Demonstration of OceanWATERS
An Autonomy Testbed and Plan Execution Platform for Planetary Landers

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Abstract

Space missions, whether crewed or robotic, are simulated long before they are launched. While most robotic missions to the Moon and Mars have had ground controllers on Earth tightly involved in mission operations, missions to more distant worlds will require a high degree of onboard autonomy due to long communication lags and blackouts, harsh environments (radiation, cold), and more limited battery and hardware life. The search for life signs and potentially habitable bodies in our solar system and beyond is one of NASA's top priorities and science's highest aims. Known as "ocean worlds", bodies containing liquid water, such as the Jovian moon Europa and the Saturnian moon Enceladus, present the best opportunity to search for life as we know it. To this end NASA has developed the *Ocean Worlds Autonomy Testbed for Exploration, Research, and Simulation* (OceanWATERS). OceanWATERS is an open-source software tool that provides a visual and physical simulation of a lander on Europa. It is a testbed for high-level autonomy that has a plan execution layer based on the open-source *Plan Execution Interchange Language* (PLEXIL) and executive. Over the past several years, under NASA grants, 6 research teams in academia and industry across the US have developed and demonstrated AI-based mission autonomy solutions on OceanWATERS. Approaches used have included machine learning, causal reasoning, and automated planning. This demonstration showcases the main features of OceanWATERS with an emphasis on its plan execution framework.

Project Background

The OceanWATERS project began in late 2018. Using JPL's 2016 Europa Lander Study (Hand et al, 2017) as a reference, a software testbed featuring the Robot Operating System (ROS), Gazebo simulation environment, and PLEXIL (Verma et al, 2005) was developed from scratch at the NASA Ames Research Center and released open source on GitHub in summer 2020. Two external projects using this testbed began in 2020 under grants from NASA's *Autonomous Robotics Research for Ocean Worlds* (ARROW) Program. Four additional projects began in 2021 under grants from the *Concepts for Ocean worlds Life Detection Technology* (COLDTech) Program. The goal of these programs is to support development of spacecraft-based technology for surface and subsurface exploration of ocean worlds in the Solar System.

System Description

OceanWATERS (Edwards et al, 2021) is an open-source software package (OceanWATERS, 2024). It is a ROS-based tool that runs on commercial-grade Ubuntu Linux computers. It provides a visual and physical simulation of a prototypical lander in a Europa-like environment. Simulated lander systems include stereo cameras and spotlights mounted on an antenna mast that pans and tilts, a 6 degrees of freedom robotic arm with a force-torque sensor and two interchangeable end effectors, and a battery pack power system. The environment consists of multiple terrain models including a highly detailed model sourced from the FROST dataset (Wong et al, 2019), simulation of surrounding planetary bodies based on an ephemeris model, and lighting from the sun with associated surface illumination, reflectance, and shadows.

Operations supported by OceanWATERS include panoramic and directed imaging of the environment and lander workspace, Cartesian and joint-level arm commanding, grinding of the terrain surface (e.g. digging a trench), and scooping of ground material which can be discarded or collected as science samples in a receptacle that can be emptied (science operations themselves are not simulated). These operations are realized as ROS Actions and are complimented by a wide selection of telemetry that is continually produced by each lander subsystem. The power system model is driven by the open-source *Generic Software Architecture for Prognostics* (GSAP) (Teubert et al, 2017) that predicts the battery's remaining useful life and other characteristics. A fault modeling framework supports the injection of hardware faults in each lander system, and the detection of faults at the hardware level.

As a testbed for high-level autonomy, it was not in the scope of the OceanWATERS project to develop a comprehensive autonomy solution for ocean world surface missions. OceanWATERS provides an execution framework based on PLEXIL, an open-source plan specification language and execution engine developed largely at NASA Ames (Verma et al, 2005).

Research Efforts

The ARROW and COLDTech projects mentioned above have now finished or are nearing completion, and a wide variety of autonomy challenges in ocean world surface missions were addressed. Prototyped and demonstrated solutions have included autonomous discovery, response and adaptation to system faults and unexpected environmental events, world model synthesis through perception, plan synthesis using learned models, methods to optimize sample target selection and prioritize science data transmission, extension of PLEXIL for stochastic decision-making, and an integration of a model of JPL's mission-ready COLDArm (Newill-Smith 2023). Technologies used in these projects include many forms of machine learning, causal reasoning, Markov decision processes, formal methods, and automated planning. A bibliography of papers published from these efforts is found at (Bibliography, 2024).

PLEXIL and Planning

As mentioned earlier, OceanWATERS provides a plan execution framework based on PLEXIL. The distribution also includes dozens of PLEXIL plans that exemplify lander operations, mission sequences, and fault handling. As a declarative, event and condition driven, synchronous language with a formal semantics, PLEXIL is well-suited for reactive autonomy. It was originally designed as a "universal" plan representation language and target language for automated planners, prior to the development of a user-oriented syntax that made it also suitable for scripting plans.

The OceanWATERS user may choose to manually author plans in PLEXIL, or such plans could be generated by an automated planner. Using ROS message publishing and/or PLEXIL's reflective features (Update nodes, executive listeners), closed-loop planning and execution is achievable.

Another viable approach for planners, or any autonomy system driving OceanWATERS, is to bypass PLEXIL and operate the lander directly via its ROS interface. Several ARROW and COLDTech teams took this approach, including the REASON-RECOURSE project (McMahon et al, 2023) that employs a planner that takes specifications in linear temporal logic.

Demonstration Video

The short video that accompanies this abstract is a brief tour of a running OceanWATERS session and an abbreviated demo of a short mission segment encoded as a PLEXIL plan. The plan includes panoramic imaging of the landing site, a visual inspection of the lander's workspace and search for a suitable sampling location, digging of a trench, removal of tailings, and collection of a regolith sample. We'd like to make a strong disclaimer that this video is a rather rough take, and we plan to improve both its content and screen resolution with a greater illustration of its PLEXIL and plan execution elements.

Furthermore, due to time limitations for the video submission, only a nominal scenario was shown. In a live conference, we will demonstrate an interactive session in which a PLEXIL plan reacts to fault injection.

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