED1, HM1)	TRUE	TRUE	If the FRED1 and Hab Module 1 are docked, TRUE, else FALSE

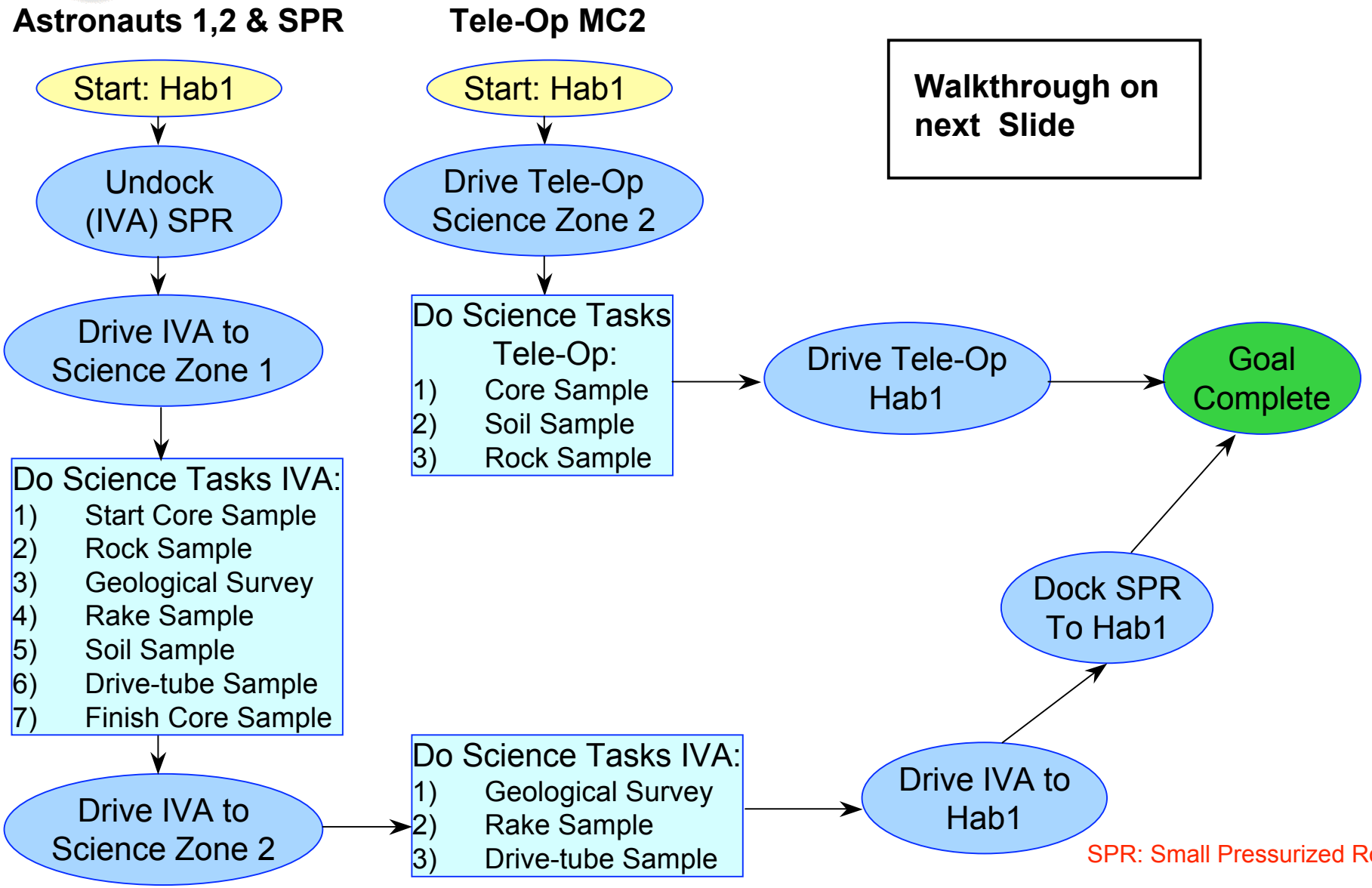
Result for Standard Scenario



SPR: Small Pressurized Rover

0. START:	Astronauts A1 and A2 are at Hab1; total EVA time = 0, IVA time = 2 hrs, PreEVA finished
1. UNDOCK:	Astronauts A1 & A2 get in the SPR and undock the SPR from Hab1; total IVA time = 2.5 hrs
2. DRIVE:	Astronauts A1 & A2 drive the SPR from habzone to Science Zone 2; total IVA time = 3 hr
3. SURVEY:	Astronauts A1 & A2 perform the suite of Science Tasks, IVA within the SPR, at Science Zone 2; total IVA time = 6.5 hrs
	Start Core Sample: Core Sample takes 3.5 IVA hrs total; start and go on to other Science Tasks
	Collect Rock Samples
	Conduct a Geological Context Survey
	Collect Rake Samples of surface regolith
	Collect Soil/Regolith Samples
	Operate Drive Tube and Collect Sample
	Finish and Collect the Core Sample
4. DRIVE:	Astronauts A1 & A2 drive the SPR from Science Zone 2 to Science Zone 1; total IVA time = 7 hrs
5. SURVEY:	Astronauts A1 & A2 perform suite of Science Tasks at Science Zone 1, IVA within the SPR; total IVA time = 10.5 hrs
6. DRIVE:	Astronauts A1 & A2 drive the SPR from Science Zone 1 to the habzone; total IVA time = 11.5 hrs
7. DOCK:	Astronauts A1 & A2 dock SPR to the Hab1 and enter Hab1; total IVA time = 12 hrs
8. GOAL:	Tasks have been accomplished;
	Total IVA time = 12 hrs
	(minimum possible EVA time 0 hrs, min IVA time 12 hrs)

Result for Teleoperated Scenario



Comparison

1. **Reference case:** Two astronauts use Pressurized Rover to execute all activities IVA before returning to base.
   The goal is achieved in 12 IVA hours.

2. **Teleoperated case:** Two astronauts use Pressurized Rover to execute all activities IVA at Science Zone 1, while the MC2 is teleoperated from Earth and executes some of the activities at Science Zone 2. The astronauts then drive to SZ2 and execute the remaining activities at SZ2 before returning to base.
   The goal is achieved in 10.5 IVA hours, and the MC2 operates for 15.6 hours.

- The results show the advantage of having a complement of human agents on the surface (astronauts) and vehicles teleoperated by human operators (which could be astronauts at the habitat or the LSAM, or controllers on Earth).
- In this example, productivity metrics and operating costs are not taken into account.

Problem 2: (tele-operated rover performs only drilling)

For Mission 5 (year 2021):

60 day mission – plan 1 day of Science tasks

Science Tasks:

- Rock samples
- Geological Context survey
- Rake sample
- Soil sample
- Drive-tube sample
- Core sample

Comparing Agent Times

Tasks	EVA Astronaut	IVA Astronaut (estimate)	Earth teleoperated MC2 (estimate)
Get Rocks	.25 hrs	-	-
Geological Context	.5 hrs	-	-
Rake Sample	.25 hrs	-	-
Soil Sample	.25 hrs	-	-
Drive-tube Sample	.25 hrs	-	-
Core Sample	1.75 hrs	-	1.75 hrs

Dropping beacons adds 10 mins to the Geological Context Survey

Parameters and Speeds

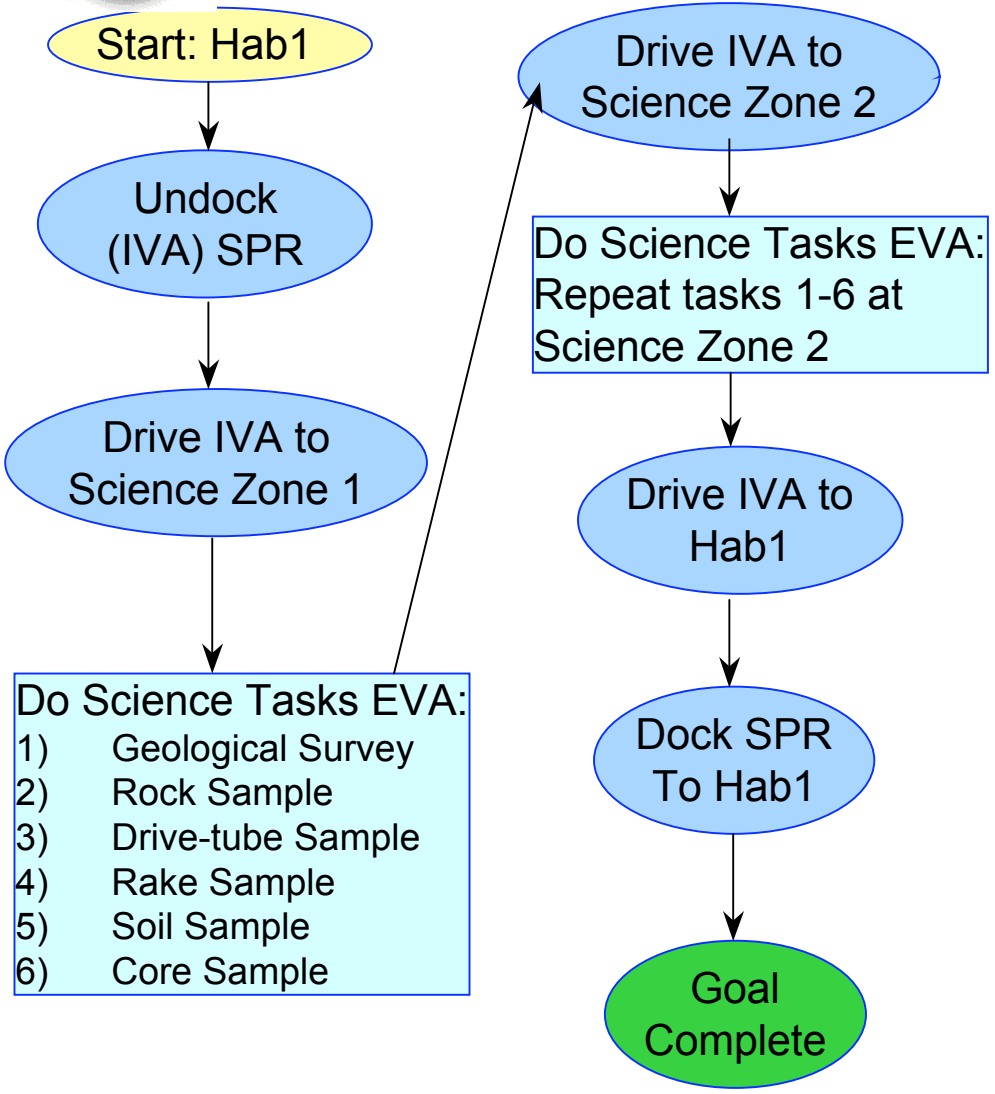
Parameters:

- Pressurized Rover speed: 10 km/hr
- MC2 Tele-operated speed: 10 km/hr (**known marked path from previous astronaut excursion**)
- ScienceZone 1: 20 km from HabZone
- ScienceZone 2: 10 km from HabZone
- Dock/Undock Pressurized Rover : 30 min
- Egress/Ingress Pressurized Rover to /from Lunar Surface: 10 min

Assumptions:

- On EVA Coring sample, Astronaut needs to be working drill entire time – cannot leave to do other science tasks at site
- No equipment failure or drill bits breaking down
- Times are “per astronaut” and task times are for astronauts working in pairs
- MC2 is tele-operated from Earth

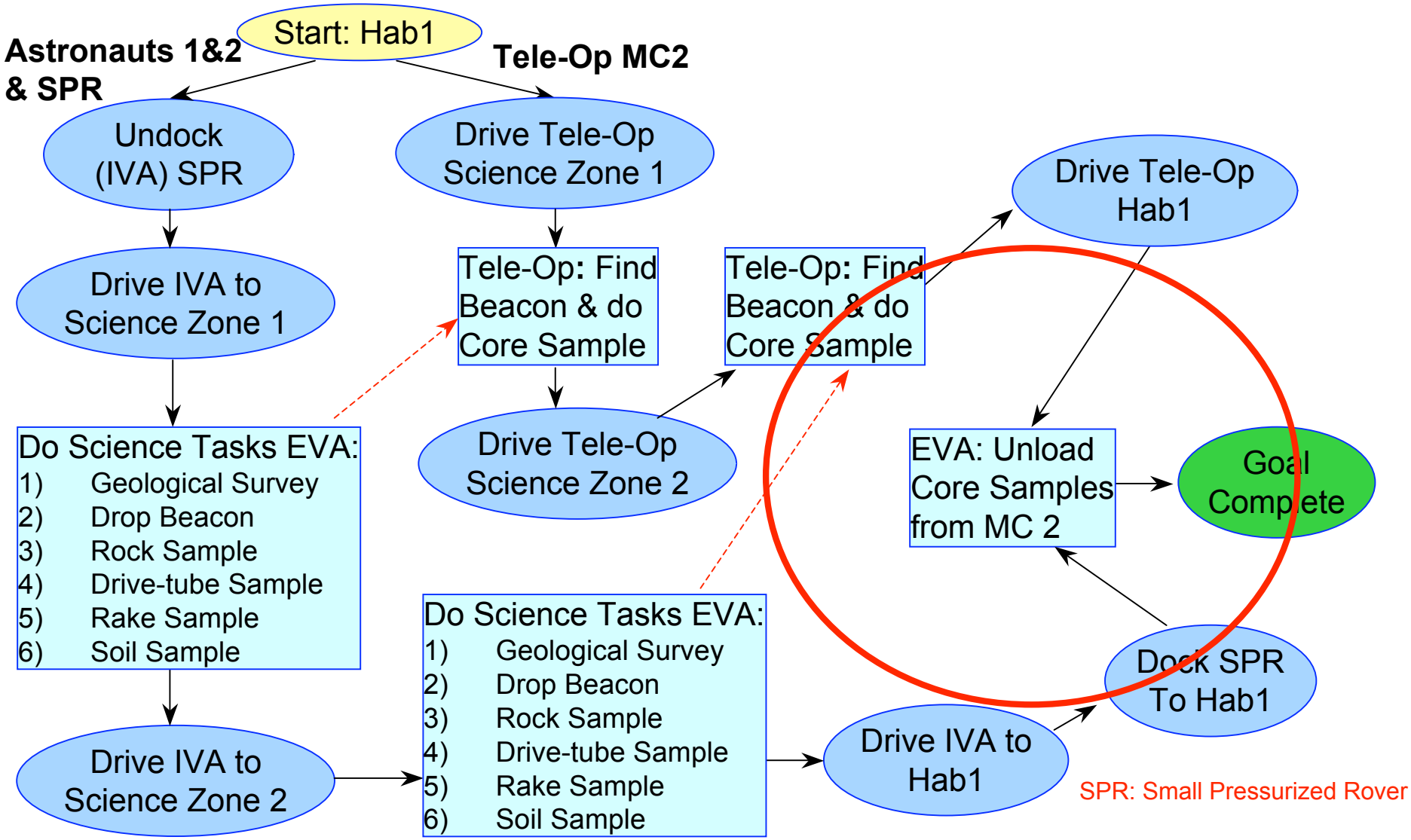
Result for Option 1: Astronauts only



SPR: Small Pressurized Rover

0. START:	Astronauts A1 and A2 are at Hab1; total EVA time = 0, IVA time = 2 hrs, PreEVA finished
1. UNDOCK:	Astronauts A1 & A2 get in the SPR and undock the SPR from Hab1; total IVA time = 2.5 hrs
2. DRIVE:	Astronauts A1 & A2 drive the SPR from habzone to Science Zone 1; total IVA time = 4.5 hr
3. SURVEY:	Astronauts A1 & A2 perform the suite of Science Tasks, EVA, at Science Zone 1; total EVA time 3.6 hrs, IVA time = 4.5 hrs
	Conduct a Geological Context Survey
	Collect Rock Samples
	Collect Rake Samples of surface regolith
	Collect Soil/Regolith Samples
	Operate Drive Tube and Collect Sample
	Operate and Obtain Core Sample
4. DRIVE:	Astronauts A1 & A2 drive the SPR from Science Zone 1 to Science Zone 2; total EVA time = 3.6 hrs, total IVA time = 5.5 hrs
5. SURVEY:	Astronauts A1 & A2 perform suite of Science Tasks at Science Zone 2, EVA; total EVA time = 7.2 hrs, IVA time = 5.5 hrs
6. DRIVE:	Astronauts A1 & A2 drive the SPR from Science Zone 2 to the habzone; total EVA time = 7.2 hrs, total IVA time = 6.5 hrs
7. DOCK:	Astronauts A1 & A2 dock SPR to the Hab1 and enter Hab1; total EVA time 7.2 hrs, total IVA time = 7 hrs
8. GOAL:	Tasks have been accomplished; Post-EVA done.
	Total EVA time = 7.2 hrs, total IVA time = 7.6 hrs
	Total Hours = 14.8 hrs
	(max EVA of 8 hrs, max IVA of 15 hrs, max hours in day; 15 hrs)

MC2 Core Sample: Need Synchronization



Time Comparisons

Astronauts do all Science:

EVA: 7.2 hrs (3.6 hrs per Science Site for all 6 Science tasks)

IVA: 7.6 hrs (Driving, Pre & Post EVA, Docking & Undocking)

Total EVA & IVA Time: 14.8 hrs (brushing against 15 hr max)

Astronauts unload cores from MC2 at end of day, and do all Science except Coring:

EVA: 5.3 hrs (2 hrs per Science Site for all but coring, 1.3 hrs unloading cores)

IVA: 7.6 hrs (Driving, Pre & Post EVA, Docking & Undocking)

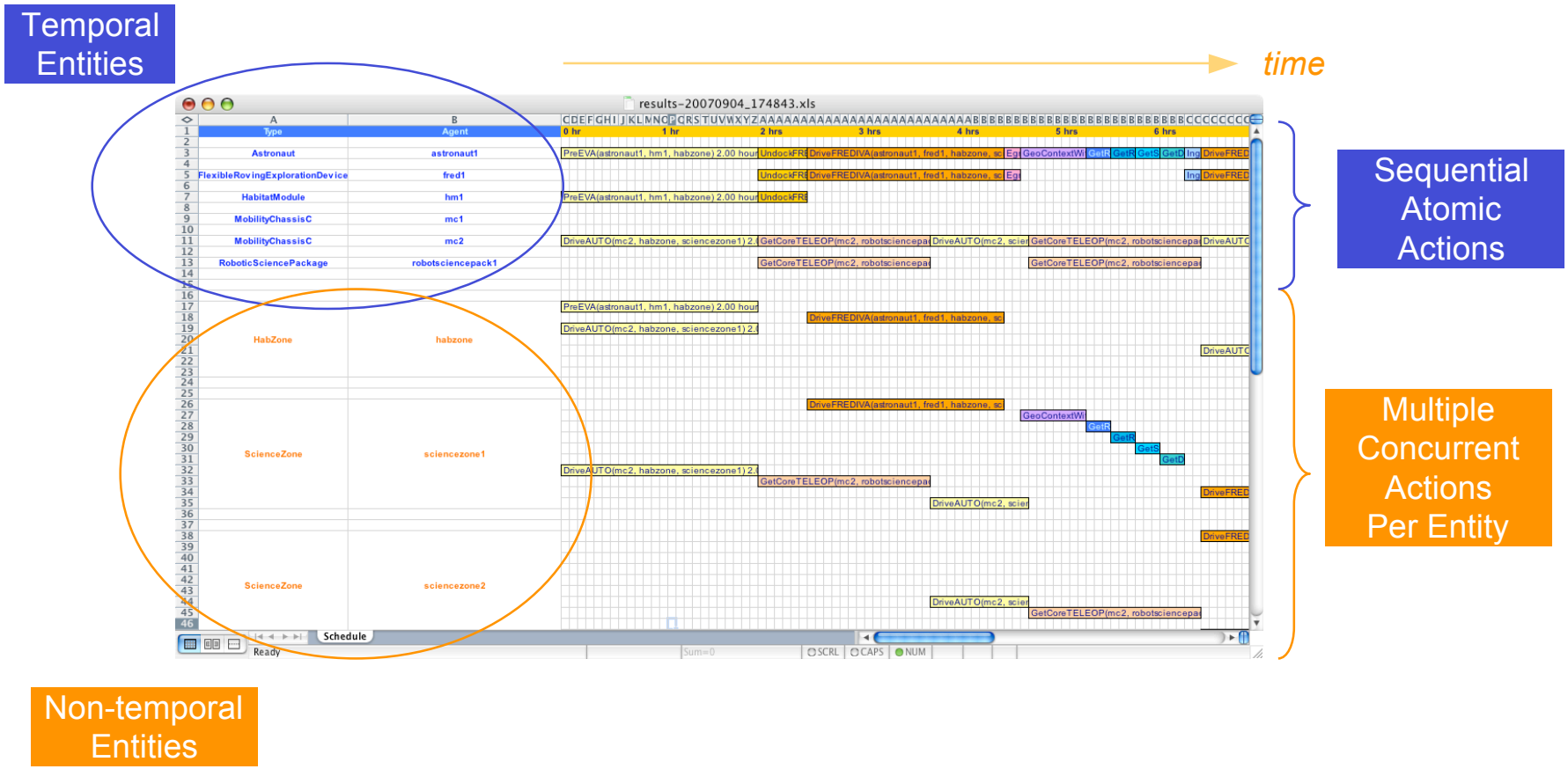
Total EVA & IVA Time: 12.9 hrs

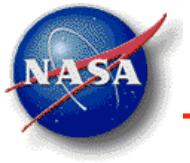
Time Saved: 1.9 EVA hrs,

MC2 Time: 7.5 hrs, plus 20 min idle (waiting for Astronauts to finishing docking and to Egress for Unloading Cores)

Excel Output of Schedule

- Develop new capability for HURON of Excel-based output showing schedule timeline





Summary of Capabilities

- Our planning software approach is **independent of the specific problem being solved**
- The software **gives the user freedom to specify agents, actions, resources, parameters, constraints, start and goal states, and the objective function to be optimized**
- Many of the large-scale planners discussed in the literature focus primarily on scheduling activities already associated with agents, tools, etc.; our approach considers alternative assignments of agents, tools, etc.
- Using constraints and a "smart" objective function, an overnight search of 30,000+ nodes was reduced to hundreds of nodes searched in 0.5 seconds.
- This methodology can be applied to **conduct systematic comparisons of different mission architectures from the point of view of mission efficiency**
- The system description used (agents, resources, actions, start/goal states, etc.) corresponds to **a high-level behavioral mission model**. This means that our approach can also be applied to **mission/technology planning**

Proposed Next Steps

a. Productivity definition and implementation (e.g. science return per unit of resources subject to constraints)

- where each of these terms are associated with an explicit definition which can be presented for community consensus/review).

b. More complex mission scenario

- considering LAT options
- including other tasks such as assembly
- Analyze different environmental conditions (e.g. terrain, lighting etc.)

c. Simulation of events such as repair and discovery

- Simulate unexpected events for which having astronauts present is highly desirable)