SCIENCE CHINA
Earth Sciences

•ARTICLE•

November 2024 Vol.67 No.11: 3515–3535
https://doi.org/10.1007/s11430-023-1390-6

An Icy Worlds life detection strategy based on Exo-AUV

Bin WANG[1,2] & Hongde QIN[1,2*]

[1] National Key Laboratory of Autonomous Marine Vehicle Technology, Harbin Engineering University, Harbin 150001, China;
[2] Shipbuilding Engineering College, Harbin Engineering University, Harbin 150001, China

Received November 20, 2023; revised July 12, 2024; accepted July 22, 2024; published online September 29, 2024

Abstract In the solar system, Icy Worlds such as Europa and Enceladus hold great potential for extraterrestrial life and may provide humanity an answer, within this century, to the age-old question of life beyond Earth. Exo-AUV technology shows promise in life detection in the icy shell, at the ice-water interface and on the seafloor of exo-ocean. Space agencies, including NASA and DLR, are enthusiastic about deploying Exo-AUVs to explore life in these regions. However, the where and how to find life, the technologies to be utilized and the goals to be achieved are crucial aspects for future Exo-AUV life detection missions on Icy Worlds. This study delves into a hypothetical mission of life detection on Europa, discussing science goals, detectable objects, potential regions and biogenic analysis for Icy Worlds. It proposes a life detection strategy for Icy Worlds based on Exo-AUVs, presents key contextual elements for Exo-AUV operations, outlines technological requirements for hull, payloads and autonomy, introduces the current state of Exo-AUV research and addresses existing challenges. This study also suggests a roadmap for conceptual development of Exo-AUV and a Concept of Operations for Multiple Exo-AUV System (ConOps for MEAS). This system aims to assist planetary scientists and astrobiologists in exploring Icy Worlds, identifying robust biosignatures and potentially discovering extant organisms, even prebiotic chemical systems.

Keywords Icy Worlds, Europa, Life detection, Biological potential, Exo-AUV

Citation: Wang B, Qin H. 2024. An Icy Worlds life detection strategy based on Exo-AUV. Science China Earth Sciences, 67(11): 3515–3535, https://doi.org/10.1007/s11430-023-1390-6

1. Introduction

In 2005, *Science* published 125 cutting-edge scientific questions to commemorate its 125th anniversary, including "Are we alone?" (Kennedy and Norman, 2005) and "Is there—or was there—life elsewhere in the solar system?" (AAAS, 2005). In 2021, Shanghai Jiao Tong University and *Science* released an updated version of these questions to honor the school's 125th anniversary, combining the previous two questions into one ultimate query "Are we alone?" (Levine, 2021). Despite Astrobiology's relatively short history of less than a century (Cockell, 2001), it has long pondered the existence of extraterrestrial life and its possible locations. The concept of "an infinite number of worlds" dates back to ancient Greek philosophers Leucippus and Democritus (Dick, 1982), while Roman poet Lucretius contemplated "other worlds, men and creatures of a different kind" in his writings (Rouse, 1975). Scholars during the European Renaissance and Enlightenment, such as Bruno, Kepler and Huygens, also supported the idea of "The Plurality of Worlds" based on celestial observations (Roush, 2020). As early as 1855, William Whewell of Trinity College, University of Cambridge, argued against the possibility of planets in our solar system hosting life like Earth, citing "physical reasons" and highlighting Earth's unique orbit as a key factor in sustaining life (Whewell, 1853).

Whewell's "physical reasons" may be outdated, but his conclusions remain forward-thinking. The Habitable Zone (Goldilocks) principle, developed in the 20th century, posits that a planet capable of sustaining liquid water on its surface

* Corresponding author (email: qinhongde@hrbeu.edu.cn)

must be situated at an appropriate distance from its star, considering factors such as planet size, density, internal structure, magnetic field, star type and etc. (Ramirez, 2018). While confirmed and potential exoplanets (Earth-like habitable planets) have yet to be found within our solar system, the discovery of a hydrothermal system and unique ecology based on chemosynthesis on the seafloor by the research submersible Alvin in 1977 has sparked hope for uncovering extraterrestrial life within our own cosmic neighborhood (Karl et al., 1980). Subsequent reports of microbial communities in polar subglacial lakes (Siegert et al., 2001), brine lakes (Murray et al., 2012), deep glaciers (Malaska et al., 2020) and deep crust (D'Hondt et al., 2019) have further expanded our understanding of life's adaptability. Microorganisms thriving in extreme environments challenge our preconceived notions of life's limits, while discoveries of Icy Worlds or Ocean Worlds like Europa in recent decades (Hendrix et al., 2019) offer hope in our quest to answer the question: "Are we alone?"

An Ice World like Europa, Enceladus or Titan has surface icy shell, subglacial ocean and rocky seafloor, all of which are crucial features that could potentially sustain life (Hoehler et al., 2020). While these Icy Worlds share common characteristics, they also present distinct differences in sustainable and detectable life forms, potentially challenging our understanding based on Earth's ecosystems (German et al., 2019). German's work succinctly raised the fundamental question of how to identify these Icy Worlds and develop the necessary technologies for successful life detection, underscoring the importance of ongoing discussion and collaboration among experts in planetary, earth and ocean sciences and technologies (German et al., 2022a). This call to action was prominently featured in the "Special Issue on Oceans Across the Solar System" of *Oceanography* in June 2022.

Among known Icy Worlds, the most promising regions for potential life are within the icy shell, at the interface between ice and water and on the seafloor (Chyba and Phillips, 2001; Marion et al., 2003; Figueredo et al., 2003). To surpass the limitations of traditional probes such as orbiters, landers, rovers and drones, the development of a specialized Autonomous Underwater Vehicle (AUV) capable of penetrating the icy shell and conducting autonomous life detection missions in ice and ocean is considered an ideal solution (Hendrix et al., 2019; Hand et al., 2020). NASA (National Aeronautics and Space Administration) and DLR (Deutsches Zentrum für Luft- und Raumfahrt, DLR, German Aerospace Center) are at the forefront of this effort with AUV projects for Europa and Enceladus. Europa, similar in size to Earth's moon, is covered by an icy shell with thickness of more than several and even tens of kilometers and exposed to intense radiation from Jupiter. Its subglacial ocean reaches depth of over 100 km with high hydrostatic pressure on the seafloor (Nimmo and Pappalardo, 2016). In this vast, dark, oligotrophic environment, the distribution of any potential microorganisms is likely to be sparse and heterogeneous (Hoehler et al., 2022). Additionally, communication delays of up to half an hour between Europa and Earth, along with limited bandwidth and communication windows, present significant challenges for AUV operations on Icy Worlds (Wronkiewicz et al., 2024). These extreme conditions call for AUVs capable of penetrating ice, voyaging and conducting intricate life detection missions autonomously in the extraterrestrial vast global ice and ocean expanse. To streamline research focus and communication clarity, this type of submersible designed for autonomous operations in extraterrestrial liquids can be termed as an Extraterrestrial AUV or Exo-AUV.

This study explores the historical science goals and methods for detecting life in the solar system and introduces an Icy Worlds life detection strategy based on Exo-AUV, with the primary science goal of biological potential, using Europa as case study. It also outlines the major contextual elements and technological requirements for Exo-AUV. Additionally, it provides a thorough examination of the evolution of Exo-AUVs and proposes a roadmap for conceptual development of Exo-AUV, as well as a Concept of Operations for Multiple Exo-AUV System (ConOps for MEAS).

2. An Icy Worlds life detection strategy

Unlike NASA and ESA, this study argues that future life detection missions on Icy Worlds should set biological potential as the primary science goal. On this basis, it outlines a framework of life detection strategy for Exo-AUVs. To make this strategy better understood, this study analyzes the superiority of biological potential as the primary science goal, using the example of Europa, proposes an inference about potential regions, based on ecological niche theory and analogue studies on Earth, lists the main detectable objects, and points out the shortcomings of current biogenic analysis and explains the advantages of the life detection strategy proposed.

2.1 Science goal

NASA's Europa Clipper and ESA's Jupiter Icy Moons Explorer (JUICE) have established science goals focused on habitability (Dougherty et al., 2011; Paczkowski et al., 2022). Nevertheless, there are problems with this set-up. The Astrobiology term "habitability", originating from the concept of "habitat" in ecology, refers to the ability of an extraterrestrial environment to support at least one known life (Cockell et al., 2016). This definition inherently presents a binary nature, where an extraterrestrial environment is either deemed habitable or uninhabitable for a specific type of known life, with no middle ground (Cockell et al., 2019). However, the term habitability has been expanded beyond this strict definition. Examples include utilizing telescopes or probes to assess habitability based on the classic "3 key requirements for life" (Nealson, 1997), studying Super Habitable Exoplanets that may be "more habitable" than Earth, comparing habitability across different environments over varying time and space scales, examining the isolated impact of environmental variables on overall habitability and employing probability to quantify habitability (Cockell et al., 2022). While these topics hold research significance, they deviate from the traditional scientific interpretation of habitability, sparking considerable debates (Cockell et al., 2016, 2019, 2022; Heller, 2020; Lenardic and Seales, 2021). The binary concept of habitability, defined within strict ecological boundaries, may not fully align with the grand, complex, interdisciplinary backgrounds and open, divergent and exploratory approaches used in the research of detecting extraterrestrial life. This discrepancy may indicate that the traditional concept of habitability is no longer fully compatible with the current and future landscape of extraterrestrial life detection. Detection methods and equipment designed with habitability as the primary science goal may not adequately address emerging criticisms. Prebiotic chemical systems may exist within Icy Worlds like Europa (Barge et al., 2022). However, it is important to note that habitability does not encompass this aspect (Cockell et al., 2016). Setting habitability on the primary science goal of life detection missions may result in overlooking significant discoveries.

The primary science goal of NASA Europa Lander was initially to search for life (Hand et al., 2017), but was later upgraded to detect biosignatures (Hand et al., 2022), both of which present certain drawbacks as below: (1) Life is inherently binary, with objects being classified as either alive or not, with no intermediate classification. Despite this, there remains a lack of a universally agreed upon definition of life (Kolb, 2019). While it is theoretically possible for a probe to identify life in known forms, the search for life should not be the primary goal of science. (2) The Europa Lander Science Definition Team (EL-SDT) defines biosignature as "features or measurements interpreted as evidence of life" (Hand et al., 2017, 2022). This definition skillfully encompasses all characteristics and measurements that could be related to biotic processes, creates a fault-tolerant framework that sidesteps a lack of agreed life definition and uncertainties of data biogenesis, hence releases the impact on equipment design, mission operations and data analysis. However, this concept of biosignature proposed by EL-SDT, rooted in experiential knowledge rather than strict scientific dialectics, is vague, unclear and constrained by understanding of life processes and the precepting of instruments. As a result, biosignatures are seen more as detectable objects rather than the primary science goal of extraterrestrial life detection missions.

Based on established scientific theories on requirements for the emergence and sustenance of life in the universe, biological potential investigates the abundance, productivity, diversity and robustness of life that Icy Worlds could potentially support, through organic molecules with functional structures, suitable biochemical reaction solvents, available energy sources, as well as the environmental physiochemical characteristics (Hoehler et al., 2020; German et al., 2022b). As the primary science goal of Icy Worlds life detection missions, biological potential has following advantages: Firstly, detection is an intact process of making assumptions on prior knowledge and then verifying or falsifying the assumptions through measurements. Estimated by measurable objects, biological potential has a natural assumption connotation, which avoids the limitations and controversies of binarity. Secondly, biological potential focuses not only on the requirements of life survival but also of its emergence, which can be used not only to discover life but also to study prebiotic chemical systems (Hoehler et al., 2020). Thirdly, investigating biological potential of unknown systems on Icy Worlds can draw on analogue studies on Earth (Arrigo, 2022), leveraging applicable tools and methodologies from other related disciplines such as Earth Sciences, Geology, Oceanography, Biogeochemistry, Environmental Sciences, Ecology, Evolutionary Biology, Cell Biology, Molecular Biology, Synthetic Biology and Systems Chemistry.

2.2 Potential regions

Given the constraints of time window and energy sources, the probe is unlikely able to thoroughly survey Europa's vast global ice and ocean expanse. Therefore, it is crucial for an autonomous probe to identify regions with greater biological potential. Based on analogue studies on Earth and ecological niche theory, an inference about region with greater biological potential is proposed below. Firstly, it's assumed that a terrestrial environment similar with that on Icy Worlds can serve as a research reference (analogue) (Klenner et al., 2020). Secondly, it's assumed that the diversity and productivity of life in an environment corelate with its habitat and ecological niche (Melo-Merino et al., 2020). Regions on Icy Worlds that share similar habitats or ecological niches with analogues on Earth that exhibit higher levels of life diversity and productivity are more likely to have greater biological potential. These regions where probes have more chances to find biosignatures or even extant life deserve a priority for in-depth investigation and are named "potential regions" for short. It is important to recognize that potential region, similar with biological potential, is also hypothetical and require verification or falsification through detection. This inference will aid as a basic assumption in the autonomous planning of tasks and missions.

The potential regions in Europa are mainly in the icy shell, at the ice-water interface and on the seafloor (Chyba and Phillips, 2001; Marion et al., 2003; Figueredo et al., 2003).

Various forms of liquid water exist within Europa's icy shell, including water between ice crystal lattices, water in brine pockets, water melted by external stimuli, water in cracks and potentially large subglacial lakes (Pappalardo and Barr, 2004). Analogues on Earth, such as deep glacier and Antarctic subglacial lakes, have been found to harbor microorganisms (Siegert et al., 2001). Europa's icy shell may act as a reservoir for nutrients from the ice surface and ocean, suggesting certain biological potential.

Due to the dynamic plates' movements of Europa's icy shell (Pappalardo et al., 1998; McKinnon, 1999; Collins and Nimmo, 2009; Ashkenazy et al., 2018; Buffo et al., 2020), oxidants from the surface and reductants from the seafloor can accumulate at the ice-water interface, concentrating in cracks, caves and other subglacial structures with distinct boundaries (Figueredo et al., 2003; Martin and McMinn, 2018). Communities of chemoautotrophic organisms have been discovered at the interface of the Antarctic shelf (Christner et al., 2006), suggesting that the ice-water interface of Europa may harbor significant biological potential.

Hydrothermal fluids on the seafloor of Europa may carry nutrients from the rocky layers, as observed in similar environments on Earth (Russell et al., 2014). These hydrothermal fields serve as oases for chemoautotrophic communities (Karl et al., 1980), with subsea alkaline hydrothermal vents being theorized as the earliest cradle of life on Earth (Russell, 2003; Martin and Russell, 2007; Martin et al., 2008). Due to active geological movements, the seabed of Europa is likely to possess outstanding biological potential and may host even extant life or prebiotic chemical systems (Vance and Melwani Daswani, 2020).

In the deep Earth, water seeps into rocky layers and produces oxygen and hydrogen peroxide through elemental decay radiation (Kargel et al., 2000), supplying nutrients and chemical energy for mineral microorganisms. The subseafloor of Europa presents comparable conditions and may present certain biological potential.

In winter, the icy shell of Europa grows downward, biosignatures, extant life, or life relics at the ice-water interface may become frozen and embedded within the icy shell. Plates' movements of the icy shell can lead to the turnover of the bottom surface, creating a new icy shell surface. Geysers erupt from shell cracks, cooling into snow and icy grains that eventually fall and cover the newly formed surface. The high latitudes of Europa receive relatively low electromagnetic radiation from Jupiter, providing protection to life relics and biosignatures underneath the thick snow, near vacuum and extremely low temperatures of the shallow surface (Paranicas et al., 2009; Patterson et al., 2012; Nordheim et al., 2018). Life relics, a unique form of biosignatures, are particularly valuable when preserving life remains in uninhabited regions. Despite the low biological potential of the icy shell surface, the local evidence of life displayed is rich, leading to a high "biosignature potential" (German et al., 2022b) in this shallow surface region. Therefore, the shallow surface of the icy shell is special kind of potential region for greater biosignature potential.

2.3 Detectable objects

Objects that can be sampled and analyzed in the Icy Worlds life detection missions are named "detectable" objects in this study, such as ice, ocean currents, seawater, terrain, plumes, radiation, particles in water, organic polymers, genetic material and etc. Precepted or collected by Exo-AUV's payloads, detectable objects can be expressed as multidimensional environmental variables and parameters encompassing morphology, structure, composition, movement, distribution and physiochemical properties under different types of sensors, including but not limited to the following: (1) Temperature, depth, thickness and porosity of ice, salts, minerals, meteorites and foreign solids in the icy shell and etc. (2) Temperature, density, salinity, depth, flow rates, pH value, transmittance, irradiance, turbidity, redox potential of water in and underneath icy shell and etc. (3) Concentration of resolved carbon dioxide, oxygen, hydrogen, methane, ammonia, nitrite, nitrate, metal ions, organic polymers and etc. (4) Gravity, magnet, electromagnetic radiation and geological and geographical features of icy shells and seafloor at different spatial scales.

These environmental variables and parameters can be used to describe habitats in ice and water, develop computational models and assess the biological or biosignature potential. They serve as the foundation for Exo-AUVs in planning tasks and missions for detecting life.

Based on current biological knowledge on Earth, certain environmental variables and parameters are attributed solely to biotic processes, while others may arise from either biotic or abiotic processes. Biogenic analysis is necessary to determine the origins of biosignatures. NASA's EL-SDT categorizes all measurements potentially linked to life as biosignatures, which may include but are not limited to these below (Neveu et al., 2018): (1) Darwinian evolution, morphology of cell at different stages. (2) Functional polymers such as pigments, DNA or RNA and functional molecular structures such as homochirality and polyelectrolyte backbone. (3) Absorption of nutrients and excretion of wastes, abnormal content of isotopes, coexisting pairs of oxidants and reductants, complex organic molecules and metal element distributions that do not conform to thermodynamic equilibrium or kinetic steady state. (4) Potential biomolecules like ATP, hopanoid, histidine, etc., that are not found in abiotic processes, as well as organic compounds such as nucleic acid oligomers, peptide chains, PAHs (polycyclic aromatic hydrocarbons) and etc. (5) The basic units of organic polymers such as amino acids, nucleobases, lipids, etc. (6) Geological features and textures such as stromatolites, hummocks, microbial-induced sedimentary structures, etc.

2.4 Strategy of detection

Interpreting whether biosignatures originate from biotic or abiotic processes, biogenic analysis is a crucial aspect of detecting extraterrestrial life. A commonly referenced judgment principle asserts: "Life is the hypothesis of last resort." Sagan argues that any measurement should only be classified evidence of life once all abiotic possibilities have been ruled out (Sagan et al., 1993). However, applying this principle in practical autonomous probe operations can be challenging.

The likelihood of directly detecting robust biosignatures such as DNA, RNA, pigments and living cells on Europa is theoretically low (Neveu et al., 2018). In contrast, the chances of finding fragile biosignatures like nutrients, metal elements and amino acids are higher, which increases the risk of false positive results (Ménez et al., 2018). As an oligotrophic system, Europa may only support a limited amount of single-cell life, and even if life exists, it may be sparsely distributed. Moreover, if life on Europa exhibits heterogeneous distribution similar to that on Earth, there is a significant risk of false negative results (Hoehler et al., 2022). Biosignatures in low-temperature environments may endure for extended period (Residence Time). When the residence time of an amino acid approaches or surpasses its chiral change period, determining origins becomes challenging (Truong et al., 2019). The recent advancements in modern Synthetic Biology (Wołos et al., 2020) have intensified these debates.

To enable the Europa Lander to autonomously conduct thorough biogenic analysis with high confidence, NASA's Ladder of Life Detection (LoLD) research team introduced a diagnostic framework consisting of 15 mutually orthogonal biosignatures (Neveu et al., 2018). This framework, utilizing a binary decision-making approach, categorizes each biosignature measurement as either "positive" or "negative", resulting in a total of 32,768 (2^{15}) possible outcomes. By ensuring the independence of each biosignature from the others, the framework eliminates redundant calculations and ambiguous results, thereby enhancing the credibility of the diagnostic system. This method, which mimics the diagnostic process of a trained doctor using validated medical knowledge, demonstrates high efficiency but lacks credibility in Astrobiology. This is primarily due to the limited availability of astrobiological samples, resulting in insufficient evaluation criteria and theoretical support. Some scholars advocate for Bayesian Method or Utility Theory to estimate the probability of life existence, criticizing the binary diagnosis method for its perceived lack of rigor (Pohorille and Sokolowska, 2020). In response to these criticisms, the LoLD research team developed the Confidence of Life Detection Scale (CoLD) to estimate probabilities based on typical biosignature measurements, incorporating feedback from critics to enhance the diagnostic process (Green et al., 2021).

In the unfamiliar and challenging environment beyond Earth, the binary diagnosis method utilizing a matrix of iconic biosignatures offers great convenience within the constraints of limited detection capabilities. Conversely, the Bayesian method relies on probability calculations derived from extensive statistical data and analytical tools with multiple parameters to theoretically produce convincing outcomes. However, both methods encounter practical limitations: Firstly, due to the sparsity and heterogeneity of robust biosignatures and existing life forms in the vast global ice and ocean expanse of Europa, random sampling is more likely to yield fragile biosignatures. This raises doubts about the accuracy of results obtained through either the binary diagnostic framework or Bayesian calculations. Secondly, both approaches heavily rely on knowledge bases or standard data sets established from Earth analogues. Therefore, any biogenic analysis method that has not been validated on Europa but is solely based on Earth data may yield questionable results when applied to the limited mission payloads of autonomous probes exploring harsh extraterrestrial environments.

An intact process of detecting at least comprises 4 procedures including assuming, sampling, analyzing and verifying. If biogenic analysis is the only focus, without considering the other three, it may be challenging to discover robust biosignatures or extant life on Icy Worlds like Europa in the future, leading to a significant decrease in the credibility of the detection results. Following previous discussions on science goals, detectable objects, potential regions and biogenic analysis, an Icy World life detection strategy is proposed as depicted below (See Figure 1).

The biological knowledge established on Earth can potentially be applied on Icy Worlds as well. Utilizing the distribution of microorganisms, related environmental variables and parameters from analogues on Earth as a reference, Ecological Niche Models (ENMs) can be constructed to speculate on the life requirements of species. By projecting these results onto potential regions of Icy Worlds, the spatiotemporal distribution and probability of the putative species can be estimated. By expanding the model library to include different species in analogues, the diversity and productivity levels of potential species in the icy environ-

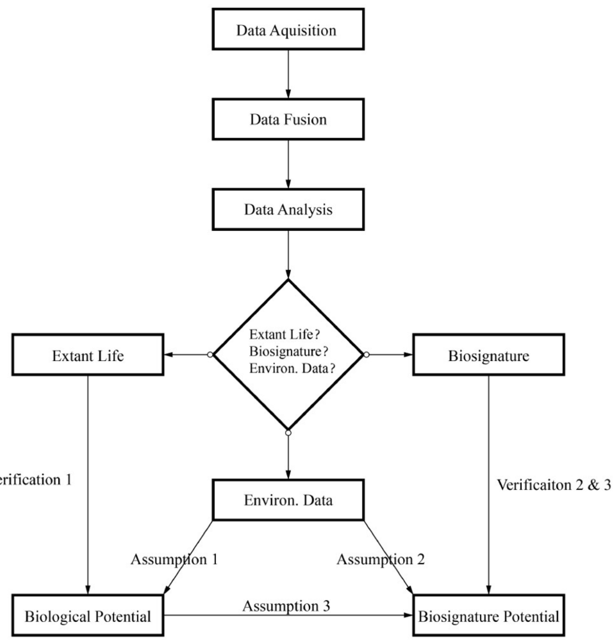

Figure 1 An Icy Worlds life detection strategy.

ment can be inferred, representing the biological potential (See Assumption 1 in Figure 1). If extant life is discovered, this biological potential assumption can be verified (See Verification 1 in Figure 1).

Certain potential regions on Icy Worlds may sustain life remnants, debris and excrement, or traces of past activity that could indicate the history of life. Additionally, specific terrain features may accumulate nutrients necessary for supporting life. By utilizing the Environmental Niche Models (ENMs) based on analogues, researchers or probe itself can assess the biosignatures potential (See Assumption 2 in Figure 1) and verify it by analyzing collected biosignatures (See Verification 2 in Figure 1).

The distribution of life on Earth is highly heterogeneous, but life changes, migrates, wears out in the environment (Hoehler et al., 2022) and exhibits as outward spreading biosignatures perceived by the payloads on probes. By examining the spatial relationship between biosignatures and life in analogues, it is possible to infer the biosignatures potential (See Assumption 3 in Figure 1) based on biological potential (See Assumption 1 in Figure 1). This inference can be further validated by locating the assumed biosignatures in the potential regions (See Verification 3 in Figure 1). As a result, revisions can be made to the models.

By utilizing Ecological Niche Models (ENMs) in analogues on Earth, researchers can speculate on the biological potential of a local area on Icy Worlds. This approach allows for the screening of potential regions and the discovery of micro-zones with peaks in biological potential, ultimately leading to a more efficient identification of robust biosignatures. Drawing from theoretical models in ecology, phylogenetics, metabolism, genetics and prebiotic chemistry, researchers can gather multi-object, multi-scale and multi-dimensional data for analysis. By focusing on key environmental variables and parameters and identifying robust, mutually orthogonal biosignatures, researchers may even detect extant life. This strategy also aims to establish specific ENMs for Icy Worlds life detection based on *in-situ* measurements, which can then be used to verify, falsify, or refine fundamental assumptions, thereby enhancing the efficiency and credibility of life detection.

Exo-AUV, with exceptional underwater maneuverability, is capable of cruising at controllable depth, speed and direction, gliding across vast expanses, hovering at or leaning on/against specific locations. Equipped with a range of telemetry devices, *in-situ* samplers and multidisciplinary analytical instruments, this autonomous vehicle can independently enhance estimation models through a series of closed-loop operations involving assumption, data acquisition, analysis and verification. When combined with the detection strategy outlined in this study, Exo-AUV is expected to greatly assist planetary scientists and astrobiologists in identifying robust biosignatures, potentially discovering extant life and validating assumptions about biological and biosignature potential.

2.5 About prebiotic chemistry detection

It is widely accepted that the fundamental building blocks of living systems, such as the precursors of functional proteins and genetic materials and basic reaction mechanisms, must have originated prior to the emergence of life. Recent research in fields like Systems Chemistry and Synthetic Biology suggests that life detections with primary science goal of biological potential, could shift focus from the conditions sustaining life to the conditions sustaining specific chemical reactions crucial for life's emergence.

However, the study of prebiotic chemical systems cannot rely on ecological theories or analogues on Earth, nor can it navigate through rare fossil records or phylogenetics spanning hundreds of millions of years to speculate on the when, where, what and how did happen. The prebiotic chemical reactions that preceded have been obscured and supplanted by later biochemical processes (Barge et al., 2022). The science community is unable to document the exact sequence of events leading to life on Earth, let alone recreate the exact physical and environmental conditions of that time. This study emphasizes the importance of identifying and exploring robust biosignatures, environmental variables and parameters in the search for life. While detecting biological potential holds promise for understanding the emergence of life and prebiotic chemical systems in the future, it is not the present focus of this study.

3. Contextual elements and technological requirements for Exo-AUV life detection on Icy Worlds

The science goals, potential regions, detectable objects and detection strategies of the Exo-AUV mission on Icy Worlds have been discussed. A conceptual image of the mission can also be envisioned. Navigating through potential regions such as the icy shell, ice-water interface, seabed and sub-seafloor, an Exo-AUV utilizes ENMs to assume biological and biosignature potential. It autonomously gathers and analyzes detectable environmental variables and parameters over extended range and endurance. The payloads, including remote telemetry and near-end *in-situ* sensors, will aid the Exo-AUV in identifying orthogonal and robust biosignatures or even potentially discovering extant life through comprehensive biogenic analysis and verifications across different objects, scales and dimensions.

Deployment of an Exo-AUV from Earth to the subsurface of Europa poses unprecedented challenges. NASA and DLR designed a system comprising a heavy lift launch vehicle, an orbiter, a lander, an ice-penetrator and a submersible. The detection mission consists of six main steps: launching, interplanetary flight, orbiting, landing, ice penetration and underwater operation (Cwik et al., 2018). Using Europa as a case study, this research focuses on the missions of ice penetration and underwater operations.

The mission is systematically broken down into a series of contexts with each context dissected into environmental conditions, Exo-AUV, measured objects and key operations, 4 groups of contextual elements. The contextual elements that may impact detection outcomes are studied. The contextual elements, along with the detection strategy, determine how Exo-AUV and its ice-penetrating carrier autonomously navigate potential regions, collect and analyze detectable objects, and transmit data back to Earth, stimulating further discussions on the technological requirements and concept of operations for Exo-AUVs.

3.1 Detection along with ice penetration

As the carrier of Exo-AUV, the ice penetrator will be started duly after the landing, autonomously penetrate the ice, access the water and detect along the way. The key contextual elements and technological requirements in this process are discussed as below.

The Europa is covered by a global icy shell, with potential thickness exceeding 100 kilometers based on the Thick Shell Theory, or around 10 kilometers according to the Thin Shell Theory (Billings and Kattenhorn, 2005). This icy shell can be simply divided into three layers: the uppermost layer, known as the conductive layer, characterized by low temperatures (approximately 100 K), high hardness, presence of foreign objects and resistance to penetration; the middle layer, referred to as the convective layer, shares physical properties similar to glacial ice on Earth; and the third layer, a loose layer with high porosity and elevated ice temperatures, reaching around 273 K at the ice-water interface (Nimmo and Pappalardo, 2016).

Similar to Earth's crust, the icy shell of Europa experiences plates' movements, extrusion, stacking and overturning. Shallow surface of the overturned sections may harbor underwater biosignatures, potentially shielded from radiation damage by the ice and snow cover. Regions rich in plume fallout on the ice surface also hold promise for biosignatures. Furthermore, brine pockets within the ice, meltwater and subglacial lakes may contain robust biosignatures and possibly even extant life (Pappalardo et al., 1998; McKinnon, 1999; Marion et al., 2003; Pappalardo and Barr, 2004;Collins and Nimmo, 2009; Ashkenazy et al., 2018).

During ice penetrating, the Exo-AUV carrier capture the visual and spectral images of the icy shell's interior and gather environmental information and biosignatures. Besides, the onboard system acquires water sample properties such as temperature, salinity, pressure, density, ion concentration, pH value and redox potential. Microscopes and Raman spectroscopy can be employed to study the morphology, structure and chemical composition of particles in water samples. Finally, separated and purified samples are analyzed using mass spectrometry and gene sequencer for invasive measurement (Dachwald et al., 2020; Lawrence et al., 2023).

To power the detection through thick icy shells, Small Modular Nuclear Fission Reactor (SMR) and Radioisotope Thermal Generator (RTG) are potential options. Particularly, waste heat from SMR power generation can be an ideal heat source for thermal ice penetration. RTG, although more established, requires examination for long-term operation (Stone et al., 2018).

Thermal, laser and mechanical methods are primarily discussed for penetrating the icy shell. The thermal method, although slow and energy-intensive, can leverage waste heat from SMR radiation, eliminating the need to worry about tools wear or debris transport. In cases where solids like minerals or meteorites are present, jetting nozzles assist in steering or clearing obstacles. Laser at 1050 nm is more effective in melting ice than water, addressing the issue of vacuum flash evaporation on icy shell surface encountered with the thermal method. While optical fibers can transmit large amounts of light energy with minimal weight, there is significant dissipation in the icy shell, resulting in around 12% light energy loss per kilometer. This limits the application of lasers for deep ice penetration. Mechanical drilling, on the other hand, can quickly break through low-temperature ice and salt minerals, but debris transport is necessary to prevent channel blockage. Additionally, mechanical wear becomes a concern for deep drilling operations. The current research trends focus on combining laser beaming or mechanical drilling with thermal heating to penetrate the low-temperature conductive layer, followed by heating in the thicker convective and high-temperature loose layer. Laser beamer and drill bit both avoid the vacuum flash of the ice surface and the huge heat absorption of the upper low-temperature ice, while thermal head relieves light dissipation, debris blockage and mechanical loss. The hybrid penetration method is an optimal solution for deploying Exo-AUVs into the under-ice ocean of Europa, with the thickness of the low-temperature conductive layer being a key factor in determining the best combination (Stone et al., 2020).

During thermal descending, cross-sectional area of the ice penetrator is the key controlling factor that affects energy consumption and penetrating speed. A larger area results in higher energy consumption and slower speed. However, an overly slender hull increases surface area and wastes greater heat (Aamot, 1968). Besides, the slender (cylindrical) chamber inside the ice penetrator constrains the Exo-AUV hull design (Durka et al., 2022).

Localization, navigation and communication are crucial under-ice. Sonar or microwave can help the ice penetrator estimate poses, percept objects, plan paths, avoid obstacles actively and enter the water in target region. Once the Exo-AUV is released, the ice penetrator can act as an under-ice base station providing navigation, communication, data exchange and charging services for Exo-AUVs (Waldmann et al., 2018).

3.2 Detection at ice-water interface

The ice penetrator descends while measuring the distance to the ice-water interface using sonar or synthetic aperture radar. It gradually decelerates until it stops upon access to the water. The submerged part of the ice penetrator can duly release the Exo-AUV for underwater detection. Contextual elements and technological requirements of Exo-AUV detection at ice-water interface are investigated as below.

The ice-water interface, also known as the eutectic interface (Deming, 2002), is where the icy shell meets the ocean below. This region experiences a continuously cycling of crystallization and dissolution of a mix of ice, brine and seawater, with the hydrostatic pressure near the icy shell pressure, temperature around 273 K and water density similar to pure water. While the hydrodynamic pump tends to keep the undersurface of the icy shell flat (Jansen et al., 2021), bines drain into the water due to gravity or crystallization. Additionally, there may be various terrains such as diapirs, ridges, cracks, caves and etc. formed by the icy shell plates' movement and flow erosion (Pappalardo and Barr, 2004).

Europa is a solid Jupiter satellite with a rocky mantle and a possible metallic core, containing essential chemical elements like carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur crucial for life, alongside transition metal elements with catalytic properties. Unlike Mars, Europa's surface lacks atmospheric protection, but the essential elements dissolves in the ocean and are shielded by the icy shell (Hand et al., 2020). Sulfur from Io is present on the icy shell's surface (Carlson et al., 1999), while the icy shell itself harbors hydrogen peroxide, oxygen and free oxygen generated by radiation from Jupiter (Delitsky and Lane, 1998). These oxidants can seep into icy shell cracks and then into the water. Reductants like hydrogen sulfide, hydrogen and organic carbon rise to the ice-water interface with ocean currents (Bire et al., 2022). The coexistence of oxidants and reductants creates thermodynamic non-equilibrium states that may drive spontaneous biochemical reactions. Water, serving as an ideal solvent, transports elements from the mantle to the ice-water interface for reactions (Jansen et al., 2021). The porous eutectic interface at the ice-water boundary provides compartmentalized shelter, mild temperature, chemiosmosis and catalytic surfaces, preserving precursors of organic polymer and nutrients for life, and facilitating metabolite release. The sharp gradients of oxidants at the interface feed life while preventing over-oxidation (Martin and McMinn, 2018). The ice-water interface shows great biological and biosignature potential, possibly hosting robust biosignatures, extant life and even prebiotic chemical systems.

The spatiotemporal distribution of life on Earth is highly heterogeneous, making it challenging to detect life in unknown oligotrophic environments. However, microorganisms change, move, wear and vanish in response to environments, leaving behind detectable biosignatures that spread outwards with life as the focal point in aquatic environments (Hoehler et al., 2022). By leveraging basic environmental data and the detection strategy outlined in this study, Exo-AUV can estimate the biological potential and speculate on spatial distribution and probability of potential organism. Life in ice and subglacial water is sparsely distributed in three dimensions, while ice penetrators detection is limited to nearly one-dimensional descending path. Despite Exo-AUV's ability to operate in three dimensions, the scarcity of detectable objects necessitates extended voyage range and endurance. The ice-water interface of Europa that gathers diverse life requirements from icy shell and sediment is a more favorable, broad, easy to access and almost two-dimensional detection space. In polar and cold regions on Earth, the distribution of microorganisms like diatoms, at the ice-water interface exhibits distinct patterns at varying observation scales, ranging from over 10 km to a couple of microns (Cimoli et al., 2020). Exo-AUV offers advantages in underwater operations. It is capable of cruising, gliding and carrying out biogeochemical detection across a large ocean space. Additionally, it's able to hover around specific micro-zones and lean against the undersurface of the icy shell for *in-situ* microscopic and molecular observations. The detection strategy proposed in this study allows for autonomous task and path planning. Notably, the ice-water interface stands out for its largest detectable space and shallowest operating depth among all subsurface potential regions. Particularly, the minimal hydrostatic pressure is friendly to the design and operation of Exo-AUV.

According to the detection strategy proposed in this study, the Exo-AUV initially takes a large-scale far-field acoustic comb scan of the icy shell undersurface to identify various geological and geographical features such as ridges, diapirs, caves, cracks and brine drainages. Throughout the navigating, continuous adaptive collecting of environmental variables and parameters including temperature, salinity, turbidity, pressure, density, ion concentration, pH value and redox potential is carried out. Subsequently, regions with greater biological and biosignature potential are identified using ENMs, and detection missions are planned. Then the near-field visual, laser and spectral scanning of the potential regions is conducted, with increasing scanning resolution and sampling rate. Water samples collected are examined by internal fluorescence microscope and Raman spectrometer to search for potential nutrients, metabolites, complex organic macromolecules, particles containing luminescent or dyeable substances, non-Brownian motion and cell-like morphology (Nadeau et al., 2016). Samples containing robust biosignatures are further purified and analyzed through onboard mass spectrometry and gene sequencing to gain insights into composition and biogenesis. In case gene fragments, living cells, or microbial communities are confirmed, Exo-AUV can lean against the undersurface of the icy shell and carries out *in-situ* observations of local micro-zones using by exterior microscopes and Raman probes to progressively validate the assumption of biological potential.

The average distance between Jupiter System and Earth is approximately 780 million kilometers, and the communication delay is over 0.5 hours, challenging the science team on Earth to remotely control or intervene in real time. Additionally, the flight of collected samples back to Earth may take several years. Therefore, in order to carry out its multi-object, multi-scale and multi-dimensional life detection mission successfully, Exo-AUV must achieve "Science Autonomy" (Wronkiewicz et al., 2024). Besides, operating in the outer solar system with limited energy and materials sources, Exo-AUV cannot rely on supplies from Earth. Consequently, detailed detection of all detectable objects is not feasible, necessitating high level of autonomy for mission and path planning.

On Earth, AUVs rely on Dead Reckoning (DR) and seafloor terrain for localization and navigation. However, accumulated errors and offsets can't be avoided during long-range voyaging, AUVs can surface up to obtain satellite signals via radio for positioning correction or utilize acoustic instruments such as Long Baselines (LBL), Short Baselines (SBL) and Ultra-Short Baselines (USBL) for precise navigation (Barker et al., 2020). Europa's icy and oceanic layers, as barriers that absorb electromagnetic signal, prevent the orbiter from mapping the under-ice features remotely. When an Exo-AUV ventures beneath Europa's icy shell, it lacks maps or prior data for assistance and cannot surface to communicate with an orbiter for positioning. Instead, it may rely on DR, Inertial Measurement Unit (IMU) and Simultaneous Localization and Mapping (SLAM) technology for basic localization and navigation and utilize single beacon acoustic signals from the under-ice base station (ice penetrator) for correction. Moreover, by gathering multi-dimensional information such as ice bottom topology, under-ice environmental variables and parameters, and even seabed topography during its voyage, the Exo-AUV may be able to gradually enhance the robustness of localization and navigation.

Electromagnetic waves are absorbed by water, making acoustic signals the predominant method of communication underwater. Exo-AUVs are designed to communicate with under-ice base station using sonar as needed. Currently, the acoustic field properties in extraterrestrial oceans are not well understood, and long-range underwater acoustic communication faces challenges such as narrow bandwidth, low signal-to-noise ratio, long delays and high bit error rates. To address these issues, Exo-AUVs should autonomously return to the under-ice base station in a timely manner, dock with it using vision or laser assistance, transmit data with high volumes through optical fibers and then relay this information to Earth through the under-ice base station. Additionally, if equipped with a rechargeable battery, Exo-AUVs can recharge while transmitting data at the under-ice base station. The science team on Earth can also communicate, transmit data, assign tasks and update firmware through the interface between the under-ice base station and the Exo-AUV.

3.3 Detection on seafloor

The seafloor of Earth was once considered a desert of life until the Alvin submersible discovered seafloor hydrothermal vents and an ecosystem with chemoautotrophic microorganisms as the primary producer in the late 1970s (Karl et al., 1980). The geological movement of Europa is relatively active, and there are probably hydrothermal fields with greater biological and biosignature potential like Earth seafloor (Russell et al., 2014; Vance and Melwani Daswani, 2020). The environment of Europa seafloor is extremely harsh, and the life detection context is complex, which puts forward more technological requirements for Exo-AUV.

The gravitational acceleration of Europa is approximately 1.3 m s^{-2}, with an average density of 2989 kg m^{-3}. The average density of the interior ocean is around 1050 kg m^{-3} (Anderson et al., 1998). At the seafloor, it's expected that the density and salinity of seawater to be higher, and the water temperature to be lower than that at the ice-water interface. The total thickness of Europa's icy and oceanic layers is estimated to range from 80 to 170 km based on different computational models, with different hydrostatic pressures on the seafloor ranging from 109,200 to 232,050 kPa. At temperatures below 251 K and pressures above 210,000 kPa pure water transforms into Ice-III, a crystalline phase with a density of about 1,650 kg m^{-3}. If the total thickness of the icy and oceanic layers exceeds 153 km, Ice-III may form and deposit on Europa's seafloor (Marion et al., 2003). The tidal movements and elemental decay within Europa release great energy, most of which maintains the vast volume of seawater in liquid, and the rest of which stored in covalent bonds as chemical energy potentially drives redox reactions providing primary energy for living systems on Europa's lightless seafloor (Hand et al., 2020).

Europa's hydrothermal fields may harbor greater biological potential due to the presence of acidic hydrothermal plumes rich in reductants like hydrogen sulfide, organic carbon and ferrous ions, as well as oxidants such as carbon dioxide, elemental sulfur, sulfur dioxide and sulfates (Kargel et al., 2000). Additionally, high-temperature (>250°C) hydrothermal vents fluids are abundant in sulfates, sulfides and various metal elements. Upon interaction with low-temperature seawater, they create "black smoker chimneys" and hydrothermal metal deposits, offering habitats for chemoautotrophic microorganisms like sulfur bacteria and iron bacteria found on Earth (Jebbar et al., 2020). Europa's mineral reserves are plentiful (Kuskov and Kronrod, 2005), with seawater seeping into rock formations through cracks and reacting with ultramafic minerals like olivine and pyroxene. This leads to the formation of alkaline hydrothermal vents at lower temperatures (<100°C), releasing calcium, magnesium ions and hydrogen (Russell, 2003). The seawater within subseafloor formations is bombarded by Alpha and Beta particles from subseafloor element decay, leading to the production of oxidants like oxygen and hydrogen peroxide (Altair et al., 2018). The heat flux from vents, along with coexisting oxidants and reductants, exhibit both thermodynamic non-equilibrium and non-steady kinetic state characteristics. This forms a typical dissipative system that can drive reactions between plumes, vent fluids and seawater, resulting in the sediments of calcium carbonate and magnesium carbonate. These sediments contain fine micropores that create an ideal habitat for chemoautotrophic microorganisms, such as methanogens and acetogens on Earth. Moreover, they provide compartmented spaces and ferrous sulfide semipermeable membranes that could facilitate potential prebiotic chemical reactions. The proton gradient across the membrane is considered the initial driving force for biochemical reactions. The capillaries between micropores act as natural flow reactors rising reaction rates. These characteristics support the hypothesis that life may have originated in alkaline hydrothermal vents in Earth's ancient oceans (Martin et al., 2008). Additionally, the Coriolis force from Europa's rotation leads to seawater washing over seafloor rock layers, enriching the mineral content, including transition metals. This leaching process enhances the occurrence of biochemical reactions in water (Camprubí et al., 2019).

Although the gravitational acceleration on Europa is much lower than that on Earth, its icy and oceanic layers are much thicker than Earth's ocean. The maximum hydrostatic pressure at the seafloor of Europa could be twice that of Earth. This pressure at 11 km at the bottom of Mariana Trench Earth is only equivalent to that at 80 km below the surface of Europa. If Exo-AUV aims to explore the deepest part of Europa's ocean with a metal shell, it with no doubts exceeds the launch vehicle's payload limit. While carbon fiber is currently under testing on Earth, its feasibility in Europa's ocean remains uncertain. Soft-body submersibles could be an alternative, but a leap of advancements in hull design, payload capacity and autonomous performance is in demand for successful life detection on Icy Worlds. Besides, ensuring that payload systems, especially sampling and onboard analysis instruments for chemistry, cell and molecular biology, function effectively in high-pressure, high-salt, high-temperature and low-temperature seawater is equally crucial.

Hydrothermal vents on Earth are typically found along the contact zones of crustal plates, such as mid-ocean ridges, trenches and transform faults (German and Seyfried, 2014). Despite having ample geological and geographical data, the exploration of deep-sea hydrothermal vents on Earth necessitates the use of large-scale ship towed seismic detection, AUV seafloor acoustic survey and ROV close-up observation. In the absence of adequate prior information, Exo-AUV can estimate the location of hydrothermal fields on Europa's subglacial ocean through tracing the hydrothermal plumes. Despite the Coriolis force on Europa is much smaller than that on Earth, resulting in less lateral drift of the plumes, the vast depth of Europa's ocean leads to significant cross-sectional area of plumes detected at shallower depths. Following the conventional approach, the voyage of Exo-AUV to trace the source of the plume, spiral down and pinpoint the hydrothermal fields on Europa may span thousands of kilometers over an extended endurance. However, the plume is unlikely to be directly beneath the under-ice base station or the previously measured object. Exo-AUV is capable of gliding across the exo-ocean with variable buoyancy. Upon finding hydrothermal fields and collecting sufficient data, Exo-AUV return to the under-ice base station to upload data, which demands extended range and operational hours. If rechargeable batteries like lithium-ion ones are insufficient, RTG or SMR could be alternatives. Moreover, there might be thermoclines close to the ice-water interface and seafloor, thus variable buoyancy design is necessary for Exo-AUV to dive down to the seafloor and return to the base station under-ice stably.

The hydrothermal fields' topography is complex, often containing detectable objects concentrated within a limited three-dimensional space. Hydrothermal vent chimneys on the seafloor can reach heights of up to 20 m (Christner et al., 2006), with multiple vents from the top to the seabed. Some fields have numerous active chimneys in close proximity, resulting in steep terrain and physiochemical gradients that create multiple micro-interfaces where chemoautotrophic microorganism communities may thrive. Based on the detection strategy proposed in this study, the Exo-AUV with sophisticated payloads are capable of exploring the putative hydrothermal fields of Europa and investigating potential "hot spots" with significant potential such as plumes, vents, chimney walls, sediment deposits and subseafloor. Upon the vents are found, Exo-AUV starts scanning with sonar, visual sensors and laser radar to perform three-dimensional images of hydrothermal fields and identify these geographical and geological features while gathering physiochemical properties. Regions with greater biological or biosignature potential are screened using ENMs for further investigation. Subsequently, the Exo-AUV approaches micro-zones with greater potential for visual and spectral observation. The biosignatures in water samples may be collected for both non-invasive and invasive chemical and biological analyses to ascertain biogenesis. Finally, the Exo-AUV can descend and lean on the seafloor, carry out seismic surveys and retrieve subseafloor samples through drilling.

The Exo-AUV faces significant challenges due to the steep three-dimensional geographical, physicochemical gradients of hydrothermal fields, as well as the presence of dense and diverse detectable objects. These factors complicate detection tasks and put high demands on the hull performance of the vehicle. The Exo-AUV must be capable of operating in extraterrestrial environments, cruising across the exo-ocean, hovering and resting at specific points when needed. It must exhibit high stability to carry out basic navigation and on-site operations efficiently. Moreover, to ensure cost-effective voyaging, the Exo-AUV should be capable of gliding with variable buoyancy at significant depths to enhance energy efficiency during plume detection and return trips. The vehicle should also be able to perform precise movements and sampling, maintain a benthic posture for extended *in-situ* observations and conduct sampling and analysis tasks continuously. Additionally, it should be equipped to carry out operations like shooting, grabbing and drilling when required.

3.4 Other requirements

Each of the three typical operating contexts mentioned has analogues on Earth such as the Antarctic ice sheet, subglacial lakes, oceans in polar and cold regions, as well as mid-ocean ridges, trenches and hydrothermal fields on seafloor transform faults (Arrigo, 2022). However, operating in similar environments does not guarantee the full ability to detect life on Icy Worlds. While the Exo-AUV and its ice-penetrating carrier are essential components of this mission, the overall detection system also encompasses launch vehicles, orbiters and landers. The entire mission involves tasks such as launching, interplanetary flights, entering Europa's orbit, landing on icy shell and other essential aspects throughout the whole mission, of which impact the research and development of Exo-AUV.

Firstly, planetary protection is crucial to prevent any potential contamination of Europa with organisms or biosignatures from Earth, which could jeopardize the entire life detection mission (Sherwood et al., 2019). The whole detection mission is complex and time-consuming, posing significant challenges for disinfection and sterilization.

Secondly, radiation protection is of utmost importance during the extended service life of the Exo-AUV system. Upon entering space, the entire detection system will be exposed to cosmic rays and the strong electromagnetic radiation with entering the realm of Jupiter's Galilean satellites. The prolonged endurance further complicates the task of ensuring sufficient radiation protection (Wang et al., 2019).

Thirdly, the importance of miniaturing and lightweighting of the payload cannot be overstated in space missions. A heavier payload requires more fuel for the spacecraft to reach the desired speed and decelerate into the target orbit. The complexity of life detection missions has led to an unprecedented demand for payloads, making the task of instrument miniaturing and lightweighting extremely challenging.

Fourthly, dealing with the bandwidth barrier is crucial for life detection. Multi-object, multi-scale and multi-dimensional detection is necessary, but the communication bandwidth is severely limited, such as the 56 Kbit s^{-1} bandwidth between the Europa Lander and Earth. To address this challenge, it is essential to intelligently summarize and organize the vast amount of data required by priority before transmitting it over the restricted bandwidth (Wronkiewicz et al., 2024).

Finally, the aerospace industry possesses specialized industrial attributes and technological characteristics. The standards and evaluation systems involved in model demonstration, research, design, verification, manufacturing and operation may differ from those of the naval and maritime industry, to which AUV belongs. This disparity potentially demands the introduction of new requirements to the traditional AUV technology paradigms.

4. Extraterrestrial autonomous underwater vehicle (Exo-AUV)

The research of Exo-AUV has a history spanning over 25 years (Horvath et al., 1997; Carsey et al., 1999), with prominent agencies such as NASA and DLR leading the way in this field. Based on the detection strategy, contextual elements and technological requirements of the Icy Worlds life detection mission discussed in this study, a review of the developed Exo-AUV has been made, a roadmap for conceptual development of Exo-AUV is proposed, and a Concept of Operations for Multiple Exo-AUV System (ConOps for MEAS) is presented.

4.1 Review of developed Exo-AUVs

Following the confirmation of Europa's interior ocean, NASA spearheaded the development of a probe capable of penetrating ice and accessing water. This included the cryobot (ice penetrator) and the hydrobot (Exo-AUV). The cryobot, evolved from the Philberth Probe, serves as carrier for the hydrobot. The hydrobot is designed for life detection upon release into the water (Aamot, 1968; Horvath et al., 1997; Muscettola et al., 1998; Zimmerman et al., 2001).

NASA's Jet Propulsion Laboratory (JPL) has introduced a range of innovative conceptual submersible. These include BRUIE, a lightweighted two-wheeled rover capable of leaning and driving against the undersurface of the icy shell to closely observe the ice-water interface (Murphy, 2021). Exobiology Extant Life Surveyor (EELS), on the other hand, is a snake-like submersible designed for Enceladus, with the ability to autonomously explore the geysers and dive into water from the cracks on the icy shell (Schreiber et al., 2020; Vaquero et al., 2024). Titan Turtle, an Exo-AUV specifically for Titan's Hexane Lakes, can submerge into the lake floor and sail on the surface, deployed by a specialized drone (Oleson et al., 2020). Radioisotopes for Icy Moons Exploration (PRIME), a thermal ice penetrator powered by RTG, is equipped with a radioisotope power supply (Bairstow et al., 2012). Sensing with Independent Microswimmers (SWIM), an Exo-AUV with variable buoyancy, is carried in ice and released in water by PRIME, with a weight of about 70 g and a length of 12 cm. A cluster of SWIMs can perform cruising and gliding under-ice, with a speed of approximately 1 m s^{-1} and a 2-hour working time. PRIME can carry up to 50 SWIMs to collect environmental data at different times on Europa (1 Europa day≈85 Earth hours). Additionally, JPL and the Woods Hole Oceanography Institute (WHOI) are collaborating on the development of the Orpheus-class full ocean depth micro Exo-AUV, with a design weight of around 250 kg (Grebmeier, 2022). This advanced vehicle features a manipulator, benthic operation capabilities and collaborative functions. It is equipped with a navigation and control system from NASA and made of a composite shell, intended for operation at the bottom of the Mariana Trench.

Funded by NASA, Georgia Institute of Technology (Gatech) in the United States developed a torpedo-like Exo-AUV named IceFin (Meister et al., 2018). This remotely controlled vehicle (ROV) is capable of detecting the ice-water interface and descending through deep holes from the ice sheet surface to the ocean beneath the Thwaites Glacier in Antarctica (Schmidt et al., 2023).

Stone Aerospace, Inc. (SAI), also funded by NASA, has successfully created 3 ice penetrators: VALKYRIE (Stone et al., 2014), ARCHIMEDES (Stone et al., 2020) and PROMETHEUS (Richmond et al., 2021); and DepthX (Kumagai, 2007), Endurance (Gulati et al., 2010), Atemis (Kimball et al., 2018) and Sunfish (Richmond et al., 2018). Notably, DepthX achieved the first three-dimensional simultaneous localization and mapping (SLAM) of underwater caves and conducted geochemical mapping of underwater life (Bio-geo-chemical Mapping, BGCM) on Earth (Fairfield et al., 2007; Sahl et al., 2010).

Germany's DLR has funded various projects such as Europa Explorer (EurEx), Enceladus Explorer (EnEx) and Technologies for Rapid Ice Penetration and subglacial Lake Exploration (TRIPLE), leading to the development of different types of Exo-AUVs. Among these, the ROBEX Tramper (Wenzhöfer et al., 2016) crawler vehicle is capable of extended operating on the seabed, while the ROBEX MOTH Glider (Waldman, 2014) features a wing-body design for long-range gliding across the ocean. AUVx (Hanff et al., 2017) is a small device with limited functions, serving as an under-ice beacon for rendezvous assistance. The DeepLeng AUV (Hildebrandt et al., 2013) has a torpedo-like hull and can be used in conjunction with the IceShuttle Teredo (Wirtz and Hildebrandt, 2016), an ice penetrator. The latest designs from DLR include nanoAUV 2 and IceCraft 2 (Nitsh and Meckel, 2023), with nanoAUV 2 featuring a torpedo-type hull equipped with gliding wings. This AUV is approximately 0.5 m in length, 0.1 m in diameter, and can reach speeds of around 1 m s^{-1}. It offers control over depth, speed, directional navigation and gliding with variable buoyancy. The entire system is scheduled to undergo field experiments in Dome-C on the Antarctic Ice shelf in 2028.

4.2 Current limitations

NASA initiated the Viking probes (Viking 1 and Viking 2) in 1975, marking the commencement of spacecraft exploration for extraterrestrial life (Klein et al., 1976; Clark, 2001).

However, cognitive limitations regarding life affected the design of testing methods and science payloads and impeded the efforts to interpreted Viking's discovery on Mars. The Viking's failure has suspended specialized missions of *in-situ* life detection for nearly 50 years.

Reflecting on past endeavors and looking towards future life detection missions in Jupiter and Saturn systems, it's incomprehensible that an Exo-AUV relies on traditional hull design and payloads, carries out predefined missions and routes and gathers environmental data passively. To fully exploit its capabilities for Icy Worlds life detection, an advanced Exo-AUV system shall navigate diverse underwater terrains, conduct comprehensive multi-scale detection, allow for multi-object, multi-dimensional data collection in situ and facilitate onboard multi-disciplinary analyses along with autonomous planning and execution of intricate underwater life detection missions.

In this study, it's suggested that current limitations on Exo-AUV development may arise from three key aspects as below: (1) The lack of a strategy or methodologies for detecting life on Icy Worlds using Exo-AUVs. (2) Inadequate exploration and discussion of potential contextual elements for Exo-AUVs to carry out life detection missions on Icy Worlds. (3) Absence of a roadmap for conceptual development of Exo-AUV tailored for life detection missions on Icy Worlds.

4.3 A roadmap for conceptual development of Exo-AUV

A roadmap for conceptual development of Exo-AUV for future Icy Worlds life detection missions is proposed (See Figure 2). This roadmap comprises two main layers, the mission layer and the solution layer. The mission layer focuses on analyzing key mission settings that impact conceptual design. On the other hand, the solution layer aims to refine technological requirements based on contextual elements and to design and evaluate Exo-AUV concepts.

Within the mission layer, the first job is to determine the science goal of the life detection mission, which forms the foundation for research and design. Subsequently, taking into account the environmental conditions of Icy Worlds, scientific assumptions and Exo-AUV capabilities, the focus shifts to identifying where, what and how to measure, encompassing potential regions, detectable objects and detection strategy.

The process of an Exo-AUV navigating, collecting, analyzing detectable objects in potential regions and verifying assumptions based on science goal and detection strategy defines the operation context. Each context can be broken down into four main types of elements, environmental conditions, Exo-AUV, measured objects and key operations. Different combinations of these contextual elements lead to

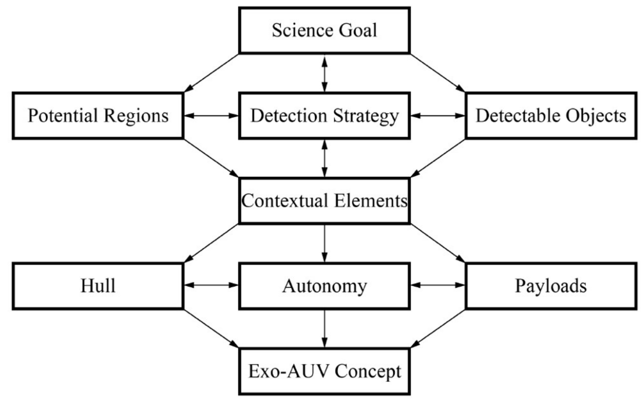

Figure 2 A roadmap for conceptual development of Exo-AUV.

varying requirements for the Exo-AUV, particularly in terms of hull design, payload capacity and autonomy features. By refining these technological requirements, potential concepts can be shaped and evaluated. An ideal concept should cover a wide range of potential regions and detectable objects, maintain high quality in alignment with the detection strategy and achieve science goal.

It's worth noting that the basic settings of the life detection mission shall adapt with our understanding of Icy Worlds gradually grows. It is essential to continuously upgrade equipment and technology to keep accuracy in the roadmap or solution. This will help mitigate cognitive biases and ensure that whatever technological or engineering obstacles do not overshadow the overall objective of the mission.

4.4 A concept of operations for multiple Exo-AUV system (ConOps for MEAS)

Developing an Exo-AUV that adheres to aerospace industrial standards, successfully lands on Europa's surface after a long interplanetary flight, penetrates several kilometers thick icy shell and access to the interior ocean, conducts independent life detection missions and promptly transmits findings back to Earth presents a formidable challenge. The Exo-AUV must not only satisfy the technological requirements for life detection but also be compact enough to fit within the chamber of ice penetrator without surpassing the loading capacity of the Jupiter system mission launch vehicle. These strict requirements place significant limitations on potential concepts for both the Exo-AUV and its ice-penetrating carrier.

By analyzing the technological requirements of Exo-AUV, two key features emerge. Firstly, the system has a higher number of requirements and greater complexity compared to any other AUV developed thus far. Secondly, many of these requirements have a very different impact on the conceptual design and are even difficult to be compatible with. For instance, the requirements for the hull and load performance of Exo-AUV are completely different in the three potential regions of the icy shell, ice-water interface and seafloor. Additionally, oceanographic and glacier features with greater characteristic length, such as ocean currents and icy shells, demands long-range navigation and adaptive sampling, while micro-zones with chemical, biological and geological objects require *in-situ*, high-precision and long-term observations due to their smaller characteristic lengths. Achieving all mission objectives by one Exo-AUV may lead to challenges such as payload idleness in different contexts, inefficient use of space, weight and energy, as well as reduced maneuverability, robustness, system survivability and operating efficiency.

The conceptual development of the Exo-AUV faces core contradictions due to the complexity of potential regions and detectable objects, limited carrying capacity and high risk of the Jupiter system detection mission. According to the detection strategy and contextual elements discussed in this study, the potential regions, detectable objects, hull and payload performance, functions and technological requirements are subdivided and reintegrated to enhance the operation of Exo-AUVs in specific contexts. A Concept of Operations for Multiple Exo-AUV System (ConOps for MEAS) that offers advantages in space, weight and energy economy, individual maneuverability and robustness, collaborative efficiency and high survivability is proposed in this study. Furthermore, by leveraging technologies of integrated circuits and microelectromechanical systems (MEMS), various payloads like sonar, lidar, cameras, spectrometers, mass spectrometers, fluorescence microscopes, gene sequencers and microfluidic systems are integrated into a Lab on a Chip (LoC), resulting in reduced weight, size and power consumption. Limited to the scope of this study, the focus is on the concept of operations for Multiple Exo-AUV Systems (ConOps for MEAS).

By sizing of characteristic length, detectable objects are simply divided into 2 categories (See Table 1). Based on the proposed detection strategy, Exo-AUV can at first identify seawater, terrain and other large objects in ice, under ice or on the seabed to model Environmental Niche Models (ENMs) on a broader spatial scale. Subsequently, it pinpoints local topography, structures and microscopic features to assess biological potential. Finally, through combining small-scale space detections, it confirms the biological potential on larger scales. To accomplish these tasks, Exo-AUV must possess the capabilities to perform comb scanning, navigating and gliding on a two-dimensional plane or in three-dimensional space, sample and analyze large detectable objects, hover stably, lean against the undersurface of the icy shell and on the seafloor, and operate in situ for extended endurance with high precision.

Different operating environments, detectable objects, sampling procedures and navigation methods necessitate different payloads and hull designs. The payloads are categorized into 2 modules based on the size of the detectable objects, with the survey module (Module S) designed for larger objects and the observation module (Module O) tailored for smaller ones (See Table 1). Corresponding hull designs are recommended for each module. Ultimately, a team of two Exo-AUVs and an ice-penetrating Exo-AUV carrier can collaborate to explore various potential regions (See Figure 3).

A hull design of torpedo-like revolved body is most suitable for the Exo-AUV Ice-Penetrating Carrier (EAC) to operate within the icy shell. While the Exo-AUV is fully enclosed within it, the EAC descends following a nearly one-dimensional vertical path along the direction of gravity. Through acoustic navigation and an intelligent steering system, the EAC plans its diving path, control speed and pose, penetrate the ice, invokes the payloads modules on the Exo-AUV for sampling and analyzing. Upon penetrating the icy layer, the EAC releases the Exo-AUVs, transitions to the under-ice base station and offers navigation, communication, data exchange and charging services for Exo-AUVs.

The Exo-AUV with Module S (EAS) prefers a flat hull, cruises in moderate speed, long range and high stability, glides across the ocean with variable buoyancy and flexible wings or a wing-body hull. If the hull structure and material are able to withstand the extreme hydrostatic pressure of Europa, the EAS is capable of carrying out large-scale detection on seafloor.

There are no strict requirements for high speed or long range in detecting small-scale two-dimensional planes under the ice, but the hull must effectively utilize the functions and performance of Module O. It should be capable of hovering or leaning against the undersurface of the icy shell at fixed points for extended endurance to maintain stability for delicate tasks in micro-zones under the ice. A flat axisymmetric hull (e.g., disc type) with full-drive thrusters and roof supports is suitable for the Exo-AUV with Module O (EAO) in this context. Similarly, in three-dimensional small-scale tasks in hydrothermal fields on the seafloor, the detection space expands to three dimensions, where a spherical hull with panoramic views for multi-dimensional observations is theoretically an optimal solution.

The Exo-AUV System (EAS) must not only cover a large detection space but also ensure its return to the under-ice base station (EAC). EAO is not intended for long-range voyages, it is able to dock and undock with EAS underwater. EAS carries EAO to a destination far from EAC. After EAO completes local detection, it waits for EAS to take it back to EAC or the next "hot spot". EAC, EAO and EAS can exchange data and ultimately transmit information back to Earth through EAC. Rechargeable batteries can be used on EAO, while EAC and EAS can be powered by SMR or micro RTG. An EAC, an EAS and an EAO together constitute the simplest Multiple Exo-AUV System (MEAS).

Table 1 Detectable objects and science payloads in different potential regions

Detectable objects		Resolutions/ characteristic length	Dimensions	Payloads
Potential region 1: Large and small scales in the icy shell				
	Spatial feature		Nearly one-dimensional line	
Bigger objects	Ice crack, Ice fault	(dm)/(km)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	Module S: Radiometers, Seismometers-Magnetometers, GravimetersSonars, CTD, DensimetersPressure Gauges, pH TestersDissolved Oxygen TestersPhotometers, Turbidimeters
	Lakes, river in ice	(dm)/(km)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Salt mineral	(dm)/(km)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
Smaller objects	Local structure in ice	(cm)/(m)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	Module O: Laser RadarStereo Camera-Exterior Spectral ImagerExterior Optical MicroscopeSamplerGunDrill BitIon Selective ElectrodeRedox Potential TesterInterior Raman SpectrometerInterior Fluorescence Volumetric Microscope-Mass Spectrometer/ChromatographGene Sequencer
	Meteorite, debris, and solid in ice	(mm)/(dm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Birne pocket	(mm)/(cm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Melted water	(mm)/(cm)	Composition, Physiochemistry	
	Particles in ice and water	(sub μm)/(mm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Organic polymer	(nm)/(sub μm)	Structure, Composition, Movement, Distribution, Physiochemistry	
	Genetic material	(nm)/(sub μm)	Structure, Composition, Movement, Distribution, Physiochemistry	
Potential region 2: Large and small scales at the ice-water interface				
	Spatial feature		Nearly two-dimensional plane	
Bigger objects	Sea current	(dm)/(km)	Movement, Distribution, Physiochemistry	Module S: Radiometers, Seismometers-Magnetometers, GravimetersSonars, CTD, DensimetersPressure Gauges, pH TestersDissolved Oxygen TestersPhotometers, Turbidimeters
	Sea water	(dm)/(km)	Composition, Movement, Distribution, Physiochemistry	
	Under-ice terran	(dm)/(km)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
Smaller objects	Local structure of ice-water interface	(cm)/(m)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	Module O: Laser RadarStereo Camera-Exterior Spectral ImagerExterior Optical MicroscopeSamplerGunDrill BitIon Selective ElectrodeRedox Potential Tester-Interior Raman SpectrometerInterior Fluorescence Volumetric MicroscopeMass Spectrometer/ChromatographGene Sequencer
	Brine drainage	(mm)/(dm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Micro-zones of eutectic interface	(mm)/(cm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Water of micro-zones	(mm)/(cm)	Composition, Physiochemistry	
	Particles in water	(sub μm)/(mm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Organic polymer	(nm)/(sub μm)	Structure, Composition, Movement, Distribution, Physiochemistry	
	Genetic material	(nm)/(sub μm)	Structure, Composition, Movement, Distribution, Physiochemistry	
Potential Region 3: Large and small scales at the seafloor				
	Spatial feature		Three-dimensional, ultradeep	
Bigger objects	Sea current	(dm)/(km)	Movement, Distribution, Physiochemistry	Module S: Radiometers, Seismometers-Magnetometers, GravimetersSonars, CTD, DensimetersPressure Gauges, pH TestersDissolved Oxygen TestersPhotometers, Turbidimeters
	Sea water, plume	(dm)/(km)	Composition, Movement, Distribution, Physiochemistry	
	Terran of hydrothermal field	(dm)/(km)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
Smaller objects	Chimney	(cm)/(m)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	Module O: Laser RadarStereo Camera-Exterior Spectral ImagerExterior Optical MicroscopeSamplerGunDrill BitIon Selective ElectrodeRedox Potential Tester-Interior Raman SpectrometerInterior Fluorescence Volumetric MicroscopeMass Spectrometer/ChromatographGene Sequencer
	Vent	(mm)/(dm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Micro-zones of sediment	(mm)/(cm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Water of micro-zones	(mm)/(cm)	Composition, Physiochemistry	
	Particles in water	(sub μm)/(mm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	
	Organic polymer	(nm)/(sub μm)	Morphology, Structure, Composition, Movement, Distribution, Physiochemistry	

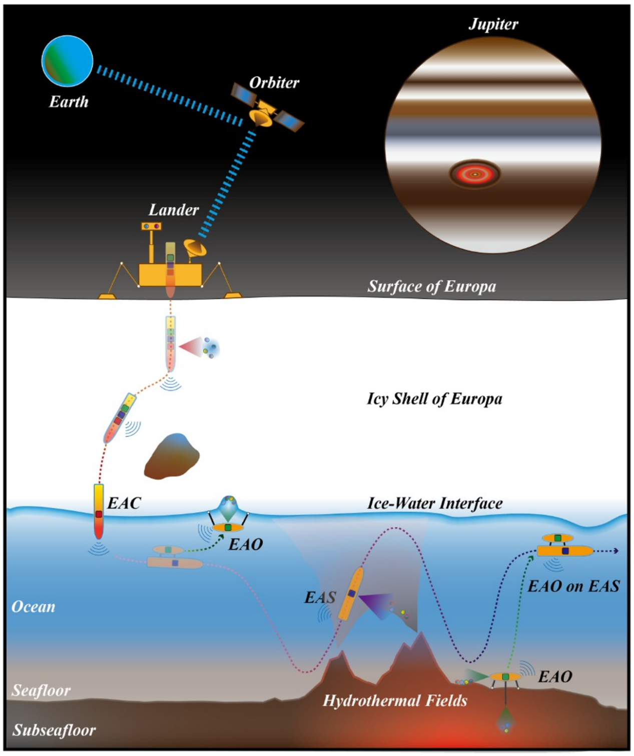

Figure 3 A concept of operations for Exo-AUV system (ConOps for MESA).

Covered by a global icy shell, Europa is characterized as an oligotrophic system, with its subglacial ocean holding twice the volume of Earth's ocean. Detectable objects in this vast global ice and ocean expanse are sparsely and heterogeneously distributed, surpassing the range capabilities of a simple MEAS. Therefore, selecting an appropriate landing site is crucial for the efficient operation of Exo-AUV and its ice-penetrating carrier, potentially leading to groundbreaking discoveries. The Chaotic Terran, located near Europa's equator, is a promising landing site: Firstly, certain regions of the Chaotic Terran have thinner icy shell that is easier to penetrate and newer surface where biosignature potential is greater. Secondly, the ice-water interface beneath this bombarded region may accumulate more oxidants from surface, increasing its biological potential. Thirdly, recent observations from the James Webb Astronomical Telescope indicate a significant presence of carbon dioxide ice on the surface, hinting at a subsurface carbon source (Villanueva et al., 2023; Trumbo and Brown, 2023).

According to the detection strategy and ConOps for MEAS outlined in this study, selecting a landing site in a Chaotic Terrain could streamline the detection missions, minimizing operation time, space, tools and energy supplies while maximizing valuable data collection. If necessary, more launch missions could be planned to expand the detection network across Europa's vast global ice and ocean expanse using several MEASs.

5. Conclusions and suggestions

Icy Worlds like Europa and Enceladus provide conditions for the survival of microorganisms. Conducting life detection in regions with high biological potential, such as the icy shell, ice-water interface and seafloor, is likely to discover robust biosignatures, extant life and even prebiotic chemical systems. Exo-AUVs are able to perform *in-situ*, multi-object, multi-scale and multi-dimensional detection autonomously and efficiently. They are expected to serve as crucial tools for planetary scientists and astrobiologists exploring Icy Worlds and searching for extraterrestrial life.

Based on Europa, it is suggested that the primary science goal of Icy Worlds life detection missions should be the exploration of biological potential which not only aligns with the hypothetical nature of a detection, but also helps avoid potential paradoxes associated with binary thinking. By focusing on biological potential, researchers are likely to uncover biosignatures, extant life and even prebiotic chemical systems. The speculation, evaluation and verification of biological potential require consideration of numerous environmental variables and parameters, some of which may serve as biosignatures indicating the presence of life. Just as on Earth, where life thrives in some regions but is scarce in others, detecting the biological potential of Europa should prioritize regions with relatively greater potential for supporting life and biosignatures. Drawing on analogies and ecological theories on Earth, researchers can identify key regions with high biological and biosignature potential, such as the icy shell, ice-water interface and seafloor. However, current detection methodologies often focus on biogenic analysis and overlook strategies for collecting robust biosignatures. In oligotrophic systems, life distribution is sparse and heterogeneous. Even in theoretically promising regions like beneath the ice or on the seafloor, fragile biosignatures may be unable to define biogenesis, regardless by the binary diagnosis or statistical methods.

The process of detecting life on Icy Worlds involves four key procedures: assuming, sampling, analyzing and verifying. The Exo-AUV, along with its ice-penetrating carrier, has the capability to explore the subsurface of the icy shell and carry various payloads for comprehensive data collection and analysis in different dimensions. By applying the ecological niche theory, a life detection strategy for Icy Worlds has been proposed. This strategy guides the Exo-AUV to autonomously identify micro-zones with high biological potential, collect diverse robust biosignatures and potentially detect extant life. The data gathered from Icy Worlds can be used to validate, refute, refine and even reconstruct models based on Earth data. By leveraging the Exo-AUV's underwater detection capabilities, this strategy overcomes limitations of passive data collection and integrates assuming, sampling, analyzing and verifying procedures into a comprehensive methodology for detecting life on Icy Worlds. Ultimately, this strategy aims to uncover robust biosignatures, potential extant life and even prebiotic chemical systems in Europa's thick icy and oceanic layers of hundreds of kilometers thick, with minimal energy and supplies.

Three typical contexts for detecting life on Europa are identified, within the icy shell, at the ice-water interface and on the seafloor. Each context is composed by 4 major contextual elements, environmental conditions, Exo-AUV, the object being measured and key operations. By analyzing these contextual elements along with other pre-procedures such as launching, interplanetary flight, orbit entry and landing, the basic technological requirements for the Exo-AUVs and their ice-penetrating carrier are proposed.

Europa's icy shell and under-ice ocean are both globally distributed. The icy shell thickness may reach about tens of kilometers, with hydrostatic pressure at the deepest ocean floor points potentially doubling that of the Mariana Trench on Earth. Ice-penetrating carriers can utilize SMR or RTG power and heat sources, employing a thermal-mechanical hybrid penetrating method and energy-efficient hull design. Navigation assistance can be provided through the use of sonar or synthetic aperture radar, with lateral nozzle jets or auxiliary heat aiding in steering and obstacle avoidance. The carrier penetrates the icy shell to deploy Exo-AUVs into the water, serving as under-ice base station for navigation, communication, data exchange and charging services. The Exo-AUVs are constructed with pressure-resistant hull materials, equipped with RTG power supplies, high-performance navigation and communication modules. They are able to cruise and glide across large space with variable buoyancy, hover around local micro-zones and lean against the undersurface of the icy shell or on the seabed, covering a range from small to large scales.

In order to discover sparse and heterogeneously distributed robust biosignatures and extant life in the vast ice and sea expanse, the Exo-AUV and its ice-penetrating carrier must take a variety of science payloads aboard. These payloads will encompass acoustics, vision, spectroscopy, electrochemistry, analytical chemistry, cell biology and molecular biology instruments. The exploration will gradually focus on objects with different characteristic lengths ranging from several kilometers to sub-micrometers. The collected in situ multi-dimensional information includes morphology, structure, composition, movement, distribution, physiochemistry and etc., and will enables online ecological niche and biogenic analysis. Europa, being far away from Earth, poses challenges due to limited payload capacity of the launch vehicle. The strong radiation from Jupiter above the icy surface demands for protective materials. To address these challenges while ensuring detection capability, MEMS technology is employed to achieve payload miniaturing and lightweighting.

The communication delay between Europa and Earth can be as long as 0.5 hours, with a narrow bandwidth and limited window for data exchange. This restricts frequent manual intervention and high-throughput data transfer. In missions focused on detecting complex life, the probe's autonomy becomes crucial. Firstly, Exo-AUV and its ice-penetrating carrier should autonomously localize, navigate and plan the path based on acoustic and optical sensors, and control the propeller, steering rudder and buoyancy to adjust the speed, depth and pose. In addition, based on the detection strategy proposed in this study, Exo-AUV should also achieve science autonomy, speculate potential regions in different scales of space, plan detection tasks, utilize a variety of payloads to complete data acquisition and analysis directly or through onboard tests, verify the assumptions of biological and biosignature potential, update the computational model, summarize, sort and transmit important data independently.

Exo-AUVs developed in the United States and Europe are examined, revealing that current designs lack the capability to tackle intricate life detection tasks and are yet to fully exploit the full potential of the Exo-AUV platform. To prevent stepping into the same old tracks of the Viking missions, a roadmap for conceptual development of Exo-AUVs tailored for detecting life on Icy Worlds is outlined. This roadmap encompasses crucial factors that shape the Exo-AUV concepts. Based on science goals, it is a guideline for the Exo-AUV developers on exploring potential regions, objects detectable and detection strategies, analyzing key contextual elements, refining technological requirements, designing and evaluating concepts with different hull design, payloads and autonomy.

A Concept of Operations for Multiple Exo-AUV System (ConOps for MEAS) is proposed. A simplest MEAS is consisting of an ice-penetrating Exo-AUV Carrier (EAC), a Survey Module-equipped Exo-AUV (EAS) and an Observation Module-equipped Exo-AUV (EAO). The EAC utilizes either an RTG or SMR for power or heat sources and employs a thermal-mechanical hybrid penetrating technique for ice penetration. The EAS and EAO can be housed within the EAC, with all three capable of communication and data sharing through acoustics or fiber optic interfaces. The EAS, featuring a foldable wing-body hull and RTG power supply, is designed for prolonged cruising and gliding within full sea depth, detecting large objects at the ice-water interface and on seafloor. Conversely, the EAO, with a disc-like hull design, full thrusters, rechargeable batteries and various MEMS task payloads, excels at detecting small objects in localized micro-zones. The EAS can connect and disconnect with the EAO in water, acting as a vehicle for transporting, charging and data exchanging. Notably, the MEAS is tailored to address the diverse contextual elements of different potential regions of Europa, where detectable objects and measuring scales vary significantly in size. By distributing technological requirements among the Exo-AUVs, the MEAS efficiently tackles challenges such as idle loads, wasted space, weight, energy and the launch vehicle loading capacity limitations. This concept also enhances maneuverability, robustness, survivability and operational efficiency. In the event of major discoveries, additional MEASs can be launched to create a detection network covering the vast global ice and sea expanse.

In recent years, China has made significant advancements in various sectors, resulting in the emergence of cutting-edge equipment and technologies. However, there is a lack of major breakthroughs in basic science (Lin et al., 2020). The search for extraterrestrial life is of great scientific importance and relies heavily on national science and engineering research projects focused on detection equipment and technology. The potential benefits extend beyond scientific exploration to societal advancements and the development of innovative technologies that improve people's lives and enhance national competitiveness. This aligns with China's national conditions, longstanding policies, and global position. While the United States and Europe have a head start in this field, they do not have absolute superiority in the crucial Exo-AUV sector. It is essential to establish a top-level organization to oversee extraterrestrial life detection projects, coordinating proposals, discussions, decision-making, development and task execution among relevant grassroots units. This effort should focus on nurturing a multidisciplinary research system, team and talent, outlining goals and objectives, project implementation and technology development routes, and executing phased, multi-level and cross-disciplinary research and tasks. Presently, leveraging Exo-AUV as a focal point for developing specialized equipment, technologies and missions of life detection on Icy Worlds bears significant strategic importance for China, a major nation entrusted with the mission of national revitalization and advancing the common destiny of humanity.

Acknowledgements *This work was supported by the National Natural Science Foundation of China for Distinguished Young Scholars (Grant No. 52025111) and the Key Projects of the National Natural Science Foundation of China (Grant No. 51939003).*

Conflict of interest The authors declare that they have no conflict of interest.

References

Aamot H W C. 1968. Instruments and methods instrumented probes for deep glacial investigations. J Glaciol, 7: 321–328

Altair T, de Avellar M G B, Rodrigues F, Galante D. 2018. Microbial habitability of Europa sustained by radioactive sources. Sci Rep, 8: 1–8

American A A S. 2005. So much more to know. Science, 309: 78–102

Anderson J D, Schubert G, Jacobson R A, Lau E L, Moore W B, Sjogren W L. 1998. Europa's differentiated internal structure: Inferences from four Galileo encounters. Science, 281: 2019–2022

Arrigo K. 2022. Research in analog environments to enable studies of ocean worlds. Oceanography, 35: 39–44

Ashkenazy Y, Sayag R, Tziperman E. 2018. Dynamics of the global meridional ice flow of Europa's icy shell. Nat Astron, 2: 43–49

Bairstow B, Lee Y H, Howell S, Donitz B, Choukroun M, Perl S. 2012. Thermal Analysis of Landers using Radioisotope Power Systems on Ice Worlds. IEEE Aerospace Conference

Barge L M, Rodriguez L E, Weber J M, Theiling B P. 2022. Determining the "biosignature threshold" for life detection on biotic, abiotic, or prebiotic worlds. Astrobiology, 22: 481–493

Barker L D L, Jakuba M V, Bowen A D, German C R, Maksym T, Mayer L, Boetius A, Dutrieux P, Whitcomb L L. 2020. Scientific challenges and present capabilities in underwater robotic vehicle design and navigation for oceanographic exploration under-ice. Remote Sens, 12: 2588

Billings S E, Kattenhorn S A. 2005. The great thickness debate: Ice shell thickness models for Europa and comparisons with estimates based on flexure at ridges. Icarus, 177: 397–412

Bire S, Kang W, Ramadhan A, Campin J M, Marshall J. 2022. Exploring ocean circulation on icy moons heated from below. J Geophys Res-Planets, 127: e07025

Buffo J J, Schmidt B E, Huber C, Walker C C. 2020. Entrainment and dynamics of ocean-derived impurities within Europa's ice shell. J Geophys Res-Planets, 125: e06394

Camprubí E, de Leeuw J W, House C H, Raulin F, Russell M J, Spang A, Tirumalai M R, Westall F. 2019. The emergence of life. Space Sci Rev, 215: 56

Carlson R W, Johnson R E, Anderson M S. 1999. Sulfuric acid on Europa and the radiolytic sulfur cycle. Science, 286: 97–99

Carsey F D, Chen G S, Cuns J, French L, Kern R, Lane A L, Stolorz P, Zimmerman W, Ballou P. 1999. Exploring Europa's ocean: A challenge for marine technology of this century. Mar Technol Soc J, 33: 5–12

Christner B C, Royston-Bishop G, Foreman C M, Arnold B R, Tranter M, Welch K A, Lyons W B, Tsapin A I, Studinger M, Priscu J C. 2006. Limnological conditions in subglacial lake Vostok, Antarctica. Limnol Oceanogr, 51: 2485–2501

Chyba C F, Phillips C B. 2001. Possible ecosystems and the search for life on Europa. Proc Natl Acad Sci USA, 98: 801–804

Cimoli E, Lucieer V, Meiners K M, Chennu A, Castrisios K, Ryan K G, Lund-Hansen L C, Martin A, Kennedy F, Lucieer A. 2020. Mapping the in situ microspatial distribution of ice algal biomass through hyperspectral imaging of sea-ice cores. Sci Rep, 10: 21848

Clark B C. 2001. Viking redux: Viking success and lessons for the future. Astrobiology, 1: 509–512

Cockell C S. 2001. "Astrobiology" and the ethics of new science. Interdisciplinary Sci Rev, 26: 90–96

Cockell C S, Bush T, Bryce C, Direito S, Fox-Powell M, Harrison J P, Lammer H, Landenmark H, Martin-Torres J, Nicholson N, Noack L, O'Malley-James J, Payler S J, Rushby A, Samuels T, Schwendner P, Wadsworth J, Zorzano M P. 2016. Habitability: A review. Astrobiology, 16: 89–117

Cockell C S, Stevens A H, Prescott R. 2019. Habitability is a binary property. Nat Astron, 3: 956–957

Cockell C S, Samuels T, Stevens A H. 2022. Habitability is binary, but it is used by astrobiologists to encompass continuous ecological questions. Astrobiology, 22: 7–13

Collins G, Nimmo F. 2009. Chaotic terrain on Europa. In: Pappalardo R T, McKinnon W B, Khurana K, eds. Europa. Tucson: The University of Arizona Press. 259–281

Cwik T, Zimmerman W, Graya A, Nesmitha B, Casillasa R P, Mullera J, Bell D, Bryanta S, Karapetiana A, Otisa R, Handa K, Brandt M, Zacny K, Senguptac A. 2018. A technology architecture for accessing the oceans of icy worlds. Bremen: International Astronautical Congress (IAC)

Dachwald B, Ulamec S, Postberg F, Sohl F, de Vera J P, Waldmann C, Lorenz R D, Zacny K A, Hellard H, Biele J, Rettberg P. 2020. Key technologies and instrumentation for subsurface exploration of ocean worlds. Space Sci Rev, 216: 83

Delitsky M L, Lane A L. 1998. Ice chemistry on the Galilean satellites. J

Geophys Res, 103: 31391–31403
Deming J W. 2002. Psychrophiles and polar regions. Curr Opin Microbiol, 5: 301–309
D'Hondt S, Pockalny R, Fulfer V M, Spivack A J. 2019. Subseafloor life and its biogeochemical impacts. Nat Commun, 10: 3519
Dick S J. 1982. Plurality of Words: The Extraterrestrial Life Debate from Democritus to Kant. Cambridge: Cambridge University Press. 9–10
Dougherty M, Grasset O, Bunce E, Coustenis A, Blanc M, Coates A, Coradini A, Drossart P, Fletcher L, Hussmann H, Jaumann R, Krupp N, Prieto-Ballesteros O, Tortora P, Tosi F, Hoolst T V. 2011. JUICE Asessment Study Report. Technical Report. ESA
Durka M J, Smith M W E, Ullman M J, Cassler B, Otis R, Cwik T A, Hockman B J, Barry M M. 2022. Modeling a class of thermal ice probes for accessing the solar system's ocean worlds. Acta Astronaut, 193: 483–495
Fairfield N, Kantor G, Wettergreen D. 2007. Real-time SLAM with octree evidence grids for exploration in underwater tunnels. J Field Robotics, 24: 03–21
Figueredo P H, Greeley R, Neuer S, Irwin L, Schulze-Makuch D. 2003. Locating potential biosignatures on Europa from surface geology observations. Astrobiology, 3: 851–861
German C R, Seyfried W E. 2014. Hydrothermal Processes. In: Holland H D, Turekian K K, eds. Treatise on Geochemistry. 2nd ed. Oxford: Elsevier. 8: 191–233
German C R, Blackman D K, Fisher A T, Girguis P R, Hand K P, Hoehler T M, Huber J A, Marshall J C, Seewald J, Shock E. 2019. Exploring ocean worlds: A systems-level approach for the search for life beyond Earth. Bellevue: AGU Astrobiology Science Conference
German C R, Arrigo K R, Murray A E, Rhoden A R. 2022a. Planetary oceanography: Leveraging expertise among Earth and planetary science. Oceanography, 35: 10–16
German C R, Blackman D K, Fisher A T, Girguis P R, Hand K P, Hoehler T M, Huber J A, Marshall J C, Pietro K R, Seewald J S, Shock E L, Sotin C, Thurnherr A R, Toner B M. 2022b. Ocean system science to inform the exploration of ocean worlds. Oceanography, 35: 16
Grebmeier J M. 2022. Applying understanding of Earth systems, including climate change, to exploration of other ocean worlds. Oceanography, 35: 45
Green J, Hoehler T, Neveu M, Domagal-Goldman S, Scalice D, Voytek M. 2021. Call for a framework for reporting evidence for life beyond Earth. Nature, 598: 575–579
Gulati S, Richmond K, Flesher C, Hogan B P, Murarka A, Kuhlmann G, Sridharan M, Stone W C, Doran P T. 2010. Toward autonomous scientific exploration of ice-covered lakes-Field experiments with the ENDURANCE AUV in an Antarctic Dry Valley. Anchorage: IEEE International Conference on Robotics and Automation. 308–315
Hand K P, Murray AE, Garvin J B, Brinckerhoff W B, Christner B C, Edgett K S, Ehlmann B L, German C R, Hayes A G, Hoehler T M, Horst S M, Lunine J I, Nealson K H, Paranicas C, Schmidt B E, Smith D E, Rhoden A R, Russell M J, Templeton A Sm Willis P A, Yingst R A, Phillips C B, Cable M L, Craft K L, Hofmann A E, Nordheim T A, Pappalardo R P, Project Engineering Team. 2017. Report of Europa Lander Science Definition Team, Technical Report, NASA
Hand K P, Sotin C, Hayes A, Coustenis A. 2020. On the habitability and future exploration of ocean worlds. Space Sci Rev, 216: 95
Hand K P, Phillips C B, Murray A M, Garvin J B, Maize E H, Gibbs R G, Reeves G E, Martin A M S, Tan-Wang G H, Krajewski J, et al.2022. Science goals and mission architecture of the Europa lander mission concept. Planet Sci J, 3: 22
Hanff H, Kloss P, Wehbe B, Kampmann P, Kroffke S, Sander A, Firvida M B, Einem M, Bode J F, Kirchner F. 2017. AUV x—A novel miniaturized autonomous underwater vehicle. Aberdeen OCEANS Conference. 1-10
Heller R. 2020. Habitability is a continuous property of nature. Nat Astron, 4: 294–295
Hendrix A R, Hurford T A, Barge L M, Bland M T, Bowman J S, Brinckerhoff W, Buratti B J, Cable M L, Castillo-Rogez J, Collins G C, Diniega S, German C R, Hayes A G, Hoehler T, Hosseini S, Howett C J A, McEwen A S, Neish C D, Neveu M, Nordheim T A, Patterson G W, Patthoff D A, Phillips C, Rhoden A, Schmidt B E, Singer K N, Soderblom J M, Vance S D. 2019. The NASA roadmap to ocean worlds. Astrobiology, 19: 1–27
Hildebrandt M, Albiez J, Fritsche M, Hilijegerdes J, Kloss P, Wirtz M, Kirchner F. 2013. Design of an autonomous under-ice exploration system. San Diego: IEEE/Mts Oceans, 1–6
Hoehler T M, Bains W, Davila A, Parenteau M, Pohorille A. 2020. Life's requirements, habitability, and biological potential. In: Meadows V S, Arney G N, Schmidt B E, Des Marais D J, eds. Planetary Astrobiology. Tucson: The University of Arizona Press. 37–69
Hoehler T M, Bowman J S, Craft K L, Willis P A, Winebrenner D P. 2022. Leveraging Earth hydrosphere science in the search for life on ocean worlds. Oceanography, 35: 23–29
Horvath J C, Carsey F D, Cutts J, Jones J, Johanson E D, Landry B, Lane A Lynch G, Jezek K, Chela-Flores J, Jeng T, Bradley A. 1997. Searching for ice and ocean biogenic activity on Europa and Earth. San Diego: SPIE Conference. 3111: 490–500
Jansen J, MacIntyre S, Barrett D C, Chin Y P, cortés A, Forrest A L, Hrycik A R, Martin R, McMeans B C, Rautio M, Schwefel R. 2021. Winter Limnology: How do hydrodynamics and biogeochemistry shape ecosystems under ice? J Geophys Res-Biogeosci, 126: e2020JG006237
Jebbar M, Hickman-Lewis K, Cavalazzi B, Taubner R S, Rittmann S K M R, Antunes A. 2020. Microbial diversity and biosignatures: An icy moons perspective. Space Sci Rev, 216: 1–47
Kargel J S, Kaye J Z, Head Iii J W, Marion G M, Sassen R, Crowley J K, Ballesteros O P, Grant S A, Hogenboom D L. 2000. Europa's crust and ocean: Origin, composition, and the prospects for life. Icarus, 148: 226–265
Karl D M, Wirsen C O, Jannasch H W. 1980. Deep-sea primary production at the Galápagos hydrothermal vents. Science, 207: 1345–1347
Kennedy D, Norman C. 2005. What don't we know? Science, 309: 75
Kimball P W, Clark E B, Scully M, Richmond K, Flesher C, Lindzey L E, Harman J, Huffstutler K, Lawrence J, Lelievre S, Moor J, Pease B, Siegel V, Winslow L, Blankenship D D, Doran P, Kim S, Schmidt B E, Stone W C. 2018. The ARTEMIS under-ice AUV docking system. J Field Robotics, 35: 299–308
Klein H P, Lederberg J, Rich A, Horowitz N H, Oyama V I, Levin G V. 1976. The Viking Mission search for life on Mars. Nature, 262: 24–27
Klenner F, Postberg F, Hillier J, Khawaja N, Reviol R, Stolz F, Cable M L, Abel B, Nölle L. 2020. Analog experiments for the identification of trace biosignatures in ice grains from extraterrestrial ocean worlds. Astrobiology, 20: 179–189
Kolb V M. 2019. Defining life: Multiple Perspectives. In: Kolb V M, ed. Handbook of Astrobiology. Boca Raton: CRC Press. 57–63
Kumagai J. 2007. Swimming to Europa. IEEE Spectr, 44: 33–40
Kuskov O L, Kronrod V A. 2005. Internal structure of Europa and Callisto. Icarus, 177: 550–569
Lawrence J D, Mullen A D, Bryson F E, Chivers C J, Hanna A M, Plattner T, Spiers E M, Bowman J S, Buffo J J, Burnett J L, Carr C E, Dichek D J, Hughson K H G, King W, Glenn Lightsey E, Ingall E, McKaig J, Meister M R, Pierson S, Tomar Y, Schmidt B E. 2023. Subsurface science and search for life in ocean worlds. Planet Sci J, 4: 22
Lenardic A, Seales J. 2021. Habitability: A process versus a state variable framework with observational tests and theoretical implications. Int J AstroBiol, 20: 125–132
Levine A G. 2021. A Sponsored Supplement to Science 125 Questions: Exploration and Discovery. Booklet, Science/AAAS Custom Publishing Office
Lin W, Li Y L, Wang G H, Pan Y X. 2020. Overview and perspectives of Astrobiology (in Chinese). Chin Sci Bull, 65: 380–391
Malaska M J, Bhartia R, Manatt K S, Priscu J C, Abbey W J, Mellerowicz B, Palmowski J, Paulsen G L, Zacny K, Eshelman E J, D'Andrilli J. 2020. Subsurface *in situ* detection of microbes and diverse organic matter hotspots in the Greenland Ice Sheet. Astrobiology, 20: 1185–1211

Marion G M, Fritsen C H, Eicken H, Payne M C. 2003. The search for life on Europa: Limiting environmental factors, potential habitats, and Earth analogues. Astrobiology, 3: 785–811
Martin A, McMinn A. 2018. Sea ice, extremophiles and life on extra-terrestrial ocean worlds. Int J AstroBiol, 17: 1–16
Martin W, Russell M J. 2007. On the origin of biochemistry at an alkaline hydrothermal vent. Phil Trans R Soc B, 362: 1887–1926
Martin W, Baross J, Kelley D, Russell M J. 2008. Hydrothermal vents and the origin of life. Nat Rev Microbiol, 6: 805–814
McKinnon W B. 1999. Convective instability in Europa's floating ice shell. Geophys Res Lett, 26: 951–954
Meister M, Dichek D, Spears A, Hurwitz B, Ramey C, Lawrence J, Philleo K, Lutz J, Lawrence J, Schmidt B E. 2018. Icefin: Redesign and 2017 Antarctic field deployment. Charleston: IEEE/MTS OCEANS Conference. 1–5
Melo-Merino S M, Reyes-Bonilla H, Lira-Noriega A. 2020. Ecological niche models and species distribution models in marine environments: A literature review and spatial analysis of evidence. Ecol Model, 415: 108837
Ménez B, Pisapia C, Andreani M, Jamme F, Vanbellingen Q P, Brunelle A, Richard L, Dumas P, Réfrégiers M. 2018. Abiotic synthesis of amino acids in the recesses of the oceanic lithosphere. Nature, 564: 59–63
Murphy R R. 2021. Planetary rovers in science fiction. Sci Robot, 6: eabh3165
Murray A E, Kenig F, Fritsen C H, McKay C P, Cawley K M, Edwards R, Kuhn E, McKnight D M, Ostrom N E, Peng V, Ponce A, Priscu J C, Samarkin V, Townsend A T, Wagh P, Young S A, Yung P T, Doran P T. 2012. Microbial life at −13°C in the brine of an ice-sealed Antarctic lake. Proc Natl Acad Sci USA, 109: 20626–20631
Muscettola N, Nayak P P, Pell B, Williams B C. 1998. Remote agent: To boldly go where no AI system has gone before. Artif Intelligence, 103: 5–47
Nadeau J, Lindensmith C, Deming J W, Fernandez V I, Stocker R. 2016. Microbial morphology and motility as biosignatures for outer planet missions. Astrobiology, 16: 755–774
Nealson K H. 1997. The limits of life on Earth and searching for life on Mars. J Geophys Res, 102: 23675–23686
Neveu M, Hays L E, Voytek M A, New M H, Schulte M D. 2018. The ladder of life detection. Astrobiology, 18: 1375–1402
Nimmo F, Pappalardo R T. 2016. Ocean worlds in the outer solar system. J Geophys Res-Planets, 121: 1378–1399
Nitsh M, Meckel S. 2023. The Triple-nanoAUV: An autonomous underwater vehicle to explore the oceans of icy moons. Technical Report. University of Bremen
Nordheim T A, Hand K P, Paranicas C. 2018. Preservation of potential biosignatures in the shallow subsurface of Europa. Nat Astron, 2: 673–679
Oleson S R, Hartwig J W, Landis G A, Walsh J, Lorenz R D, Paul M V. 2020. Titan Turtle: NIAC Phase II Design for a Submersible Vehicle for Titan Exploration. Las Vegas: ASCEND (Accelerating Space Commerce, Exploration, and New Discovery) Conference
Paczkowski B, Ray T, Choukroun M, Brooks S, Steinbruegge G, Gudipati M, Piqueux S, Blacksberg J, Cochrane C, Diniega S, Elder C, Roberts J, Ernst C, Luspay-Kuti A. 2022. Europa Clipper Instrument Summaries. Technical Report. NASA
Pappalardo R T, Barr A C. 2004. The origin of domes on Europa: The role of thermally induced compositional diapirism. Geophys Res Lett, 31: L01701
Pappalardo R T, Head J W, Greeley R, Sullivan R J, Pilcher C, Schubert G, Moore W B, Carr M H, Moore J M, Belton M J S, Goldsby D L. 1998. Geological evidence for solid-state convection in Europa's ice shell. Nature, 391: 365–368
Paranicas C, Cooper J F, Garrett H B, Johnson R E, Sturner S J. 2009. Europa's radiation environment and its effects on the surface. In: Pappalardo R T, McKinnon W B, Khurana K, eds. Europa. Tucson: The University of Arizona Press. 529–544
Patterson G W, Paranicas C, Prockter L M. 2012. Characterizing electron bombardment of Europa's surface by location and depth. Icarus, 220: 286–290
Pohorille A, Sokolowska J. 2020. Evaluating biosignatures for life detection. Astrobiology, 20: 1236–1250
Ramirez R M. 2018. A more comprehensive habitable zone for finding life on other planets. Geosciences, 8: 280
Richmond K, Flesher C, Lindzey L, Tanner N, Stone W C. 2018. SUNFISH®: A human-portable exploration AUV for complex 3D environments. Charleston: IEEE/MTS Oceans. 1–9
Richmond K, Hogan B, Lopez A, Harman J, Myers K, Guerrero V, Lanford E, Ralston J C, Tanner N, Siegel V, Stone W C. 2021. PROMETHEUS: Progress toward an integrated cryobot for ocean world access. New Orleans: AGU Fall Meeting
Rouse W H. 1975. Lucretius: On the Nature of Things. Cambridge: Harvard University Press. 177–180
Roush W. 2020. Extraterraestrials, Cambridge: The MIT Press. 25–29
Russell M J. 2003. The importance of being alkaline. Science, 302: 580–581
Russell M J, Barge L M, Bhartia R, Bocanegra D, Bracher P J, Branscomb E, Kidd R, McGlynn S, Meier D H, Nitschke W, Shibuya T, Vance S, White L, Kanik I. 2014. The drive to life on wet and icy worlds. Astrobiology, 14: 308–343
Sagan C, Thompson W R, Carlson R, Gurnett D, Hord C. 1993. A search for life on Earth from the Galileo spacecraft. Nature, 365: 715–721
Sahl J W, Fairfield N, Harris J K, Wettergreen D, Stone W C, Spear J R. 2010. Novel microbial diversity retrieved by autonomous robotic exploration of the world's deepest vertical phreatic sinkhole. Astrobiology, 10: 201–213
Schaler E, Ansari A, Howell S, Lee H J, Smith M, Rajguru A, Tosi L P, Hao Z, Kim J D. 2022. SWIM: Sensing with Independent Micro-swimmers. Authorea Preprints
Schmidt B E, Washam P, Davis P E D, Nicholls K W, Holland D M, Lawrence J D, Riverman K L, Smith J A, Spears A, Dichek D J G, Mullen A D, Clyne E, Yeager B, Anker P, Meister M R, Hurwitz B C, Quartini E S, Bryson F E, Basinski-Ferris A, Thomas C, Wake J, Vaughan D G, Anandakrishnan S, Rignot E, Paden J, Makinson K. 2023. Heterogeneous melting near the Thwaites Glacier grounding line. Nature, 614: 471–478
Schreiber D A, Richter F, Bilan A, Gavrilov P V, Lam H M, Price C H, Carpenter K C, Yip M C. 2020. ARCSnake: An Archimedes' Screw-Propelled, Reconfigurable Serpentine Robot for Complex Environments. Paris: IEEE International Conference on Robotics and Automation (ICRA). 7029–7034
Shank T M, Machado C, German C R, Bowen A, Leighty J, Kelsh A, Smith R, Hand K P. Development of a new class of autonomous underwater vehicle (AUV), Orpheus, for the exploration of ocean world analogues. 2019. The Woodlands: Lunar and Planetary Institute Ocean Worlds 4 Conference. 2168: 6021
Sherwood B, Ponce A, Waltemathe M. 2019. Forward contamination of ocean worlds: A stakeholder conversation. Space Policy, 48: 1–13
Siegert M J, Ellis-Evans J C, Tranter M, Mayer C, Petit J R, Salamatin A, Priscu J C. 2001. Physical, chemical and biological processes in Lake Vostok and other Antarctic subglacial lakes. Nature, 414: 603–609
Stone W C, Hogan B, Siegel V, Lelievre S, Flesher C. 2014. Progress towards an optically powered cryobot. Ann Glaciol, 55: 2–13
Stone W, Hogan B, Siegel V, Harman J, Clark E, Pradhan O, Gasiewski A, Howe S, Howe Troy. 2018. Project VALKYRIE: Laser-Powered Cryobots and Other Methods for Penetrating Deep Ice on Ocean Worlds. In: Badescu V, Zacny K, eds. Outer Solar System. Cham: Springer. 47–165
Stone W, Siegel V, Hogan B, Richmond K, Hackley C, Harman J, Flesher C, Lopez A, Lelievre S, Myers K, Nathan W. 2020. Novel Methods for Deep Ice Access on Planetary Bodies. In: Bar-Cohen Y, Zacny K, eds. Advances in Extraterrestrial Drilling. New York: CRC Press. 215–245
Trumbo S K, Brown M E. 2023. The distribution of CO_2 on Europa indicates an internal source of carbon. Science, 381: 1308–1311

Truong N, Monroe A A, Glein C R, Anbar A D, Lunine J I. 2019. Decomposition of amino acids in water with application to *in-situ* measurements of Enceladus, Europa and other hydrothermally active icy ocean worlds. Icarus, 329: 140–147

Vance S D, Melwani Daswani M. 2020. Serpentinite and the search for life beyond Earth. Phil Trans R Soc A, 378: 20180421

Vaquero T S, Daddi G, Thakker R, Paton M, Jasour A, Strub M P, Swan R M, Royce R, Gildner M, Tosi P, Veismann M, Gavrilov P, Marteau E, Bowkett J, de Mola Lemus D L, Nakka Y, Hockman B, Orekhov A, Hasseler T D, Leake C, Nuernberger B, Proença P, Reid W, Talbot W, Georgiev N, Pailevanian T, Archanian A, Ambrose E, Jasper J, Etheredge R, Roman C, Levine D, Otsu K, Yearicks S, Melikyan H, Rieber R R, Carpenter K, Nash J, Jain A, Shiraishi L, Robinson M, Travers M, Choset H, Burdick J, Gardner A, Cable M, Ingham M, Ono M. 2024. EELS: Autonomous snake-like robot with task and motion planning capabilities for ice world exploration. Sci Robot, 9, http://doi.org/10.1126/scirobotics.adh8332

Villanueva G L, Hammel H B, Milam S N, Faggi S, Kofman V, Roth L, Hand K P, Paganini L, Stansberry J, Spencer J, Protopapa S, Strazzulla G, Cruz-Mermy G, Glein C R, Cartwright R, Liuzzi G. 2023. Endogenous CO_2 ice mixture on the surface of Europa and no detection of plume activity. Science, 381: 1305–1308

Waldmann C, Kausche A, Iversen M, Pototzky A, Looye G, Montenegro S, Bachmayer R, Wilde D. 2014. MOTH—An underwater glider design study carried out as part of the HGF alliance ROBEX. IEEE/OES Autonomous Underwater Vehicles (AUV). 1–3

Waldmann C, de Vera J-P, Dachwald B, Strasdeit H, Sohl F, Hanff H, Kowalski J, Heinen D, Macht S, Bestmann U, Meckel S, Hildebrandt M, Funke O, Gehrt J J. 2018. Search for life in ice-covered oceans and lakes beyond Earth. New Orleans: 2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)

Wang J Z, Ma J N, Qiu J W, Tian D, Zhu A W, Zhang Q X, Zhou A S. 2019. Optimization design of radiation vault in Jupiter orbiting mission. IEEE Trans Nucl Sci, 66: 2179–2187

Wenzhöfer F, Lemburg J, Hofbauer M, Lehmenhecker S, Faerber P. 2016. TRAMPER. Monterey: IEEE/MTS OCEANS. 1–6

Whewell W. 1853. Of the Plurality of Worlds: An Essay, London: John W. Parker West Strand Press. 208–259

Wirtz M, Hildebrandt M. 2016. IceShuttle Teredo: An ice-penetrating robotic system to transport an exploration AUV into the ocean of Jupiter's moon Europa. Guadalajara: 67th International Astronautical Congress (IAC). 26–30

Wołos A, Roszak R, Żądło-Dobrowolska A, Beker W, Mikulak-Klucznik B, Spólnik G, Dygas M, Szymkuć S, Grzybowski B A. 2020. Synthetic connectivity, emergence, and self-regeneration in the network of prebiotic chemistry. Science, 369, http://doi.org/10.1126/science.aaw1955

Wronkiewicz M, Lee J, Mandrake L, Lightholder J, Doran G, Mauceri S, Kim T, Oborny N, Schibler T, Nadeau J, Wallace J K, Moorjani E, Lindensmith C. 2024. Onboard science instrument autonomy for the detection of microscopy biosignatures on the ocean worlds life surveyor. Planet Sci J, 5: 19

Zimmerman W, Bonitz R, Feldman J. 2001. Cryobot: An ice penetrating robotic vehicle for Mars and Europa. Big Sky: IEEE Aerospace Conference. 311–323

(Editorial handling: Yong WEI)