Autonomous Ocean World Exploration: Advancement of a Virtual Testbed

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The search for life (extinct or extant) and potentially habitable bodies in our solar system and beyond is one of the 12 priority science questions outlined in the National Acadamies' 2022 decadal survey [5]. Extraterrestrial destinations containing liquid water present an opportunity to search for life as we know it, and in recent years an increasing number of such locations have been discovered within our solar system. Several Jovian moons—Europa, Ganymede, and Callisto [10]—and the Saturnian moons Enceladus [8] and Titan [9] are known or suspected to harbor massive subsurface oceans. Of these "ocean worlds", Europa is the focus of at least one planned NASA orbiter mission, Europa Clipper [4], and an early lander mission concept, the Europa Lander [2, 3].

Whereas most robotic missions to the Moon and Mars (e.g. orbiters, rovers, landers) to date 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 past decade has seen great advances in both AI technologies and computing scalability and performance that offer promising solutions for spacecraft autonomy and motivate the software system and research programs described in this paper.

The *Ocean Worlds Autonomy Testbed for Exploration, Research, and Simulation* (OceanWATERS) [1], which has been in development at the NASA Ames Research Center since 2018, is a virtual environment for testing lander autonomy solutions. It is built on the Robot Operating System (ROS), runs on consumer-grade Linux workstations, and was released as open source in 2020. OceanWATERS provides a physical and visual simulation of a prototypical lander in a Europa-like environment (Figure 1). The lander was modeled after requirements and specifications made in JPL's Europa Lander Study of 2016 [3]. Simulated lander systems include stereo cameras and spotlights mounted on an antenna mast that pans and tilts, a 6 degrees of freedom (DoF) 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 [11], 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

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the terrain surface (e.g. digging a trench), and scooping of ground material (Figure 2) 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) [11] that predicts the battery's remaining useful life and other characteristics. As a testbed for high-level autonomy, OceanWATERS provides an execution framework based on PLEXIL [12], an open-source plan specification language and execution engine developed largely at Ames.

NASA's initial development of OceanWATERS, as well the *Ocean Worlds Lander Autonomy Testbed* (OWLAT) [6], a complimentary physical testbed developed at JPL, was the first step in a plan for realizing candidate onboard autonomy solutions for such planetary landers. In 2020 NASA solicited applications for its *Autonomous Robotics Research for Ocean Worlds* (ARROW) program, and in 2021 the similar *Concepts for Ocean worlds Life Detection Technology* (COLDTech) program. Collectively six research teams, based in universities and companies across the United States, were awarded grants to develop and demonstrate autonomy solutions on OceanWATERS and OWLAT. These 1–2-year projects 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 [7]. Technologies used in these projects include many forms of machine learning, causal reasoning, automated planning, Markov decision processes, formal methods, and other advanced techniques. A more detailed summary of the ARROW and COLDTech projects is given herein.

OceanWATERS has had significant enhancements since its open-source release in 2020. Many of its new features were driven or shaped by feedback from the ARROW and COLDTech teams and requirements of their projects. In support of enabling autonomous adaptation to spacecraft faults (a specific capability solicited by both programs), a fault injection and detection framework was developed that supports a wide and growing range of fault types such as locked joints, image loss, and battery failures. The power system model was completed and integrated into the simulator, starting as a single-cell battery model and later upgraded to a multi-cell model with associated faults such as cell disconnection. Arm/terrain interaction was improved by adding a force-torque sensor and associated faults, and an analytic dig force model based on the Balovnev bucket force equations. Environment fidelity was increased by modeling terrain deformation resulting from digging and scooping; visual improvements were made in textures, lighting, and shadows. To facilitate interoperation with OWLAT, a unified command and telemetry interface between the testbeds was developed at the ROS level, along with a PLEXIL interface. The number of lander operations was greatly expanded (e.g. with Cartesian-based arm and antenna movement), and a framework was designed for users to build their own lander actions. A GUI for PLEXIL plan selection was created (Figure 3), and an expansive set of plans were added, such as those that illustrate patterns for fault handling.

This paper provides a self-contained high-level description of OceanWATERS, focusing on more detailed coverage of the aforementioned enhancements. It provides a high-level summary of the projects undertaken by participants in the ARROW and COLDTech programs and how these efforts have helped shape OceanWATERS. Finally, potential future work and directions for the testbed are listed, as likely informed by the recent planetary science decadal survey [5].

A. Images, Figures, and Tables

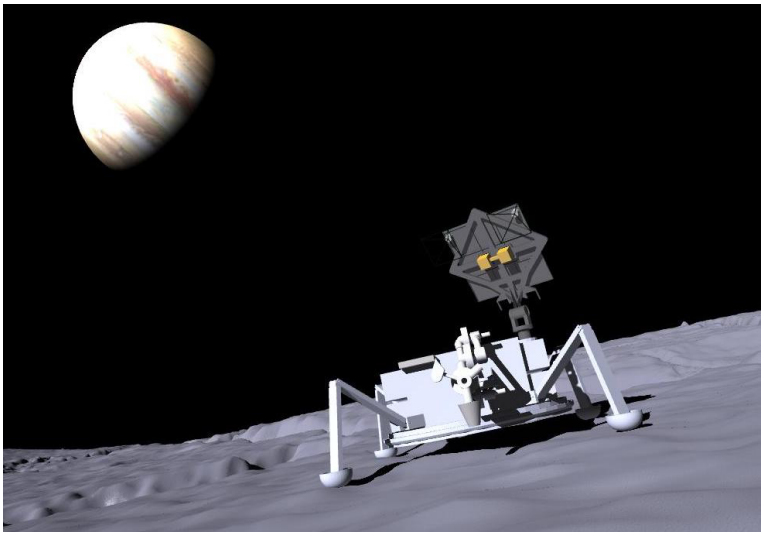


Fig. 1 Lander on Europa as simulated in OceanWATERS

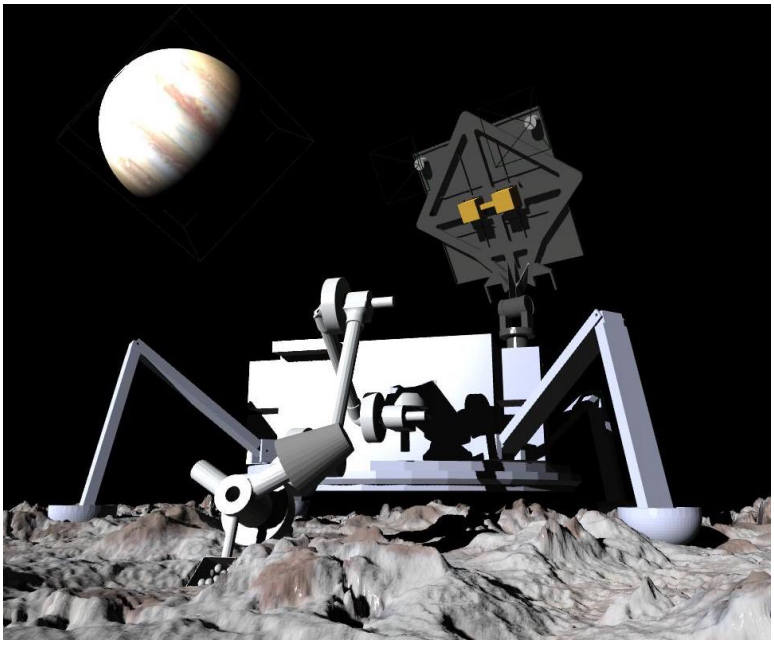


Fig. 2 Excavation of regolith

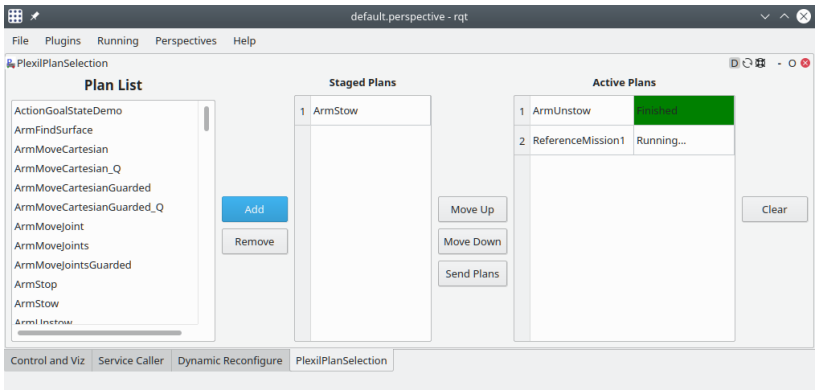


Fig. 3 Interface for PLEXIL plan selection and execution

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