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REVIEW

Developing technological synergies between deep-sea and space research

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Recent advances in robotic design, autonomy and sensor integration create solutions for the exploration of deep-sea environments, transferable to the oceans of icy moons. Marine platforms do not yet have the mission autonomy capacity of their space counterparts (e.g., the state of the art Mars Perseverance rover mission), although different levels of autonomous navigation and mapping, as well as sampling, are an extant capability. In this setting their increasingly biomimicked designs may allow access to complex environmental scenarios, with novel, highly-integrated life-detecting, oceanographic and geochemical sensor packages. Here, we lay an outlook for the upcoming advances in deep-sea robotics through synergies with space technologies within three major research areas: biomimetic structure and propulsion (including power storage and generation), artificial intelligence and cooperative networks, and life-detecting instrument design. New morphological and material designs, with miniaturized and more diffuse sensor packages, will advance robotic sensing systems. Artificial intelligence algorithms controlling navigation and communications will allow the further development of the behavioral biomimicking by cooperating networks. Solutions will have to be tested within infrastructural networks of cabled observatories, neutrino telescopes, and off-shore industry sites with agendas and modalities that are beyond the scope of our work, but could draw inspiration on the proposed examples for the operational combination of fixed and mobile platforms.

Keywords: Deep-sea robotics, Exo-oceans, Biomimicking, Artificial intelligence, Miniaturized life-tracing sensors, Marine observatory networks

Introduction

The deep sea is the largest and the most unknown biome on Earth (Danovaro et al., 2020), appearing to the observer as continuous and monotonous at first sight. Notwithstanding, this vast, three-dimensional system is neither environmentally homogeneous nor stable

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(Robison, 2004), and contains a huge complexity of ecosystems and biodiversity (Proud et al., 2017; Reygondeau et al., 2017). The pelagic (within the water column) and benthic (seafloor) domains present marked environmental gradients (e.g., along depth and latitude) and cover vast geographic regions (Levin et al., 2018), with several geomorphological habitats described for deep continental margins and abyssal plains, such as hydrothermal vent and cold seep fields, canyons and seamounts, among others (Levin and Sibuet, 2012; Cormier and Sloan, 2018). To date, limited information exists on the ecosystem boundaries separating major depth strata in the pelagic realm (i.e., the epi-, meso-, bathy- and abyssopelagic zones), leaving the relationship of deep-sea benthic and water-column communities with major biosphere gradients in temperature, depth/pressure, light, salinity and latitude still to be discovered on various spatial scales. Within this context, marine technology is enabling the exploration of the deep ocean at a rapidly increasing pace, reshaping at each step our understanding of the adaptation and evolution of life, and in turn, expanding our concept of habitability of extreme environments (Mapelli et al., 2016).

Alongside the deep sea, space represents the future frontier for human exploration and exploitation, with both subject to the rapid development of robotic technologies. Intensive industrial exploitation of marine ecosystems started centuries ago, with modern ocean industries (e.g., fisheries, oil and gas or projected mining extractions) continuing in the willingness to exploit unstudied deep-sea ecosystems. This continuing exploitation is stressing the competition between economic gain and the acquisition of scientific knowledge, including for the aim of sustainable use of the resources (Danovaro et al., 2017c; Folkersen et al., 2019). Given this situation, marine scientific and industrial technologies anticipate robotic solutions for autonomous acquisition of multidisciplinary data; biological, oceanographic, geochemical and environmental, as well as for in-situ manipulation and sampling (Jones et al., 2019). Presently, a large portion of space research is already applied to the field of remote sensing of the ocean surface, serving both industrial and scientific purposes (Anderson et al., 2017), with operations now extending into deep-sea pelagic and seafloor areas (e.g., Wedler et al., 2018, 2020; Aguzzi et al., 2020b). For example, data on the ocean interior are used to calibrate and validate satellite readings, a connection enabled by various degrees of continuity in combined data collection via vessel-assisted autonomous underwater vehicles (AUVs), multiparameter coastal cabled observatories, and moored buoys and Argo floats (Riser et al., 2016; National Aeronautics and Space Administration [NASA], 2018). Moreover, underwater neutrino telescopes initially conceptualized and deployed to detect astroparticles, have been integrated into water-column research (e.g., Martini et al., 2014), detecting life in the form of bioluminescence.

The objective of this review is to provide a vision for the future development of deep-sea robotics based on the engagement of space technology within three major research areas: biomimetic structural and energetic designs, artificial intelligence (AI), and miniaturization of life-detecting sensor technologies. To do so, we hypothesize that deep-sea scientific and industrial permanent infrastructures can be used as operational proving grounds for the testing and control of the new robotic solutions that will be developed in the upcoming decades. We propose these aforementioned topics for deep-sea robotic development in a moment of central interest for marine technologies according to the United Nations Ocean Decade Initiative, with growing collaborations between the European Space Agency and the World Ocean Council and others, including NASA and NOAA in the United States. Our ultimate goal is to suggest how the exploration and monitoring of our abyssal realms could also benefit future exo-ocean (i.e., extraterrestrial ocean) exploration activities, as marine habitat equivalents.

Liquid water is potentially present beyond Earth in the form of exo-oceans in several solar system bodies, including several satellites of Jupiter (i.e., Europa, Ganymede and Callisto), Saturn (i.e., Enceladus, Titan and Dione), and Neptune (i.e., Triton), as well as dwarf planets such as Pluto and Ceres (Iess et al., 2014; Henin, 2018; Hendrix et al., 2019; Kamata et al., 2019). In particular, salty oceans are likely present on Enceladus, Titan, Europa, Triton and even on Ceres (Hendrix et al., 2019), while additional evidence of hydrothermal venting has been found on Enceladus and Europa (Hsu et al., 2015). Exo-oceanic conditions seem to be similar to those on Earth. Enceladus, for example, has a vast salty exo-ocean (Fifer et al., 2019) of 30–50 km depth (Iess et al., 2014; Hemingway and Mittal, 2019), kept liquid by geothermal activity and tidal friction. It mechanically decouples the rocky core from the exterior ice shell (Saxena et al., 2018; Neveu and Rhoden, 2019), with a thickness around 20–30 km (Lucchetti et al., 2017). Strong geothermal gradients and high pressure produce fluxes of hot water, transported through the ice shell via cracks and crevasses that erupt into space, evaporating and freezing, to later fall back on the surface as snow (i.e., cryovolcanism; Běhounková et al., 2017). That condition of thermodynamic disequilibrium with abundant dissolved carbon compounds is of relevance to the possible emergence of life in such extraterrestrial environments (e.g., Deamer and Damer, 2017; Postberg et al., 2018; Schwieterman et al., 2018). In this framework, there is a growing need to identify potential synergies and transferable technologies within robotic design, mission autonomy and sensor integration in order to tackle the interrelated challenges of exploring Earth's abyssal areas and the subsurface oceans of icy moons as potentially analogous environments.

Biomimetic structure, along with systems for power storage and generation of propulsive mobility are a relevant aspect to be considered for both exploration scenarios. At the time of writing, robotic designs similar to traditional underwater vehicles (e.g., AUVs, Argo floats, crawlers, rovers, etc.) are envisaged for the exploration of extra-terrestrial ocean worlds. A comparison of different habitat scenarios for the development of cooperative marine and space robotic research with platforms and concept designs of the past (**Table 1**) provides evidence of previous cooperation. Different layers on Earth, such as the deep sea and the ice caps with their internal lakes, can

Table 1. Evidence of cooperative scenarios for marine and space robotics. DOI: https://doi.org/10.1525/elementa.2021.00064.t1

Planet of Moon, Region	Type of Layer[a]	Technology
Earth, polar areas, and deep sea	Ice shell (ice shelf)	IceFin (ROV[b]/AUV[c] hibrid), and BRUIE[d]
	Liquid salt water	ROV, AUV, Mesobot, Argo floats, neutrino telescopes, moored buoys, and Eelume-IMR[e]
	Seabed	ROV, AUV, crawlers, rovers, landers, and cabled observatories
Europa	Ice shell	Cryobots, BRUIE, ENDURANCE AUV[f], and EELS[g]
	Internal lakes/brines	Cryobots and EELS
	Liquid salt water (deep-sea equivalent)	DEPTHX[h], BRUIE, ENDURANCE-AUV, and EELS
	Seabed	Leng-AUV[i]
Enceladus	Ice shell	Cryobots, BRUIE, ENDURANCE-AUV, and EELS
	Internal lakes/brines	Cryobots and EELS
	Liquid salt water (deep-sea equivalent)	DEPTHX, BRUIE, Leng-AUV, ENDURANCE-AUV, and EELS
	Seabed	Leng-AUV
Titan	Liquid hydrocarbon	AUV (Titan Submarine; Titan Sub[j])
Ganymede, Callisto, Dione, Mimas, Triton, and polar areas on Mars	Equivalent layers unknown/absent	Not yet conceptualized

AUV = autonomous underwater vehicle.

[a] Types of targeted environments for terrestrial and space missions. Exo-oceans are completely covered by icy shells, many kilometers thick; terrestrial ice shelves can serve as analogues. The internal structures of these icy shells are hypothesized about, but currently unknown, potentially containing lakes/brines (Hussman et al., 2015). Titan hosts a methane-based hydrological cycle, supporting liquid hydrocarbon surface lakes and potentially subsurface reservoirs (Mastrogiuseppe et. al., 2019).

[b] Remotely operated vehicle.

[c] Autonomous underwater vehicle.

[d] Buoyant rover for under-ice exploration (Berisford et al., 2013).

[e] Inspection, maintenance, and repair.

[f] Environmentally nondisturbing under-ice robotic Antarctic explorer (Stone et al., 2009).

[g] Exobiology extant life surveyor.

[h] Deep phreatic thermal explorer (Greenberg et al., 2005).

[i] Deutsches Forschungszentrum für Künstliche Intelligenz (2012).

[j] National Aeronautics and Space Administration (2014).

serve as proxies for exo-oceanic masses and fluid hydrocarbon bodies on other planets and icy moons. On the other hand, there are specific technical challenges which cannot be (or have yet to be) resolved through traditional engineering, which may benefit from an alternative, biomimetic approach. For example, bio-inspired structural design solutions may enable mobility paradigms not feasible with traditional vehicles, such as navigating through complex surface terrain, spatially constrained geomorphologies, and highly hydrodynamic regimes, while simultaneously minimizing the footprint on the environment (e.g., Ono et al., 2019; Picardi et al., 2020).

At the same time, energy sources for submarine vehicle propulsion are currently limited by battery technologies, as the addition of extra battery space is often not a viable solution because it would enlarge the platforms and alter their overall buoyancy (Li et al., 2020). For space research, power supply approaches are often centered on the use of Radioisotope Thermoelectric Generators (RTG's), such as the multi-mission RTG prototypes with lower thermal inventory assessed by Whiting (2021) and the Perseverance mission. RTGs however, are inapplicable to marine exploration on Earth, due to tight control from concerns over radioisotopes being accidentally released and polluting the environment (Barco et al., 2020). This limitation may open the possibility to develop new forms of energy provision based on bacterial fuel cells (at least for deep-sea research; Aguzzi et al., 2021). The task of self-sustainable energy production on a molecular level to sustain artificial cells represents a relevant field of biomimicking metabolic research (e.g., Jeong et al., 2020). Artificial cell systems may even be used to sustain locomotion (or some functionalities associated to it) in robots. For space exploration, however, this solution may violate the planetary protection principles set by the Committee on Space Research (COSPAR); i.e. carrying bacterial communities that present a potential source of contamination for alien environments.

Moreover, deep-sea exploration requires an increase in AI functionalities. Missions will benefit from growing autonomy and the creation of intelligent platforms, endowed with software solutions for, for example, on-board, real-time automated data processing and transmission (Marini et al., 2020). Augmented platform intelligence should increase fault tolerance in the exploration of unknown environments by swarms of cooperative vehicles. This aspect would reduce (or be resilient to) the risk of losing single units (Ayre, 2004), although in general terms such swarms would not necessarily need to be autonomous and can also add mission complexity to deep-sea exploration. This cooperation would also imply inter-platform communication capability (e.g., Masmitja et al., 2020), with strong advances being made in this field by national and international research consortia.

Life-detecting technologies are also of relevance for both deep-sea research (e.g., ecological monitoring actions; reviewed recently by Rountree et al., 2020) and spatial exploration. The presence of liquid water alone is not a sufficient condition of habitability, and habitable environments do not necessarily contain life, such as a freshly formed habitat on Earth not yet colonized (Cockell et al., 2016) and artificial (i.e., lab-created) habitats (Cockell et al., 2017). Notwithstanding, liquid water is considered to be a necessary requirement of an environment for habitability and the possibility of extraterrestrial life (Schulze-Makuch et al., 2020). Thus, in the marine environments of icy moons that are geothermally active (where life would need to be chemosynthetic due to the absence of sunlight), sensors should target the identification of life at different levels of complexity, from molecular and environmental traces of its activity (e.g., chemical disequilibria, signs of biofilms, bioturbation or sounds) to the direct identification of the presence of uni- and multicellular organisms (e.g., Carr et al., 2017; Aguzzi et al., 2020b; Dachwald et al., 2020). In relation to such targeting, the achievements made by the marine science community can provide space technology with highly-integrated life-detecting, oceanographic and geochemical sensor technologies (Aguzzi et al., 2019).

Biomimetic structure and propulsion

Operating in extreme environments, such as the deep sea, requires consistent advances in robotics, and innovative engineering solutions that enable navigation in unknown and dynamically changing environments (**Figure 1A**). This capacity relies on the development of robotic systems capable of efficient and multi-modal locomotion, exploiting metabolic-like renewable energy provision, and cooperating in heterogeneous swarms to maximize the effectiveness of future missions. Such advances may also be of interest for tackling future industrial challenges (e.g., Liljebäck and Mills, 2017). At the time of writing, most of the robotic systems employed in deep-sea and exo-ocean exploration have been designed following a traditional engineering approach (e.g., crawlers, rovers or AUVs; **Table 1**), which grants high reliability and robustness to certain commonly encountered classes of problems, such as reduced mobility in uncharted terrains (Purser et al., 2013; Farley et al., 2020). In some cases, where traditional designs fall short, effective solutions may be provided by biomimetics, i.e. the approach of reverse engineering to simulate characteristics that are typically associated with biological systems (Ayre, 2004). Biomimetics is a broad field, which could contribute to solutions for the aforementioned engineering challenges for both marine exploration scenarios (i.e., on Earth and within icy moons).

Agile terrestrial locomotion on irregular terrains can be pursued through the construction of multi-legged robots as conceptual arthropod-like structural designs (Aguzzi et al., 2021). This approach has been applied to the coastal marine domain, such as the Silver2 crab (Picardi et al., 2020), as well as in the deep sea (e.g., Crabster CR6000; Jun et al., 2017). Within the global exploration strategy of cross-thematic projects (Wedler et al., 2018, 2020), multi-legged platforms were envisioned, in addition to the development of more traditional crawlers, rovers and AUVs, to cooperate in exploring, deploying, and maintaining scientific instrumentation in deep-sea environments as equivalents to planetary surfaces. Another notable example of adaptation and multi-modal operations for space is represented by the RoboSimian (Hebert et al., 2015), a multi-legged robot developed at NASA-JPL capable of terrestrial locomotion, climbing, and manipulation through its articulated limbs, for which an underwater version has also been envisioned. Adapting to an evolving scenario, such as different phases of an exploratory mission, has been pursued in another project from NASA-JPL, the Exobiology extant life surveyor (EELS; Ono et al., 2019), where a robot with a snake-like morphology was designed to crawl on the surface of Enceladus, penetrate an icy crevasse and swim in an underground water ocean. A similar morphology has also been envisioned for deep-sea, off-shore industrial surveillance (Eelume; Liljebäck and Mills, 2017).

The adaptation to dynamically changing environments, while being delicate in the interactions with the surroundings and resilient to possible faults, can be achieved by employing soft materials in the construction of robots (Calisti et al., 2017). This achievement would imply the development and manufacturing of new lighter compounds shaped and assembled via novel 3D printing techniques (Phillips et al., 2019), achieving a density close to seawater. Recently, a soft-bodied robot with distributed electronics was successfully deployed in the Mariana Trench (Li et al., 2021), proving the ability to protect electronics from high-pressure water using elastomeric materials. In addition, the use of bio-inspired functionalized soft materials in the construction of robots will enable

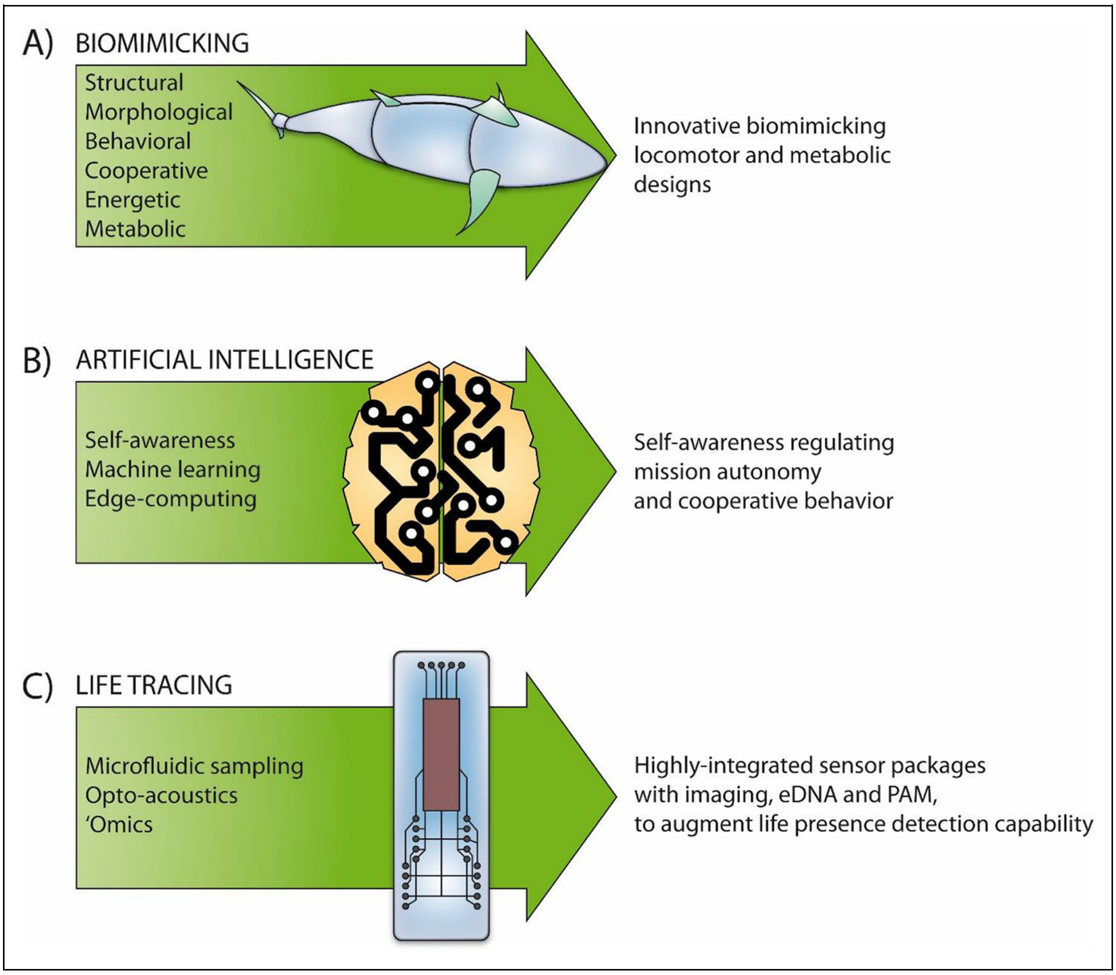

Figure 1. Major lines of action within each field for research development. (A) Novel biomimicking designs in locomotion, energy generation concepts, and use of swarms are needed as a step toward expanding accessible zones and increasing the likelihood of mission success. (B) Artificial intelligence and cooperating networks have to be able to process large datastreams without human intervention, while at the same time balancing the exploration objectives and engineering constraints (i.e., communications power, budget to optimize mission execution, etc.) and offering adaptive resilience to disturbances and unexpected factors. (C) New designs for life-detecting instrumentation have to minimize size and increase the capability to detect life based on the identification and quantification of biological molecules, used in parallel with other optoacoustic methods. PAM = passive acoustic monitoring. DOI: https://doi.org/10.1525/elementa.2021.00064.f1

advanced behaviors, such as self-healing properties (Hager, 2017) and distributed sensing and actuations (Asadnia et al., 2015). Both functionalities will enhance the resilience of the platforms to damage and their ability to react to the changing environmental conditions.

Another major challenge related to the use of (semi-)autonomous robotic systems in deep-sea exploration is energy independence (Aguzzi et al., 2021). Traditional engineering solutions are limited by the development of efficient batteries, increasing their size or utilizing alternative energy carriers such as hydrogen. Additionally, the use of local water currents or temperature gradients has been investigated as a source of energy (Chiu et al., 2017). On the other hand, organisms rely on the generation of energy through different biological processes that can be replicated in artificial systems. Biomimicking the metabolism of deep-sea organisms may provide renewable energy provision, through the in-situ processing of substrata (feeding-like functions) as potential gain for space exploration. For instance, mimicking life solutions for bioluminescence (i.e., the production of light by organisms) at low energetic cost would allow low-light imaging (see section on Life-detecting technologies) and/or substrate-harvesting capabilities would likely be accompanied by concomitant biomimetic development in animal-like grippers and toothed mouths.

Space exploration employs long-lasting energy solutions such as RTGs (Konstantinidis et al., 2015), the use of which is not applicable in the marine research because of the associated environmental threat (Barco et al., 2020), concerns over nuclear proliferation, and extremely tight control over relevant radioisotopes, such as highly-refined plutonium. At the same time, marine robotics aim to find solutions to increase long-lasting operational autonomy complementary to traditional battery technologies, such as the Piezo-Acoustic Backscatter (PAB; Jang and Adib,

2019) for battery-less underwater networking and microbial fuel cells (e.g., Guzman et al., 2010). For example, AUVs are already operating with hydrogen power (Marini et al., 2020), and hydrogen-oxygen (H_2-O_2) fuel cells are currently being developed (Aguzzi et al., 2021) to feed lithium polymer battery systems. Nevertheless, these fuel cells still require human maintenance and recharge, and in order to eliminate that drawback innovative cells systems that harvest in-situ methane are being conceived for use in seepage areas (DeLong and Chandler, 2002).

Energy extraction by metabolic mimicking could provide new alternatives for long-lasting autonomous robotic functionalities in deep-sea exploration. A new generation of microbial fuel cells aims at producing energy in an autopoietic manner (Santoro et al., 2017), using catabolism by-products in circular energy loops (e.g., Ieropoulos et al., 2013). In the future, these cells may completely eliminate the bacterial components, with biochemical reaction routes inferred with reverse engineering approaches (e.g., Kim et al., 2020b). These energy systems may even become diffuse in the whole robotic structure (e.g., Jeong et al., 2020), sustaining slow locomotor functionalities, and could be associated to energy harvesting by other physical forces directed to the robot itself (e.g., hydrostatic pressure) through piezoelectric sensors (Salazar et al., 2018; Han et al., 2019).

Research on the performance of these cells in extreme marine environments (e.g., geothermal or polar areas) to monitor energy generation and storage efficiencies may also contribute to space research at the level of life support systems. Biology-based fuel cells for energy provision are controllable, replicable, low-cost experimental microcosm ecosystems with bacterial communities, used to test for cost-benefit and stability in mass-energy exchange (e.g., Escobar and Nabity, 2017). Specific in-situ manipulation capabilities could allow experimentation on bacterial metabolism (e.g., within chambers), adapting that metabolism to the hostile space environment via genetic engineering and using deep-sea volcanic systems as natural laboratories (Danovaro et al., 2017b). The up-scaling of results to larger volumes will provide valuable insights on water, gases, organic matter and overall energy recycling loops within artificial ecosystems. Although for some space applications this solution may violate the COSPAR principles of preventing the cross-contamination of life, it will inspire how we conceive self-sustained recharging microcosm and life-support systems. In this respect, COSPAR does not yet have explicit guidance for exo-ocean hardware contamination restrictions. COSPAR Policy on Planetary Protection is establishing guidelines with 5 categories, to avoid forward contamination of other planets and to prevent backward contamination of the Earth when samples are returned (Cheney et al., 2020; COSPAR, 2020). Category IV, mostly comprised of probe and lander missions, targets chemical evolution and/or the origin of life. For these types of missions, scientific consensus acknowledges a noteworthy chance of contamination, which could compromise future investigations. Category V, on the other hand, includes all Earth-return missions. The principal concern regarding those missions is to avoid contamination of the terrestrial system, the Earth and the Moon. This concern is also relevant to missions to icy moons such as Europa and Enceladus. Bioburden reduction will have to be applied to minimize the probability of inadvertent contamination of a Europan or Enceladan ocean, targeting towards $< 10^{-4}$ per mission. The missions will have to address specific forward contamination risks and follow strict protocols to limit and document bacterial systems during spacecraft testing, apply sterilization, determine survival during cruise phases and specific environments, and consider constraints for the termination of a mission that will be compatible with planetary protection guidelines.

AI and cooperating networks

The continuous development of autonomy is paramount in order to maximize the efficiency of remote robotic operations in extreme environments (**Figure 1B**). Platforms can acquire very large amounts of heterogeneous data, which can be processed in real-time (as well as preserved in their original form) to extract knowledge for autonomous functionalities. Key autonomous functionalities can be categorized into mission planning, navigation/trajectory planning, adaptive sampling/sensing, and summarization of collected data. The requirement for mission autonomy is further enforced by the challenge of data transmission, which is impaired by water itself over great depths/distances. When these operational considerations are contextualized to ocean exploration at unknown depths, with shielding ice-sheets and astronomical bodies, and over immense distances, analogous conditions observed in the deep sea are of immense value as a testbed operational scenario for such autonomous capabilities.

The success of long-term, complex deep-sea and exo-ocean exploration missions relies on appropriate handling of competing objectives (e.g., seafloor versus water column) and constraints (e.g., power and communications). Autonomous mission planning and execution methods may be used to optimize the behavior of the respective vehicle, based on a given utility function and set of constraints (Gaines et al., 2020; Aguado et al., 2021). Due to the dynamic operational environments, these methods must be robust to unexpected disturbances and capable of adapting the overall mission plan and objectives based on the state of the vehicle and collected data.

Other key difficulties are navigation and vehicle trajectory planning. Exo-oceans are completely covered by icy shells, potentially tens of kilometers thick (Hussman et al., 2015). Accessing these subsurface oceans requires penetrating this icy shell, imposing a number of key constraints on missions targeting these bodies. Such a bore hole would be limited in diameter, on the order of 10 cm, restricting the vehicle and instrument form factor. The ice cover restricts direct radio frequency communication with orbital assets and navigation based on global navigation satellite systems. The cost of transiting through many kilometers of ice likely prohibits using multiple boreholes. Finally, the restrictive energy budget of such a vehicle would require low-power solutions. Navigation would be limited to methods based on acoustics, terrain relative navigation/simultaneous localization and mapping (SLAM), and dead-reckoning. Acoustic multi-lateration, combined with dead reckoning presents a solution for in-ice cryobot navigation (Kowalski et al., 2016; Dachwald et al., 2017). Additionally, these navigation methods could be augmented with tether payout and pressure/density profile information. This type of in-ice navigation paired with maneuverability would significantly increase the robustness of transit through the icy shell.

For an AUV tasked with exploring the exo-ocean below the ice shell and given the above constraints, acoustic navigation with a single acoustic beacon would be critical. Ultra-short baseline systems offer a potential solution to this problem (e.g., Masmitja et al., 2020); however, they are generally severely range-limited due to the required high-frequency acoustics. Methods using a lower frequency, range-only acoustic beacon would improve the operational range and robustness of navigation solutions (McPhail and Pebody, 2009; Webster et al., 2012). Even in mission concepts in which multiple disparate beacons are deployed, single beacon navigation methods would improve overall robustness of the navigation system. Terrain relative navigation and SLAM methods can also be used to assist in navigation, when acoustic signals are not available for localization (Paull et al., 2014). Such methods benefit from being independent from any infrastructure external to the vehicle, but only provide navigation in local coordinates that ultimately must be referenced back to a global frame. These navigation methods are complicated by the expected difficulty in determining and maintaining heading in an exo-ocean. The potential absence of magnetic fields and the induced magnetic fields of bodies such as Europa could limit the use of magnetic navigation, while dynamic platforms and operations at high latitudes could limit gyroscopic methods (Hussman et al., 2015). Finally, vehicle trajectory planning would be required to improve the navigational solutions and reduce the power consumption required to achieve a mission's stated objectives (De Carolis et al., 2018). These navigational methods are also relevant to terrestrial extreme marine environments such as the deep-sea and under ice. As such, deep-sea operational test beds will be critical in the development and refinement of robust navigational solutions for use in exo-oceans. Steps towards this direction are being made within the global exploration strategy of the cross-thematic projects Robotic Exploration of Extreme Environments – Deep Sea and Earth's Moon (ROBEX) and Autonomous Robotic Networks to Help Modern Societies (ARCHES) (see also Supplemental Material Text 1).

The traditional AUV command cycle (for both terrestrial marine exploration as well as current space probes such as Mars rovers) involves human operators sending fixed commands to the vehicle, the vehicle executing those commands, transmitting the acquired data to ship/shore, and then repeating the process. In remote marine and exo-ocean mission scenarios, having humans regularly involved in the decision loop is not feasible. Thus, fully autonomous on-board interpretation of data and re-command of the vehicle is required to maximize the utility of the collected data (Zhang et al., 2019). Some methods of this so-called adaptive sampling/sensing approach have been developed to target scientific features of interest such as ocean fronts (Zhang et al., 2016; Branch et al., 2019), hydrothermal/chemical plumes (Farrell et al., 2005; Ferri et al., 2010; Mason et al., 2020), and phytoplankton patches (Zhang et al., 2021). However, especially in the case of completely unobserved environments such as exo-oceans, the most interesting scientific features that eventually should be targeted may not be known a priori. In such cases, techniques for adaptive online exploration may be used that seek out "unexpected" new observations autonomously, based on previous history (Girdhar et al., 2013), as already demonstrated in polar regions (Clark et al., 2018).

As marine robotic platforms acquire a huge amount of heterogeneous data, a relevant effort has been dedicated to the autonomous data treatment, with the support of the European Commission and the European Marine Board. AI technology, centered on machine learning, is designed to identify patterns in available data and then apply that knowledge to new data without human intervention (Jordan and Mitchell, 2015; Karpatne et al., 2017). Intelligent applications must be capable of not only detecting and extracting useful information to reduce the memory storage and ease the communication activities, but also of explaining autonomously why such information is relevant and how it has been extracted from data. These capabilities are important, especially for explaining the dynamics of unknown environments and for inferring relationships that may be beyond the human cognitive reach (Barredo Arrieta et al., 2020). Significant progress has been made here in the context of marine science, including AI algorithms for the processing of multivariate time series and multi-spectral analysis of oceanographic, geochemical and biological data (Cordier et al., 2017; Beyan and Browman, 2020; Makiola et al., 2020; Malde et al., 2020). These approaches may be of benefit for space oceanic exploration research, where large amounts of data cannot be easily transferred but whose interpretation would have relevant scientific value.

A hardware architecture capable of controlling sensors and executing algorithms in real time, for the independent interpretation of content-based data from remote computational resources, is the core of the edge-computing paradigm (Shi et al., 2016). Such a technological approach, together with the Internet of Underwater Things (Qiu et al., 2020; Jahanbakht et al., 2021), results in the continuously growing development of intelligent, communicating observing systems, comprised by swarms of cooperative robots, used for scientific exploration and industrial monitoring (e.g., Berlinger et al., 2021). Multiscale exploration of marine and extra-terrestrial environments could be enforced by cooperating vehicles equipped with heterogeneous sensors, as for example in the case of continental margin and abyssal plain areas (Aguzzi et al., 2019; Rountree et al., 2020), icy-moon oceans (Aguzzi et al., 2020b; Blanc et al., 2020) or the hydrocarbon lakes on Titan and polar ice caps (embedding water lakes) on Mars (e.g., Mastrogiuseppe et al., 2019).

In this framework, deep-sea operations can benefit from the synergies between complex teleoperations of semi-autonomous robotic systems conceived for lunar and planetary (sub-)surfaces (Ehrenfreund et al., 2012). Architectures of robotic villages on moons and planets have been considered, including systems of support infrastructures and services, with various degrees of autonomy and intelligence. The partnership of robots with human habitats has some common challenges for the deep sea, lunar and planetary surfaces (Heinicke and Foing, 2021).

Life-detecting technologies

Life-detecting technologies (i.e., instrumentation and techniques to detect life) conceived for astrobiological research should be sufficiently repeatable, sensitive, and reliable in detecting life signatures we know from Earth and under similar environmental conditions (Neveu et al., 2018). If possible, samples should be collected across different spatial scales in a complementary manner. Increasingly, life detection in the deep sea will combine image and molecular sensor technologies into highly integrated payloads, which require miniaturization in order to be fully portable in different marine and exo-ocean environments (**Figure 1C**). Marine research is developing ‘omics sensors to trace environmental DNA and/or RNA (eDNA and eRNA), and at the same time, the exo-ocean community is implementing a path of coupling cameras with microfluidic samplers for multi-molecular analyses, as described in this section.

Marine biological sensors are getting progressively smaller. Animal-borne technologies such as data loggers and video cameras are being miniaturized and can now store complex biological and environmental information about investigated seascapes (e.g., Wilmer et al., 2015; Fehlmann and King, 2016; Nassar et al., 2018). Similar sensors can be implemented on planetary rovers or even in space suits to monitor extravehicular activities. As an example, micro-cameras (e.g., OmniBSI by OmniVision) could be assembled into diffuse imaging systems that recompose the field of view into photomosaics, hence not only surveying the environment but also detecting changes within mosaic quadrants with highly efficient functional responses similar to flies (Bogue, 2013). Research effort on reducing sensor size in marine platforms (Zereik et al., 2018) has a clear value for astrobiology in exo-ocean exploration scenarios that require optimization in volume and weight with new pressure and atmosphere resistant materials. For example, icy-moon shells that need to be penetrated pose severe technological constrains in platform and sensor payload transport (Ono et al., 2019; Bryson et al., 2020).

Bio-ecological and genomic sensors for the identification and quantification of small organic molecules (e.g., amino acids), biopolymers (i.e., polyamides, polynucleotides, and polysaccharides), and lipids as universal markers for life (Georgiou and Deamer, 2014) or DNA/RNA are being developed in association with microfluidic sampling capabilities. Microfluidic sensors act as molecular laboratories (Beaton et al., 2011) and are currently used in diverse fields such as the detection of waterborne pathogens (Rainbow et al., 2020), the oil and gas industry (Sieben et al., 2017) and ocean monitoring (Wang et al., 2020). The most recent application of such Lab-on-a-Chip technologies to marine research has involved the use of the 3 rd Generation Environmental Sample Processor (Scholin et al., 2018) employed in different field experiments (Zhang et al., 2019), including multi-omics analyses of marine microbes (Evans et al., 2019). DNA sequencing technology has also evolved, thanks to the nanofabrication of high-performance microfluidic chips comprising modules for DNA extraction, library preparation using protocols integrated with magnetic particles (e.g., VolTRAX by Oxford Nanopore Technologies), and the single-channel structure nanopore for sequencing (e.g., MinION; Oxford Nanopore Technologies), upgradable to a multi-channel microfluidic system (Fu et al., 2020). A further step in fluid handling for microfluidic devices may consider the implementation of paper-based analytical devices for multi-step assays, including ‘omics applications (Kim et al., 2020a).

New tools for the determination of biodiversity are focusing on eDNA/eRNA detection and semi-quantification (Cordier et al., 2021). This focus is paving the route for the creation of in-situ bio-ecological detecting tools and sensors, scouting for the presence of signatures of life in extreme environments such as the trenches and deep-sea floors, hydrothermal vents or at high latitudes. Such a development will converge with in-situ microfluidic sampling capability in the near future. Although presently far from being achieved in the marine medium, this technological convergence is relevant for detecting life within thick ice shells while the probe penetrates into the exo-ocean (e.g., Fukuba et al., 2011; Scholin et al., 2018). For icy moons (and Mars), a biomarker detector equipped with a bioaffinity-based sensor has been conceived for a future astrobiological mission (Fairén et al., 2020).

Image analysis with high definition and high magnification can improve considerably our ability to detect different forms of marine life (Bicknell et al., 2016). Combining high-density, low-light and acoustic cameras (morphologic approach), hydrophones (passive acoustic approach) and ‘omics (molecular approach) allows the quantification of the presence and activity of deep-sea life within a broad range of ecological sizes (Aguzzi et al., 2019; Danovaro et al., 2020). However, species traceability by ‘omics coupled to concomitant image acquisition requires a careful calibration phase in order to understand the matching feasibility between the markers and the portrayed species (Mirimin et al., 2021).

In astrobiology, the effort in the integration of sensor payload is currently centered on microorganisms (e.g., Moissl-Eichinger et al., 2016; Merino et al., 2019) with conceived prototypes such as the NASA-JPL Ocean Worlds Life Surveyor that integrates molecular analyses with the micro-imaging and spectral analysis of liquid samples. A deep-sea inspired technological development may contribute to shifting the focus of astrobiology research from micro- to larger-sized multicellular organisms. Although such a possibility remains remote according to current knowledge, its theoretical framework (e.g., Levin et al.,

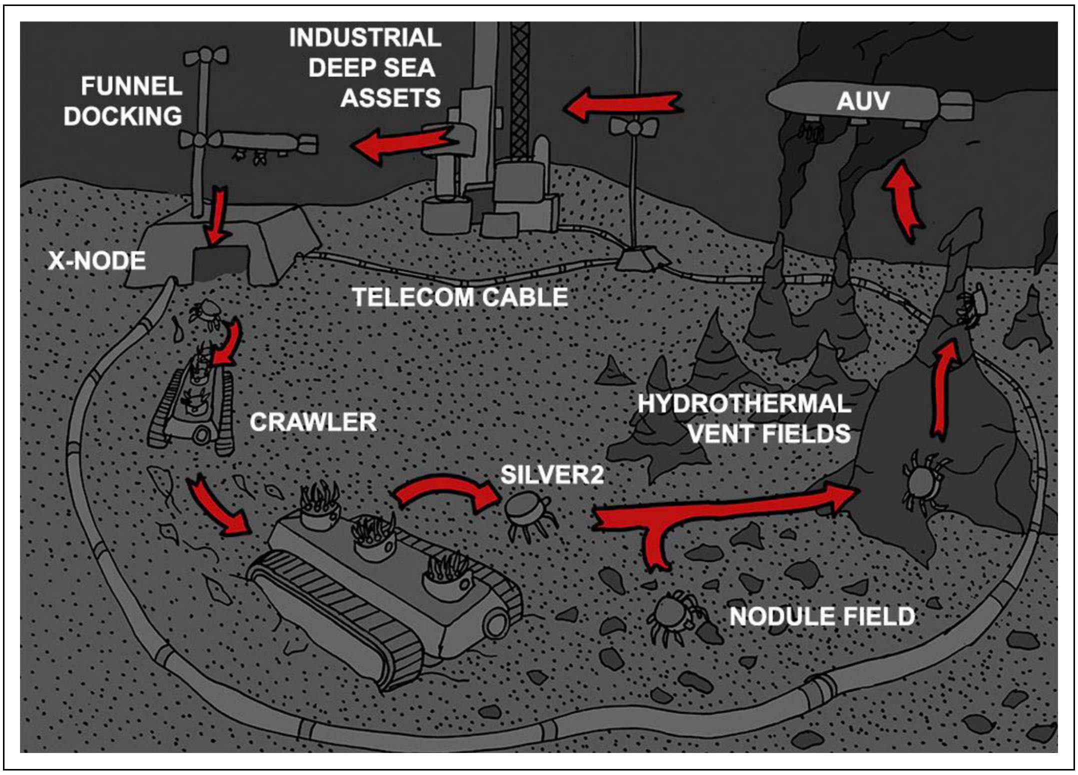

Figure 2. Innovative biomimicking applications in a scenario of extreme environment exploration. Bioinspired solutions beyond the current state of the art in deep-sea robotics such as the Silver2 crab (Picardi et al., 2020), coupled with cabled observatories equipped with docking garages (see Aguzzi et al., 2020a, for X-Node specifications) powered by industrial assets (telecommunication cabled and off-shore platforms) and transported by crawlers and autonomous underwater vehicles. This combination of established and innovative biomimicking platforms could be implemented to solve the problem of accessing remote deep-sea environments (hydrothermal vents and nodule fields), resulting in a test bed for exo-ocean exploration. DOI: https://doi.org/10.1525/elementa.2021.00064.f2

2017; Newman, 2018) may provide the opportunity for an interactive dialogue between marine and space scientists on invention and application of new and deep off-the-shelf life-detecting technological solutions (Arora et al., 2019; Dachwald et al., 2020).

Perspectives and future outlook

The three major research areas discussed here are centered on the technological challenges of the exploration of remote deep-sea environments, considering at the same time the potential gains for space research within the oceans of icy moons as extreme habitat equivalents. Biomimicking solutions should open a new operational line in the exploration of marine extreme environments. Already established assets (cabled observatories and deep-sea off-shore installations, docked AUVs and crawlers) will be combined with innovative robotics, incorporating biological components in their morphology, energy generation and cooperative behavior (**Figure 2**). Highly mobile, crab-like platforms could act as small surveying satellites, operating within areas around permanent marine infrastructures, while being carried, recharged and controlled via crawlers and AUVs. This combination of platforms may promote a step forward in the use of autonomous, intelligent biomimetic robotics for the exploration of exo-oceans.

In this scenario, we postulated a new framework for dialogue on robots and sensors within three major research topics of interest to produce a new class of services (**Figure 3**). For example, off-shore industries could benefit strongly from robotic developments for surveillance and maintenance of their infrastructures. For mining, these developments could include multi-legged (e.g., arthropod-like) platforms cooperatively interacting in the selective picking of dispersed metal-rich nodules and gathering them into piles (rather than wheel-tracked vehicles eroding and bulldozing) to be targeted later by suction recollects from ships or large AUVs.

Marine scientific and industrial off-shore infrastructures may provide innovative test-bed services for robotics development (**Figure 3**), if we assume a growing momentum in the exploration of abysses and exo-oceans as their habitat equivalents, identified in the NASA Roadmap for the Exploration of Ocean Worlds (Hendrix et al., 2019). Permanent networks of cabled observatories, together with their expanding water-column projections, are becoming the core of the first in-situ ecological laboratories, establishing operational control fields for docking mobile robots with in-situ manipulation capabilities (Rountree et al., 2020). To date, this achievement is imminent at the European Multidisciplinary Seafloor and water-column Observatories, the US National Science

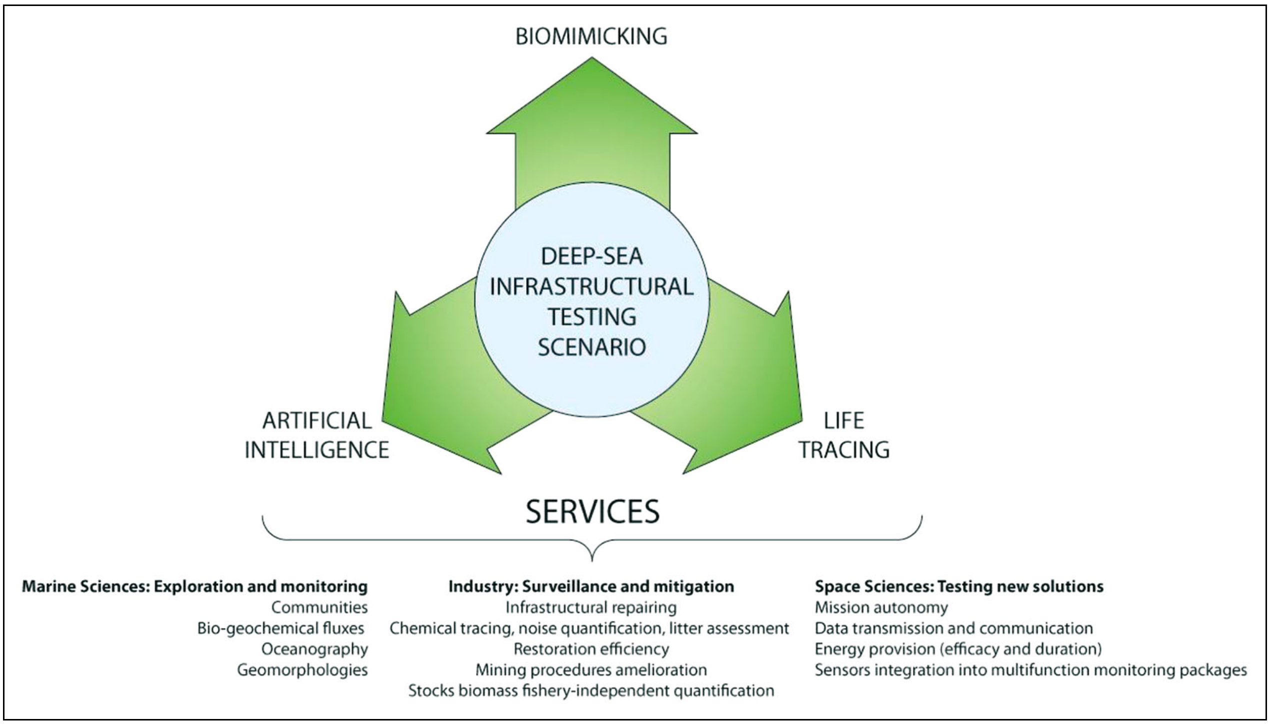

Figure 3. Deep-sea infrastructural testing scenario. The deep-sea operational scenario serves as an analogue for other liquid saltwater habitats in planetary bodies of our solar system, as an innovative context for cooperation among marine and space sciences plus off-shore industry. The three research topics for cooperation (see **Figure 1**) generate a wide spectrum of innovative scientific and industrial services. DOI: https://doi.org/10.1525/elementa.2021.00064.f3

Foundation Ocean Observatories Initiative and Ocean Networks Canada among others (Aguzzi et al., 2019). Their fixed platforms are allowing full sensor coverage of a vertical cross section of the marine biosphere, by integrating water-column and seabed oceanographic, geochemical and biological data with atmospheric (by surface buoys) and satellite readings (Danovaro et al., 2017a). In the past decade, neutrino telescopes of the KM3Net network (Agostini et al., 2020) also joined the monitoring efforts of cabled observatories, with their moored towers added to the previous water-column sensing technologies (Chatzievangelou et al., 2021).

The United Nations has declared the 2020s as the Decade on Ecosystem Restoration, and environmental exploration and monitoring technologies are increasingly taking a central stage (Howell et al., 2020; Waltham et al., 2020). By combining marine with space robotics exploration solutions for the monitoring and surveillance of ecologically important and sensitive habitats (reefs, fishing grounds, deep-sea floors and trenches) or at oil and gas platform decommissioning sites, some major technological breakthrough will possibly arise in the near future:

1. New life-inspired morphologies and bio-derived materials with innovative and miniaturized sensor packages will advance robotic hardware with more diverse sensing systems, to sustain new intelligent approaches for mission/activity planning and knowledge gain. This upgraded design will improve the success of complex autonomous missions in unknown environments, through more efficient energy management and control of on-board instrumentation. The intelligent tools needed for the interpretation of the collected data will allow the acquisition of new knowledge inferred from the explored environment.
2. AI-sustained decision-making will provide a step forward in adapting the functionalities of individual platforms in extreme aqueous environments. This autonomy will advance the deployment of long-lasting missions with limited human intervention, adaptively controlling reciprocal navigation, communication, and data collection. Additionally, this adaptation will allow for further behavioral upgrades for cooperated missions.
3. Ecological monitoring technologies will augment their capability by integrating molecular and imaging approaches into robotic platforms able to extract information with AI. The autonomous data collection by eDNA sensors will revolutionize our understanding of marine biodiversity, by tracing the presence (and possibly abundance) of organisms within a wide spectrum of sizes and complexity, with this paradigm contributing to the search for life in equivalent exo-ocean habitats.

As a concluding thought, we suggest that the efforts of recreating bio-inspired deep-sea robots with innovative locomotor designs, energy acquisition and storage systems, coupled to the development of new sensing and behavioral functionalities (e.g., bioluminescence), will teach us new insights on potential biological adaptations and their limits in extreme environments. This reverse-engineering approach may even expand the paradigm under which the search for extra-terrestrial life is envisaged, suggesting newly conceived and artificially constructed morphologies and energy-providing mechanisms that could favor life to survive and operate under the constrains of exo-ocean habitats.

Supplemental files

The supplemental files for this article can be found as follows:

Text S1. Figure S1. PDF

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Author contributions

Contributed to conception and design: JA, SF, SM, LT, JAl, PW, MT, RD.

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Contributed to the description of biomimicking advanced design and energy provision: SF, LT, GP, MC, CL, FV, AP.

Contributed to the description of implementations of artificial intelligence: SM, PW.

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