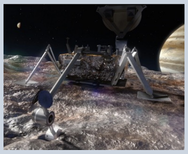

Onboard Scheduling and Execution to Address Uncertainty for a Planetary Lander

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Introduction

The Europa Lander Mission Concept presents a number of challenges. The current mission concept would land with a fixed amount of energy, an expected mission lifetime of approximately 30 days, and would be able to communicate with the Earth in less than 42 out of every 84 hours due to the Europa-Jupiter orbit. Additionally, planned activities such as trenching and sampling, will interact significantly with a largely unknown environment and therefore may encounter failure or highly variable duration or energy consumption when executing. All of these factors present challenges for a conventional ground operations paradigm.

The Jet Propulsion Laboratory has completed a multi-year effort to prototype and study system level autonomy software for a Europa Lander Mission Concept. The goals of this effort are to:

• identify key risks and and assess maturity for such software for a potential future Europa Lander Mission; and
• identify liens on hardware (e.g. sensing, computing), mission concept and operations concept (degree of interaction) and how those affect the autonomy software.

As part of this prototyping, two execution systems were studied as part of the software effort: TRACE - an execution system, and Mexec an integrated planner/scheduler and execution system.

TRACE (Traceable Robotic Activity Composer and Executive) is a tool designed to holistically address the modeling, verification, and execution of planned, opportunistic, and contingency activities during robotic missions from an event- driven execution perspective.

TRACE tailors BPMN to the robotics domain. Automated tasks, like service tasks, correspond to robotic activities, like navigation or grasping an instrument with a robotic arm. Data-driven elements, like conditional events or exclusive gateways, use system data to allow the executive to make decisions on how to flow through the mission.

We are also prototyping system level autonomy using MEXEC, an integrated planner and executive originally built for NASA's Europa Clipper mission. Using MEXEC we compare four approaches to planning on the Europa Lander problem similar to those used in prior missions: a static plan without failure recovery mechanisms, a static plan with ground input for failure recovery (similar to current Mars Rover operations), flexible execution without replanning, and flexible execution with replanning optimization. We explore the value of onboard autonomy: flexible execution and replanning with plan optimization, and examine these techniques' effects on utility in these scenarios. We demonstrate that, true to our model's prediction, each technique shows significant improvement in utility achievement in the Europa Lander domain.

Europa Lander Mission Overview

The primary goal of the Europa Lander mission concept is to excavate and sample the surface, analyze the sampled material for signs of biosignatures, and communicate that data back to Earth [Hand2017]. Additionally, there are secondary objectives to take panoramic imagery of the Europan surface and collect seismographic data. Lander operations are generally limited to the accomplishment of these two overarching goals. This provides significant structure to the problem, since the concept mission clearly defines the sequence of actions required to achieve these goals. Figure 1 displays the strong dependency structure inherent to the Europa Lander concept mission. In order to sample, the lander needs to have excavated a trench; in order to analyze, the lander needs to have collected a sample; etc. Critically, for a mission to achieve any actual utility, those data products must be communicated back to Earth.

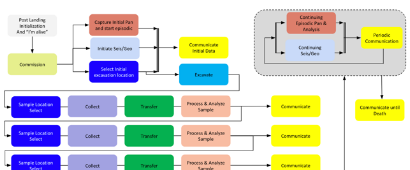


Figure 1. Europa Lander Mission Concept Basic Mission Task Network.

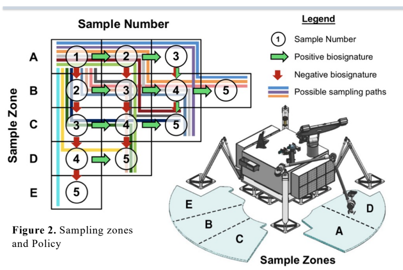
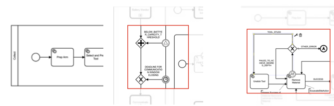


Figure 2. Sampling zones and Policy

Adaptation of TRACE for Europa Lander

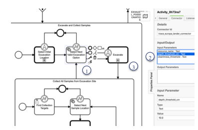
TRACE models the Europa Lander Tasks and dependencies using Constraints, Events, Contingencies.



1 Constraints: Some activities require hardware to be preheated.

2 Events: Communication windows close and primary battery drains.

3 Contingencies: If an activity fails (tool stuck), executive must respond.



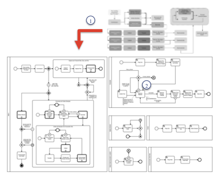
1 Service tasks are activities to be completed by the FSW.

2 Activities have input (request) parameters. Outputs are automatically stored internally.

3 Call activities (as well as, subprocesses, pools, and lanes) are used to organize diagrams.

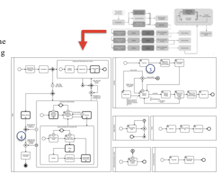
1 Modeled Basic Surface Mission 1 (BSM-1), which prototypes a simple mission focused on excavation, sampling, and downlink.

2 Demonstrated handling multiple failure paths during excavation, such as material slumping, drill stuck, and not making enough progress.



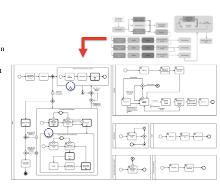
3 Thirteen (13) activities in the FSW were executable, including PrepArm and PrepHGA, to preheat the spacecraft prior to other activities.

4 Model included boundary events to abort excavate or sampling prematurely if they exceeded energy use or if the communication window is closing.



5 Decisions about excavation and sampling sites (i.e., selections) were made based on data in the state database.

6 Secondary activities were initiated (seis/geo and panoramas) if excavation and sampling completed.



Simulated Missions: Representative Scenarios (TRACE and Mexec)

1. All samples positive (baseline)
2. All samples negative
3. Low starting battery state-of-charge
4. Ground input changes excavation order
5. First sample negative
6. Ground input changes mission model
7. Increased decisional data volume
8. Sudden low battery
9. Higher comm energy allocation
10. Slower heating
11. Sudden downlink slowdown
12. Increased mandatory data volume

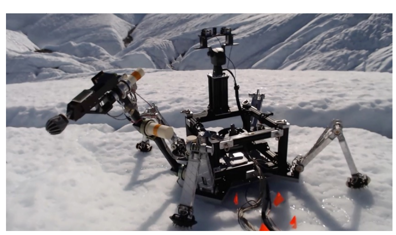
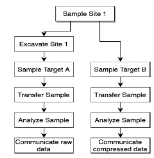


Figure 3. TRACE driving robotic sampling at Matanuska Glacier, AK, USA July 2022.

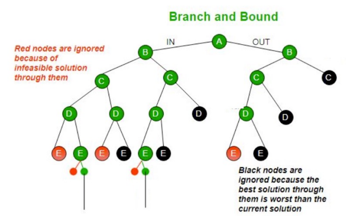
Adaptation of Mexec for Europa Lander (EL-Mexec)

Mexec uses an activity model for Europa Lander tasks and performs optimizing planning using Hierarchical Task Network (HTN) techniques and Flexible Execution (FE).

- Hierarchical task network (HTN)
  - Leverage domain knowledge and dependency structure
  - Decompositions of high-level parent tasks.
- Utility maximization
  - Assign potential utility to sampling tasks
  - Assign lesser potential utility to seismograph/panorama tasks
  - Primary Utility is only achieved after communication to ground



EL-Mexec uses branch and bound search to find high utility plans.



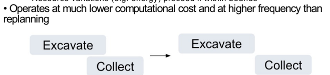
Cost bound = available energy
e.g. can expand plans downwards until all energy used

Value = plan utility
e.g. try to find plan that maximizes utility which is derived from downlinking science results to ground

Bound → prune plans that cannot possibly exceed utility of best solution so far. Unfortunately this is not often clearly the case so search is close to exhaustive (rule out high utility, high energy chains that exceed remaining energy).

Flexible Execution

- Enables handling of minor variations in execution
  - Activities can start early or run late within bounds
  - Resource variations (e.g. energy) proceed if within bounds
- Operates at much lower computational cost and at higher frequency than replanning



Replanning with Plan Optimization

- Constructs search within HTN space to optimize utility
- Within Europa Lander scenario enables coordination of activities with
  - Exogenous conditions such as Earth in view (required for communications)
  - Resource limits (energy, thermal)
- Enables changing of excavation and sampling target
  - In response to ground direction (utility updates)
  - Onboard utility/cost estimates
    - Site imaging to estimate time/energy to excavate/sample
    - Estimation of "science promise" of site
- When to re-plan? fixed cadence or event-based

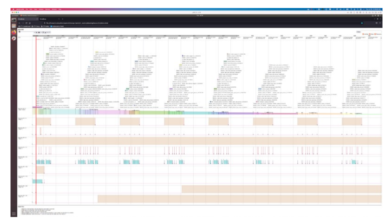


Figure 4. Sample of a full mission schedule: 3 sites excavated, 9 samples collected over multiple sols, plus episodic imagery, fixed exogenous uplink windows, downlinks. Mission ends when battery depleted.

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