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Application of AI planning and MBSE to the Study and Optimization of ConOps for Autonomous Robotic Space Exploration Systems

By

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Abstract

The study conducted in the thesis aims to conceptualise, study and test concepts of operations for future deep-space robotic missions. There is no accurate simulation of the autonomous operations of planetary robots. How to effectively validate the ConOps and verify the requirements associated with autonomy is still an open discussion point. If operational models can be executed, it is also possible to debug the described behaviour to match the expected performances or what the engineer meant to capture. This analysis would be complementary to the usual ConOps analyses that mostly focus on evaluating the power consumption or data generation per mode for an aerospace system. This objective is concretised in the definition of two frameworks leveraging MBSE and AI planning. They guide the designer from the conceptualisation of ConOps up to their testing on a simulated or analogue platform. If the focus of the analysis is on the functional architecture, the first simulation framework based on Hierarchical Task Networks (HTN) provides a feasible operational plan for the defined functions, activities and actions. The HTN plan can then be coupled with straightforward scheduling algorithms for an initial assessment of resources allocation. For a more detailed resource allocation, a Markov Decision Process (MDP) can be modelled following the guidelines of the second framework. The formulation with MDP provides an optimised plan respecting complex numeric constraints while maximising a set of given performances. This second framework relies on inputs from the expected physical architecture to evaluate a given set of performances. A simulation of a relevant exploration scenario is run, and a tree traversal algorithm is used to evaluate the best succession of actions to accomplish the scenario objectives. The output of this framework is a complete operational plan with the variation of the parameters of interest, like covered distance or sampled volume. The development of the two frameworks is detailed in this thesis by leveraging different applications. The thesis relies on three case studies: the lunar lava tubes mission, IGLUNA and the MIRS instrument mission. The lava tube mission is the initially envisioned case study for this thesis. It has been the base to generalise a set of operations typical of autonomous systems. Moreover, a detailed preliminary mission design has been studied in parallel with the definition of the two frameworks, from the mission statement definition to the initial mass estimation. On the other hand, the IGLUNA analogue mission has been the test bed for the first framework and provides fundamental inputs for the second framework. The testing conducted during IGLUNA aimed to test the fundamental operational capabilities of an autonomous system identified during the

lava tube mission study. The MIRS instrument is one of the payloads of the MMX mission set to be launched in 2024 by JAXA. The study conducted at CNES was used as a further test bed to validate scheduling algorithms developed primarily for IGLUNA. The first part of the thesis details the study's purpose and the gaps in the literature that justify the need for this research. The second part examines the case studies and their peculiarity. The mission analysis related to the lunar lava tubes will be detailed as well. The third part focuses on the frameworks and the results linked to their application to the case studies analysed earlier. The last chapter will provide the take-at-home lessons from the study and the possible future developments.