# Synthesis of ”*Toward system level autonomy for planetary subglacial access missions*”

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Abstract

Future planetary exploration missions are increasingly targeting remote and challenging environments, exemplified by the icy terrains of Saturn's moon Enceladus. These environments pose significant challenges due to extensive light round-trip times from Earth, high environmental uncertainty, harsh radiation environments, and extreme terrains. Recognizing these challenges, this dissertation emphasizes the necessity of system-level autonomy capabilities for successful mission execution in such uncertain and extreme environments.

The main application of this research is the EELS project (Exobiology Extant Life Surveyor) - a JPL-sponsored research effort to develop a next-generation planetary subglacial access robotic platform. This work delves into the detailed software architecture and infrastructure that was developed to support system-level autonomy for the EELS project, and it describes the decision-making algorithms that were deployed in the field and laboratory conditions. Although this research is applied primarily to the EELS project, it is broadly applicable to other floating-base robotic systems that require system-level autonomy to operate in extreme or uncertain environments. The architecture description detailed in this work encompasses a full robotics stack but focuses on mission planning, plan execution, and behavior implementation. Risk-aware algorithms for sequential decision-making under uncertainty are also outlined, with a review of pertinent literature and the formulation, engineering, and testing of several planners. This use-case that this work targets is surface mobility, where the robotic platform navigates to a user-defined goal, subject to exteroception failures. Under these conditions, high-level planning helps balance information-gaining actions with trying to reach the goal directly. This mission planning challenge is framed as a Task And Motion Planning (TAMP) problem under uncertainty. It is formulated through various planning paradigms, including a classical two-stage approach, a Partially Observable Markov Decision Process (POMDP) formulation, and a novel Chance-Constrained Mixed Integer Linear Program (MILP) formulation. Through computational experiments, the effectiveness of these planning methods is rigorously evaluated. The MILP planner, in particular, demonstrates superior performance over other approaches and is subsequently integrated into hardware. The feasibility of this integration is showcased through laboratory testing. The algorithms and architectural considerations presented in this work are not solely applicable to planetary exploration, as the problem of creating risk-aware robotic platforms capable of operating in highly uncertain environments is widely applicable to terrestrial, marine, aerial, and planetary robotics alike.

Thesis Objective

System-level autonomy is a vast discipline that encompasses both theoretical and experimental research. Clearly, this work does not focus on every aspect that would enable system-level autonomy.

Rather, the objective of this dissertation is twofold: the development of a system-level autonomy architecture, and the creation of risk-aware task and motion planning algorithms. This work is centered around making progress toward enabling subglacial access planetary exploration missions, particularly applied to the Exobiology Extant Life Surveyor (EELS) project, whose details will be outlined in the next chapter.

The primary focus of this work is the development of novel risk-aware task and motion planning algorithms. These algorithms are essential for decision-making under uncertainty, a critical aspect when operating in the unpredictable and harsh environments of icy moons. The research introduces a Mixed Integer Linear Programming (MILP) based planner, which offers a novel approach to balancing information-seeking actions with trajectory optimization. Additionally, two other planning paradigms are implemented and evaluated: a Partially Observable Markov Decision Process (POMDP) solved through Monte Carlo Tree Search, and a classical approach that decouples task planning from motion planning. Through computational comparisons, the effectiveness of these planners is tested, demonstrating their potential to enhance the autonomy and operational capabilities of the EELS robot.

This work not only contributes to the specific goals of the EELS project but also provides valuable insights and methodologies applicable to other robotic systems operating in extreme and uncertain environments. To enable the deployment of these decision-making algorithms, this work also delves into the development of a system-level autonomy architecture. This architecture is based on a classical hierarchical robotics software stack and is tailored to meet the unique challenges posed by extraterrestrial exploration.

## Conclusions

This research began by outlining the capabilities needed to operate autonomously in extreme, uncertain environments and argues in favor of including elements of motion planning and risk awareness in system-level autonomy.
Subsequently, the EELS system was described alongside a robotic software architecture capable of supporting high-level autonomy functionality.
The architecture presented focuses on modularity and proved well-suited for fast-paced research projects where planning requirements often change.
However, the main purpose of this architecture was to provide a minimal scaffolding needed to run and test the main contributions of this work, which are the decision making under uncertainty algorithms developed for the EELS surface locomotion problem.
Therefore, the architecture description does not outline in detail the inclusion of risk and fault management components, and is not evaluated quantitatively in the experimental section.
In the development of decision-making algorithm, emphasis was placed on task and motion planning under uncertainty and approached through three families of planners.

- A classical two-stage approach that decouples motion from task planning and solves them separately in stages.
- A planner based on a Partially Observable Markov Decision Process (POMDP) formulation coupled with an MCTS solver and several different reward-shaping strategies.

- An entirely novel planner based on a Mixed Integer Linear Program (MILP) formulation capable of jointly optimizing task and motion planning and providing guarantees on solution existence and quality.

These planners were quantitatively compared against each other in a computational framework, and the MILP planner was implemented on hardware and tested in a laboratory setting because of its promising characteristics.
The main limitation of these planners is scalability.
Both the POMDP and MILP planners exhibited the capacity to find good solutions, but with increases in planning horizon, action space size, and number of obstacles, these belief-space planners fail scale due to the fundamentally NP-hard nature of the problem they are trying to solve.
An inclusion of true risk-awareness - defined as the capacity to reason jointly about probability of failures, and the consequences of these failures - is left for future work, as the planners treated in this work reason with a fixed consequence level.

An immediate direction of research for future work is seeking ways to improve these algorithm's scalability in terms of the number of obstacles and actions they can handle.
Belief-space planning is very challenging and generally scales poorly, but quality solutions can be found by sacrificing optimality guarantees.
Perhaps, there is a broader challenge of cultural nature at play here.
The aerospace industry often requires algorithms with provable mathematical guarantees of safety and performance, which disqualifies a large set of algorithms that could nevertheless be good enough, and have much improved scalability.
The question of how build trust and verify algorithms that do not come with mathematical guarantees is likely going to be central to the future of system-level autonomy research.

A particularly promising technical research direction, that does not require significant modifications to the MILP algorithm, is seeding the planner with a feasible solution generated with a faster algorithm, and terminating the search early.
This strategy would forsake optimality guarantees, but could lead to both high-quality solutions and low computational cost.
Additional ways of dealing with the scalability issues introduces by belief-space planning could be (a) remove belief space planning in favor of integrating Task and Motion Planning into system-level autonomy and deal with uncertainty implicitly through the planner's constraints, or (b) explore data-driven approaches.
Achieving safe behavior when neglecting beliefs could be achieved similarly to the two-stage approach, which could be vastly improved with iterative planning techniques.
Another interesting research direction is to further improve the proposed robotics software architecture to include fault management and mesh reactive system-level behaviors with deliberative planning.
Ensuring that the deliberative planning is aware of localize reactive behaviors is another interesting architectural challenge.
Additionally, system-level reactive behaviors might be necessary to recover from certain failures, and there is an opportunity to design a unified architecture for high-level autonomy capable of both reactive behaviors and deliberative planning.

It is also necessary to work on finding ways to formulate risk-aware planners capable of assessing consequences and finding scalable ways of solving these formulations.
A work focused more on architectural changes would benefit from quantitative experiments analyzing the effect on mission-level performance metrics of architectural changes.

True system-level autonomy will likely only be achieved through artificial general intelligence (AGI), whose future prospects are fundamentally unknowable.
However, even in the absence of AGI, there is still a lot of value that can be found in furthering the state of the art of system-level autonomy.
Many decision-making technologies have proven their value in Operations Research, Field Robotics, and Space Exploration, and their usefulness is only bound to grow as autonomous systems become more widespread.

With an appropriate set of simplifying assumptions, and incremental technological improvements, planetary subglacial access could soon be within humanity's reach - if a political choice is made to prioritize it.