OPERATIONS FOR AUTONOMOUS SPACECRAFT: WORKFLOWS AND TOOLS FOR A NEPTUNE TOUR CASE STUDY.

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Introduction: Advanced onboard autonomy capabilities including autonomous fault management [1,2], planning and scheduling [3], execution [4], selection of scientific targets [5], and on-board data summarization and compression [6] are being developed for future space missions. These autonomy technologies hold promise to enable missions that cannot be achieved with traditional ground-in-the-loop operations cycles due to communication constraints, such as high latency and limited bandwidth, combined with dynamic environmental conditions or limited mission lifetime. Classes of missions enabled by autonomy include in situ and subsurface exploration of icy giant moons, coordinated deep space fleet missions, and fast flybys in which changing features or a lack of a priori knowledge of position requires fail-operational capability and autonomous planning, detection and pointing. Onboard autonomy capabilities can also increase science return, improve spacecraft reliability, and have the potential to reduce operation costs. As a compelling example, autonomy has already significantly increased the capabilities of Mars rover missions, enabling them to perform autonomous long-distance navigation and autonomous data collection on new science targets [5,7].

While there has been a focus on the development of onboard autonomy capabilities, the challenges of *operating* a deep space spacecraft with these autonomous capabilities and the impact on ground operations have never been studied to a level of detail sufficient for consideration in mission concepts. To enable scientists and engineers to operate autonomous spacecraft, new operations workflows and tools must be developed. In this paper, we study the problem of *operations of autonomous spacecraft* and, specifically, we identify workflows and software tools that are well-suited for this problem, with a focus on future exploration of the Neptune system.

Operations Concept and Mission Case Studies: We focus our work on a concept of operations for a spacecraft exploring the Neptune-Triton system. Such a mission offers an especially interesting and challenging setting because of its significant light-speed latency, low available bandwidth, short duration of flybys, and the likely presence of dynamic scientific phenomena such as plumes and storms - features which make autonomy highly attractive to fulfill primary mission objectives, but also make operations of such a mission very challenging.

We identified three classes of autonomy-enabled science campaigns and, within these, eight scenarios that instantiate our effort and exercise a variety of autonomy capabilities, including autonomous event detection, planning, scheduling and execution, and failure detection, identification, and recovery.

Science campaign classes and scenarios: The scenarios considered in this work can be separated into three broad classes of scientific observations that benefit from onboard autonomy, namely, 1) autonomous monitoring, 2) event-driven opportunistic observations while mapping, and 3) event-driven opportunistic observations during targeted observations.

Monitoring: In monitoring campaigns, an instrument or suite of instruments monitors a physical system or natural phenomenon by collecting an extended observational data set with the goal of characterizing the behavior of the observed system. With onboard autonomy, the data collection campaign is adapted based on observation data. Within the monitoring class, we considered two scenarios, namely, *magnetospheric variability detection*, where autonomy selects whether to store high-frequency, losslessly-compressed readings or low-frequency, binned data (thus leaving more room for other data products) based on the level of magnetospheric activity, and *magnetospheric reconnection event detection*, where autonomy monitors high-frequency data from the plasma and particles instrument, looking for magnetospheric reconnection events, and only stores data corresponding to such events.

Event-driven opportunistic observations while mapping: Mapping of a body's surface is typically a pre-planned activity; autonomy can enhance mapping by (i) changing observation parameters on the fly (e.g., camera parameters), (ii) adjusting the schedule in response to unexpected events (e.g., a camera reset), and, crucially, (iii) allowing mapping to be executed in parallel with other opportunistic activities, scheduling opportunistic observations for high-value but fleeting events. Within this class of science campaigns, we considered three scenarios, namely: *mapping Triton and plume detection*, where opportunistic observation of transient plumes are inserted in a pre-planned mapping schedule; *fault detection, isolation, and recovery during mapping*, where the spacecraft replans mapping activities in response to camera resets; and *mapping Neptune and storm detection*, where opportunistic storm observations are interspersed with pre-planned mapping activities.

Event-driven opportunistic observations during targeted observations: Similar to mapping, targeted observations are typically a pre-planned activity; autonomy can provide increased science returns by adapting observation parameters, revising observation opportunities if more or less time than expected is available for observations, and, critically, interspersing opportunistic observations with pre-planned observations. We considered three scenarios within this class: *target selection*, where the spacecraft replans observations onboard based on priorities provided by scientists on the ground; *observation replanning with FDIR*, where non-critical observations are rescheduled (rather than dropped) in response to a failure; and *instrument capture parameter selection*, where observation parameters (e.g., exposure time and number of exposures to stack) are adjusted autonomously based on observed noise levels.

Workflows and Tools: Once we identified a set of enabling scenario where spacecraft and instrument autonomy can enhance science returns, we analyzed current operations workflows and identified new roles and new tools that will need to be added to support *operations* of such a mission, and, specifically:

1. Uplink: capture the *intent* of spacecraft operators and scientists in a way that can be interpreted by on-board autonomy
2. Downlink: to provide operators with an understanding of *what* decisions autonomy made, and *why*, fostering trust in the autonomy.

Workflow. Operations workflows for future autonomy-enabled missions will see new roles (specifically, an *autonomy engineer*). Uplink workflows will see significant use of simulations (at varying levels of fidelity) to reassure operators that the inputs to onboard autonomy match the desired intent; in addition, tools to explore simulation outputs, and to inspect and explain unexpected outcomes, will be required. Downlink workflows will also be challenging, as identifying “nominal” behavior will require a deep understanding of the spacecraft state (as sensed by the autonomy) and on the intent expressed by uplink. To this end, the workflow will make heavy use of comparisons with predicted spacecraft behavior (which is expected to be highly multimodal), and of software tools to relate downlinked data (in particular, channelized data, event records, and engineering data products) to each other, so as to provide operators with situational awareness.

User Interface Tools: to support these workflows, we designed a number of user interfaces (UI) to support the workflow described above, both for uplink and for downlink operations. Tools were organized in three areas: intent capture (uplink), outcome prediction (uplink), and downlink analysis (downlink). We refer the interested reader to [8] for a detailed description.

Software tools: We also designed several software tools to support the proposed workflow. In particular, we are developing (i) a *prediction engine* that can provide high-fidelity simulations through use of cloud computing capabilities, and (ii) an *inference engine* that is able to estimate the spacecraft state, and support explanation of the on-board autonomy’s decisions, through model-based state estimation.

In order to qualitatively evaluate the performance of tools and initial autonomous planning procedures, we conducted a light-weight design simulation [9]. The design simulation showed that the proposed workflow is able to support autonomous operations, and resulted in a number of recommendations that will be incorporated in future iterations of the tools.

Conclusion and Next Steps: This effort showed that user interfaces and software tools can effectively help scientists and operators interact with onboard autonomy, effectively enabling the infusion of autonomy in future robotic exploration missions. Efforts are underway to implement the tools described in this paper and integrate them with existing operations workflows. Lessons learned, along with the tools and workflows developed under this effort, will directly inform future science and exploration missions across a variety of mission classes, including surface missions (e.g., Europa and other Icy World Lander, Mars surface missions, and Venus Lander), and small body exploration (e.g., fast flybys, Centaur rendezvous).

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References:

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