

Marine robots for coastal ocean research in the Western Indian Ocean

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ABSTRACT

Marine robots have the potential to enhance WIO marine research to improve regional adaptation to the challenges presented by climate change by providing enhanced research capacity that bypasses the requirement for expensive infrastructure, such as large research vessels. This paper tests this potential and assesses the readiness of WIO communities to adopt autonomous technologies to meet its marine research priorities.

We apply a range of analyses to a marine robots case study undertaken in waters around the island of Pemba, part of the Zanzibar archipelago, in Tanzania in 2019. The campaign formed part of a multinational project focused on increasing WIO capacity to meet food security and ocean sustainability challenges. A community engagement programme with six Tanzanian coastal communities resulted in positive changes in attitudes towards marine robots with reported increases in understanding and acceptance of such technologies. Suspicion of the robots was reduced and a lower risk of removing operational equipment was recorded following the provision of educational material. Cost, risk and benefit analysis shows that marine robots are perceived to provide high level benefits, but come at a high cost that is difficult to achieve using national or regional funding. An assessment of the capacity of WIO marine institutes to adopt such technologies shows that prior to this work, few skills or infrastructure related to marine robots were available to researchers and further confirmed that funding opportunities were perceived to be largely unavailable at institutional, national, regional or international levels. Responses from regional partners following completion of the case study however, revealed an uplift in perceived capacity, particularly related to access to infrastructure and expertise as well as support and opportunities for funding at each level. The presented case study is shown to have been a valuable demonstrator of the benefits of using marine robots to meet WIO coastal ocean research requirements and regional capacity was shown to be substantially increased within the broad range of marine institutes surveyed throughout the case study period.

This study demonstrates that taking early steps towards adopting marine autonomous robots has increased WIO regional marine research capacity and increased the confidence and willingness of local researchers to seek alternative solutions to ongoing marine research challenges. Recommendations for future action that will continue to increase the capacity and readiness for regional adoption of marine robots include investment at local, national and regional levels to provide accessible training opportunities and to facilitate regional and international collaborations; investment in a regional hub, or centre of excellence for marine robotic technology; early adoption of newly emerging smaller, cheaper autonomous technologies; investment in local skills and support facilities to aid local buy-in and acceptance while supporting regional capacity.

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Author contributions

Abbreviations

| | |
|-----------|-------------------------------------------------------------------------------------------------------------------|
| AUV | Autonomous Underwater Vehicle |
| BMU | Beach Management Units |
| CORDIO EA | Coastal Oceans Research and Development Indian Ocean, East Africa |
| CTD | Conductivity, Temperature, Depth. Instrument used to measure ocean temperature, salinity and depth coincidentally |
| EU H2020 | European Union Horizons 2020 funding programme |
| GOOS | Global Ocean Observing System |
| HIPC | Heavily Indebted Poor Countries (HIPC) |
| IMS | Institute of Marine Sciences (Stone Town, Zanzibar, Tanzania) |
| LDC | Least Developed Countries |
| NMU | Nelson Mandela University (Port Elizabeth, South Africa) |
| NOC | National Oceanography Centre (Southampton, UK) |
| PI | Principle Investigator |
| SDG | (United Nations) Sustainable Development Goal |
| TAFIRI | Tanzania Fisheries Research Institute (Dar El Salaam, Tanzania) |
| WIO | Western Indian Ocean |
| WIOMSA | Western Indian Ocean Marine Science Association |
| WWF | World Wide Fund |

MP was the lead author and contributed to each section and was coordinator of all other contributions. Co-author contributions include for Section 1 (MR, EP, BB, KO, JW, SAs, SP), Section 2 (SAL, EP, MR, JW, SAs), Section 3 (YS, JH, BB, CA, KO, JW, EP, MR, SP), Section 4 (JC, SAs, EP), Section 5 (JW, EP, MR, SAL, SAs, YS, BS, JK) and Section 7 (MR, EP, YS, JW, SA, KO, BB, SP). All authors made significant contributions to the contents of the paper.

1. Introduction

The Western Indian Ocean (WIO) region currently faces some serious challenges. Its coastal region has one of the fastest growing coastal populations on the planet with approximately 60 million people (Obura et al., 2017) inhabiting an extensive coastline provided by the African continent and the many islands in this part of the ocean basin. Madagascar is most notable with a total coastline equivalent to 2/3 of the total east African mainland coastline. The majority of this coastal population are highly dependent on the ocean for food and livelihoods (Taylor et al., 2019). Of the nine countries in the WIO – Tanzania, Somalia, Mozambique, Comoros, Madagascar, Mauritius, Kenya, Seychelles and South Africa – all except one are UN-DAC (Development Assisted Committee, 2020) listed (Seychelles having been removed in 2018), with the former 5 classified as among the Least Developed Countries (LDC) and most Heavily Indebted Poor Countries (HIPC) (WESP, 2020). In addition to a burgeoning population, the WIO faces extreme ocean warming (Jacobs et al., 2020a) and reduced marine productivity (Roxy et al., 2016) due to climate change. Projections (under the RCP8.5 scenario) point towards a 4–5 °C sea surface temperature increase over the next 80 years, with year-long ‘marine heat-waves’ being predicted from 2035 to 2045 onwards (Jacobs et al., 2021). A near collapse of marine resources and fisheries has been predicted (Hughes et al., 2017) with at least 70% of marine species likely to undergo biomass declines during the 21st Century. Collectively, such

change presents an emerging major food security challenge as well as the reduction of marine biodiversity in the WIO region, with similarly dramatic challenges predicted related to rainfall and agriculture (Niang et al., 2014). Urgent measures are therefore needed by the national governments of the WIO region to address these challenges, and to ensure sustainable development of the ocean environment to maximise its role in sustaining the region’s food security and economic growth.

But the ocean is complex, and understanding the influence of climate change on marine ecosystems requires substantial research capability to provide relevant scientific knowledge for policy makers to act upon (Leslie and McLeod, 2007). In this regard, a more immediate challenge is to address the limited capacity of marine research institutions in the WIO related to staff numbers, high-end technical and scientific skills, research infrastructure and equipment, which severely limits its ability to undertake its own oceanographic research. While ‘desk-top’ state-of-the-art technologies such as satellite observations (e.g. Jebri et al., 2020) and ocean models (e.g. Jacobs et al., 2020b) enable great strides to be taken in understanding the WIO, physical, chemical and biological measurements, which are a cornerstone for ocean science, remain poorly resolved. Conventionally these have been collected by research ships, but regionally only South Africa and Kenya own such vessels, and moreover, visits by foreign-owned vessels and ‘ships of opportunity’ are few and far between (Groeneveld and Koranteng, 2017).

Marine robots, on the other hand, are changing the way we conduct marine research (Wynn et al., 2014). Profiling drifting floats, such as those used in the Argo programme (e.g. Riser et al., 2016), have provided a step change in capability for marine scientists in terms of global coverage and resolution of deep-ocean dynamics and physical structure (Jaffe et al., 2017) and offer similar advances in biogeochemistry (e.g. Johnson et al., 2010). Alongside satellite observations, Argo arguably provides the most valued contribution to global operational oceanography and the Global Ocean Observing System (GOOS, Moltmann, 2019). Within coastal waters, however, the drifting nature of such floats combined with shallow water makes them less effective. Higher levels of control are required to provide ocean data from shallow and highly dynamic coastal waters, with the close proximity of shoreline hazards and an intensification of shipping and fishing activity providing elevated levels of risk. In situ ocean observing and marine monitoring of coastal waters has therefore traditionally depended largely on boat or ship-based campaigns complemented by moored instrumentation (e.g. Cocquempot et al., 2019; Howarth and Palmer, 2011). Such methods, however, require high levels of sustained investment in both infrastructure and skilled personnel, which is often beyond the capability of all but the wealthiest coastal States. A new generation of marine autonomous vehicles is, however, making significant progress in extending the capability of coastal oceanographers and marine managers. Autonomous underwater vehicles (AUV) are rapidly becoming a regular part of the toolbox available to oceanographers. Such vehicles are capable of collecting high-resolution, multi-parameter data over 100s or even 1000s of kms, continuously and for durations extending into multiple months. Such methods are often reported to come at a fraction of the cost per unit data than is achievable through traditional research vessel dependent activity (e.g. Schofield et al., 2007; Wynn et al., 2014; Wölfel et al., 2019; Testor et al., 2019) and so provide a manageable and accessible platform that has the potential to extend state-of-the-art observational capability to LDCs and the Small Island Developing States (SIDS) of the Western Indian Ocean (WIO) region (Osuka et al., 2021).

Recent decades provide a growing number of examples of marine robots providing sustained ocean observations, capable of operating in remote areas, beyond major supporting research infrastructure. While a long way from the WIO, high-latitude research with marine robots (e.g. Lee et al., 2017; Heywood et al., 2014; Carvalho et al., 2016; Testor et al., 2019 and references therein) demonstrate both the potential and challenges of accessing environmentally hostile regions remote from

major infrastructure. Pioneer adopters of marine robots in tropical environments have successfully established repeat campaigns in remote areas over many years (e.g. Gourdeau et al., 2008; Davis et al., 2012; Davis et al., 2019; Scott and Schofield, 2009). Such operations are, however, undertaken by some of the best funded marine research institutes, and while these efforts are commendable as progressing global scientific objectives, efforts are not typically targeted at meeting the marine science or marine monitoring priorities of local States.

These and other initiatives across the globe have led to marine robots, particularly ocean gliders, being recognised as a key component of GOOS through the formation of the OceanGliders program (Testor et al., 2019), the vision of which is for a mature, sustained, global glider observing network by 2030, with aims to contribute to United Nations Sustainable Development Goals (SDG; UN, 2015); SDG2 (Zero Hunger); SDG13 (Climate Action) and SDG14 (Life Below Water; Conserve and sustainably use the oceans, seas and marine resources for sustainable development). For such aspirations and SDGs to be achieved by such groups however, adoption of marine robots by developing countries is essential to support their own coastal ocean research and marine monitoring objectives. This important step requires progression in two key areas, 1) increased regional capacity, providing access to marine robots infrastructure and enhancing skills and sustained support at institutional, national and international levels; and 2) increased confidence of regional marine researchers, marine managers and funders that such technologies will meet their requirements and offer a sustainable solution, which warrants a shift in limited effort and resources away from traditional, more familiar methods. Recognition is also required that LDCs and HIPC are likely to conserve traditional coastal communities that are heavily dependent on artisanal fishing for subsistence and food security, and that are culturally and spiritually linked to the sea. Additional effort is therefore required to ensure that these communities are willing to accept the introduction of new and unfamiliar technologies in their marine environment.

This paper seeks to assess the potential for marine robots to meet current and future marine and fisheries research and management objectives of coastal LDCs and SIDS in the WIO region and to provide some assessment of the readiness of these States to adopt such technologies.

We introduce a case study that includes a research campaign undertaken using marine robots in the Pemba Channel (Fig. 1; Semba et al., 2019) and coastal waters around the island of Pemba, part of the Zanzibar archipelago in Tanzania, during June and July 2019 as part of a multi-national project, SOLSTICE-WIO (Sustainable Oceans, Livelihoods and food Security Through Increased Capacity in Ecosystem research in the Western Indian Ocean). The case study, which addresses the challenges in understanding marine ecosystem response to climate change, has strong implications for urgent fisheries and local community problems, and lends itself to upscaling from local to regional scales.

The paper uses a number of methods to meet its objectives. Following an overview of the development of objectives and delivery of the robots mission, methods and results are presented from a 1) Coastal Community Survey: assessing the readiness of fishers and community leaders to accept such technologies, 2) Costs, Risk and Benefits Assessment: testing the transferability of the chosen technologies to the WIO region and 3) Regional Capacity Development Assessment: examining capacity development in four of the regional partner institutes over the duration of the SOLSTICE-WIO project.

2. Methods

2.1. Objective setting

The SOLSTICE-WIO marine robots case study was developed following an extensive programme of engagement and consultation by the project team with coastal communities, regional NGOs, Tanzanian national and regional coastal resource managers and marine policy makers. An objective of this engagement activity was to introduce regional partners to available marine robot technologies and to identify current regional capacity, priorities and aspirations of local and regional coastal ocean researchers, marine managers and decision makers and use this to develop the objectives and plan for the marine robots mission. Following a period of engagement in 2016 between the UK team and WIO partners during the development of the project proposal, SOLSTICE-WIO community engagement activity started at the November 2017 Western Indian Ocean Marine Science Association

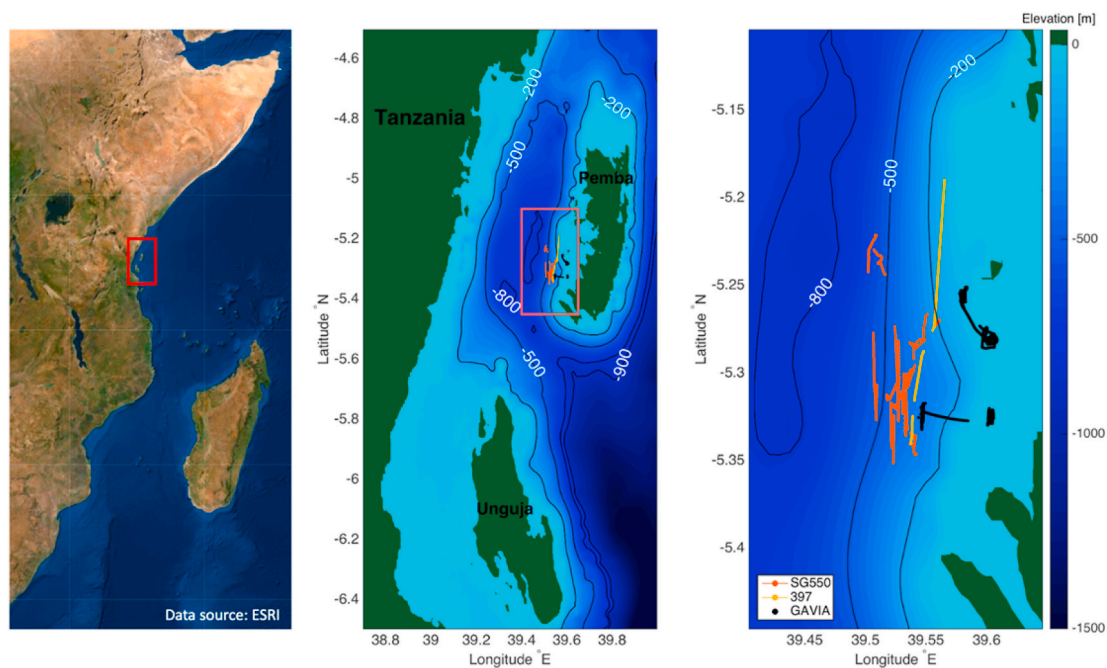


Fig. 1. Left: Regional map showing location of the Zanzibar archipelago. Centre: map indicating primary area of marine robots mission activity. Right, tracks followed by individual robot deployments, SG550 (red) and 397 (orange) submarine gliders; GAVIA (black), Teledyne offshore surveyor vehicle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(WIOMSA) symposium (Wynn, 2017) with regional representation from project partners in Tanzania, South Africa, Kenya, Mozambique and from regional NGOs including, World Wide Fund for Nature (WWF) and Coastal Oceans Research and Development – Indian Ocean, East Africa (CORDIO EA). A subsequent Tanzania Fishery Communities Stakeholder Workshop (March 2018) brought together 30 regional stakeholders including fisheries officers, marine protected area (MPA) managers, NGO representatives, journalists, and SOLSTICE partners to discuss the potential for the proposed marine robots mission and to plan further community engagement activity.

Outcomes of this workshop highlighted that marine artisanal fishing in Tanzania makes a substantial, but often under-estimated contribution to coastal livelihoods and food security due to severely limited knowledge of catch trends, underpinning ecosystem functioning, its variability and regionally specific impacts of accelerating climate change (Sekadende et al., 2020; Rehren et al., 2020). While major efforts by governments and NGOs are aimed at collecting fisheries data, little investment is made in capacity development in ecosystem research at local and WIO regional scales, which were considered essential in the development of effective options for adaptation and management of the local fisheries in response to climate change. Coastal communities in Tanzania, like many in the WIO region, are among the poorest population groups in the country and are facing the challenge of diminishing food security, compounded by growth in both population and food demand (Sekadende et al., 2020). Coastal communities are therefore among population groups that are the most vulnerable to the challenges of future climate change. To help address these priority areas the marine robots fieldwork was subsequently proposed to meet the following overarching objective:

To improve understanding of the connectivity between large-scale and local physical and biogeochemical drivers on the marine ecosystem of the Pemba Channel.

This objective was designed to support the sustainable management of the small pelagic fish resource, which is of critical importance to the coastal communities and artisanal fishers in Tanzania and the Zanzibar archipelago for food security, social cohesion and economic stability (Sekadende et al., 2020).

A second stakeholder workshop was held in Unguja to provide further engagement and community outreach opportunities, with a specific focus on the communities and agencies with interests in the chosen area of activity, the Pemba Channel. This workshop was attended by 25 representatives including local fisheries managers, community leaders, district fisheries officers, the Tanzania navy and local government and research institute representatives. The challenges of the overarching objective were discussed alongside priorities for local stakeholders. Based on identified knowledge priorities and data gaps of local researchers the following mission objectives were developed.

2.2. Mission objectives

1. Provide high-resolution seabed maps to better inform managers and policy makers responsible for fisheries and conservation as well as coastal and offshore development.
2. Improve understanding of the current state of physical and biogeochemical conditions in the Pemba Channel.
3. Improve understanding of the physical connectivity between open ocean, Pemba Channel and coastal waters that are considered important to small pelagic fisheries in Pemba.
4. Identify the physical and biogeochemical pathways that support biological productivity in the steep slope regions and coastal waters of Pemba, which are most accessible to fishers.

2.3. Marine robots mission

The marine robots mission was undertaken under the guidance of expert researchers, engineers and technicians from UK project partners,

the National Oceanography Centre (NOC) and Scottish Association for Marine Science (SAMS), with science direction and technical assistance provided by regional institutes and agencies:

IMS - Institute of Marine Science, University of Dar es Salaam. Stone Town, Zanzibar.

TAFIRI - Tanzania Fisheries Research Institute. Dar es Salaam, Tanzania.

KMFRI – Kenya Marine and Fisheries Research Institute. Mombasa, Kenya.

NMU – Nelson Mandela University. Port Elizabeth, South Africa. with additional participants from NGO.

CORDIO-EA - Coastal Oceans Research and Development, Indian Ocean-East Africa and advisors from Pemba Fisheries Department.

The area of operation covered waters on the south-eastern side of the Pemba Channel (Fig. 1) from around 500 m depth onto shallower reef platforms, that were typically separable at around the 100 m depth contour, and featuring steep topography seaward of the reef system. Mission tasks were characterized by the different depths and the two types of AUV used in this study. Shallow water (typically less than 200 m) work was undertaken using a Teledyne Gavia offshore surveyor (Howe et al., 2019; Osuka et al., 2021, Fig. 2). This AUV was designed to produce seabed maps (bathymetric, side-scan, habitat) and seafloor photography (e.g. Wynn et al., 2014; Huvenne et al., 2018) with additional mid-water hydrographic surveys.

The Gavia team included an experienced interdisciplinary team of marine mappers with a long history of joint venture projects and experienced in the use of the latest available technologies. The team worked with local partners to develop a field programme that (i) captures and encompasses existing local knowledge, (ii) builds on that information, and (iii) demonstrates the use of robot and autonomous technology in tackling local environmental and sustainability concerns. To meet Objective 1, a mutually developed fieldwork programme of approximately 2-weeks duration was planned, aimed at covering sites and areas within both: (a) the Tanga Coelacanth Marine Park (Northwest Pemba Channel), and (b) the Pemba Channel Conservation Area (Northeast Pemba Channel). Unfortunately, logistics delays and weather constrained this programme to a smaller area in the southwestern coastal region of Pemba (Fig. 1) and an additional survey in the Tumbatu Shoal area, NW sector of Unguja (Osuka et al., 2021).

To meet the deeper water elements of Objectives 2–4 two types of submarine ocean glider were used: the Teledyne Webb Slocum G2 Underwater Glider (Fig. 3, left panel; Jones et al., 2014) and the Kongsberg M1 Seaglider (Fig. 3, right panel). The gliders operated in deeper waters than the Gavia AUV (typically greater than 200 m) and included sensor suites designed to measure the physical, chemical and biological properties (e.g. Palmer et al., 2015; Vincent et al., 2018) of WIO water arriving at the southwestern tip of Pemba and tracking this water as it travels northwards along the steep slope that separates the deep Channel with shallow coastal waters (Mahongo and Shaghude, 2014; Painter et al., 2021). The glider team consisted of highly experienced personnel from the UK National Oceanography Centre (NOC) including two technical and two science team members. An additional NOC specialist engineer was in attendance to prepare and maintain specialist lab-on-chip nutrient sensors (Nightingale et al., 2015) that were to be used on the Kongsberg Seaglider to help identify nutrient pathways that might be critical drivers for local productivity. Additional support was provided by partner teams from TAFIRI, IMS, NMU and local advisors from the Pemba Fisheries Department.

Tanzania partners did not have easy access to research vessels or other boats that met the safety standards that were required by this UK funded project, following International Convention for the Safety of Life at Sea (SOLAS) and the UK Health and Safety at Work Act (1974). Support vessels therefore required sourcing from third party providers. Two vessels were chartered to meet the differing requirements of the Gavia AUV and gliders. The RV *Angra Pequena* (Fig. 4) met the size, weight, and technical requirements for deployment and recovery of the



Fig. 2. Photographs showing the Gavia AUV being prepared and deployed from the RV Angra Pequena during the SOLSTICE-WIO marine robot campaign. In the configuration chosen for this mission, the Gavia measured 4.2 m long, had an in-air weight of approximately 130 kg and had 8-h maximum endurance.



Fig. 3. Photographs of the two different gliders being deployed (Slocum unit 397, left panel) and recovered (Seaglider SG550, right panel) from the fishing vessel Huntress. The gliders were approximately 2 m in length and had an in-air weight of 60–65 kg.



Fig. 4. RV Angra Pequena, used for transport, deployments and recoveries of the Gavia AUV. The accompanying deck crane and small support boat were essential for Gavia operations.

Gavia AUV. This 72 ft, 99 ton vintage, wooden expedition motor yacht and its crew were chartered from regional NGO, WILDOCEANS, based in South Africa.

Glider operations required a boat with easy access to the waterline for manual deployment and recovery. High manoeuvrability and a shallow draft were also required in case of the need of emergency recoveries in shallow or fast flowing waters. A local game fishing boat, *Huntress* (Fig. 5), was chartered from a company based in Unguja to meet these requirements. The vessel met all safety requirements and had suitably experienced and qualified crew, however, significant additional work was required to add required instruments that might be considered as standard on marine research vessels.

2.4. Coastal community survey

Increased accessibility of marine robots and their use in areas of intense fishing activity presented the potential for contact between the robots and other resources users that indicated a need for community integration of such technologies and their purpose. Assessment was also required of the ethical implications of using such technology in close proximity to small-scale fisher communities where access to information may be limited. In this context, a coastal community survey was undertaken to assess the preliminary understanding of fishers' perceptions of marine robots, their readiness to accept such technologies and how a future increase in exposure might impact their livelihoods.

Community leaders requested information for stakeholders that could be easily distributed and understood to help inform and educate communities, particularly artisanal fishers that were most likely to come into direct contact with the robots. Workshops were subsequently provided on the islands of Unguja, Pemba and in the mainland city of Tanga, up to one year in advance of the mission. These workshops communicated information on the types of data the robots were designed to collect and what benefits coastal communities in Tanzania might expect from the outcomes of the project. Educational material was designed in collaboration with regional partners to increase the likelihood of information being understood by the target audience, and included information on what to do if fishers or community members encounter an AUV on the beach or in the sea. The communication material included an educational video and leaflets translated to Swahili (Appendix B). Workshop participants and other community leaders were asked to disseminate this information to their respective communities.

Tanzanian coastal communities were surveyed during the months of July and August in both 2018 and 2019. Survey teams from Rhodes

University, the University of Dar Es Salaam and IMS visited a total of six small-scale fishing communities from across Tanzania and the Zanzibar Archipelago. Working with the local Beach Management Units (BMU), fishers were selected using a snowball and purposive (Rohe et al., 2017) sampling method (Fig. 6). Using an integrative framework approach, a total of 292 fishers were interviewed, for a comprehensive assessment of fishers' vulnerability to climate change and the associated implications for food security and economic wellbeing. In addition, semi-structured interviews gathered perceptions to climatic and environmental changes and their associated adaptations from 278 fishers. To further investigate the spatial dimensions of fishers' perceptions of change, six focus group discussions were conducted for a participatory mapping exercise. Participation was not exclusive for each survey with some fishers participating in multiple survey exercises.

Fishers' perceptions were assessed using an interview strategy designed to investigate the effect of community engagement on knowledge of and behaviour towards AUVs should they come into contact with such technology during the course of a fishing trip. These studies took place during the months of July and August in 2019 in three Tanzanian small-scale fishing communities; Bweni and Kilindoni (situated on the eastern side of the Mafia Channel) and Petukiza (situated on the western shore of the Pemba Channel in the Tanga region). Fishers were selected to provide a range of experience, such as fishing experience, fishing areas visited (Table 1), desired target species and fishing methods (Fig. 7). Participants were shown an educational leaflet (Appendix B) translated into Swahili and asked to examine the illustrations of a variety of AUV models. Attempts to provide a realistic physical model from the UK were unfortunately prevented due to logistical problems. They were then asked if they had seen one before, what they thought it was and its function, whether they believed it would be of benefit to them personally, to their community or to their nation, and finally what they would do if they were to come across it on the beach or in the ocean whilst fishing. They were subsequently shown an educational video on AUVs developed within the SOLSTICE-WIO project that was narrated in Swahili. Upon completing the video, participants were asked the same questions again to record any change in perception. Their responses were then coded into a standard set of responses for analysis. Four participants did not complete the survey after watching the video; therefore analysis was adjusted for post-video data to account for the slightly smaller sample size.

The Pemba Channel case study provided a valuable demonstration of the potential research that can be conducted in the WIO region with current state-of-the-art marine robots and dedicated resources and



Fig. 5. Fishing vessel *Huntress*. Modifications were required to make the boat viable to support the marine robot campaign. Visible on the starboard rear quarter is a specially made frame and clamp that was designed at the NOC to enable attachment of a retractable acoustic current profiler (ADCP). Also visible on the starboard side is a meteorological sensor package mounted on a pole on the roof and a GPS package that enabled geolocation of data and for corrections to the ADCP data for vessel motion. The platform at the vessel stern was useful for safe deployment and recovery of the gliders.



Fig. 6. A team translator from the University of Dar Es Salaam, discusses the local environmental changes perceived by fishers during a participatory mapping focus group in Bweni, Mafia Island.

Table 1
Participants characteristics as well as fishing attributes.

| | Mafia | | Mkinga | All |
|--------------------------------|-------|-----------|----------|-------|
| | Bweni | Kilindoni | Petukiza | |
| No. Participants | 11 | 5 | 11 | 27 |
| Mean Age | 64.36 | 58 | 47.64 | 56.37 |
| <i>Education (%)</i> : | | | | |
| None | 18.18 | 40 | | 14.81 |
| Primary | 81.82 | 60 | 91.91 | 81.48 |
| Secondary | | | 9.09 | 3.7 |
| <i>Main Fishing Area (%)</i> : | | | | |
| Deep Sea | 18.18 | 60 | 81.82 | 51.85 |
| Fringing reefs | 27.27 | 40 | 9.09 | 22.22 |
| Lagoon | 54.55 | | 9.09 | 25.93 |
| Avg. Experience (Years) | 41.09 | 37 | 14.27 | 29.41 |
| Use a boat (%) | 54.55 | 100 | 100 | 81.48 |

expertise from a well-funded international project. The transferability of such technologies and capability to LDCs however is dependent on the sustained access and affordability of marine robots along with the supporting skills and infrastructure required to maintain them. We assessed the costs, risks and benefits of such methods against locally accessible funding and requirements using a score matrix (Table 2) to help identify the suitability of this mission in meeting the marine research requirements of local and regional coastal States within achievable funding frameworks. Scores of cost, risk and benefit are used to identify the readiness and need for the future use of robots in the WIO. This exercise is also designed to highlight the potential for improvements that might help guide future associated infrastructure investment. The focus of this assessment will be on how to build on local capacity development to bring down cost and risk while increasing regional benefits from marine robots for coastal ocean research.

For the purpose of this analysis, cost, risk and benefit are scored using the following criteria.

2.5. Assessing regional capacity development

Assessing the capacity development attributable to any one project is inherently difficult since the development of skills and knowledge as

well as the availability and investment in associated infrastructure is not managed in isolation. Each of the institutes and individuals that participated in the robots fieldwork conduct a range of ongoing marine research activities and pursue multiple funding opportunities with multiple national and international partners throughout the timeframe of the project and so consideration must be made for overlapping interests and associated capacity development. Within this context, a simple approach of self-assessment was adopted to capture the perceived capacity within four of the partner institutes that were engaged with the SOLSTICE-WIO marine robots campaign; IMS, KMFRI, TAFIRI and NMU. While this does not provide an explicit assessment of the capacity development attributable to the project, it does provide an assessment of perceived capacity and opportunities with marine robots within organizational, national and international frameworks. An assessment matrix was produced in consultation with project partners that included a range of five capacity levels from a low-level baseline (1) towards aspirational levels of capacity and opportunity (5). This Capacity Assessment Matrix is shown in Table 3. Scores of 1–5 were provided from Principal Investigators (PIs) from each partner institute at the beginning of the project, prior to the marine robot focused workshops and fieldwork being undertaken. Scores were then updated over 12-months after completion of all fieldwork to identify changes in perceived capacity within the timeframe of the project. The capacity and disciplinary focus or expertise within each institute was expected to be quite varied, so to help calibrate scoring from PIs an example response was provided that met the mid-point capacity score of 3 (Table 3).

3. Results

3.1. coastal community survey

Upon being shown the educational illustrated leaflet (Appendix B), all respondents acknowledged they had not previously seen examples of marine robots. When asked what they perceived a picture of an ocean glider to be, 25.9% respondents thought it might be an aeroplane, 25.9% responded with “I don’t know” and 11.1% thought it was a robot (Fig. 8). One fisher believed it was a device used to spy on fishers, whereas another thought it was suspicious. Responses following the educational video differed significantly ($X^2 [13, N = 27] = 22.67, p =$

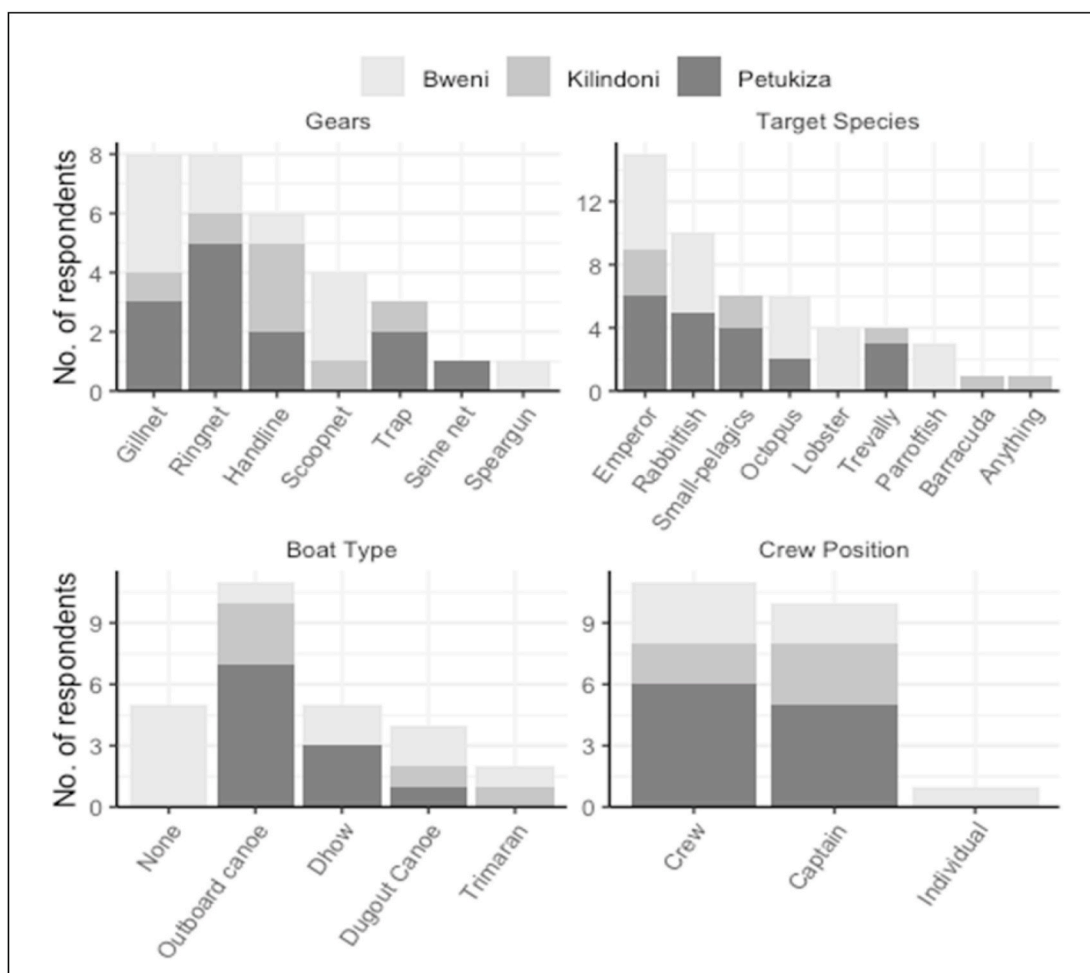


Fig. 7. Bar graphs illustrating the proportion of participants from each community across gear type, target species, boat type and position in crew. Costs, Risk and Benefit Assessment.

Table 2
Cost, Risk and Benefit score matrix.

| Score | 1 | 2 | 3 | 4 | 5 |
|---------|-----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Cost | Zero cost or provides immediate saving on current efforts. | Cost can be met within institutional budgets. | Costs can be met within national science/monitoring funding budgets. | Cost requires international funding support. | Costs are currently beyond all available funding options. |
| Risk | Zero | Low | Medium | High | Unacceptable |
| Benefit | No potential to meet requirements and provides less benefit than is currently achieved. | Potential to meet some requirements and provides equivalent of current capability. | Potential to meet the majority of requirements and provide a new level of capability, surpassing current benefits. | Potential to meet all requirements and national targets and standards. | Potential to meet all requirements and regional/international targets and standards. |

0.04), with 47.8% of respondents identifying the glider as a robot, 17.4% believing it to be a boat and 13.0% identifying it as a research instrument. When asked its function, 37.0% didn't know, 25.9% understood it was involved in conducting research and 14.8% thought it was involved in transport, either for flying passengers or transporting people as a boat. Post video responses were significantly different ($X^2 [6, N = 27] = 13.99, p = 0.03$) with the majority, 69.6%, perceiving that it was used to conduct ocean research.

When asked if they believed it would benefit them or their families (Fig. 9), 37.0% thought it would. Of the benefits, 22.2% believed it would provide valuable information. After the video, the number of fishers believing it would be of benefit to them increased to 47.8%, with 34.8% of fishers believing the information provided would be of direct benefit to their fishing. When increased to the community level (Figs. 9),

59.0% believed it would benefit their community, with 33.3% of participants attributing the benefit to the information provided. After the video this value increased to 78.3% believing it would benefit their community, with 39.1% linking the benefits with the information it provided. At a national level (Figs. 9), 59.3% thought it would be beneficial, 18.5% perceived that it would improve the country's economy, mainly through improved catches, and 7.4% thought it would help with government fisheries policy. After the video, all the fishers believed it would be beneficial to their country, with the information provided and improvements to the economy cited by 34.8% and 21.7% of participants respectively.

If a marine robot was discovered on a beach (Fig. 10), 70.4% said they would leave an ocean glider alone, with 48.1% adding that they would also report it. One participant added that although they would

Table 3
Capacity Assessment Matrix.

| No | Category | Please indicate the present status of your institution for each of the categories listed. Your responses should be <u>specifically related</u> to: | | | | | Simple test question for Level 3 |
|----|-----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| | | Use of autonomous marine robotic systems to monitor marine ecosystems and climate change impact | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | |
| 1 | Skills to undertake processing and analysis of data collected from marine robotic platforms | No skills available to work with data obtained by robotic systems. | Some basic skills available, but core training in data processing and analysis is required. Basic oceanographic data interpretation skills are not available. | Some data processing skills are available from one or two individuals but further training in processing and analysis specific to marine robotics is required. Basic oceanographic data interpretation skills are available. | Good understanding of oceanographic data processing techniques, analysis and interpretation. Further training or assistance is required to develop interpretation into peer reviewed publications. Some mentorship is available from senior colleagues. | Broad skillset available, competent skills are available in processing, analysis and interpretation of new observations with the ability to lead on peer reviewed publication in international journals. Expertise is being continuously broadened and brought up to date via regular training. | If provided with raw binary file, multi-variable data from ocean gliders could you produce a processed and quality controlled dataset and produce plots demonstrating changing mixed layer depth and relative location of the chlorophyll maximum throughout the deployment? |
| 2 | Infrastructure of marine robotic systems and ability to manage datasets to international standards. | No access to marine robotic systems or technical support. No access to data collected from marine robotic systems. | No access to robotic platforms and technical support but limited access to data collected by partner institutes. Limited skills or infrastructure to manage observational data collected using robotic platforms. | Able to participate in experiments with marine robotic platforms undertaken by partner institutes. Sufficient skills available to manage (e.g. provide quality assurance and control) and securely store data collected. | Access to marine robotic systems and relevant technical support from partners. Able to direct the use of robotic systems to meet objectives and technical objectives. Every effort is made to ensure high data quality following "best practice" guidelines. | Direct access to Marine robotic systems either by ownership or via a national facility, including access to technical support. Data quality protocols follow internationally recognised standards. Proven track record of reports/peer-reviewed literature presenting data gathered using marine robotic platforms. Research into future development of robotic systems is planned/ or undertaken. | If requested, could you plan the deployment of an ocean glider to provide 1 month of repeat transects between two fixed stations in the West Indian Ocean, and deliver the resulting multivariable data at a suitable quality for use in a peer reviewed publication? |
| 3 | Access to international expertise / networks | No contacts/collaborations with marine robotics international community or identified partnerships with other institutions using marine robotics. | Limited contact or collaboration with marine robotics international community (scientists and technologists). Attendance of relevant personnel at international meetings or workshops that include emerging users of marine robotics. | Working in collaboration with international groups to address scientific or technical questions in the marine environment using robotic systems. Have developed suitable contacts within the marine robotics international community to provide training and assistance in operation and data analysis. | Working in collaboration with international partners addressing scientific and technical questions in the marine environment using robotic systems. Able to request assistance and training as required. Representation on international groups associated with marine robotics. Co-authoring papers with international partners. | Taking a leading role in international groups that coordinate or develop oceanographic research proposals associated with marine robotics. Provide lead authorship of peer reviewed papers in international journals regarding operation and application of marine robotic systems. Providing assistance and training to international partners. | Can you host a workshop to provide training for local scientists and technologists on the deployment and recovery of ocean gliders using internationally recognised expertise? |
| 4 | Recognition and support at organisational level | Use of marine robotic systems for ocean research is not considered a valuable undertaking for policy and business development. | There is some appreciation of the benefits of using robotic systems for oceanic research but it is insufficient for significant investment. | Use of robotics to conduct oceanic research is perceived as a valuable activity and opportunities for local development have been identified. | Some investment has been made into facilities and training of personnel to help deliver local objectives with marine robotics to deliver policy needs and business development with the assistance of external partners. | The use of marine robotics to conduct ocean research is highly valued by management and receives sufficient funding to enable outputs to feed into policy needs and to support business developments without the need for partner contribution. | Can you produce a cost-benefit analysis of the use of marine robotic systems for use in a future marine monitoring programme? |
| 5 | Recognition and funding by National /African/ Global Institutions, policy making and funding bodies | The use of robotic systems to investigate marine ecosystem function or climate change impacts does not appear in funding calls and national marine programmes | The use of robotic systems to investigate marine ecosystem function or climate change impacts does appear in funding calls and national marine programmes, but is identified as one of the areas where capacity development is needed. | Use of robotic systems appears in funding calls and national marine programmes. Use of robotic systems is identified as one of the priority areas in capacity development by national and international African bodies. | Use of robotic systems and the impact of climate change on the ocean are a regular subject of funding calls or a required component of funding calls. Strong national and/or international capacity development efforts exist in this area. | A national facility or coordination programme exists that enables open access to marine robotics and technical support that is actively encouraged to be accessed through targeted funding calls. | Can you identify two current nationally funded projects in the last year, where marine robotic systems form a critical component of the research programme? |

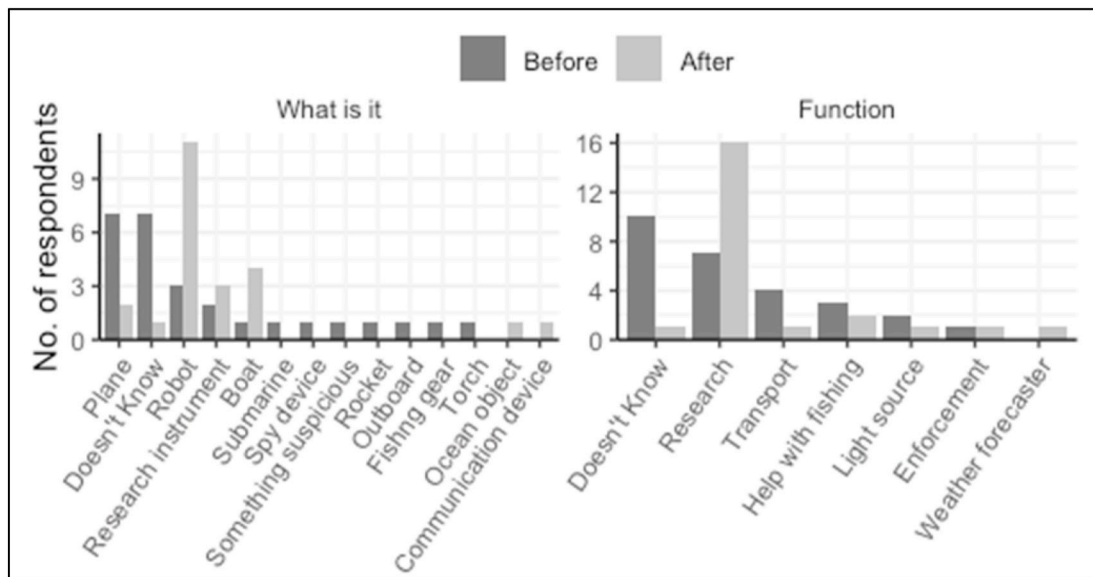


Fig. 8. Bar graphs illustrating fishers' perceptions on what the AUV is, and its function.

leave it alone, it would scare them. In contrast, 29.6% of respondents said they would take the device, with 7.4% and 3.7% adding to hand in or to sell respectively. There was significant change in responses after

the video ($X^2 [6, N = 27] = 15.61, p = 0.01$), with 78.3% saying they would leave it, 17.4% saying they would launch it when the tide came in and only one respondent (4.3%) said they would take it to sell.

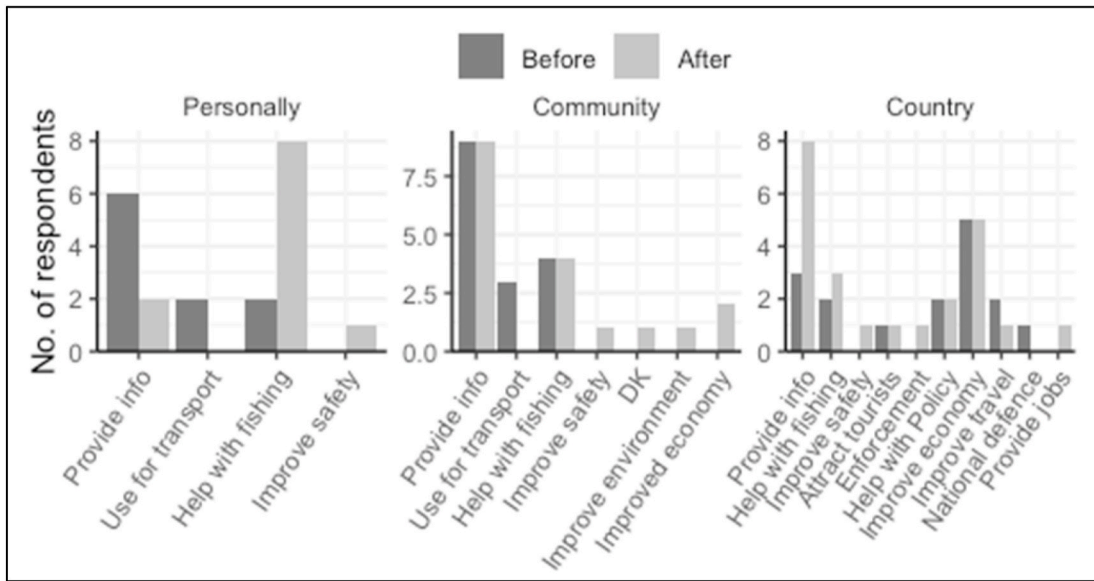


Fig. 9. Responses for fishers on the perceived benefit of marine robots to them personally, their community and their country.

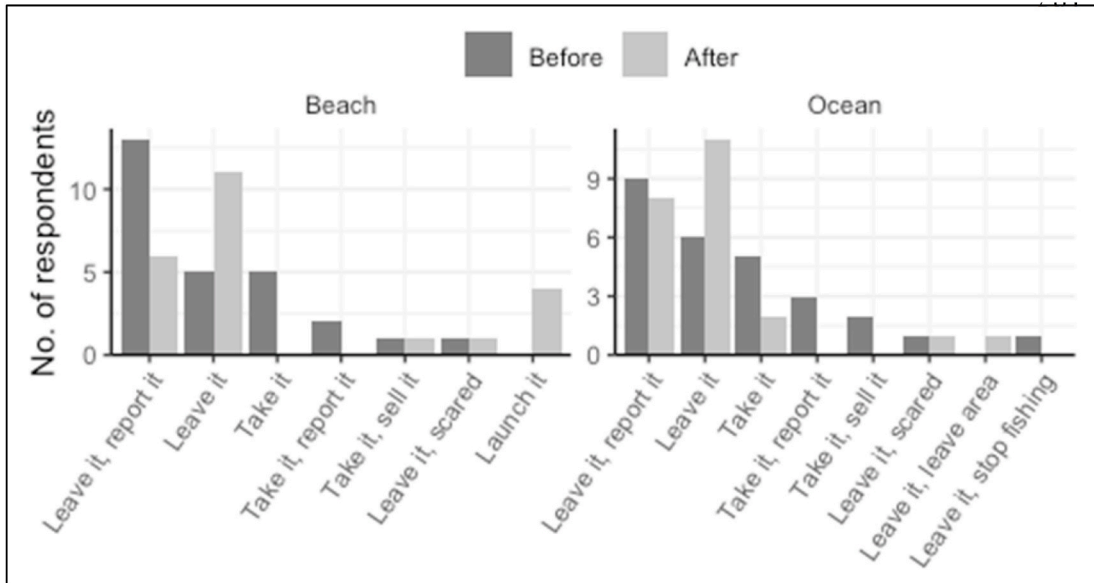


Fig. 10. Bar graphs illustrating the behavioural responses of fishers, should they come across an AUV either on the beach or out to sea.

If come across in the ocean (Figs. 10), 63.0% of respondents said they would leave the robot, compared to 37.0% declaring they would take it. One fisher (3.7%) added that whilst they would leave it alone, they would also stop fishing due to possible danger. After watching the video, the same respondent said although they wouldn't stop fishing, they would leave the area. Responses after watching the video were generally similar, with the exception of 91.3% of respondents now reporting they would leave the device alone should they come across it in the ocean.

3.2. Cost, risk and benefit

The different types of AUV used in this study differed in their overall capability, however, their associated costs, risks and benefits to the mission were considered comparable and so they are considered collectively. Scores using the Cost, Risk and Benefit matrix (Table 2) are shown in Table 4.

Since each of the AUVs used in the mission were provided from the

UK, much of the cost and risk of the mission relates to provision and transport costs of assets and the accompanying specialist technical support. None of the identified costs were considered beyond all available funding options, however, 4 of the 6 categories were at the second highest cost level (4), indicating that financial support was required from international programmes. The remaining two cost categories were perceived to be within national funding capability. Much of the risk associated with this project derived from a continued lack of long-term investment in infrastructure and skills. The highest risk was associated with the hire of support vessels, which was deemed unacceptable. The perceived benefits from the robots mission were generally high with 4 of 6 categories scored at the highest level (5), indicating 'potential to meet all requirements and regional/international targets and standards.' The provision of AUVs and expert personnel from UK partners for technical and data processing support brought substantial benefit to the project through adding the internationally recognised expertise and so increased the accountability of data collected and used by WIO

Table 4
Attributed scores for Cost, Risk and Benefit for separable elements of the Pemba Channel marine robots mission.

| Item: | Costs | # | Risk or Disadvantage | # | Benefit/Reward | # |
|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|
| AUV direct hire cost from provider. | Financial cost. | 4 | No long-term investment in local infrastructure. Potentially unfamiliar equipment. Dependency on limited availability. Unsuitability for local conditions. | 3 | Provides of State-of-the-art equipment, fully serviced and ready for deployment. Capable of meeting Internationally recognised standards. Avoids capital costs. Accountability. | 4 |
| Transport of equipment back and forth. | Shipping. Insurance. Import/export, customs etc. | 3 | Risk associated with international transport. Unpredictable delays. Transporting dangerous goods (e.g. lithium cells). | 2 | Avoids long-term infrastructure, storage and maintenance costs. | 5 |
| Provision of expert personnel for training and mission delivery. | Highly paid staff. Work and research visas. | 4 | No sustained access to skills or individuals. Potential for cultural or linguistic conflict. | 3 | Avoids long-term investment in personnel and training. Accountability. | 5 |
| Running costs inc. battery, Iridium satellite communications, technical supplies. | Dependent on use. | 3 | AUV security and operability dependence. Data quality dependence. | 3 | Available internationally. Can be tailored to requirements and available funding. | 5 |
| Hire of support vessels. | Variable and dependent on use and requirements. Staff training (e.g. safety at sea). | 4 | No long-term provision or investment in local infrastructure. Potentially unfamiliar equipment. Limited availability. Seasonal availability and viability. Suitability to scientific research. | 4 | Avoids long-term investment in infrastructure, personnel and training. | 4 |
| Processing and analysis of data | Dependence on UK staff support and training. | 4 | No sustained access to expertise. | 3 | Avoids long-term investment in expert personnel. Accountability. | 5 |

researchers. Hiring of local vessels did not provide the same level of benefit as state-of-the-art equipment brought from the UK and so scored lower, but was still perceived to have ‘potential to meet all requirements and national targets and standards’ and presented an increase in capability to Tanzanian coastal ocean research, albeit limited for the duration of the fieldwork.

Capacity development scores (Table 5) from the four institutes surveyed at the beginning of the project identify a varied level of

experience, confidence and access to marine robots. This was to be expected since each has very different experience in and requirements for collecting the types of ocean data that the AUVs provided. Responses after the fieldwork and data processing had been completed suggests a marked increase in capacity within each of the four partner institutes. Each perceived an average increase across the five provided categories increasing of in excess of one level, and NMU perceiving a notably greater average increase in capacity in excess of two capacity levels.

Table 5
Capacity assessment matrix (Table 3) scores are presented from each partner institute before and after marine robots workshops and fieldwork were undertaken within the SOLSTICE-WIO project. The colour scheme reflects that used in the Capacity assessment matrix.

| Capacity indicator: | | 1. Skills to undertake processing and analysis of data collected from marine robot platforms | 2. Infrastructure of marine robot systems and ability to manage datasets to international standards. | 3. Access to international expertise / networks | 4. Recognition and support at organizational level | 5. Recognition and funding by National /African/ Global Institutions, policy making and funding bodies | Average | Change |
|---------------------|--------|----------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|-------------------------------------------------|----------------------------------------------------|--------------------------------------------------------------------------------------------------------|---------|--------|
| IMS | Before | 3 | 2 | 2 | 3 | 2 | 2.4 | +1.2 |
| | After | 3 | 4 | 4 | 3 | 4 | 3.6 | |
| TAFIRI | Before | 1 | 1 | 1 | 1 | 1 | 1 | +1.4 |
| | After | 2 | 2 | 2 | 3 | 3 | 2.4 | |
| KMFRI | Before | 3 | 1 | 2 | 2 | 1 | 1.8 | +1.2 |
| | After | 4 | 3 | 2 | 4 | 2 | 3 | |
| NMU | Before | 4 | 2 | 1 | 3 | 1 | 2.2 | +2.4 |
| | After | 5 | 4 | 3 | 5 | 3 | 4 | |

These average scores however, are not evenly represented across categories.

The average increase in capacity related to data processing and analysis was 0.75. While none of the partners had prior experience using marine robots, or in processing, analysis and management of associated data, confidence in meeting likely processing and analysis requirements associated with marine robots varied greatly, ranging from levels 1 to 4. Only incremental improvements were reported in perceived capacity, increasing on only one level across each institute except IMS, who reported no increase in related skills.

Access to infrastructure underwent an average increase of 1.75 levels, with 3 of 4 partners reporting a 2 level increase and 2 of 4 reporting direct access to marine robot systems and technical support at the end of the project, indicating a substantial increase in capacity. TAFIRI reported the lowest increase in access, reporting a continuation of no access to marine robots platforms.

Perceptions of access to international expertise and networks increased at 3 of the 4 institutes, with an average increase of 1.25 but with varying levels of development despite similar levels of initial scores, which were each within the 2 lowest levels. Two partners reported a 2 level increase, one reporting 1 level and the remainder perceiving no increase in access and only IMS reporting the capability of collaboration and co-authorship with international partners and the ability to request assistance and training.

Increased recognition and support at organizational level was reported in all but 1 partner, in clear disparity to the remaining 3 partners, who each reported a 2 level increase in capacity, resulting in an average increase 1.5. An increase in perceived recognition at national, regional or international levels was recorded by each partner, again with 2 levels of progression reported by each partner institute except KMFRI, which identified only 1 level of development in this area.

4. Discussion

This work addresses a commonly voiced hypothesis that autonomous systems offer a potential mechanism for greater democratization of marine scientific research by providing access to relatively low-cost and low-infrastructure sensor platforms. The Pemba Channel case study has provided a valuable demonstrator of what is possible by providing state-of-the-art robots and dedicated resources and expertise to WIO partners that otherwise had little to no experience with, or immediate access to, marine robots and maintained similarly low levels of access to the international marine robots community. A coordinated engagement programme within the SOLSTICE-WIO project has provided substantial uplift in the perceived capacity of WIO regional partners to adopt and access such technologies.

Of particular importance to the WIO region, is that successful integration of marine robots into regional coastal ocean research strategies is managed with suitable acceptance from coastal communities. This study found opinions to be somewhat split. Fisheries managers communicated a generally positive perception to the introduction of marine robots to the region as a potential future source of income, training and jobs. Perceptions from fishers were generally more cautious, although the provided educational resources were shown to alleviate many of the initial concerns and improved the security of deployed robots. While difficult to draw conclusive evidence from community responses, valuable insight has been gained into the perception and likely reactions of fishers, and moreover, the potential for conflict between researchers and other resource users. This may require ethical consideration if marine robots are to proliferate in the WIO and similar regions. Direct impacts include a potential for detrimental effects on fishers' livelihoods and wellbeing due to a fear of unknown or suspicious devices, including fishing trips being cut short in case of an encounter.

Perceived benefits to coastal communities are derived mainly from assumptions that outcomes and impacts of the research undertaken

would eventually reach those communities, with the potential for ultimately leading to increases in resource extraction. It is worth noting therefore, that if perceptions of future increases in resource extraction or income are not met, or are not the objective of researchers using marine robots, then support may be lost and additional conflict may occur. Similar concerns exist if the open transfer of knowledge across the community does not occur, which may prompt assumptions of competitive advantage to those that have access to such information. Future community engagement activities would benefit from provision of an AUV (or replica) as their physical size was often misinterpreted by fishers from the information provided by leaflets and video. Community engagement did however prove effective in providing an increase in understanding and awareness of the functionality of marine robots and reduced the likelihood of removal or theft of the equipment. Further community engagement is advised to accompany similar research activity in areas with an abundance of artisanal fishing activity.

The perceived benefits of marine robots to coastal ocean research in the WIO are high, but come with some level of risk or disadvantage and at relatively high cost. The dependency on services provided by international partners presented high reward through the direct provision of state-of-the-art equipment and highly trained and experienced personnel. It was however deemed too costly at the national or institutional level for WIO partners. While the use of external equipment and services was also considered to be of high value, it was perceived to limit investment in local and regional skills and infrastructure, and so limit regional capacity development that might otherwise deliver future missions with marine robots. The need for additional ship and boat support also highlighted a lack of local capacity that would be a major hindrance for future studies of this type in LDCs. Solutions were found from regional commercial and NGO partners, but both instances were deemed beyond the funding capability of institutional and national marine research budgets.

The current cost of marine robots is often considered relatively low within wealthy States, where funding for marine research infrastructure follows medium to long-term strategic investment (typically 4–5 years for strategic research programmes to several decades for large infrastructure investments such as for research vessels) and robots provide a potential saving on large infrastructure costs such as those typically attributable to large research vessels. The WIO partners surveyed in this study however, still view such technologies as beyond the scope of current or near future national funding and only accessible from additional international funding support. Mitigated cost and risk may be achieved through acquisition of emerging developments such as: small, easily operable AUVs (e.g. Phillips et al., 2017) that reduce or potentially remove the need for support vessels and large support teams; autonomous command and control capability (e.g. Harris et al., 2020) reduces dependency on highly trained AUV pilots; more robust designs and sensor stability, further reduce dependency on highly skilled technical support. But these developments may still take considerable time to be commercially or openly available to WIO researchers. This study, however, demonstrates that taking early steps towards adopting marine autonomous robots has not only increased regional marine research capacity, but also increased the confidence and willingness of local researchers to seek alternative solutions to ongoing marine research challenges.

While this case study provided an opportunity to bring new marine technologies to the WIO, the manner in which they were managed within Tanzania was steered by external factors that were dependent on limitations set by the UK funders and lead institute, with implications for the provision of resources, investment in local capital, working practices and project duration. Such limits were reflected in perceived high levels of cost and risk and hence reduced perceived benefits to Tanzania and WIO partners. Through this experience, future international funding opportunities might look to increase the level of available investment to local infrastructure, personnel and training to provide further increases in regional capacity. Our analysis suggests however, that there is still

only a medium level of confidence from regional PIs in accessing the infrastructure and national, regional or international funding required to bring marine robots to the WIO region. Further consideration is therefore encouraged on how best to capitalise on the lessons learned within this study to initiate the next steps in regional capacity development.

5. Conclusions

This study demonstrates that marine robots offer significant potential for WIO States to meet national coastal ocean research objectives and to contribute to international marine science programmes. The introduction of these technologies to WIO researchers and coastal communities within this project has increased the capacity and readiness for regional adoption. The ‘next steps’ will require further investment and commitment at both national and regional levels. There does however, appear to be some scalable options that may provide incentives for a progressive funding initiative rather than immediate investment in expensive capital infrastructure. At regional levels, providing accessible opportunities for skills development through training and facilitating international collaborations would build on the capacity development that has already been achieved within the SOLSTICE-WIO project and other initiatives. Enabling a regional host facility, or centre of excellence for marine robots, where sufficient skills, facilities and experience exist to host collaborative international partnerships, would provide a key route to attracting future funding and international partnerships while supporting further regional capacity

development. The emerging availability of smaller, cheaper marine robots may provide one accessible way to continue the development of skills, confidence and reputation that has been achieved in this study, and while less capable than the robots demonstrated here, would help ensure future inclusion in related international coordination efforts. Investment in local skills and support facilities would also help promote local buy-in and likely reduce cost and risk while feeding further into regional capacity and benefits for future marine research activity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Community engagement leaflets



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