2018 Workshop on Autonomy for Future NASA Science Missions: Ocean Worlds Design Reference Mission Reports

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NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

Introduction

Autonomy is changing our world; commercial enterprises and academic institutions are developing and deploying drones, robots, self-driving vehicles and other autonomous capabilities to great effect here on Earth. Autonomous technologies will also play a critical and enabling role in future NASA science missions, and the Agency requires a specific strategy to leverage these advances and infuse them into its missions. To address this need, NASA sponsored the 2018 Workshop on Autonomy for NASA Science Missions, held at Carnegie Mellon University, October 10-11, 2018.

The Workshop goals included:

- Identifying emerging autonomy technologies (10-15 years) that will:
    - Enable or enhance mission capabilities
    - Reduce risk
    - Reduce cost
- Identifying potential collaborations, partnerships, or linkages involving government, industry, and/or academia to enable these technologies

Capturing crosscutting autonomy technology requirements for future NASA missions
Over 90 individuals from industry, academia, and NASA participated in the workshop, which included presentations by keynote speakers, panel discussions, and small group discussions.

To provide structure for workshop discussions and post-workshop analysis, NASA established eight teams to examine the following Design Reference Mission (DRM) areas: Astrophysics, Earth Science, Heliophysics, Mars, Moon, Ocean Worlds, Small Bodies and Venus. Each DRM team was led by a scientist and a technologist, and team members consisted of workshop participants with relevant experience and interest. NASA asked each team to develop one or more mission scenarios that would be enabled by infusion of autonomous technology. The Agency provided guidance to support these team discussions; in particular, NASA urged the DRM teams to "think out of the box" and to consider bold missions that would be enabled by autonomous technology to provide valuable science results. Each DRM team developed mission scenarios that included defined science objectives, capability and technology needs, system requirements, and a concept of operations. Teams also identified gaps where autonomy technologies and other supporting technologies need to be developed and/or infused to enable each mission.

The DRM teams conducted small group discussions at the workshop and then presented a summary of their findings to all workshop attendees. Each DRM team continued to refine its mission scenarios after the workshop, creating both a full report and a summary report to document team findings. DRM teams also reported results at the December 2019 meeting of the American Geophysical Union.

This document contains the full report and summary report generated by the Ocean Worlds DRM team. Full and summary reports generated by all eight DRM teams, plus a summary of workshop results are available online.

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The Ocean Worlds Design Reference Mission Report

Part I: Executive Summary

One of the most profound discoveries in planetary exploration is the evidence for large quantities of liquid water on several bodies in our Solar System, aptly named “Ocean Worlds.” In an effort to extrapolate our understanding of life on Earth to the cosmos, “go to the water” has become the guiding principle in our search for evidence of extraterrestrial life. Thus, Ocean Worlds have become key astrobiology targets, and many outstanding questions can only be answered through direct contact with their subsurface liquid water.

The challenges involved in implementing robotic subsurface missions on Ocean Worlds are immense, and advanced autonomy may be among the most demanding technology developments that will be required. The current state of practice for autonomous operations of Mars rovers and distant spacecraft is highly *robust*, *deliberative*, and *protective*; that is, the system makes a plan that is “safe” with respect to known uncertainties and promptly triggers a “safe mode” in the event of any anomalies. Ocean Worlds, however, present an environment that is far more uncertain, dynamic, and communication-constrained, which will require autonomy that is *adaptive*, *reactive*, and *resilient*. For example, the dynamic nature of plume ejecta on Enceladus or the harsh radiation of Europa prohibit human-in-the-loop control, especially during long-duration communication blackouts such as the two-week period during solar conjunction. Ocean World probes must be equipped with the ability to *learn* from their interactions with the environment, *react* to imminent hazards, and *make real-time decisions* to respond to anomalies.

The goal of this Design Reference Mission (DRM) is to survey the key autonomy technologies that will *enable* robotic subsurface missions to Ocean Worlds, identify technology gaps that warrant further research and development, and recommend next steps. Though mission concepts for subsurface ocean access are broad and in an early stage of development, we focus our attention on two specific architectures that represent the exploration approaches: a “cryobot” probe for penetration of Europa’s or Enceladus’ ice crust, and a “crevasse explorer” for the surface entry and descent into active vents on the south pole of Enceladus or potential crevasses on Europa. These DRM scenarios constitute a subset of all possible architectures, however, we attempt to address them in a general way that highlights key autonomy requirements across a broad range of Ocean World missions. In short, we find that, while there are technology gaps in almost all domains of autonomy, a few categories stand out as high priority for development in the case of both DRM scenarios: (1) Knowledge and Model Building, (2) Hazard Assessment, (3) Execution and Control, (4) Verification and Validation, and (5) Autonomous Science.

The systems needed to accomplish the goals of this DRM require a long runway to succeed. A key driver is time and critical mass of work to develop the technology to a point of maturity that reduces the risk for mission implementation. The development must be 'requirements-driven and managed,' rather than a 'best effort tech-push' approach. The DRM team finds that the following key steps need to begin to propel successful development.

Develop quantified requirements for the Ocean Worlds Design Reference Mission with clearly defined metrics for autonomy system maturation

- The ocean worlds environment should be defined with fidelity necessary to define environmental requirements for the autonomy technology at the system capability level and at the component level, as defined in Part III and Part IV, respectively. This allows for measurement of technology maturity directly in the context of the DRM.
- A product breakdown structure of the complete autonomy system is needed to organize and support maturation of the technology. This structure is a comprehensive, hierarchical structure of deliverables — physical and functional — that make up the autonomy system.

Specify a software simulation and hardware validation and verification (V&V) environment that the national community will ultimately build and use to assess autonomy systems

- Build an ocean worlds software system simulation environment that can simulate the performance of autonomy subsystems and components. Build high-fidelity models of the subsystems and components that will be simulated in the larger system simulation environment.
- Build hardware testbeds to experimentally test autonomy subsystems and components.
- Construct a community V&V certification framework that will assess proposed autonomy systems against the quantified metrics developed above.

Build system and component technologies as described in Section IV. The developments will utilize the defined DRM environments, product breakdown structures, and V&V environments described above.

Part II: The Case for Ocean Worlds

The NASA Outer Planets Assessment Group (OPAG) Roadmaps to Ocean Worlds (ROW) group has outlined the scientific content and priorities for investigations that are needed for the exploration of ocean worlds[1]. They begin by stating:

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[1] Hendrix, Amanda R., T. A. Hurford, and ROW Team. *Roadmaps to Ocean Worlds*. Planetary Science Vision 2050 Workshop #8171. 2017.

"The overarching goal of an Ocean Worlds exploration program as defined by ROW is to 'identify ocean worlds, characterize their oceans, evaluate their habitability, search for life, and ultimately understand any life we find.' … There are several—if not many—ocean worlds or potential ocean worlds in our Solar System, all targets for future NASA missions in the quest for understanding the distribution of life in the Solar System."

These worlds beckon with ingredients that potentially harbor extant life. Beginning with the Galileo and Cassini missions, measurements have revealed the presence of global oceans under the icy crust of several moons of Jupiter and Saturn. Other such worlds have been recognized and are being examined by additional missions. Among the moons of Jupiter and Saturn, Europa and Enceladus have their ocean in contact with the rocky core, providing an environment similar to the conditions existing on the terrestrial sea-floor where life has developed at hydrothermal vents[2].

The National Research Council (NRC) reports[3, 4] and NASA Advisory Groups[5, 6] have placed a high priority on the science exploration of our solar system's Ocean Worlds, such as Europa and Enceladus. Three major themes are a focus[7]:

- Geodynamics: What is the structure and dynamic state of the icy crust and ocean interface?
- Habitability: Does the Ocean World's past or present state provide the necessary environments to support life?
- Life Detection: Did life emerge on one of these Ocean Worlds, and does it persist today?

In order to pursue answers to the questions in these themes, new and unique robotic system capabilities will be necessary. Accessing the oceans presents considerable difficulty due to a number of issues including the depth and composition of the icy crust, the time needed to travel through the crust or crevasse, the power needed to propel a probe, communication of scientific and engineering data though the ice and back to Earth, entry and mobility in the ocean, and autonomous operations for the life of the mission. To quantify and outline

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[2] Hand, K. P., et al. *Report of the Europa Lander Science Definition Team*. [https://europa.nasa.gov/system/downloadable_items/50_Europa_Lander_SDT_Report_2016.pdf] Posted February 2017.

[3] Space Studies Board, National Research Council. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. The National Academies Press. 2012.

[4] Committee on the Astrobiology Science Strategy for the Search for Life in the Universe, Space Studies Board, National Research Council. *Astrobiology Science Strategy for the Search for Life in the Universe.* doi:10.17226/25252. The National Academies Press. [http://nap.edu/25252] 2018.

[5] Hendrix, Amanda R., et al. *Roadmaps to Ocean Worlds*.

[6] Outer Planets Assessment Group Steering Committee. *OPAG Priority Science Questions: Letter to Dr. Lori Glaze, NASA PSD Director*. [https://www.lpi.usra.edu/opag/meetings/aug2019/OPAG-ScienceLetter-to-Glaze_27Aug19.pdf] August 27, 2017.

[7] Hand, K. P., et al. *Report of the Europa Lander Science Definition Team*.

capabilities for ocean worlds autonomous systems, two concepts for the design reference mission are defined – a Cryobot concept that would travel through the icy crust to the expected ocean below, and a Crevasse Explorer that would be mobile on the surface of the body and descend into a crevasse. These concepts are meant to be an abstraction of the autonomy capabilities for vehicles that can travel 'through-the-ice' or 'into the crevasses' and can apply to general ice environments. The autonomy capabilities can directly trace to the currently known environments and system objectives for the exploration of Europa and Enceladus; they would also trace to the surface and subsurface of Titan; it is expected that they would also trace to additional ocean worlds that, as they become better understood, have characteristics similar to those of these bodies.

The exploration vehicles will be required to operate in an environment that is not characterized with enough fidelity to create scripted a priori operational scenarios, or teleoperate with humans in-the-loop. The environment may be dynamic, as in crevasse-plumes, or require adaptable operations, as in vehicle movement through the ice, and obstructions must be sensed and avoided. It is assumed that the environment cannot be characterized with enough fidelity, even from prior remote sensing missions, to allow unattended operations and the ability to 'pull-over to the shoulder' and wait for direction. The in situ operation on and in the crust of ocean worlds therefore requires a unique level of autonomy to *enable* exploration and meet the goals as described above.

Part III: Design Reference Mission Scenarios

Two concepts are considered to organize the Ocean Worlds Design Reference Mission. They will be outlined separately – in some detail – before collapsing the driving autonomy capabilities needed into one set. The key differences between the two concepts will be identified.

Cryobot Concept

To answer the questions within the scientific themes, one robotic capability is a Cryobot capable of rapid penetration and scientific sampling of thick ice shells down to the ice-ocean interface, where it would deliver an autonomous undersea explorer. Past and current efforts aimed at identifying mission architectures, key concepts of operations, and technologies trades for accelerating the landing and deployment of a Cryobot have highlighted the need for a high level of autonomy throughout many of the mission phases, as described below.

Concept of Operations of the Cryobot Concept

The representative concept of operations is shown in Figure 1. The Cryobot mission concept of operations consists of:

A. **Descent and landing** onto a safe and scientifically interesting region of the surface.
B. **Commissioning and deployment** of the Cryobot to the icy surface.

C. **Initial cryogenic ice entry** phase that requires handling sublimation at the vacuum-ice interface with potentially dry, brittle, particulate-filled material.
D. **Descent** phase through cryogenic ice that slowly warms with depth to near freezing point.
E. **Detection of the ocean-ice interface** followed by safe probe anchoring at that interface.
F. **Ocean exploration:** Deployment of an ocean explorer payload and operations within the water near the interface.

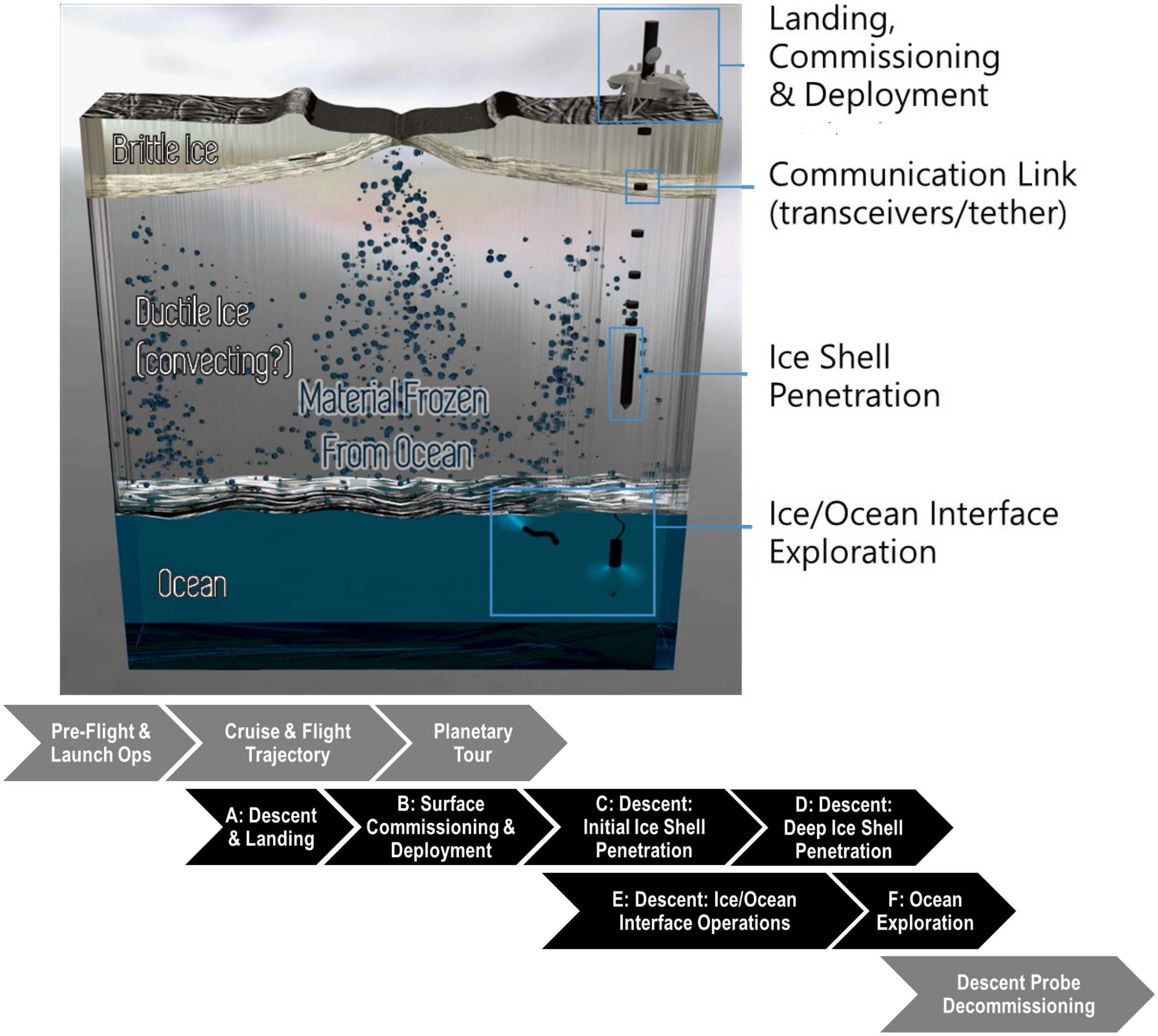

Figure 1. Mission illustration and Concept of Operations for a Cryobot and its ocean-exploring payload.

Autonomy Capabilities needed for the Cryobot Concept

For the full set of operational phases, a set of autonomous mission capabilities are defined. They are shown in Table 1. The mission capabilities are described through a set of high-level objectives that will guide the autonomous development of subsystems for each capability. The assessed level of autonomy needed is described to the right of each capability. Following this assessment, the capability is mapped to the Concept of Operation (CONOPS) phase that would require it. Some capabilities map to one or more concept of operation phases. Within each high-level autonomous capability are several component capabilities (also listed in Table 1) as well as the primary NASA Autonomous Systems Capability Leadership Team (AS-CLT) taxonomy class(es) attributed to each.

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Table 1. Autonomous technology mapping for the Cryobot: Mission capabilities, level of autonomy, mapping to CONOPS, component capabilities, and primary AS-CLT taxonomy class for each.

Autonomous Mission Capability	Description and Objectives	Level of Autonomy	Mapping to CONOPS						Component Capabilities	Primary CLT taxonomy class(es)
			A	B	C	D	E	F		
Decelerate, descent, and landing (DDL)	Land within "safe" target region defined from orbital imagery. Redirect as map is refined to maximize landing safety, ice penetration feasibility, and science potential.	High	▓						Terrain relative navigation Real-time hazard detection and avoidance Real-time 3D surface mapping Real-time optimal landing site selection	1.2 1.4, 2.3 1.3 2.1
Ground reconfiguration	Safely transition from landed configuration to communication-ready configuration.	High	░	▓					Initial checkout: life-support management and control Execute deployables to orient Cryobot and HGA	2.5 2.4
Cryobot deployment	Ensure safe entry of Cryobot into surface within a few weeks after landing to limit radiation dose. Update model of environment for effective control.	Medium		▓					System health management Assess surface properties and penetration performance Control Cryobot insertion	1.2, 2.2 1.3 2.4
Deposit electronics below surface	Ensure all radiation-sensitive electronics are safely deployed below surface behind the Cryobot.	Medium		▓					Detect hole closure and Cryobot state deployment of tethered surface electronics behind	1.2 2.2, 2.4
Automated science	Perform science measurements during descent. For example, some measurements include: imaging, temperature, pressure, grain size, porosity, pH, Ion concentrations, and turbidity.	High			░	▓		▓	Estimate Cryobot depth Trigger measurements at regular intervals Detect interesting or anomalous measurements Detect and image dynamic events	1.2 2.2 1.6, 2.5 1.6
Hazard avoidance	Detect and avoid potential hazards during descent.	High			▓	▓			Reconstruct hazard map of the anterior subsurface from Plan a 3D path with complex constraints Estimate risk in real time and trigger safe mode for Control Cryobot by steering and varying penetration Estimate and control Cryobot pose to track trajectory	1.3 2.3 1.4, 1.6 2.4 2.4
Deployment of Communication link	Ensure successful deployment of ice transceiver communication pucks and/or tether.	Medium			▓	▓			Estimate Cryobot depth and bandwidth to previous puck Control puck deployment (position and orientation)	1.2 2.4
Cryobot mobility management	Control heat, waterjet, and drill to achieve descent rate and steering. Monitor and mitigate debris build-up.	High			▓	▓			Control fluid heat pumps, drill, and water jet for desired Estimate and mitigate debris build-up Cryobot pose estimation	2.4 1.4, 2.2 1.2
Ice/ocean interface behavior	Stop at ice-ocean interface and do ocean science.	High				░	▓		Detect ice-ocean interface ahead of Cryobot Detect interface penetration Enact "anchoring" strategy Characterize interface environment	1.3 1.3 2.2, 2.4 1.3
System health and resource management	Manage overall system health and resource allocations.	High	▓	▓	▓	▓	▓	▓	Prioritize data products and manage queue Manage power resources Active thermal management	2.2 2.2 2.4

			▨	▨	▨	▨	▨	▨	Estimate health of communication link to surface	1.2
									Detect and respond to faults	2.5, 2.6
In-Ocean Exploration	Operate hydrobot with science instruments in the sub-surface ocean tethered from the Cryobot anchored in the ice.	High	▨	▨	▨	▨	▨	▨	Relative pose estimation of hydrobot w.r.t Cryobot	1.2
									buoyancy control for regulating proximity to ice ceiling	2.4
									measure time-varying ocean currents	1.5
									Sample environment at multiple locations with science	2.1, 2.2

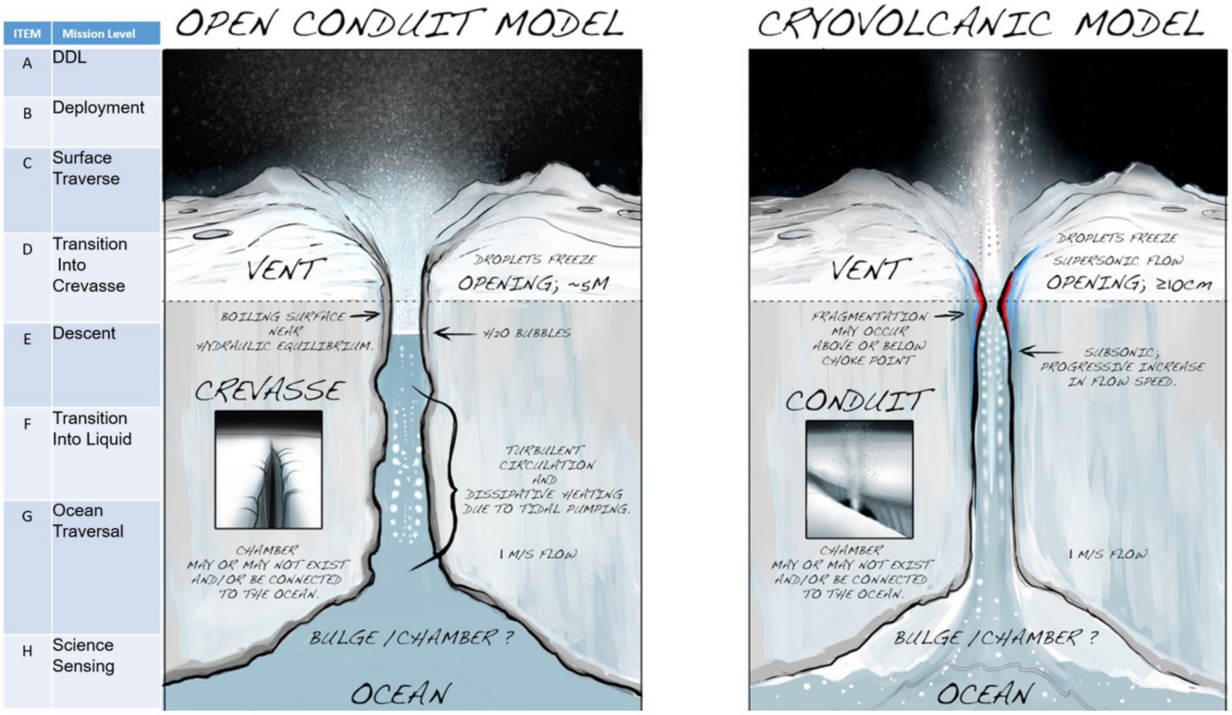
A Crevasse Explorer Concept

A second Ocean Worlds exploration concept focuses on crevasses that have been observed to emit plume material, 'bringing the ocean to the surface.' The Cassini mission shows data on a number of Enceladus crevasses including the Tiger Stripes. The active plumes originating from these crevasses suggest an open conduit to a liquid body. Other Ocean Worlds may potentially have similar crevasses. Exploring crevasses and the nearby surfaces creates many challenges including resisting plume forces, dealing with the phase change of water, water vapor occluded imaging, constrained dynamic environments, liquid mobility, and others. The operations and scientific discovery will require deep autonomous capabilities to work in this environment.

Concept of Operations of the Crevasse Explorer Concept

The design reference concept of operations is shown in Figure 2. The crevasse mission concept of operations consists of:

A. **Direct descent and Landing** with pinpoint guidance to one of the largest mass flux vent plumes.
B. **Deployment** of the crevasse explorer.
C. **Surface traverse** to the vent opening.
D. **Transition into Crevasse** requiring bracing or anchoring to react plume forces (this includes science sensing).
E. **Descent** against plume forces through open conduit warmed by active plume (including possible plume chock point traversal).
F. **Transitions into Liquid** including detection and reaching the liquid interface.
G. **Ocean Traversal** and operations within the water.
H. **Science sensing** at the ice-water interface.



ITEM	Mission Level
A	DDL
B	Deployment
C	Surface Traverse
D	Transition Into Crevasse
E	Descent
F	Transition Into Liquid
G	Ocean Traversal
H	Science Sensing

Figure 2. Crevasse Explorer CONOPS Phases

Autonomous Mission Capabilities needed for the Crevasse Explorer Concept

Table 2 shows a mapping of the Autonomous Mission capabilities to the CONOPS of the mission concept.

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Table 2. Autonomous technology mapping for the Crevasse Explorer: Mission capabilities, level of autonomy, mapping to CONOPS, component capabilities, and primary AS-CLT taxonomy class for each.

Autonomous Capability	Description / Requirements	Level of Autonomy	Mapping to CONOPS								Component Capabilities	Primary CLT taxonomy class(es)
			A	B	C	D	E	F	G	H		
Decelerate, descent, and landing (DDL)	Landing within ~XXm from target.	High	■								Terrain relative navigation	1.2
											Real-time hazard detection and avoidance	1.4, 2.3
											Real-time vent characterization and target selection	2.1
Descent module deployment	Safely deploy the descent module from lander and anchor to the surface under 0.01g	Medium		■							System health management	2.5
											Release and verify deployment	2.4
Power/ Communication management	Manage power and communication health.	High		■	■	■	■	■			Prioritize data products and manage queue	2.2
				■	■	■	■	■			Manage power resources	2.2
				■	■	■	■	■			Active thermal management	2.4
				■	■	■	■	■			Estimate health of communication link to surface	1.2
Surface Traversal	Traversal from lander to vent opening.	Medium		■							Handle environmental state	2.3
											Traversability analysis	1.2
				■							Localization	1.1, 1.2
				■							Path/motion planning	2.3
Hazard avoidance	Detect hazards and plan a path to avoid them; make XX m progress over YY hours.	High		■	■	■	■	■	■	■	3d Perception/motion planning	1.3
				■	■	■	■	■	■	■	Plan a 3D path with complex constraints	2.3
				■	■	■	■	■	■	■	Sense anomalous events, adapt to mitigate effects	1.4, 1.6
Situation awareness	Estimate the environmental states (e.g., flow speed/direction, crevasse opening/closing).	High				■	■	■	■		Onboard model-based inference with multiple sensory inputs	1.2, 1.3, 1.5
Surface/crevasse transition	Detect approaching transition and ensure ability to react to plume forces prior to entering the flow.	High				■					Plume detection	1.3
						■					Implement anchoring strategy	2.1, 2.4
						■					Characterize transition environment	1.3
						■					Plan initial mobility strategy	2.3
Automated science	Perform target selection, data & sample collection, and analysis partially or fully autonomously.	High			■	■	■	■	■	■	Automated science target detection	1.6, 2.5
					■	■	■	■	■	■	Automated in-situ observation	1.6

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Autonomous Capability	Description / Requirements	Level of Autonomy	Mapping to CONOPS								Component Capabilities	Primary CLT taxonomy class(es)
					▨	▨	▨	▨	▨	▨	Automated sampling	1.3, 2.1, 2.2, 2.4
					▨	▨	▨	▨	▨	▨	Onboard analysis, data triage	1.3
FDIR	Fault detection, isolation, and recovery.	High	▨	▨	▨	▨	▨	▨	▨	▨	Fault detection (Diagnosis)	2.5
			▨	▨	▨	▨	▨	▨	▨	▨	Fault isolation	2.6
			▨	▨	▨	▨	▨	▨	▨	▨	Recovery	2.6
Activity planning & scheduling	Plan & schedule engineering/science activities given high-level goals.	High			▨	▨	▨	▨	▨	▨	Onboard planning & scheduling	2.1, 2.2
Ice/ocean Interface Behavior	At ocean interface, anchor the descent module and asses ocean currents.	High						▨			Detect liquid/ice interface	1.3
								▨			Characterize transition environment	1.3
In-Ocean Exploration	Operate EELS with science instruments in the sub-surface ocean.	High							▨		Relative pose estimation	1.2
									▨		buoyancy control for regulating proximity to ice ceiling	2.4
									▨		measure time-varying ocean currents	1.5
									▨		Liquid mobility operation	1.2

Part IV: A Common set of Autonomy Component Capabilities

While nearly all areas of the Autonomous Systems - CLT taxonomy will be important to the successful execution of an Ocean Worlds mission, the following autonomous system CLT areas are highest priority for the two mission concepts described above.

1.3 Knowledge and model building

The surface, vent, and subsurface environments of ocean worlds will present significant operational uncertainty, which must be resolved and modeled autonomously. Local-scale models are needed to inform reactive controllers and ensure operational safety, while “global” models are needed to anticipate (and plan for) critical transition points (e.g., entering the plume stream or the ice-ocean interface). Key technology capabilities for each DRM are outlined below.

Cryobot:
- Monitoring and modeling of ice penetration performance (e.g., descent rate, steerability, etc.)
- Fore-field mapping and hazard detection via acoustic, RF, and/or optical sensors
- The anticipatory detection of and reaction to the ice-ocean interface

Crevasse Explorer:
- Proprioceptive sensing of surface contact properties
- Modeling the flow field using multiple sensors (e.g., pitot tubes and pressure sensors), as well as the flow-induced forces on the robot
- Mapping the 3D geometry of the crevasse and estimating the robot’s location within it
- The anticipatory detection of and reaction to operational transition points, including the plume stream, flow choke points, bulge chambers, boiling interface surfaces, and the ice-ocean interface

*Note that Knowledge and model building heavily leans on CLTs 1.1 – “Sensing and Perception” and 1.2 – “State Estimation and Monitoring,” particularly regarding robot localization.

1.4 Hazard Assessment

For novel robotic mobility systems, strategies for the modeling, assessment, detection, and avoidance of potential hazards remain a key technology gap for both the Cryobot and Crevasse Explorer. Key capabilities particularly related to *autonomy* for each DRM are highlighted in *italics* in the table below.

	Cryobot	Crevasse Explorer
Hazard model - Characterization of "performance hazards" that negatively impact operations and critical hazards that pose mission-ending risks.	*Characterize penetration performance (e.g., speed) over a wide range of ice conditions, and define ice "impurities" that must be avoided, such as salt deposits, rocks, and voids.*	*Characterization of surface hazards (e.g., steep slopes) that impede traverse and entry into crevasse, and the conditions under which the upward dynamic pressure on the robot prevents descent.*
Hazard assessment – An a priori assessment and uncertainty quantification of potential hazards in the environment.	Quantify the range of possible subsurface ice conditions based on various geologic models. (See CLT 4.1, V&V)	Quantify the range of possible vent conditions such as the geometry, surface, and flow properties. (See CLT 4.1, V&V)
Hazard detection – The ability for the robot to detect potential hazards with sufficient resolution and range to allow for avoidance or mitigation maneuvers.	Create a fore-field map of potential hazards from acoustic, RF, and optical sensing data at sufficient resolution to allow for avoidance maneuvers.	*Real-time 3D surface mapping and flow estimation.*
Hazard avoidance – Actions the robot can take to avoid or mitigate hazards.	*Risk-aware decision-making and motion-planning algorithms for subsurface guidance given a probabilistic hazard map.*	*Motion-planning algorithms to avoid hazardous terrain during surface traversal and "aerodynamic" maneuvers to mitigate plume back-pressure.*

*Note that Hazard *avoidance* has significant overlap with CLT 2.3 – "Motion Planning," and Hazard *detection* has significant overlap with CLT 1.1 – "Sensing and Perception."

2.4 Execution and control

The Cryobot and Crevasse Explorer constitute novel mobility systems which must reliably operate for long periods of time and beyond the horizon visible to ground control. Thus, actuation and control for interacting with their environment as well as regulating internal health remain key technology gaps for both systems. Key technology capabilities for each are outlined below.

Cryobot:

(1) *Ice Penetration*: Drilling, water jetting, and thermal redistribution will be required for penetration through various types of ice as well as a method for differential melting to enable steering.

(2) *Deployables*: The Cryobot will need to deploy a surface electronics package several meters below the surface, continuously deploy a communications tether and/or periodically deploy communication transceivers ("pucks"), and finally, deploy an ocean exploration module. Deployable anchors may also be required to slow or, at the ice-ocean interface, stop the Cryobot.

(3) *Thermal Control*: active control of a working fluid will be required to redistribute several kilowatts of thermal power from an RTG heat source around the Cryobot for effective ice penetration as well as maintaining safe working temperatures for all critical subsystems.

Crevasse Explorer:

(1) *Mobility*: Novel control strategies will be required to negotiate a wide variety of terrain types during the approach to and descent through a vent, such as anchoring with scalable

reaction forces, handling uneven surfaces, conforming to the internal shape of the vent, and potentially variable buoyancy for ocean exploration.

(2) *Power and communications management* requires an onboard power solution with a repeating communicator solution or a tether. A combination of these features may also be feasible.

4.1 Verification and validation

System level V&V approaches for Cryobot and Crevasse Explorer autonomy will require significant development on three primary fronts: (1) Uncertainty quantification, (2) physical test beds, and (3) software (simulation) test beds.

	Cryobot	Crevasse Explorer
Uncertainty quantification	There is currently little consensus in the scientific community regarding models of the Europan subsurface.	There are currently competing models in the scientific community regarding the geometry and flow physics of the vents on Enceladus.
	Rigorous and quantitative studies will be required to define the uncertainty bounds and performance requirements for autonomous operations.	
Physical test beds	Earth analog tests in large-scale ice sheets will help to validate some autonomous Guidance, Navigation and Control (GN&C) subsystems. A large cryogenic hypobaric chamber will also be required to assess penetration performance in more realistic "Europan" conditions.	A variety of Earth analog sites may capture a range of potential crevasse terrain geometries for testing some autonomous GN&C subsystems. A laboratory test bed will also be required to emulate the high-velocity plume flow and reduced gravity.
Software test beds	A comprehensive, physics-based simulation environment will be required to validate autonomous components as well as the full, integrated autonomy system.	

*Note that V&V has significant overlap with CLTs 4.2 – "Test and Evaluation," and 4.4 – "Modeling and Simulation."

Autonomous science:

Due to the multi-hour communication latency to Europa and Enceladus and the dynamic nature of the environments (e.g., due to the inability to stop for the Cryobot and the time-varying nature of plume ejecta for the Crevasse Explorer), autonomy will be required to perform opportunistic science measurements (e.g., in response to anomalous events or local features that are deemed "interesting") in addition to regularly scheduled measurements. Also, extremely limited data rates will demand a large degree of autonomous data interpretation, compression, and downlink prioritization.

Part V: Potential Challenges, Risks and Needed Supported Technologies

Three key technologies and challenges have been identified to accomplish the technology development defined above.

1. **System capability that integrates component capabilities including a verification and validation system.**

Nearly all of the AS-CLT building blocks will be essential to a successful Ocean Worlds mission. However, they cannot be considered isolated components. A key investment is in integrated system capability, where the AS-CLT building blocks highlighted above are the key tall poles to be validated in an integrated system. For example, a mobility system, while very different for a Cryobot and Crevasse Explorer, requires integration of knowledge and model building, state estimation and monitoring, hazard assessment, execution and control, and motion planning. Key system-level capabilities include mobility, health management, and autonomous science. These system-level capabilities must be verified and validated to achieve the mission goals for unknown situations including dynamic environments and evolving, potentially degrading internal systems.

2. **Building system adaptability to the environment as well as being reactive to the environment, where the environment is dynamic and not well prescribed.**

While the autonomy for the Cryobot/Crevasse Explorer must consist of a diverse set of capabilities as described in Section IV, we found there are a few notable common denominators. First, it has to be not only robust but also *adaptive*. The significant environmental uncertainty will likely prohibit us from finding a fixed design of autonomous behaviors that robustly work for any imaginable situations; rather, it has to adapt its behaviors by continuously learning about the new environment. Second, it has to be *reactive* rather than deliberative. Unlike Mars rovers, visibility is highly limited, environment is dynamic, and orbital reconnaissance is unavailable. Therefore, it has to quickly react to observed situations instead of making a long-range plan deliberatively. Third and finally, it has to be *resilient* rather than protective. Encountering anomalous situations will be likely unavoidable however cautious it is; rather, it has to be designed such that it keeps making progress resiliently even while experiencing anomalies.

3. **Taking advantage of technologies being developed external to NASA.**

A wide range of technologies are being developed external to NASA for industries that are not specifically space-related. These entities have resources much larger than NASA can commit in this area. Some of these technologies have strong overlap with the NASA Ocean Worlds systems and have convincing synergies, if not direct use. One such area is in verification and validation of autonomous systems that are used to certify self-driving cars. Finding approaches that will increase such synergies is essential for success.

Part VI: Findings

The systems needed to accomplish the goals of this DRM require a long runway to succeed. A key driver is time and critical mass of work to develop the technology to a point of maturity that reduces the risk for mission implementation. The development must be requirements driven and managed, rather than a 'best effort tech-push' approach. The DRM team finds that the following key steps need to begin to propel successful development.

Develop quantified requirements for the Ocean Worlds Design Reference Mission with clearly defined metrics for autonomy system maturation

- The ocean worlds environment should be defined with fidelity necessary to define environmental requirements for the autonomy technology at the system capability level and at the component level, as defined in Part III and Part IV, respectively. This allows for measurement of technology maturity directly in the context of the DRM.
- A product breakdown structure of the complete autonomy system is needed to organize and support maturation of the technology. This structure is a comprehensive, hierarchical structure of deliverables — physical and functional — that make up the autonomy system.

Specify a software simulation and hardware validation and verification (V&V) environment that the national community will ultimately build and use to assess autonomy systems

- Build an ocean worlds software system simulation environment that can simulate the performance of autonomy subsystems and components. Build high-fidelity models of the subsystems and components that will be simulated in the larger system simulation environment.
- Build hardware testbeds to experimentally test autonomy subsystems and components.
- Construct a community V&V certification framework that will assess proposed autonomy systems against the quantified metrics developed above.

Build system and component technologies as described in Section IV. The developments will utilize the defined DRM environments, product breakdown structures, and V&V environments described above.

Part VII: Ocean Worlds DRM Team

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Ocean Worlds Design Reference Mission Report Summary

One of the most profound discoveries resulting from planetary exploration is the evidence for large quantities of liquid water on several bodies in our solar system, aptly named "Ocean Worlds." In an effort to extrapolate our understanding of life on Earth to the cosmos, "go to the water" has become the guiding principle in our search for evidence of extraterrestrial life. Thus, Ocean Worlds have become key astrobiology targets, and many outstanding questions can only be answered through direct contact with their subsurface liquid water. National Research Council (NRC) reports[8,9] and NASA Advisory Groups[10,11] have placed a high priority on the science exploration of our solar system's Ocean Worlds such as Europa and Enceladus. Three major themes are a focus[12]:

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[8] Space Studies Board, National Research Council. V*ision and Voyages for Planetary Science in the Decade 2013-2022*. The National Academies Press. 2012.

[9] Committee on the Astrobiology Science Strategy for the Search for Life in the Universe, Space Studies Board, National Research Council. *Astrobiology Science Strategy for the Search for Life in the Universe*. doi:10.17226/25252. The National Academies Press. [http://nap.edu/25252] 2018.

[10] Hendrix, Amanda R., T. A. Hurford, and ROW Team. *Roadmaps to Ocean Worlds*. Planetary Science Vision 2050 Workshop #8171. 2017.

[11] Outer Planets Assessment Group Steering Committee. *OPAG Priority Science Questions: Letter to Dr. Lori Glaze, NASA PSD Director*. [https://www.lpi.usra.edu/opag/meetings/aug2019/OPAG-ScienceLetter-to-Glaze_27Aug19.pdf] August 27, 2017.

[12] Hand, K. P., et al. *Report of the Europa Lander Science Definition Team*. [https://europa.nasa.gov/system/downloadable_items/50_Europa_Lander_SDT_Report_2016.pdf] Posted February 2017.

- **Geodynamics:** What is the structure and dynamic state of the icy crust and ocean interface?
- **Habitability:** Does the Ocean World's past or present state provide the necessary environments to support life?
- **Life Detection:** Did life emerge on one of these Ocean Worlds, and does it persist today?

The challenges involved in implementing robotic subsurface missions on Ocean Worlds are immense, and advanced autonomy may be among the most demanding technology developments that will be required. Ocean Worlds present an environment that is uncertain, dynamic, and communication-constrained, which requires autonomy that is *adaptive*, *reactive*, and *resilient*. For example, the dynamic nature of plume ejecta on Enceladus or the harsh radiation of Europa prohibit human-in-the-loop control, especially during long-duration communication blackouts such as the two-week period during solar conjunction. Ocean World probes must be equipped to *learn* from their interactions with the environment, *react* to imminent hazards, and *make real-time decisions* to respond to anomalies.

The Ocean Worlds DRM team suggests two autonomous DRM scenarios.

DRM Scenario: A Cryobot Concept

This mission consists of a lander that will visit a scientifically interesting spot on the Ocean World's icy surface and deploy a cryobot to search for life without humans in the loop. The cryobot will be capable of rapid penetration and scientific sampling of thick ice shells down to the ice-ocean interface, where it will deliver an autonomous undersea explorer.

Past and current efforts aimed at identifying mission architectures, key concepts of operations, and technology trades for accelerating the landing and deployment of a cryobot have highlighted the need for a high level of autonomy throughout many of this mission's phases.

DRM Scenario: A Crevasse Explorer

This mission consists of a lander that will land near a vent plume and deploy an explorer to traverse to a vent opening, anchor and brace itself, and then enter the crevasse to explore. Exploring crevasses and the nearby surfaces on Ocean Worlds presents many challenges including resisting plume forces, dealing with phase changes of water, water vapor occluded imaging, constrained dynamic environments, liquid mobility, and more. Mission operations and scientific discovery will require autonomous capabilities to function in this environment

These DRM scenarios both require a level of autonomy that is not currently available. Advancements in autonomy technology are required for these mission scenarios to perform the following:

Knowledge and Model Building: The surface, vent, and subsurface environments of Ocean Worlds will present significant operational uncertainty, which must be resolved and modeled autonomously. Local-scale models are needed to inform reactive controllers and ensure operational safety, while “global” models are needed to anticipate and plan for critical transition points (e.g., entering the plume stream or the ice-ocean interface).

Hazard Assessment: Mission assets must be capable of characterizing performance hazards that could negatively impact operations and critical hazards that pose mission-ending risks. For example, the Cryobot must be capable of characterizing penetration performance (e.g., speed) over a wide range of ice conditions and defining ice “impurities” that must be avoided, while the Crevasse Explorer must be able to characterize surface hazards (e.g., steep slopes) that will impede traverse and entry into the crevasse and the conditions under which the upward dynamic pressure on the robot will prevent descent. In addition to developing such models, mission assets must be able to conduct an a priori assessment of potential hazards in the environment, detect potential hazards with sufficient resolution to avoid or mitigate them, and then autonomously take preventative action.

Execution and Control: The Cryobot and Crevasse Explorer constitute novel mobility systems that must reliably operate for long periods of time without human intervention. Thus, the capability for autonomous actuation and control to interact with the environment as well as the ability to regulate internal health remain key technology gaps for both systems.

Verification and Validation: System level verification and validation (V&V) approaches for Cryobot and Crevasse Explorer autonomy will require significant development on three primary fronts: (1) uncertainty quantification: rigorous and quantitative studies will be required to define the uncertainty bounds and performance requirements for autonomous operations in the Ocean World environments, (2) physical test beds, and (3) software (simulation) test beds.

Autonomous Science: Due to the multi-hour communication latency to Europa and Enceladus and the dynamic nature of the environments (e.g., the inability to stop for the Cryobot and the time-varying nature of plume ejecta for the Crevasse Explorer), autonomy will be required to perform opportunistic science measurements (e.g., in response to anomalous events or local features that are deemed “interesting”) in addition to regularly scheduled measurements. Also, extremely limited data rates will demand that mission assets perform a large degree of autonomous data interpretation, compression, and downlink prioritization.

To enable autonomy in these DRM scenarios, advancements in the following supporting technology areas are required:

- Communications: Deployable RF/acoustic communication puck transceivers to relay data at distance in warm and cryogenic ice; electromechanical tether to support power, communications, and structural support at cryogenic temperatures (70K)
- Mobility Systems: A melt/drill probe that can penetrate an ice sheet and be steerable with a turning radius small enough to avoid obstacles detected with acoustic/RF

sensors; a tethered, instrumented, pressurized vessel able to maneuver at the ice-ocean interface; surface mobility systems to traverse to the rim of a crevasse and descend through the crevasse, reacting against plume forces

- Forward-looking acoustic/RF sensors able to detect hazards and ice/ocean interface: Depth sensing through surface ranging using communication pucks and a sensor architecture for situational awareness in an ocean; visual navigation for surface traversal; flow gradient sensors to follow vent streamlines
- High-performance space computing for inversion of acoustic signals and for real-time visual-inertial navigation across the surface and through vents

Findings

The systems needed to accomplish the goals of these DRM scenarios require a long runway to succeed. Key drivers include time and the critical mass of work required to develop the technology to a point of maturity that reduces the risk for mission implementation. Due to the unique and constraining specifications, the technology development must be requirements-driven and managed, rather than a best effort, technology-push approach. The Ocean Worlds DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above.

1. Develop requirements with traceability to science requirements to be met in the Ocean Worlds environment and that include clearly defined metrics to be used to mature the autonomy systems.
    a. The Ocean Worlds environment should be defined with the fidelity necessary to define environmental requirements on the autonomy technology at the system capability level and at the component level to allow for measurement of technology maturity directly in the context of the DRM.
    b. A product breakdown structure of the complete autonomy system is needed to organize and support maturation of the technology. This structure is a comprehensive, hierarchical structure of deliverables—physical and functional—that make up the autonomy system.
2. Specify a framework for a software simulation and hardware V&V environment that the national community will ultimately build and use to assess autonomy systems. After the framework is specified:
    a. Build an Ocean Worlds software system simulation environment that can simulate the performance of autonomy subsystems and components. Build high-fidelity models of the subsystems and components that will be simulated in the larger system simulation environment.
    b. Build hardware testbeds to experimentally test autonomy subsystems and components.

    c. Construct a community V&V certification framework that will assess proposed autonomy systems against the quantified metrics developed above.

3. Build required system and component software and hardware technologies. The developments will utilize the required DRM environments, product breakdown structures, and V&V environments.