Getting up close and personal: the need to immerse autonomous vehicles in coral reefs

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Abstract— **Coral reefs are facing a range of cumulative impacts and pressures and are amongst the first major ecosystems to be impacted by climate change. In order to understand and manage these systems we need much improved monitoring tools. The current best effort diver based systems in developed countries only monitor a few percent of the reefs within their area of control, while in many developing areas this figure is significantly lower. One solution is the development of cost-effective Autonomous Underwater Vehicles (AUVs) that are able to overcome the current limitations of using divers (depth, endurance, safety and costs) to increase our knowledge of reefs, especially remote and deep reefs. While some AUVs are approaching the level of performance that would be usable, there are a number of factors that limit their use. This paper describes the type of transformational change required to develop new tools, not just as an evolution of existing systems, but utilizing expertise from a range of domains to deliver a revolution in how shallow water complex systems are monitored. In conjunction with advances in the platforms available there needs to be co-investment in image processing pipelines to give end-to-end knowledge solutions that provide outcomes to scientists and managers. Finally, delivering transformational outcomes will require a new way of working and a change to how projects are funded, managed and delivered. Coral reefs are managed by developed and developing nations alike, with countries like the USA, Australia, England (via the British Indian Ocean Territory) and France (via New Caledonia) managing approximately 20% of the world's reefs via systems of marine parks and protected areas. It is incumbent on developed economies to develop and transfer to other reef custodians the tools required to help sustain coral reefs into the future.**

Keywords—coral reefs; autonomous; monitoring; AUV; Autonomous Underwater Vehicles

I. Background and Rationale

Among the world's technologically developed nations, Australia, America, France and England, amongst others, share a common marine challenge – the management of very large marine protected areas critical to the long term sustainability of the globe's coral reefs. The Australian Great Barrier Reef Marine Park, the US Marine National Monuments (Pacific Remote Islands and Papahanaumokukea), the New Caledonian Le Parc Naturel de la Mer de Corail (Natural Park of the Coral Sea) and the British Indian Ocean Territory Chagos Marine Protected Area together cover over 4.9 million square kilometers of ocean [1] containing some 20% of the world's coral reefs [2, 3]. Monitoring on such a scale for management cannot depend on human observation alone, while traditional automated approaches, such as remote sensing, are unable to be the complete solution. Nations must embark on a transformative technology innovation program with a particular focus on increased use of autonomous monitoring in reef environments as an extension to the work currently undertaken.

However, a glaring gap in the armoury of autonomous tools available to marine scientists is reliable, cost-effective autonomous devices, tailored to shallow, rugose and complicated systems on continental shelves (e.g. coral and rock reefs and shelf slope escarpments) that are characteristically high energy environments subject to waves, tides and currents. Throughout the world, these shallow water environments are suffering the cumulative impacts of human pressures [4] and are amongst the first marine environments to be impacted by climate change [5]. Our ability to manage these impacts depends on our ability to observe and collect data – "we can't manage what we can't measure". Thus, there is a compelling need to develop technologies that will allow more effective, cost-efficient and safe ways of working in shallow water marine environments.

Driving this need are predictions that we can expect to see large scale changes in coral reefs by the end of the century [6] and potentially in the next twenty to thirty years [7]. This gives a new urgency to the need to develop tools that will more fully document the current status of reefs and to detect subsequent changes over these large reef systems. While countries such as Australia and the USA have the 'luxury' of being able to use a

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range of management options, many of these options, such as reef closures and limited reef access, are not as easily available to managers of reefs in developing areas such as parts of South East Asia and Central America. A review in 1998 showed that 66% of Caribbean and 90% of Sea East Asian Marine Protected Areas (MPAs) had not reached their management goals [8], mostly due to ongoing funding issues as well as lack of local community involvement [9].

As a result, the types of tools developed need to have equal applicability to developed and developing nations.

II. Current Status of Available Tools

Traditional tools for coral reef monitoring are mostly based on human observers [10, 11] and suffer from a number of issues:

- They are limited to diving or snorkeler depth (typically 30m for diving, 10-15m for snorkeling);
- They are labor and time intensive and so this limits the area that can be covered;
- They typically can only operate during good weather conditions, in areas of relatively sheltered water and mostly during daylight hours;
- They are limited to areas that are safe for diving or snorkeling, this normally excludes off-shore areas, very turbid areas and areas with marine pests such as jellyfish, sharks and crocodiles (many of which have extended their range recently due to changes in management (e.g. crocodiles in northern Australia) or through climate related range extensions (e.g. some jellyfish [12]));
- They require extensive training of personnel including regular between-observer calibrations [13] and can be prone to observer bias [14].

There is a general move away from using divers for monitoring work for Occupational Health and Safety reasons. Often when scientific work is being done in conjunction with commercial activities, regulations require the work to be done under commercial diving regulations and not those for scientific diving [15], limiting the type of work possible. In these cases, diver-less solutions are urgently required to allow for the scientific work to be conducted in conjunction with the commercial work. Examples of where this has already had an impact are the use of ROVs for deeper water scientific investigations that previously were undertaken by deep water divers.

A final issue is that many of the current methods collect only observer summaries of the area surveyed (such as the Manta-Tow method [11]) and so there is no permanent record that can be used for later analysis or to investigate other questions or document fine scale change. This means that the historical record based on observer summaries is, at best, an incomplete measure of the system at that time.

The reality is that current person based methods are too slow, too limited, too expensive and potentially pose a number of health and safety risks. As a benchmark, the Long Term Monitoring Project undertaken along the Great Barrier Reef of Australia [16] manages to undertake diver/snorkeler based coral cover surveys of around 80 reefs per year (out of a total of some 3000 reefs, or less than 3%; most of these are inner and mid-shelf reefs in the southern part of the Great Barrier Reef complex). One solution is to apply advances in autonomous systems seen in other areas (such as aerial drones and self-driving vehicles) to shallow water marine systems.

There are a range of existing autonomous tools that are used for coral reef monitoring which range from drones to animals (bio-logging) although all have their limitations. Unmanned aerial vehicles (drones) can only monitor the few meters near the sea's surface and while they are valuable in supplementing and validating satellite data, they do not provide detailed information on deeper areas, especially areas of high structural complexity. There are a number of emerging Autonomous Surface Vessels (ASVs, e.g. the ASV C-Enduro [17] and the Liquid Robotics Wave Glider [18]). While these allow for deeper penetration of the marine system, they cannot reach far beyond 10 meters, although they may be suitable as towing platforms for deeper towed sleds.

While towed platforms (e.g. [19, 20]) are currently a valuable tool for monitoring deep areas, the complex three dimensional nature of reefs comprise significant snagging obstacles that limit the use of underwater vehicles operated through cable tethers (remotely operated vehicles, towed underwater vehicles). Currently these systems require significant pre-mapping in order to locate suitable hazard-free areas and then intensive operator control to run the towed platform at the correct height above the bottom without risk of collision or snagging.

Stationary platforms, such as moorings, do not have issues with collisions but are spatially limited as well as being expensive. In the same way, bio-logging is bound spatially by the animal's movements and often it is difficult or impossible to recover the instruments.

There are a few Autonomous Underwater Vehicles (AUVs) that have been deployed in reef environments [21-23] but these tend to be slow and cautious – preferring to go over the reef rather than flying through it. While these have proved useful for mapping small parts of reefs [22, 23], they are expensive, complex to support, and are not at the stage where large scale mapping can be undertaken without human intervention.

III. The Need for a Better Tool

There is a need for a better toolto better investigate, document and understand our marine systems. Coral reef scientists need a reliable, cost-effective autonomous underwater vehicle that can navigate in physically intricate environments exposed to strong, complex currents. Such a device must also be able to operate from simple mother ships to allow the device to be used by much more of the research and scientific communities than that which can access large research vessels.

These tools will also allow investigations beyond the limits of human endurance (e.g. long missions), physiological tolerances (e.g. depth or limited air supply), or visibility (e.g. turbid waters, night-time or deep) as well as addressing a number of health and safety risks. Doing so will increase the reach of marine science, painting a more complete picture for policy-makers, managers and decision-makers.

Married with this increase in our ability to generate data from new places, collected at times not usually accessible, will be the need for even more seamless pipelines for data ingestion and extraction of the knowledge buried within. A major portion of this data is imagery, as digital cameras become more powerful and commonplace. But visible imagery is just the tip of the iceberg, with hyperspectral and multispectral tools becoming more affordable and robust. Automated image analysis for visible imagery is improving but more slowly than progress with cameras.

The gulf between our ability to generate data and extract the required knowledge needs to be bridged, and quickly. Technological advances are making simple yet increasingly powerful computing power (e.g. the Odroid [24] and Jetson [25] computing platforms) available for performing unsupervised data analysis on the autonomous platform itself. This computing power will only increase, become less expensive and even more portable. Research and development (R&D) in this space must now consider how tools can be deployed on the platform to accelerate information generation from collected data.

IV. Use-Cases for Coral Reef AUVs

Understanding what the problem that a coral reef AUV is trying to solve is the first step in being able to define what types of missions an operational system would need to undertake. To do this a number of Use-Cases have been developed; the two presented (out of many that are equally as relevant) reflect current diver based monitoring programs and so reflect current needs.

A. Use-Case: Synoptic Monitoring [what's there]

This Use-Case is based on synoptic level surveys of reef margins to understand and map basic benthic types and cover, as well as potentially looking for specific targets such as crown-of-thorns starfish (COTS) or areas of coral bleaching or disease. The method is analogous to the Manta-Tow method [10, 11] currently used to undertake large area coral surveys. This Use-Case can also apply to the current sled based mapping of deep reefs and the inter-reefal areas between them.

1) Mission Profile:

Synoptic Monitoring uses surveys of reef margins (following a set depth contour) to map benthic cover types and potentially percentage cover of the main benthic types. Field of view is to be equivalent to a manta-tow, giving high-level synoptic data. Spatial repeatability is not essential, but the AUV should do a roughly repeatable track around the reef. Spatial accuracy should allow points identified on the imagery to be located in the field. Synoptic Monitoring potentially has the ability to use existing bathymetry or features to navigate from (e.g. multi-beam data) or position data from other sources (e.g. USBL link). It also provides the ability to work at night using a range of provided illumination (e.g. UV light).

2) Data Capture:

This involves high resolution approximately geo-located stereo image pairs, accompanied by lower resolution video including water column (i.e. view ahead / side) video. It can use bathymetry data using multi-beam sonar, laser or other sensors to produce a 3D bathymetry map for the area surveyed.

3) Data Analysis:

This includes automated classification of the main benthic types, geo-rectification into a benthic cover map, identification of areas of change, and potential image analysis to identify areas of coral bleaching / COTS feeding scars. Synoptic Monitoring also has the potential to deliver 3D bathymetry maps.

4) Outcomes:

Synoptic Monitoring produces surveys showing equivalent data to the manta tow method with geo-rectified maps of broad benthic cover types across a belt transect around the reef perimeter. Surveys could identify benthic cover types, map rough changes year to year, and potentially look to identify coral bleaching / COTS feeding scars or other identifiable features. It also has the ability to survey deeper areas producing benthic habitat maps that include deeper reef slope areas.

5) Applications:

Synoptic Monitoring can be used for coral cover monitoring, rapid census of reefs to map benthic cover and rapid identification of potential COTS outbreaks. It also makes it possible to map deeper water reefs and reef areas, including areas currently inaccessible to divers, at the level of gross benthic types / habitats.

B. Use-Case: Detailed Mapping [how is it changing]

While the synoptic surveys give an indication of what is present for key areas, there is a need to know how these areas are changing. To give this level of information, detailed surveys are required with a high level of repeatability so that equivalent information can be obtained at two or more times and then directly compared (overlaid) to look at changes.

1) Mission Profile:
This involves repeated detailed mapping of benthic transects using high resolution stereo imagery with a high level of spatial precision and repeatability. Data is analysed down to functional group/genus or for some forms to species. Long term changes are mapped using repeat samples, with a number of replicate/duplicate sites done at the one reef. Detailed mapping can involve the use of permanent underwater markers or locators (such as terrain features) for the AUV to ensure repeatability without surface location information. It could also involve a mix of natural light and UV/IR lighting, including day/night sampling, along with spectral analysis to help identify some life forms.

2) Data Capture:
Detailed mapping requires high resolution geo-located stereo image pairs, potentially using hyper-spectral or IR/UV light and cameras either through dual cameras or overlapping imagery.

3) Data Analysis:
This includes manual and semi-automated classification of benthic forms, manual classification of taxa groups and manual identification of the change in individual corals/colonies. It creates a permanent record of spatial distribution of taxa/benthic organisms and any change in composition and distribution. It also includes automated identification of key species such as COTS and feeding scars/coral bleaching.

4) Outcomes:
Detailed mapping creates permanent records of changes at key locations, tracking of the fate of individual coral colonies and identification of key species such as COTS. It could move to automated intelligent processing to reduce the level of user input andmay be able to replace manual line-transect sampling, allowing for increased in-field sampling and reduced in-laboratory analysis effort.

5) Applications:
Detailed mapping can be used for regular monitoring of sites of interest, especially in deep water or diver inaccessible areas, and change analysis. It provides documentation of key sites for future change studies and can be used for monitoring the fate of individual coral bommies/colonies as part of other experimental work.

These Use-Cases require a number of image processing pipelines to manage, store and process the image data through to usable information and knowledge products. Imagery systems have the capacity to generate large volumes of data, so managing image and video data becomes an important task in its own right.

Coupled with managing the data are systems to turn the images and video into standardized imaging products. These include benthic mosaics (as 2D and 3D products) with images' time and location stamped, overlay of various imagery so that lower resolution images and video can be seamlessly supplemented with higher resolution data where it exists, tagging of video with time and location data, stitching video into 360˚ video panoramas (e.g. 360˚ GoPro rigs [26]) suitable for Virtual Reality (e.g. Oculus Rift and Samsung Gear-VR [27]) and visualization systems (e.g. the Caitlin survey [28]).

These image products then need to be analyzed using manual and automated systems. Example information products include routine un-supervised classification of benthic images to give percent cover maps, first level image recognition of key targets to give hot spots for manual analysis, and 3D maps that can be used in GIS mapping systems.

V. Performance of current reef AUV Systems

A recent survey undertaken by the authors on available coral reef or complex shallow water AUVs identified only a short list of autonomous platforms that have been used and tested in coral reef environments.

The Woods Hole Oceanographic Institute's SeaBed AUV [29] has been adapted to undertake coral reef surveys on the Great Barrier Reef through the University of Sydney's Field Robotics program [30], co-funded under the Australian Integrated Marine Observing System (IMOS) program [31]. The 'Sirius' AUV has completed a number of surveys on the Great Barrier Reef examining seagrasses and deep reef areas [32]. The University of California at San Diego has an engineering project developing the 'Stingray' AUV which they plan to use for coral reef surveys [33] while the CoralBot project looks to develop AUVs for coral reef restoration and monitoring work [34].

One way of understanding where these designs are in the context of readiness for end-users is to use a Technology Readiness Level (TRL) index such as that used by NASA [35, 36]. This allows an understanding of just where various solutions are in the scale from initial idea to operational system.

The NASA levels are (modified for marine application):

- TRL 1 Basic principles observed and reported
- TRL 2 Technology concept and/or application formulated
- TRL 3 Analytical and experimental critical function and/or characteristic proof of concept
- TRL 4 Component and/or breadboard validation in laboratory environment
- TRL 5 Component and/or breadboard validation in relevant environment
- TRL 6 System/subsystem model or prototype demonstration in a laboratory test environment

- TRL 7 System prototype demonstration in a field test environment
- TRL 8 Actual system completed and "flight qualified" through test and demonstration (test environment)
- TRL 9 Actual system "flight proven" through successful mission operations

Whiles these levels are subjective they can be used to evaluate the few systems that do exist:

SeaBed 'Sirius' AUV [29, 30]:

- Shallow water uniform environments with low wave energy or currents: TRL-9
- Shallow water complex environments with low wave energy or currents: TRL-7/TRL-8
- Shallow water complex environments with high wave energy or currents: TRL-6

Stingray AUV [33]:

- Shallow water uniform environments with low wave energy or currents: TRL-6
- Shallow water complex environments with low wave energy or currents: TRL-4
- Shallow water complex environments with high wave energy or currents: TRL-2

CoralBot AUV [34]:

- Shallow water uniform environments with low wave energy or currents: TRL-4
- Shallow water complex environments with low wave energy or currents: TRL-3
- Shallow water complex environments with high wave energy or currents: TRL-2

Clearly the only system close to what is required in terms of functionality is the SeaBed AUV but this is expensive, complex and requires extensive technical support. The other designs meet the cost and simplicity criteria, but are far from having the required field functionality.

Looking at the capability of the SeaBed 'Sirius' AUV closer, for the deep reef study [32] the AUV 'flew' 2m above the bottom at 0.5 m/sec (around 1 knot) for deployments of 2-4 hours. It collected high resolution stereo images and multi-beam scans of the benthos as well as a range of environmental data. While this gives an impressive survey area of around 7,200 m^2 per hour (presuming a wide angle camera field of view of around 100° or a 4m wide view at 2m height), a typical reef is some eight nautical miles around, and the reef crest to slope can be 50 meters wide, which means that the AUV would need ten hours to cover just the margins of one reef.

The deep reef work demonstrated that the 'Sirius' AUV, under ideal conditions, has a field capability that is not too far from what is required (for example the platform speed and mission times would need to double). What is uncertain is how this translates into real world shallow reef conditions where structural complexity is higher, as are waves and currents. The issues with this approach are the cost (the unit costs many hundreds of thousands of dollars); the requirement for two to three technicians to operate the unit; the need for a surface vessel to give it positioning information; and, at 2m long and 200 kilograms, the need for a considerable support vessel to launch and recover the vessel.

VI. BUILDING THE PERFECT TOOL

The current solutions tend to be either cheap and simple, but immature with very limited capability; or very expensive and complex, but with some of the required functionality especially in simple environments. It is tempting to think that further work on a platform like the SeaBed is suitable for further development but this just makes it more complex, more expensive, and require greater levels of support. The other designs, while immature, probably represent development pathways that will lead to a solution that is cost effective, robust, simple and suitable for use in a range of developed and developing nations.

What needs to be transformational in a reef AUV is the ability to deal with truly complex and chaotic environments; that is, to use adaptive and learning approaches from other domains and apply that to shallow water AUVs. This application of new approaches and new ways of solving problems using low cost components is driving innovation in aerial drones and this model of innovation and transformation is what is needed in the marine field.

What is required is a transformational set of features including:

- *Instinctive Autonomy:* Much like a person who will recover after a stumble without thinking, these devices need to be able to instinctively maintain their mission. They need to be able to react rapidly to suddenly changed circumstances like surge waves and return to their mission parameters. Unlike persistent autonomy, this form of autonomy needs to be far more rapid in terms of failure/error detection and response to immediately start correcting course and position. This will also be critical to maintain platform stability during data acquisition, particularly imagery, to maximize its quality.
- *Underwater cognition:* Missions will be complex and the platform needs to not necessarily be intelligent but to be aware of and understand its surrounds, create short term memories and make simple decisions. This will allow the craft to avoid objects which are either static (e.g. reefs) or mobile (e.g. other vessels, both large commercial and small recreational).

- *Visual perspective:* Critical to navigation is the recognition of what is around and what parts of the scene are near or far. Being able to recognize what is in the field of view and where objects are relative to one another will enable the AUV to have situational awareness and react appropriately.
- *Precise, real-time, underwater geolocation:* Knowing one's location in space and time is a prerequisite for good navigation. The required precision depends on the task at hand, but to be able to reproduce transects through time and rapid course correction will require precise, quick and reproducible geolocation.
- *Energy, energy, and a bit more energy:* New technologies and energy management tools are essential to maximize mission duration in 2-4 knot currents, what capabilities that can be deployed on the AUV and its ability to react to rapidly changing circumstances which will be a drain on energy. Underwater imaging (visible, fluorescent, hyperspectral) requires energy sapping lighting.

These requirements need to be linked to rapid prototyping using advances in 3-D printing to provide opportunities for cost-effective manufacture and easy transfer of designs between users to rapidly manufacture parts and replacements. Projects such as the Open-ROV [37] may be suitable templates as to how the development can be shared amongst a number of agencies as well as driving a large user base.

Fundamental to the design is the need to keep unit costs down, to ensure the final design is small and light enough so that it does not require large vessels to deploy and retrieve, and to make it modular so that functionality can be easily added or developed.

Some basic design specifications may include:

- A bare-bones cost, with no sensors, of less than fifty thousand US dollars per unit;
- Small enough to be manually deployed and retrieved off a small (6-8m) vessel using two or three people and minimal lifting or deployment equipment;
- Endurance of around 4-8 hours at two knots or better using internal swappable battery packs;
- Modular design with the ability to replace most parts in the field with no specialized tools, ability to source or manufacture spare parts locally through use of standardized components or via open source designs amenable to 3D printing or other automated forms of manufacture;
- Open-sourced control and computing systems with the ability to easily add functionality or additional computing power;
- Rated to 50m initially with the development of deeper versions a priority;
- Ability to operate in shallow areas (3m depth) in complex topographical environments with medium to high wave energy;
- Support for various payloads including oceanographic sensors, imaging sensors, sonar and so on.

Importantly the unit needs to be robust enough to require only basic technical support and to be functional in areas without a high level of technical resources. The need is to do more with less – the system needs to free up human resources for other tasks, not just require the same number of people but with differing skills.

The ability to better collect observations needs to be matched with an increase in our ability to process, store and analyze the data. This means that equal effort needs to be applied to developing a number of standardized but flexible image processing pipelines so that automated systems can at least do a first level analysis of the collected data. For example, an image recognition system may be able to identify images that are potentially 'interesting' and do a first level cull of hundreds or thousands of images down to a number that can be examined by hand.

Extending these ideas is the ability to do the first level image processing on the AUV itself, so that it becomes possible to build learning systems whereby the AUV can change its mission based on its first level analysis of the data it has collected. This would allow the AUV to re-survey areas that were 'interesting', to use differing sensors to gain additional data and to optimize the mission to spend less time on areas that were uniform and more on areas that are complex or diverse. A simple set of rules could be used to define what is considered to be 'interesting' and the subsequent actions to take.

VII. Coral Reefs as an Extreme Example of a Generic Problem

While many of the requirements for AUVs in coral reef environments may seem extreme (such as navigating around complex structures, working in high energy zones and having to cover large areas), they are just one end of a spectrum that includes coastal areas with uniform topography, less wave energy and smaller spatial extent. It is therefore possible to develop solutions that initially target simpler environments and, as technologies and approaches allow, move towards a more complex environment such as a coral reef.

It is possible to envisage a series of development steps, or phases, from shallow sheltered sandy areas through to open reef fronts, where technologies can be applied and adapted. This gives a path to adoption that has many stages, each of which has a number of potential real world (and commercial) applications.

While coral reefs represent an extreme environment for AUVs, there is a development path with many practical milestones along the way.

VIII. A Co-operative Model of Development

Underlying the vision of a new type of monitoring tool is a new way of developing the tool. Typically, institutes will develop technology around an existing core set of competencies and will be pushed to invest in designs that are evolutionary or have a narrow focus reflecting current needs. To develop truly transformational products requires expanding the domain of expertise far outside that found in any individual agency. This then dictates a new model of development encompassing ideas such as crowd-sourced funding (e.g. Kickstarter [38]), putting technical problems out to crown-sourced solutions (e.g. Kaggle [39]), close involvement with commercial companies and foundations (such as the X-Prize [40]) and the use of the open-source model for development (e.g. Open ROV [37]).

The challenge becomes one therefore not just of developing and packaging technology, but in developing business and development models that are sustainable, equitable and actively engage with domains outside the immediate area of development. Creating a robust collaborative business and development model that supports transformational outcomes is an early challenge that needs to be solved.

IX. Conclusion

This paper is somewhat of a call to arms. This generation may be the last to see coral reefs as they are [4, 7] (coral reefs will not disappear but they will change, as all systems do) and the need to document, understand and manage these resources grows as the environmental pressures on these systems also grow. The scale of the problem, both in spatial scale and in terms of current knowledge gaps, requires a new set of approaches and a new way of working. The goal or challenge of this paper is to develop autonomous monitoring systems to the point where within five years there is a fleet of cheap, easy to use, effective, reef monitoring devices.

Australia, the USA, England (via the British Indian Ocean Territory), and France (via New Caledonia) all have custodianship of large parts of the world's coral reefs, with a major fraction of those reefs protected by comprehensive management systems. It is beholden on these countries to develop tools and techniques to better manage these resources, and just as importantly, to help other countries manage theirs.

While coral reefs can represent an extreme environment to deploy AUVs, there are a logical set of stages for a development path from more simple environments that has real world commercial and science applications and outcomes. While there is a logical pathway from where AUVs are today to where developed nations want them to be, it is important to understand that the end point needs to be transformational – revolution not evolution. The world is looking for a totally new type of tool, logically and technically related to what currently exists, but operationally unique. There is no point replacing an expensive research vessel taking a number of qualified marine scientists to the reef with an equally expensive research vessel taking the same number of qualified robotic technicians.

The transformational component will be to develop a solution that is cost controlled, robust, simple to deploy, and requires only modest infrastructure such as vessels and technical support. This tool needs to be supported by advanced image processing pipelines that produce a range of standardized information products. In turn, this data can be analyzed using novel image analysis and recognition techniques, turning it into higher order knowledge products. This requires a melding of traditional oceanographic engineering with consumer electronics bound together with crowd-funding and open source code.

The challenge to the traditional ocean institutes is just how to meld the best of the emerging technology, much of which is outside the marine domain, with the robust ocean engineering that is a hallmark of most marine projects to deliver a solution that provides an order of magnitude increase in the ability to monitor the coral reefs that have been entrusted to their care.

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