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Low-Cost, Deep-Sea Imaging and Analysis Tools for Deep-Sea Exploration: A Collaborative Design Study

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A minuscule fraction of the deep sea has been scientifically explored and characterized due to several constraints, including expense, inefficiency, exclusion, and the resulting inequitable access to tools and resources around the world. To meet the demand for understanding the largest biosphere on our planet, we must accelerate the pace and broaden the scope of exploration by adding low-cost, scalable tools to the traditional suite of research assets. Exploration strategies should increasingly employ collaborative, inclusive, and innovative research methods to promote inclusion, accessibility, and equity to ocean discovery globally. Here, we present an important step toward this new paradigm: a collaborative design study on technical capacity needs for equitable deep-sea exploration. The study focuses on opportunities and challenges related to low-cost, scalable tools for deep-sea data collection and artificial intelligence-driven data analysis. It was conducted in partnership with twenty marine professionals worldwide, covering a broad representation of geography, demographics, and domain knowledge within the ocean space. The results of the study include a set of technical requirements for low-cost deep-sea imaging and sensing systems and automated image and data analysis systems. As a result of the study, a camera system called Maka Niu was prototyped and is being field-tested by thirteen interviewees and an online AI-driven video analysis platform is in development. We also identified six categories of open design and implementation questions highlighting participant concerns and potential trade-offs that have not yet been addressed within the scope of the current projects but are identified as important considerations for future work. Finally, we offer recommendations for collaborative design projects related to the deep sea and outline our future work in this space.

Keywords: ocean exploration, marine science, technology, capacity development, artificial intelligence, machine learning, co-design, participatory design

1 INTRODUCTION

The deep seafloor (>200 m) represents 92.6% of the global seabed (**Figure 1**; Eakins & Sharman, 2012) but only a tiny fraction of this percentage has been scientifically explored and characterized[1,2]. Yet, the deep sea provides regulating, provisioning, and cultural services, including many that support life on our planet, such as the cycling of ocean water and nutrients and the regulation of the Earth's climate by acting as a carbon and heat sink (Thurber et al., 2014; Le et al., 2017). The deep sea is also a growing source of living and non-living resources, including fisheries, conventional and non-conventional energy resources, and genetic resources (Ramirez-Llodra et al., 2010; Ramirez-Llodra et al., 2011; Armstrong et al., 2012; Jouffray et al., 2020). In addition, it has the potential to be a source of minerals, although there are significant questions about the sustainability and responsibility of deep-sea mining (Rogers et al., 2014; Levin et al., 2020; Amon et al., 2022b; Amon et al., 2022c). While it is clear that deep-sea exploration is vital to our understanding of planetary biodiversity and function and how to mitigate impacts on them, studying these remote environments has thus far been limited by insufficient technological development, inequitable global access to available resources, and the concentration of expertise in only a few regions.

A critical component of characterizing and understanding the deep seafloor is imaging (Katija et al., 2021), a non-invasive method for observing habitats, identifying organisms, and understanding interactions between organisms and their environment (Huvenne, 2022). Imaging also provides a way to connect humans with remote and inaccessible environments which are therefore "out of sight, out of mind" to most people (Fundis & Bell, 2014; Katija et al., 2021; Genda et al., 2022). Despite the importance of imaging for understanding the deep sea, the tools necessary to undertake this research, as well as the collection of basic parameters such as salinity, temperature, and depth (CTD) to understand environmental conditions, are not available to many researchers around the world (IOC-UNESCO, 2020; Amon et al., 2022d; Bell et al., in prep). For example, preliminary analysis of data from the 2022 Global Deep-Sea Capacity Assessment shows that 19-48% of survey respondents for Africa, Oceania, Latin America, and the Caribbean have access to imaging tools and CTDs, while 48-90% of respondents for Asia, Europe, and Northern America have access to the same tools (Bell et al., in prep). Similar trends are exhibited in access to deployment methods, such as ROVs, AUVs, benthic landers, drifters, towsleds, and HOVs, showing large disparities in access to these deep submergence systems between different regions of the world (Bell et al., in prep).

Our limited understanding of the deep sea is primarily a consequence of not prioritizing the development of affordable, efficient, and equitable approaches to deep-sea exploration and characterization. Many sensors, vessels, and deployment systems can cost tens of thousands to millions of dollars to develop, purchase, and/or operate. Because of their high expense and low availability, the technologies that exist today are more accessible to scientists in wealthy nations, biasing regions explored and motivations for exploration, and creating massive knowledge gaps (IOC-UNESCO, 2020; Amon et al., 2022d; Bell et al., in prep). These tools are still relatively slow at exploring and characterizing the deep sea, especially given the urgent need for robust science to inform management decisions related to increasing exploitation pressures. Furthermore, existing data lack

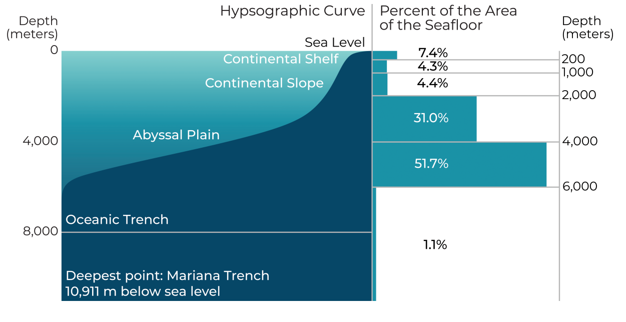

FIGURE 1 | The deep seafloor greater than 200 meters below sea level (mbsl) covers 92.6% of the seabed, 82.7% of which lies between 2,000 to 6,000 mbsl (Eakins & Sharman, 2012).

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[1] *We use the following definitions from OSTS, 2020: Ocean exploration provides a multidisciplinary first look at an unknown or poorly understood area of the seafloor, sub-bottom, and/or water column and an initial assessment of an area's physical, chemical, and biological characteristics. Ocean characterization provides comprehensive data and interpretations for a specific area of interest of the seafloor, sub-bottom, and/or water column in direct support of specific research, resource management, policymaking, or applied mission objectives.*

[2] *Developing Economies and SIDS are identified by the UN Statistics Division M49 Standard (https://unstats.un.org/unsd/methodology/m49/).*

sufficient standardization, formatting, aggregation, and access (Brett et al., 2020; Katija et al., 2021), rendering global synthesis and understanding extremely difficult, if not impossible. Finally, even within nations with the tools necessary to conduct deep-sea exploration and characterization, the field has historically been overwhelmingly white and male (Orcutt & Cetinić, 2014; NSF, 2018; Bell, 2019), potentially resulting in biases and gaps due to homogeneity and/or homophily.

Today, humankind is sitting at an inflection point. New technologies, research methods, and communities of people have the potential to transform what it means to explore and characterize the ocean in the 21st century. It is now possible and necessary to accelerate the pace and broaden the scope of exploration by adding low-cost, scalable tools for data collection and AI-driven methods for data analysis to the traditional suite of research assets. Exploration strategies should increasingly employ collaborative research methods to promote inclusion, accessibility, and equity to ocean discovery globally.

Here, we present one step toward this new paradigm: a participatory and collaborative design study on technical capacity needs for deep-sea exploration and characterization. This work was conducted in partnership with twenty marine professionals from around the world representing very different domains, including educators, divers, navigators, scientists, engineers, indigenous peoples, and conservation practitioners. The study focused on opportunities and challenges related to deep-sea exploration and research in developed and developing areas worldwide.

These findings informed our development of a low-cost, deep-sea imaging and sensing system called Maka Niu and a forthcoming artificial intelligence (AI) video analysis tool. We report on the broader collaborative design process and our early steps towards technology prototypes that are currently being tested in nine countries. We close with lessons learned and recommendations for future participatory and collaborative design work in ocean exploration and characterization and outline plans for the Maka Niu and automated video analysis development process. We hope, by presenting our process and learnings, to (1) inform the research and design agendas of others working toward advancing equity in deep-sea exploration; (2) provide insight on the design needs for low-cost sensing and imaging systems and AI-driven image and data analysis; (3) encourage others to utilize collaborative design methods to build low-cost, accessible tools that enable their fields to become more inclusive and equitable; and, (4) increase familiarity and exposure to the deep sea for local communities to encourage literacy, advocacy, sustainable economic opportunities, and effective stewardship.

2 BACKGROUND

In this section, we explain the history and emerging role of participatory design (PD), the current status of low-cost, deep-sea technology development, and share the process that facilitated this collaborative research.

2.1 Participatory and Collaborative Design Approaches

The field of Participatory Design (PD) emerged alongside workplace democracy movements led by Scandinavian trade unions in the 1970s. As workplaces modernized with new technologies, early practitioners of PD argued that workers ought to have a say in the design and management of their changing working conditions (Simonsen & Robertson, 2013). PD (also called *co-operative design* or *co-design*) argues for direct participation by stakeholders in design activities—from setting the initial terms for collaboration to scoping and framing design challenges to making decisions about proposed solutions.

Over the past fifty years, technology designers have begun to embrace and apply participatory and collaborative approaches around the world to contexts well beyond the workplace (Simonsen & Robertson, 2013; Vines et al., 2013; Emilson et al., 2014; Bannon et al., 2018). Researchers in the field of Information and Computing Technology for Development commonly leverage participatory and collaborative approaches to design digital technologies that can lead to socio-economic development for marginalized communities in low- and middle-income countries (Kendall & Dearden, 2020). The growth of participatory methods in this field responds to a history of failed initiatives, including power dynamics in development projects whereby control of funding and decision-making rests in the hands of those in wealthier, so-called "developed" regions and not those with lived experience of problems to be solved (Brown & Mickelson, 2019). As Irani et al. (2010) argue, many "well-intentioned efforts to 'migrate' technologies from industrialized contexts to other parts of the world have foundered either on infrastructural differences or on social, cultural, political, or economic assumptions that do not hold."

Many technology development efforts seek "universal" design solutions that are uniform and scalable across cultures and contexts, often with the laudable goal of making interfaces accessible to all people no matter their ability level (Shneiderman & Plaisant, 2009). However, Bardzell (2010) suggests that a universal approach to design can also "quietly and usually unintentionally impose—without transparent or rational justification—Western technological norms and practices."

In contrast with universalist approaches that flatten difference and encourage conformity, Bardzell suggests using pluralist design approaches. Unlike universalist design approaches, pluralist approaches to design "foreground questions of cultural difference, encourage a constructive engagement with diversity, and embrace the margins both to be more inclusive and to benefit from the marginal as resources for design solutions" (Bardzell, 2010). In other words, pluralist approaches are not intended to be "one size fits all," and are thus more likely to produce culturally-relevant and sustainable solutions.

Participatory design approaches embrace the philosophy of pluralism and are offered as a way forward for intercultural collaborations with diverse stakeholders. Such approaches involve building relationships of trust and mutual benefit, respecting and building on local knowledge, and challenging power dynamics often present in top-down collaborations where groups with more funding and power direct priorities, often at the expense of local partners.

In ocean science, participatory approaches have also been applied to the practice of natural resource management. Co-management—an approach where governments and stakeholders work together to manage natural resources by incorporating local knowledge of resources and different stakeholder priorities—was proposed in response to "increasing criticism of the traditional model of top-down management as a method of governance" (Smith, 2012). According to Smith, co-management requires stakeholders (e.g., scientists, researchers, industry representatives, conservation organizations, community members, and more) to be involved in "making decisions about the resources in question in some capacity, and thus involves significant sustained participation."

Community-driven capacity development work aligns with a new global effort—the UN Decade of Ocean Science for Sustainable Development, which launched in 2021 (United Nations, 2018; IOC-UNESCO, 2021). The Ocean Decade aims to transform ocean science by providing a collaborative framework that can account for different disciplines, sectors, and stakeholder communities. This framework supports the co-creation of knowledge about science and capacity needs. In addition to defining globally-set objectives and priorities among research and development areas, a series of regional consultation workshops helped establish Ocean Decade's strategies based on locally- and regionally-defined objectives, priorities, and needs promoting the use of bottom-up processes from its conception (IOC-UNESCO, 2021).

2.2 Toward Low-Cost in the Deep Sea

Until recently, the most sophisticated and reliable equipment for deep-sea environments have been ROVs, AUVs, and HOVs that cost ~$100k-10M USD to purchase, develop, and/or operate from comparably expensive vessels (Kohnen, 2013; Teague et al., 2018). Increasingly, emerging technologies for ocean exploration and research cost ~$10k-100k USD and are more portable, easier to operate, and offer a variety of capabilities, accuracy levels, and robustness (Sheehan et al., 2016; Dominguez-Carrió et al., 2021; Giddens et al., 2021). For the past few years, "do-it-yourself" and open-sourced shallower tools (<300 m) have been developed using microcontrollers, single-board computers, and commercially available components to create camera and/or sensor systems within ~$100-$1000 USD (Simoncelli et al., 2019; Greene et al., 2020; Lertvilai, 2020; Mouy et al., 2020; Bilodeau et al., 2022; Butler and Pagniello, 2022). Two low-cost camera systems are designed for depths of 5,500-6,000 m (Phillips et al., 2019; Purser et al., 2020), and commercially available cameras such as GoPros can be after-market housed to ~3,000 m; none of these options, however, include sensors such as depth or temperature, which are critical for scientific understanding of the environment.

There is room for innovation in this space, and the collaborative design approach introduced in this paper is an example of how to build upon this movement. By aligning the earliest development stages of ocean technology to the requirements of a diversity of users–for example, the intersection of imaging, sensing, affordability, and ease of use we–can establish a collaborative process and design community to create a new system that meets the community's needs.

2.3 Our Approach

The Open Ocean Initiative incubated the work presented here at the MIT Media Lab in collaboration with individuals and organizations around the world, several of whom are interviewees, test users, and co-authors of this research. Co-development and co-production of knowledge were essential to this study, allowing us to surface interconnected challenges related to ocean exploration across various domains, emphasized as an important approach in the recent work of Woodall et al. (2021). Several other recent publications about capacity building also call for more knowledge sharing in deep-ocean science (Markus et al., 2018; Miloslavich et al., 2018; Howell et al., 2020b).

In 2018, Open Ocean facilitated and participated in the launch of two pilot projects: My Deep Sea, My Backyard, which aimed to grow deep-sea capacity in two Small Island Developing States (SIDS) (Amon et al., 2022d), and FathomNet, an open-source image database that AI algorithms can use to help us understand our ocean and its inhabitants (Katija et al., 2021). Nascent at the time, both efforts have since become critical components of making deep-sea exploration and research less expensive, more efficient, and more equitable (Márquez, 2018). Parallel to these initiatives, a network of researchers and stakeholders was coalescing, building a community of research and practice *via* two events held at the MIT Media Lab: *Here Be Dragons* (Bell et al., 2021) and the *2018 National Ocean Exploration Forum: All Hands on Deck* (Bell et al., 2019; Bell et al., 2020a). These events and projects provide context for building diverse communities from which collaborative, transdisciplinary research and design projects have emerged organically, including this participatory design study to further Maka Niu and AI tool development. In 2021, Open Ocean spun out of MIT as the non-profit Ocean Discovery League (ODL), aiming to accelerate deep-sea exploration by developing accessible systems to broaden the community of those who explore and understand the deep sea.

2.3.1 Maka Niu

Maka Niu, loosely translated as "coconut eye" in Hawaiian, was conceived in February 2020 as an educational tool in collaboration between Open Ocean/ODL, the Polynesian Voyaging Society (PVS), and the MIT Future Ocean Lab (now Oceanic Labs). Maka Niu was envisioned to be a tool that could go deep in the water column to illuminate what is underneath the wa'a (canoe), allowing the community to see and safeguard what extends beyond the loko i'a (fishponds) of the ahupua'a (watershed). Due to COVID-19, the design process took longer than anticipated. However, the delay allowed the Design Research and Engineering Teams to incorporate learnings from the summer 2020 interviews into the design and implementation of the camera systems. While initially conceived as a system for educational use, a broader range of marine users and applications became apparent throughout the interview and engineering design process. Today, Maka Niu is 'a low-cost, modular imaging and sensor platform that leverages off-the-shelf commodity hardware along with the efficiencies of mass production to decrease the price per unit and allow more global communities to explore previously unseen regions of the ocean' (Novy, Kawasumi et al., in prep).

2.3.2 Automated Artificial Intelligence Video Analysis Tools

Our automated ocean video analysis product strategy builds on four years of work on FathomNet, an open-source, expertly annotated database of underwater imagery (Katija et al., 2021). A new effort will take this work further by creating an easy-to-use platform that enables users to analyze their video data with AI algorithms without prior computer programming experience.

The platform aims to create an accessible online tool for holistically analyzing deep-sea video and environmental data using machine learning. Algorithms will rapidly analyze visual ocean data, observations, and associated environmental metadata to automatically localize and classify marine species and features. By dramatically accelerating the ability to analyze ocean video and creating a collaborative environment for open data sharing of discoveries, we will dramatically expand our understanding of global ocean biodiversity and habitats.

3 METHODS

Since July 2020, the Design Research Team has conducted a collaborative design study with our growing global network of colleagues. Our overarching goals are to (1) collect feedback on feature and capability requirements from potential users of the new technologies before and while they were developed; and (2) assemble interested users from the study to test prototypes of the tools created in an interactive, collaborative way.

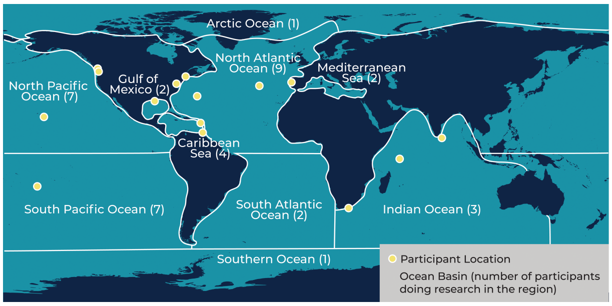

FIGURE 2 | Nineteen out of twenty interviewees self-reported their location of residence (yellow dot) and fieldwork location(s) (ocean basins). Locations of residence include Bermuda (2), Canada, Cook Islands, Montserrat, Portugal (2), Seychelles, South Africa, Sri Lanka, Trinidad and Tobago, and the United States (8). Many participants conduct fieldwork in different ocean basins from their home location.

3.1 Interview Goals and Participants

We used qualitative methods to conduct the interview phase of the collaborative design study from 27 July to 7 August 2020. Interview invitations were extended to project collaborators and network colleagues. A total of twenty people were interviewed during nineteen semi-structured virtual sessions; two participants were interviewed in the same session. Nineteen of the twenty interviewees are co-authors of this manuscript. The purpose of the interviews was to seek feedback on Maka Niu and AI analysis tools. Interview input was reviewed, coded, and analyzed by the interview team. Its synthesis was reviewed and edited by the interview participants in a shared online document such that our findings were collaboratively established. This follows established practices in participatory-collaborative design processes where lead researchers assume the role of facilitators of knowledge production rather than acting as translators between interview subjects and designers (Scariot et al., 2012).

The twenty interview participants were marine professionals representing a broad cross-section of domain expertise such as education, diving, traditional navigation, science, engineering, indigenous knowledge, and conservation. Interviewees were located in ten countries and conducted fieldwork in every ocean basin (**Figure 2**). One-third of the interviewees live in countries or territories with developing economies[3], including 21% who live in SIDS. Of the nineteen interviewees who self-reported their demographic backgrounds, 63% are female, and 37% are male (**Figure 3A**). At the time of the interviews, 37% were between the ages of 30-39 years old, 58% were 40-49, and 5% were 50-59 (**Figure 3B**); and 16% had completed a bachelor's degree, while 37% had a master's degree, and 47% had a doctoral degree (**Figure 3C**). In terms of ethnic/racial origin, seven (37%) of the nineteen interviewees identified as White or Caucasian, two (11%) as Black/African-American, and one each as Native Hawaiian/Pacific Islander, Asian, Afro Caribbean/Latina/White, Asian/Native Hawaiian/White, Black Caribbean, Indian Ocean Islander/African, Mixed, and Jewish/White. One each selected 'A race/ethnicity not listed here' and 'Prefer not to answer' (**Figure 3D**).

3.2 Interview Set Up

Before the interview, interviewers acquainted themselves with the work of each interviewee, and interviewees were provided with background materials on Maka Niu and AI analysis tools and the Open Ocean value-guided design principles (Hope et al., 2019).

3.3 Interview Protocol

All interviews were conducted over two weeks in English *via* video teleconference calls, recorded with permission from each interviewee. The typical interview duration was one hour. Interviewers worked in pairs, with an interviewer and a rapporteur, both among the authors of this paper. A universal set of eighteen questions were asked of each interviewee

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[3] *Developing Economies and SIDS are identified by the UN Statistics Division M49 Standard (https://unstats.un.org/unsd/methodology/m49/).*

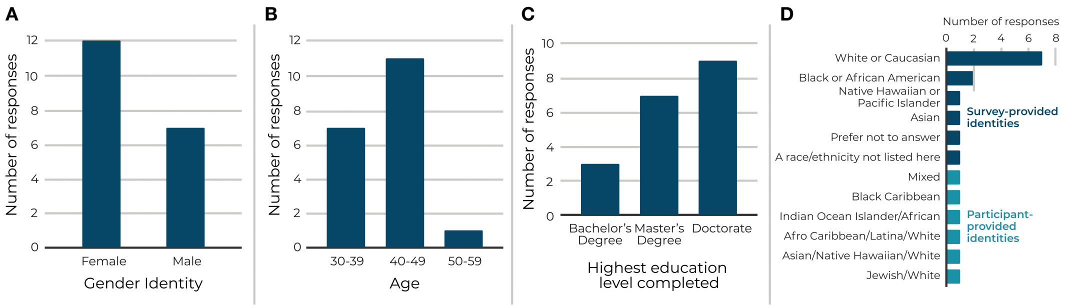

FIGURE 3 | Nineteen out of twenty interviewees self-reported their: **(A)** gender identity, **(B)** age, **(C)** highest level of education completed, and **(D)** race/ethnicity/origin identity.

(see **Supplementary Material**), allowing for qualitative data analysis that yielded comprehensive input to the Maka Niu and AI design teams. The interviews covered four main topics: (1) the interviewee's ocean-related background, interests, and community; (2) low-cost deep-sea imaging tools, with a focus on the capabilities of Maka Niu; (3) AI-driven data analysis, with a focus on capabilities of AI tools; and, (4) the interest and availability for user testing of Maka Niu and/or future AI tools.

Because of its exploratory nature, a semi-structured interview methodology (e.g., Blandford, 2013) was used to conduct this collaborative design study. This approach allowed for emergent data and the identification of broadly-shared challenges in deep-sea exploration and individual mission-critical requirements for each interviewee. Instrumental to developing the interview questionnaire and protocols was having one member of the interview team with experience working in participatory and collaborative design projects in other domains to train and orient the other interview team members.

Each interview began with introductions, followed by a brief description of Maka Niu and the AI tools. The interviewer mainly engaged with the interviewee, guided by the questions while adaptively tuning the conversation flow to listen, acknowledge, and interact responsively to the interviewee's input. The questionnaire was designed to situate the interviewee and their network in the global marine community and determine their interest and needs to explore the deep sea with Maka Niu and automated video analysis tools. At the conclusion of the interview, the interview team provided the interviewees with additional information as requested.

3.4 Data Analysis

Using the Background Materials, the research team created a preliminary *a priori* codebook (Glaser & Strauss, 1999). The team then followed an open coding process, adding emergent codes to the *a priori* codebook. At least two researchers independently coded each interview to increase researchers' exposure to data, prompting new connections and discoveries and supporting team discussion of emergent codes. Emergent codes were discussed as a group. Themes were then generated from codes, and connections were noted between themes. After the themes were generated, the team drafted an initial "Interview Synthesis" document (Bell et al., 2020b) and shared it with all interview participants for their feedback on how their needs and ideas were represented in our dataset. In some cases, the analysis was modified to reflect clarifications provided by interviewees to move toward a collaborative model of developing the study.

4 RESULTS

4.1 Interviewee Archetypes

As part of our data analysis process, we identified different archetypes to represent the interviewees' professional domains, experiences, motivations, and requirements (**Table 1**). Archetypes can be a valuable tool to synthesize concerns and identify differences between stakeholder priorities and requirements. We shared these archetypes with the interviewees to solicit their feedback on how well they reflected their motivations and requirements and made modifications as needed. Archetypes are not meant to be conclusive or dogmatic but rather are offered as a starting point for talking about different perspectives and needs.

Eighteen out of twenty interviewees self-identified up to three archetypes they consider to represent themselves (**Figure 4**). The most frequently represented archetypes were Scientist/Researcher and Formal or Informal Educator (78% each). These were followed by: Policy Maker or Manager (28%), person in Aquatics/Recreation (22%), Engineer (17%), and Traditional Knowledge Holder (17%). Individuals identified as different combinations of these archetypes (**Figure 4**), resulting in specific motivations and requirements that guided ideation and decision-making processes (**Table 1**).

Furthermore, 42% of the interviewees live and/or work in countries or territories with developing economies, highlighting the need for low-cost, low-logistics tools for deep-sea exploration and research. Motivations of those who live and/or work in these areas include: enabling locally-led science while dissolving "parachute science"; sharing local ocean knowledge with people to encourage them to conserve and protect it; engaging populations not usually engaged in scientific research (e.g., fishers, youth, tourists); and, preparing local people for marine jobs. These motivations resulted in specific requirements for deep-sea tools, including:

- low-cost, easy-to-use, and robust;
- no dependence on big boats or internet access;

TABLE 1 | Interviewee archetypes, motivations, and requirements, listed in order of frequency.

Archetype	Motivations	Requirements
Scientist or Researcher	● Getting more eyes on the seafloor, and more data everywhere, especially in deep water (>200 m) ● Ensuring data quality and making analysis easier ● Being able to make more global conclusions vs hyper-localized ones ● Collaborating with other researchers	● Low-cost, easy-to-use and to deploy ● No dependence on research vessels ● Standardization of data ● Accurate AI tools ● More specific toolsets (e.g. additional modules) ● Ability to reach depths to thousands of meters
Formal or Informal Educator	● Broadening access to ocean-linked tools, skills, and knowledge ● Sharing local ocean knowledge with people to encourage them to conserve and protect it ● Making learning engaging ● Preparing people for marine jobs	● Low-cost, easy-to-use, and error-proof ● Integrated with software, works on multiple mobile platforms ● Ability to deal with a variety of internet access conditions
Policy Maker or Manager	● Having more information for better-informed management and policy decisions ● Being able to collect and analyze data without relying on outsider expertise (from other countries and companies), particularly for countries/communities that currently don't have deep sea assets or expertise	● High data quality ● Data ownership ● Data accessibility and comprehensibility
Works in Aquatics/Recreation	● Broadening access to ocean-linked tools, skills, and knowledge ● Making learning engaging ● Preparing people for marine jobs	● Low-cost, easy-to-use and to deploy
Traditional Knowledge Holder	● Recognition of marine traditional knowledge ● Protection of culturally significant regions ● Connections between traditional knowledge, cultural values, and scientific research ● Storytelling to honor heritage and connections to the marine environment	● Low-cost, easy-to-use and to deploy ● Ability for science to be driven by traditional knowledge and local communities ● Ability for students and local communities to be involved and leading efforts
Engineer	● Allowing for a long-term presence in the ocean ● Minimizing potential losses of material	● Low-cost hardware for testing ● Long-duration hardware ● Open-source ● Made of easily accessible parts ● Coordination of multiple assets

- ability to deal with maintenance and repair issues locally; and,
- additional language support for software and training.

While we were not able to incorporate all of these requirements into the first iteration of Maka Niu and AI tool development, we took as many into consideration as possible and aim to include others in future work.

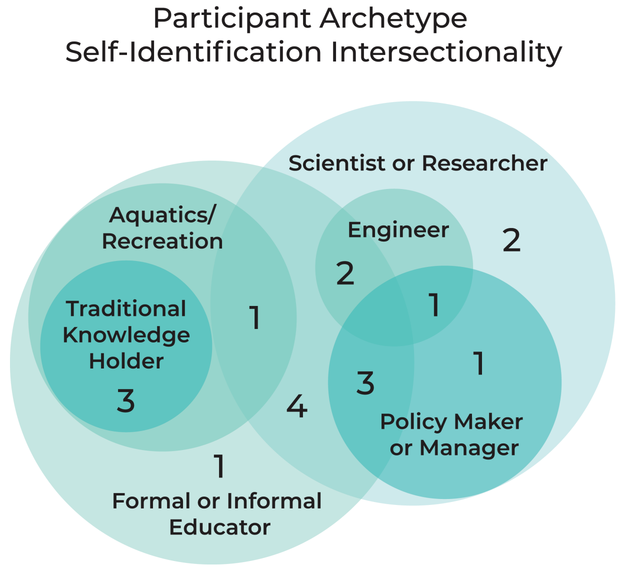

FIGURE 4 | Participant archetype self-identification. Interviewees were asked to identify up to three out of six domains/communities which they represented the most. Eighteen out of twenty interviewees responded.

4.2 Community Involvement: How Access to This Technology May Differ by Sector

The ocean community includes a wide range of disciplines, levels of expertise, and stakeholder groups such as researchers, engineers, policymakers, indigenous peoples, NGOs, students, fishers, tourists, and offshore industries. Each of these groups uses the ocean for a variety of reasons, including exploration, exploitation, recreation, and conservation. Interviewees are local experts who belong to different combinations of archetypes and regularly interact with different stakeholders in their regions (**Table 2**). They were therefore suited to advise how various communities can play a role in ocean exploration, including testing, improvement, and use of Maka Niu and AI analysis tools, once available. In some cases, financial and other support

TABLE 2 | Communities and areas of potential involvement in low-cost, deep-sea exploration and research.

Community Group	Description of Potential Involvement
Fishing	Fishers were mentioned as key stakeholders in ocean management by 15 of 20 interviewees. Building relationships with the local fishing industry allows for expanding research capabilities. Using Maka Niu and AI analysis tools, fishers can connect with their marine ecosystem and contribute to continued ecosystem monitoring. Interviewees suggested that giving fishers access to data collection methods and the resulting data would allow them to contextualize and value scientific research.
Offshore Industry	The vast majority of data and imagery collected by offshore industries, such as oil and gas, currently tend to be proprietary. Maka Niu provides an opportunity to share deep-sea ecology with this community and encourage future partnerships that prioritize greater transparency and access (e.g., SERPENT).
Tourism	A few interviewees have direct relationships with local tourism. Inviting tourists to form deeper connections with the local ecology and researchers through environmental monitoring and exploration would enhance their experiences and inform them of their impacts while traveling. Partnering with tourism companies that operate in the same regions over long periods would be an opportunity to increase our understanding of regional changes over time.
Policy Making & Management	Data usage may differ between scientists and decision-makers. The versatility of our system should allow data collection and use to be conducted through the lens of different sectors, including management and policy making. Our systems can bridge the gap by using Maka Niu and AI analysis tools to illustrate how deep-sea ecosystems work, how data can be used to inform management, and how they are in turn impacted by policies.
Local Communities	Coastal communities themselves were noted as vital assets for marine research. Suggestions for engagement included local cultural centers like village gathering places and museums. Interviewees proposed strengthening relationships between the local community and their underwater ecosystems to encourage sustainability and marine management. Each community has unique priorities that are driven by its cultural heritage. Accessible, low-cost oceanographic tools provide an educational platform that can enable communities to invest in long-term ecological monitoring and learning opportunities for local people to develop their scientific skills and lead their own projects. Interviewees were also excited by the possibility of building multi-generational community connections around ocean exploration.
Education and Training	All interviewees suggested opportunities for students from K-12 through college to use Maka Niu and AI analysis tools to experience the ocean, learn about marine life, and contribute to a global knowledge base. Younger learners would be able to observe life in the ocean using annotated videos to learn the important species in their area. Middle and high school students would be able to deploy a camera system, collect their own data, begin to contribute to scientific research, and learn valuable technical and scientific skills. Classroom dialogue and partnerships with local college students can identify regional questions which can be explored using these new tools. There is also the opportunity for intergenerational training.
Aquatics and Recreation	Our aquatics and recreation interviewees addressed the role of ocean exploration in inspiring youth to consider future marine careers. Using oceanographic tools that mirror those researchers use allows youth to contribute to scientific knowledge while building interest, enthusiasm, and advocacy for careers in science.
NGOs	Several interviewees lead or are strongly connected to local non-government organizations (NGOs). NGOs offer structured organizations to connect with an important community of volunteers. Interviewees noted that these volunteers would be excited to participate and deploy cameras under the supervision of the NGOs and contribute to the gathering of scientific knowledge.

would be required for involvement. The tailoring of technology and skillshare training to each archetype's research and mission objectives with systems like Maka Niu and AI analysis tools could allow for a more inclusive co-creation of ocean knowledge with different sectors of the community.

4.3 Maka Niu: Data Collection Design Considerations and Implementation

Low-cost imaging and sensing system development is critical for increased efficiency of deep-sea exploration and equitable access to the deep sea. The first technological topic of discussion during the interviews focused on recommendations and requirements for the Maka Niu imaging and sensing system. The interviews pointed to various considerations, including sensor development, features, and capabilities that would ensure the usability of a low-cost system and deployment scenarios to support the interviewees' work. The priority levels in each section below reflect the relative consensus amongst participants about the need for these capabilities.

4.3.1 Sensor Recommendations

The following are the highest priority deep-sea sensing capabilities that interviewees identified as important for their work:

- 1st Priority: Temperature, Imaging, Depth, Salinity
- 2nd Priority: GPS, Oxygen, pH, Acoustic tags, Light attenuation, eDNA
- ● Imaging Recommendations: High definition, Stereo, 360°

Various types of water-quality indicators were also noted, but less consistently than the 1st and 2nd Priority measurements. These included chlorophyll, methane, nitrates, phosphates, alkalinity, and turbidity. Additional work could be done to further refine and prioritize sensing capabilities for the deep sea, similar to the

Essential Ocean Variables defined by Miloslavich et al. (2018) and Exploration Variables identified by the NOAA Office of Ocean Exploration (Egan et al., 2021).

4.3.2 Feature Requests

In addition to specific sensing capabilities, interviewees also discussed other kinds of features that would make the design of Maka Niu easy to use. These included:

- 1st Priority: Easy to access video/database, depth capability of hundreds to thousands of meters
- 2nd Priority: Long duration (days to months), access to live stream
- 3rd Priority: Easy to use and fix, modular, programmable missions

4.3.3 Deployment Scenarios

The Maka Niu system was initially envisioned as a standalone imaging and sensing system that could deploy from various platforms. We discussed some deployment scenarios, listed in order of capacity and interest, and aggregated them into categories:

- On a deployed benthic structure (e.g., lander, elevator)
- Deployed from a small boat (e.g., kayak, fishing vessel, wa`a)
- On a fixed structure (e.g., buoy, mooring)
- By people (e.g., SCUBA diver, snorkeler)
- On a tethered system (e.g., ROV, fishing line)

These deployment scenarios are not mutually exclusive; for example, one might deploy a lander from a small boat. Some additional features of a standalone deployable system could include the ability to: A) deploy/retrieve quickly and easily; B) deploy as a drifting system; C) work without the need for an anchor; D) be baited and, E) deployed as an array of units to simultaneously image/sense larger areas of seafloor.

4.3.4 Maka Niu Prototype Imaging & Sensing System

Following the interviews in the summer of 2020, the Maka Niu Engineering Team designed and built a deep-sea imaging and sensing system over six months (Novy, Kawasumi et al., in prep; see **Supplementary Material**). The Maka Niu Design Research and Engineering Teams considered as many of the design requirements and considerations listed above as possible, particularly the 1st Priority capabilities (**Table 3**). Several 2nd and 3rd Priority items were also incorporated, including GPS, ease of use, and easily programmable missions. Finally, we experimented with the design and prototyping additional modules with different capabilities, such as a light module, through student design projects at MIT and the University of Porto, Portugal, demonstrating the system's modularity. Many of the current Maka Niu system components were designed to be extendible and reusable such that additional Maka Niu modules with different capabilities can be driven by its modular parts, allowing users to address their specific research and exploration needs. Additional details on the design, engineering, and modularity of Maka Niu, including student projects, can be found in Novy, Kawasumi et al. (in prep).

Seventeen Maka Niu deep-sea imaging and sensing systems were built in the spring of 2021 (**Figure 5**). The systems are roughly the size of a large flashlight (**Figures 5A, B**): they are 261 mm long, 64 mm in diameter (76 mm including the button), and weigh 870 g in air (150 g in water). The Delrin housings are rated to 1,500 m water depth and have been designed to increase the operational depth to 6,000 m with aluminum housings. Maka Niu uses a Raspberry Pi single-board computer for controls with an 8-megapixel Pi Camera Module V2 for still, video, and timelapse image recording. The sensing suite includes temperature, depth, GPS, and 9-axis motion tracking. The control collar enables easy switching between six modes: Off, Wi-Fi, Still Capture, Video Capture, Mission 1 (user-programmed video), and Mission 2 (user-programmed time-lapse). The user can modify missions using a graphical programming interface, allowing easy customization of the mission to their operational needs (**Figure 5C**). After retrieval, users can access recorded imagery on any Wi-Fi-enabled device (e.g., smartphone, tablet) while in the field, enabling them to verify their data before returning to shore without internet access. Once data capture is complete, the user can download data directly to their device *via* Wi-Fi or upload it to the online, open-source video annotation web platform, Tator[4] (**Figure 5D**), where they can annotate their images for scientific analysis and/or contribute them to FathomNet[5].

4.3.5 Current and Next Steps

Of the twenty interviewees, thirteen were shipped a Maka Niu system in 2021 to test in eleven locations: Bermuda, Cook Islands, Montserrat, Portugal (2), Seychelles, South Africa, Sri Lanka, Trinidad & Tobago, and the United States (Hawai'i and Louisiana). Systems were provided at no cost to the test user; however, test users assisted with customs fees and logistics in some cases. There were limited systems available; priority was given to interviewees who had time and interest to train and test in winter 2021/2022, had access to seawater, and were geographically distributed worldwide. Members of the Engineering and Design Research Teams also have systems for deployment and testing (see **Supplementary Material** for sample video). Here we highlight key aspects of the testing and iterative technology development phase.

First, the test users were provided with a brief description of our testing goals and an online User Manual, written and continually updated by the Maka Niu Engineering Team. Soon after receiving the systems, virtual training sessions were offered to introduce test users to the hardware and software. Throughout the testing phase thus far, we have maintained technical and administrative support to the test users through various online communication tools.

The collaborative components of the technology development process involve soliciting test user feedback, offering quick and individualized technical support, identifying common issues among test users, and reworking the hardware and software

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[4] *Tator Online. https://www.tator.io/*

[5] *FathomNet. http://fathomnet.org/*

TABLE 3 | Implementation of sensing and feature capabilities for Maka Niu identified during interviews, listed by priority.

	Priority	Capability	Implementation
Sensing	1	Temperature	Keller Series 7LD Temperature and Pressure Sensor; Operating range -40-110°C ± 2°C
	1	Depth	Keller Series 7LD Temperature and Pressure Sensor; Operating range 3-200 bar/30-2,000 meters ± 0.15% Full Scale
	1	Salinity	NA
	1	Imaging	1080 high definition video, still, and time lapse imaging
	2	GPS	Sierra Wireless AirPrime XM1110 GNSS GPS receiver with sensitivity of -165 dBm and update rate of 1 Hz.
	2	Oxygen	NA
	2	pH	NA
	2	Acoustic Tag	NA
	2	Light Attenuation	NA
	2	eDNA	NA
Features	1	Easy to access video/database	Post-deployment, video and images can be accessed *via* any Wi-Fi-enabled device using the Tator video annotation platform.
	1	Depth capability	1,500 m depth rating with delrin housing; designed for 6,000 m with aluminum housing
	2	Long duration	Up to 2 days, depending on frequency and quantity of data recording
	2	Access to live stream	NA
	3	Easy to use and fix	With technical support from the Maka Niu Engineering Team, test users have been able to troubleshoot and fix several issues remotely.
	3	Modular	Two student design projects at MIT and the University of Porto demonstrated that the housings and battery control boards could be used to create additional modules such as lights and an anchor release mechanism.
	3	Programmable missions	Users can program custom missions with a user-friendly, block programming-style interface.

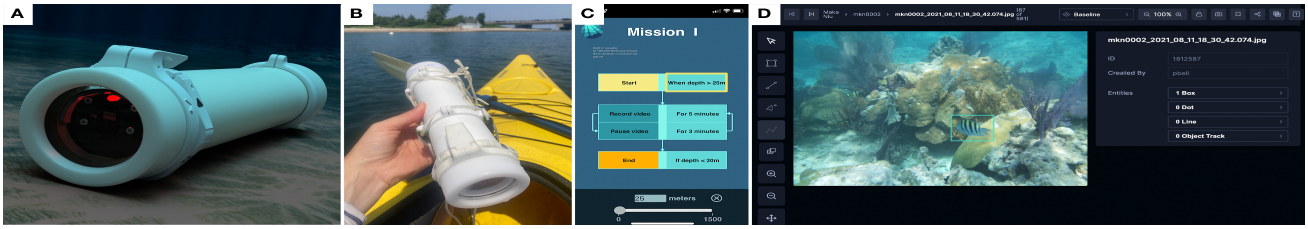
to address these issues. The goals of our testing phase include feedback on the user experience; data on the sensor and camera system accuracy; feedback on the camera and sensor system performance at depth and in various environmental situations; establishing a community among the test users for direct technical support with the Maka Niu system and career and personal support while in pursuit of their organizations' mission. In the future, we intend to report on the test users' assessment of the Maka Niu system and the strengths and weaknesses of this iterative technology development process.

4.4 Image & Data Analysis Design Considerations

In parallel with the development of accessible data collection systems, we must also consider the volume of data collected and plan for an easy-to-use way to train and enable efficient and automated video and data analysis. The second technical discussion focused on developing an online platform that would use machine learning and AI to quickly and easily analyze imagery and associated environmental data. Interview questions focused on what features would be helpful for users, what kinds of people might need to use it, accuracy requirements, and technical requirements such as connectivity.

4.4.1 Key Feature and Capability Requirements

The most important feature identified for an image and data-analysis platform is utility: ease of use and accessibility. Interviewees emphasized the simplicity of design as a high priority, keeping in mind that this system will be implemented with users from different cultures, educational backgrounds, and age groups.



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Created By pbell

Entities

FIGURE 5 | (A, B) Maka Niu is small, lightweight, and easy to deploy. It is roughly the size of a flashlight and weighs 870 g in air (<1 lb). The control collar allows easy switching between modes, and the button triggers actions, for example, starting and stopping video recording. LED flash patterns indicate status information, such as video recording, satellite connection, and battery life. **(C)** The user can modify missions using a graphical programming interface, allowing the user to easily tailor their mission to their operational needs. **(D)** In the online, open-source video annotation platform, Tator, users can localize (green box) and identify the organisms and features observed in their video and still images for analysis and optionally submit them to FathomNet. Image **(B)** by KLC Bell deploying a Maka Niu from a kayak in Narragansett Bay, Rhode Island, USA. Image in **(D)** by T. & K. Noyes using a test Maka Niu system in Bermuda.

The data-analysis experience must be designed with different user groups in mind, and the level of data access and user experience should therefore vary. The interface used by classroom students should look and function differently than the interface for marine researchers. The entire toolset must also be developed for both desktop and mobile devices, internet-limited use, and real-time capabilities.

Interviewees noted that the value of AI is greatly dependent on accuracy; therefore, higher accuracy identification at coarser taxonomic levels (phylum/class) is of greater importance than lower accuracy identification at finer (genus/species) levels. Compatibility with existing databases and collaboration with other image identification efforts may expedite the development of AI-enabled video analysis products and prevent the creation of yet another data silo. Access, storage, and data flow management were also common concerns among interviewees.

Key Features and Requirements include:

- Software must be easy to use; assume no computer programming background.
- Participants desire to combine different data sets (e.g., imaging and environmental sensing).
- Higher accuracy at coarser taxonomic levels is more useful.
- Assume low/no bandwidth situations.
- Consider different user groups, what their experiences are, and what their level of access to data could/should be, including youth, teachers, researchers, and policymakers.
- Governance concerns include data management, access, storage, and ownership.

4.4.2 Current and Next Steps

Maka Niu users can upload their imagery and sensor data wirelessly to the online video annotation platform, Tator. Users can then use Tator to annotate (localize and characterize) their observations directly on the video and still images. The resulting annotations can be used for their own research and/or submitted to FathomNet, an open, online, expertly annotated underwater image database. Each step in this process is optional, and up to the user to decide which are appropriate for their purposes.

The FathomNet database contributes to algorithm development for ocean AI analysis tools. This study's key features and requirements have informed further user interviews in the design and development process of these products.

An online, AI-enabled video analysis prototype is currently in development with numerous partners and organizations, including federal agencies, academic institutions, and non-profit organizations, funded by National Geographic Society/Microsoft AI for Earth (PI: Author KLCB) and NSF Convergence Accelerator Track E (PI: K. Katija, MBARI).

4.5 Open Design Questions and Considerations

Our interviews revealed several design and implementation questions that highlight participant concerns and potential trade-offs. These questions have not yet been addressed, but doing so will be necessary to ensure that these systems have long-term impact where intended. Six major categories of these open design questions include deployment, sensor development, software, data sharing, funding, and storytelling (**Table 4**).

5 DISCUSSION & RECOMMENDATIONS

The future of scientific deep-sea exploration will require radical and creative solutions to accelerate the pace of discovery. Low-cost tools and smaller, low-logistics technologies for the deep sea are being developed (Hardy et al., 2013; Cazenave et al., 2014; Phillips et al., 2019; Purser et al., 2020; Giddens et al., 2021) and cited as one solution to accelerating deep-sea research and broadening its participation (Amon et al., 2022d; Hand & German, 2018; United Nations, 2018; Bell, 2019; Howell et al., 2020a; Howell et al., 2020b; Pizarro & Pace, 2021). At the same time, the challenge of increasing volumes of underwater video and image data is being addressed with systematic and automated annotation and analysis systems (e.g. Langenkämper et al., 2017; Katija et al., 2021).

Given these technological movements, we sit at an exciting time in oceanographic history—it is now technically possible to lower the cost to these tools and therefore increase access to the deep sea. In doing so, we must also take a participatory and collaborative design approach to ensure that these low-cost data-collection technologies and AI-driven data analysis tools will indeed be transformative and lead to both acceleration of discovery and equitable access to the deep ocean. Below, we share six recommendations for deep-sea collaborative design projects and outline our future work in this space.

5.1 Build Balanced Relationships: Cross-Cultural and Trans-Disciplinary Exchange Is Essential for Conceptualizing and Implementing Innovative, Inclusive Projects

The Maka Niu project was the direct result of long-term engagement and relationship building between Open Ocean/ODL and PVS. Actions that led to this collaboration experience include: (1) investing time in relationship building and cultural exchange; (2) constraining technology development to that which is feasible and mutually beneficial; and (3) respecting each others' knowledge systems through action, such as conscious effort applied to learning and engaging in multiple perspectives (i.e., knowledge pluralism; Parsons et al., 2016; Bingham et al., 2021). As our organizations' relationship deepened, our ways of knowing expanded, and the quality of project ideas evolved towards those that better intertwined shared goals and had tangible outcomes. Working across intersecting differences—those of culture, gender, geography, institution, and sector—requires time, trust, and respect built through a commitment to a shared set of values and the

TABLE 4 | Open design questions and considerations.

Deployment	*How can we support people in developing deployment plans?* Some participants have significant experience in and around the water but not in deploying tools in the deep sea. Options—including physical hardware and training—for deployment should be developed and shared with users. Duration of deployment was a question that came up a lot, as well as stability of the system in high-current or otherwise difficult environmental conditions. The community around Maka Niu may be able to help provide support and best practices for deployment-related challenges.
Sensor Development	*What additional sensor modules should be prioritized for development?* The environmental sensor modules are a value-add for researchers and educators alike. While our research suggests which sensors may be most useful to work on in the immediate future, there is less consensus about the prioritization of future modules.
Software	*How can we make the software (both camera mission programming and data analysis) easy to use and robust?* We repeatedly heard the need for mobile-friendly, accessible, and simple software solutions. The software needs to be stable and easy to use in multiple environments. UI/UX design is a major area for future research and design efforts. Low/no internet access must be taken into consideration, particularly for situations with unreliable and/or inconsistent bandwidth.
Data Sharing	*How do we balance the desire to share data with concerns about privacy and exploitation?* Our participants indicated concern about exploitation (e.g., who has access to whose data? How will it be used? Will there be a central repository? How will quality be assured?). Some participants also had copyright concerns. Data sharing is critical for global-scale analysis; however, concerns ensuring that it is done equitably and securely are paramount.
Funding	*How can we support local researchers and collaborators to take on the work?* Our interviews pointed to the need for financial support to make the use of these systems possible by people around the world. For Maka Niu and AI analysis tools to have the biggest impact, we will need to determine how to value and support local researchers and collaborators to take on the work and make it their own.
Storytelling	*How can storytelling be integrated into the use and deployment of these tools?* Information from research programs shared with the public is too often limited to the final output of an entire process of scientific and tool development, data gathering, and analyzing. How can we catalyze mutual understanding among the different communities and scientists and demonstrate a long process of learning that allows us to place the gathered information in its context and render it more concrete and impactful for everyone?

principle of mutual learning (Bratteteig, 1997; Lang et al., 2012; Parsons et al., 2016; Bingham et al., 2021; Trisos et al., 2021; Woodall et al., 2021).

5.2 Expect to Pivot Your Priorities: Viewing Expectations as a Complex Path as Opposed to a Firm Resolution Allows for Flexibility and Promotes Equitable Collaboration

The results of the interview study (Section 4) affected research and design timelines, the allocation of funds, and redirected team responsibilities. For example, less technical staff time was spent on developing additional sampling system modules for Maka Niu, while more time was devoted to technical training and support. In addition, the detailed feedback on what criteria an AI video analysis platform must satisfy to be ultimately adopted by the field of ocean exploration resulted in a pause of research and prototyping, then subsequently a reorganization of the approach (Section 4.4.2), which involves new funding and the collaboration of numerous partners and organizations. To arrive at a locally sustainable project, where all partners feel ownership and gain some benefit, early action should be taken to include individuals having a variety of different perspectives and critically reflect on assumptions that underlie your priorities. Open dialogue around individuals' or groups' priorities and expectations can facilitate project planning that aptly addresses social equity, feasibility, necessary compromise, accountability, and resilience to unexpected and unanticipated course corrections (Tebes, 2018).

5.3 Consider the Accessibility of Low-Cost Tools : The Low Financial Risk and Ease of Deploying Low-Cost, Low-Logistics Oceanographic Tools Make Them a Powerful Driver for Capacity Development, Technical Training, and Novel Field Deployment Opportunities

Building on the experience of My Deep Sea, My Backyard (Amon et al., 2022d), the priority for Maka Niu was to create a high-fidelity prototype of a deep-sea camera and sensor system, quickly getting the system in its early phase of development into the hands of as many test users as possible for feedback (Novy, Kawasumi, et al., in prep). Unanticipated, the collaborative-design research revealed that the potential impact of such a low-cost system appeared tied to the tools' dollar value. Several interview participants reported that Maka Niu, with a material cost of <$1000 USD, will be in a low-stakes realm where it is seemingly more approachable, experimental, and versatile. For example, the low-logistics design and low-cost build make it easier for test users to view the Maka Niu prototype as an opportunity to take on new hardware and software skills and deploy it in new conditions and locations, without fear of great financial risk. Participants explicitly stated their intention to try deploying Maka Niu in areas they've long been interested in exploring and sampling, but the conditions were not conducive with their existing larger and more expensive equipment.

5.4 Create Opportunities for Capacity Development: Consider the Engineering Design Process and Open Hardware as Opportunities for Capacity Development

To accomplish the Ocean Decade's challenge of "skills, knowledge, and technology for all" (IOC-UNESCO, 2020; IOC-UNESCO, 2021), the transfer of marine technology—including data collection, analysis, and management tools—and the skills necessary for development, operation, and maintenance of those tools are required. Currently, Maka Niu test users participate in the engineering design cycle—lab and field testing, collecting data, identifying issues, and iterating to improve the system. Through this exposure, test users new to engineering may build valuable hardware and software skills that could translate to the in-country maintenance of these tools, a need identified by multiple interviewees. In addition, our goal is to make these designs open source so that anyone can use them to build–and modify–their own systems. By including partners in the engineering process and making designs and data openly available, we hope that a new model of technology capacity building will emerge, leading to locally-led community of practice that eliminates the dependency on outsider expertise or technical support and development (de Vos, 2020; Stefanoudis et al., 2021; Asase et al., 2022; de Vos, 2022; Harden-Davies et al., 2022; Johnson et al., 2022). These efforts go beyond collaboration and help avoid "parachute science" by responding to the realities on the ground and to what skills people would like to acquire (Genda et al., 2022; Asase et al., 2022).

5.5 Dedicate Sufficient Resources: Ensure Appropriate Time, Funding, and Other Resources Are Allocated to All Steps Above and for the Long-Term, as Needed and Desired by Collaborators

While pressures from research and funding timelines can accelerate the pace of design and development work, we have learned that a slow and thoughtful approach results in increased trust between partners and allows for pivoting in response to what is learned along the way. This shift in mindset also requires funders' understanding that the co-design process takes time and does not always proceed linearly. Unfortunately, much funding is short-term and project-based versus long-term and visionary, forcing work to be completed within an arbitrary timetable that may not be appropriate, particularly for those projects that require long-term relationship-building. It is also critical to compensate people for their time and expertise in the participatory design process. While some design projects expect people to participate simply because they care about the challenge, not compensating participants is unrealistic about the demands on human time and attention and can lead to exploitation. Finally, time spent on the personal growth and development of researchers and organizations is well spent on cross-cultural collaboration. All organizations should consider taking additional time to educate themselves on issues related to exploitation, marginalization, and colonization, as well as positions of privilege, power, and access (Bennett et al., 2021; Trisos et al., 2021; Amon et al., 2022a).

5.6 Follow Through on Commitments: Focusing on the Ideal, Far-Future Outcomes of Co-Design, Co-Development, and Co-Management Projects Will Demand Accountability Among Partners and Operational Planning for a Long-Term Thriving That Grows and Evolves Under the Leadership of Local Ocean Experts

Common causes of failure in collaborative design projects are the lack of sustainable funding, mismatch in stakeholder priorities and benefits gained from the work, and competing demands of other commitments (IOC-UNESCO, 2021). Relationship building helps create a culture of long-term collaboration. However, establishing a code of conduct or a framework to assess the fairness and sustainability of the project's time and resource demands on each partner is essential for overcoming challenges to its success. This framework may take the form of measuring impacts and progress toward capacity development and the transparent documentation of success and failures, as well as conscientious monitoring of ongoing funding, staffing time, needs being met, and project milestones (Bennett et al., 2021; Harden-Davies et al., in review). Ultimately, an inclusive plan should be developed for the project to become financially sustainable, and entirely locally run as it evolves per the needs of local ocean heroes and communities (WWF, 2015; de Vos, 2020; de Vos, 2022; WWF, 2020).

6 CONCLUSION

Historically, deep-sea technologies have been inefficient, expensive, and inequitably distributed around the globe. Deep-sea data are siloed, controlled, unstandardized, and fragmented (Brett et al., 2020). Now, it is not only possible, but critical, to create powerful, low-cost, robust deep-sea sensing systems and share, aggregate, and analyze data on a massive scale. Tremendous changes to the system are not only possible but are on the near horizon.

We are at a critical moment in time. The emergence and expected proliferation of low-cost sensors and systems, combined with the power of cloud computing and AI-driven analysis, could widen the gap between those who have access to the deep sea and those who do not, thus exacerbating the existing inequities in deep-sea exploration and research. Or, if undertaken with an intentional and collaborative design approach, these technological changes could usher in an inclusive and equitable future for deep-sea exploration and research. By building balanced relationships with each other and remaining open and flexible to the perspectives and requirements of others, we can successfully design and deploy new systems–both technological and human–to enable new opportunities for exploration, research, collaboration, and discovery.

We challenge the deep-sea community to address the issues with access to the field of deep-ocean exploration by breaking down the barriers, both technical and human. Only by making the tools and systems significantly more accessible, efficient, and inexpensive will we make meaningful progress toward exploring the deep sea, thereby better understanding this critical biosphere and our impact on it. The data and learnings presented here are our first steps along a long-term path of continued co-development of accessible technologies and holistic capacity development activities dedicated to increasing access to and broadening participation in deep-ocean exploration.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article, with the exception of identifying information, will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

KB, JSC, AH, MQ, KC conceived and designed the study. KB, JSC, AH, MQ, KC, DA, RR, LK, AV, ST, JEC, VW, ZF, KN, ML, SB, AK, JS, CB, NL, BK, CM, TN, PG participated in and executed the study. KB, JSC, AH, MQ, KC, DA, RR, LK drafted the article. AV, ST, JC, VW, ZF, KN, ML, SB, AK, NL, PG critically revised the article. All authors gave approval of the submitted version and agree to be accountable for all aspects of the work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.873700/full#supplementary-material

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