Needs and gaps in optical underwater technologies and methods for the investigation of marine animal forest 3D-structural complexity

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Abstract

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Marine animal forests are benthic communities dominated by sessile suspension feeders (such as sponges, corals, and bivalves) able to generate three-dimensional (3D) frameworks with high structural complexity. The biodiversity and functioning of marine animal forests are strictly related to their 3D complexity. The present paper aims at providing new perspectives in underwater optical surveys. Starting from the current gaps in data collection and analysis that critically limit the study and conservation of marine animal forests, we discuss the main technological and methodological needs for the investigation of their 3D structural complexity at different spatial and temporal scales. Despite recent technological advances, it seems that several issues in data acquisition and processing need to be solved, to properly map the different benthic habitats in which marine animal forests are present, their health status and to measure structural complexity. Proper precision and accuracy should be chosen and assured in relation to the biological and ecological processes investigated. Besides, standardized methods and protocols are strictly necessary to meet the FAIR (findability, accessibility, interoperability, and reusability) data principles for the stewardship of habitat mapping and biodiversity, biomass, and growth data.

Contribution to the field

This perspective paper aims at identifying factors that limit the study and the conservation of underwater animal forests. The main technological and methodological needs for the investigation of 3D structural complexity at different spatial and temporal scales are discussed. Within this paper, authors want to share their vision about the current gaps in data collection and analysis with the international community. Despite recent technological advances, several issues in data acquisition and processing need to be solved, to properly map marine animal forests, their health status and monitor them through time. The need for standardized methods and protocols is mandatory.

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Abstract

Marine animal forests are benthic communities dominated by sessile suspension feeders (such as sponges, corals, and bivalves) able to generate three-dimensional (3D) frameworks with high structural complexity. The biodiversity and functioning of marine animal forests are strictly related to their 3D complexity. The present paper aims at providing new perspectives in underwater optical surveys. Starting from the current gaps in data collection and analysis that critically limit the study and conservation of marine animal forests, we discuss the main technological and methodological needs for the investigation of their 3D structural complexity at different spatial and temporal scales. Despite recent technological advances, it seems that several issues in data acquisition and processing need to be solved, to properly map the different benthic habitats in which marine animal forests are present, their health status and to measure structural complexity. Proper precision and accuracy should be chosen and assured in relation to the biological and ecological processes investigated. Besides, standardized methods and protocols are strictly necessary to meet the FAIR (findability, accessibility, interoperability, and reusability) data principles for the stewardship of habitat mapping and biodiversity, biomass, and growth data.

1 Introduction

Precise maps are nowadays easily available on the land surface, providing location, extent, and topography of terrestrial ecosystems. Interestingly, it is roughly calculated that only 5% of the oceans floor is accurately mapped at the ecological community level (Rossi and Orejas, 2019). Thus, a complete 3D and semantically enriched description of benthic habitats is required through a technologically improved and methodologically robust approach.

Marine animal forests are benthic communities dominated by sessile suspension feeders (such as sponges, gorgonians, scleractinian corals, and bivalves) able to generate 3D frameworks with high structural complexity (Rossi et al., 2017). These organisms act as habitat-forming species, since they "modulate the availability of resources (other than themselves) to other species by causing physical state changes in biotic or abiotic materials" (Jones et al., 1994). The complex structures resulting from their growth significantly enhance the heterogeneity in most environmental factors (such as light, current, food availability or sediment suspension), providing habitats for other species, enhancing species diversity, and directly or indirectly participating in or promoting building of biogenic reefs (Rossi et al., 2017).

The overall bioconstruction rate of the biogenic reefs made or promoted by animal forests varies according to different prevailing species, but has often low values: for example, growth in height is estimated to range from less than a millimeter to few centimeters per year, depending on species and environmental conditions (Coma et al., 1998; Kružić et al., 2012; Ordoñez et al., 2019). Higher rates are typical of healthy tropical coral reefs dominated by branching corals, while lower rates occur in temperate and cold seas dominated by sponges, gorgonians or bivalves. Negative growth rates of biogenic structures may arise when biological and chemical-physical erosion processes dominate over the bioconstruction ones (Davidson et al., 2018). For example, in the Mediterranean biogenic reefs, the integrity of gorgonian populations is threatened by: i) mechanical damage due to fishing lines and nets, anchorages, and recreational divers; ii) suffocation by mucilaginous benthic aggregates; iii) increased water turbidity and sedimentation rates as a result from poor land management (Ponti et al., 2018 and references therein); iv) the invasion from non-indigenous and/or predator species (Maldonado et al., 2013; Righi et al., 2020). Moreover, climate change is one of the most concern threat since seawater warming, and higher frequency and severity of marine heatwaves have increased the mass mortalities of animal forests in both tropical and temperate seas (Garrabou et al., 2009, 2019). The vast decline of erect sponges and gorgonians in the Mediterranean Sea (Cerrano et al., 2000; Turicchia et al., 2018) is reducing considerably the structural complexity of these ecosystems, with important consequences for ecosystem biodiversity, functioning, and the services they provide (Verdura et al., 2019).

The study of marine animal forests down to the mesophotic zone, is usually performed by scuba-diving surveys (Cerrano et al., 2019), using visual estimations, photo-sampling, and direct assessments of variables (e.g., colony size, percent cover, presence of necrosis/bleaching). Yet, accuracy of measurements and spatial replication are often not taken into consideration and some direct measures (e.g., annual growth rates) may still be based on destructive sampling (Peirano et al., 2001; Marschall et al., 2004). Since many invertebrates and their symbiotic algae contain fluorescent pigments, fluorometry and photographic image analysis are increasingly employed as a non-invasive proxy for organism health state and pathogenesis patterns (see Caldwell et al., 2017 for references), and to analyze their population dynamic; however, these studies are labor-intensive and require manual interpretation (Zweifler et al., 2017; Montero-Serra et al., 2019).

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Technological developments have made optical and acoustic techniques practical to provide non-destructive measurement estimates of large sections of tropical coral reefs in 3D (House et al., 2018; Rossi et al., 2020), but their application in cold and temperate animal marine forests is still limited (Palma et al., 2018). Moreover additional efforts are still needed to obtain high definition reconstructions that range from aggregations to single organisms as well as subsequent reconstructions to allow tracing of possible structural shift over time. Indeed, ranging from small to broad spatial scale of marine animal forests (Figure 1), the use of photogrammetry for georeferencing the samples and for spatial data acquisition is a promising tool to study many aspects of these communities and evaluate ecological key parameters, from organism health to the species interactions at the basis of bioconstruction and bioerosion processes. Within this viewpoint paper we mainly focus on optical techniques, in particular photogrammetry. Acoustic techniques are effective and widely used, but at present they do not guarantee to reach the same accuracy and resolution as photogrammetry (Czechowska et al., 2020). At the scale of single organisms, accurate reconstructions of 3D individual morphology may considerably enhance the capability for species recognition, as well as the accurate quantification of survival and growth rates under variable environmental conditions (Olinger et al., 2019). At the population level, morphological information about organisms may allow for a precise description of the population size structure, its dynamic variation through time (Montero-Serra et al., 2019) and its functioning (Ledoux et al., 2010). At the community level, the careful reconstruction of the framework built up by the structural and the associated species may allow to precisely describe the community structure in terms of species composition, abundance, and evenness. Finally, at the large scale of habitat or ecosystems, 3D georeferenced reconstructions may allow for the application of landscape indexes and descriptors to the analysis of benthic communities.

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Animal forests represent a perfect natural lab to develop complex new methodologies, aiming at understanding long-term dynamics and evolutionary processes (Ledoux et al., 2020) shaping these high-biodiversity and structurally complex systems, and eventually the existence of recovery mechanisms that can enhance their resilience to increasing threats (Kersting and Linares, 2019).

2 Technologies and methodologies

2.1 Data acquisition

The underwater environment poses multiple challenges to 3D reconstruction-oriented explorations based on optical methodologies, such as low visibility, turbidity, light attenuation, and low data transfer rates. It is still challenging to acquire spatial data through photogrammetric methods at a wide area (wider than few square meters) at a few centimeters level of accuracy, which could be limiting for the study of large benthic species. New technologies and automation are required both in data acquisition and analysis to quantify the structural complexity of animal forests. Besides, survey planning and adaptation strategies, that are tailored for optical and acoustic 2D/3D maps reconstruction, dynamically adapted to local conditions, and oriented towards the optimal coverage of a site, need to be explored.

Scuba divers are still widely employed for surveying tasks at accessible diving depths, in clear warm and turbid/cold waters complying with safety limitations (Nocerino et al., 2019; Piazza et al., 2018). However, remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) have become increasingly reliable tools and have led to inspections at depths and across spatio-temporal scales hostile both to divers and crewed vehicles (Figure 1) (Montseny et al., 2019; Shihavuddin et al., 2013; Gori et al., 2011). In both cases, reference information is required to support spatial continuous methodologies and produce a georeferenced 3D model. The position of stable reference

points, installed on the sea floor, or the position of sensors can be performed through classic survey technique or acoustic positioning, depending on the dimension and depth of the investigated site (Rossi et al., 2020; Bruno et al., 2019) (Figure 1). Moreover, acoustic positioning systems, combined with underwater tablet, may allow divers to plan specific paths to be followed during the survey (Scaradozzi et al., 2018), thus optimizing the acquisition phase and guaranteeing repeatable and complete data. For deeper surveys, acoustic positioning and ROV/AUV navigation data may only provide approximate georeferencing information that may be too coarse for adequately scaling the 3D models when these are created from a single camera. In such cases, the use of laser calipers can solve this problem (Istenič et al., 2020).

Undoubtedly, automatic optical and acoustic imagery classification, as well as 2D mapping (Franchi et al., 2018), would speed up and enhance animal forests investigation allowing non-destructive visual surveys, measuring morphological variables, and paving the way to more specific 3D reconstruction-oriented explorations. Acoustic based techniques are well suited in large areas of interest (from 10 m to 10 km), and acoustic 3D mapping is successfully employed to map a wide portion of the sea floor at various depths, but in case of organism biometry, higher accuracy and resolution techniques are required. These systems operate in the long-range acquisition and do not suffer from turbidity, but the resulting 3D reconstructions have low resolution and accuracy compared to the optical ones (Lagudi et al., 2016) (Figure 1).

On the other hand, optical systems are well suited for close-range acquisition (a few centimeters to tenths of meters). Active optical 3D imaging techniques project different patterns on the investigated area. The triangulation is computed by intersecting the laser beam that passes through a pixel lit up by the pattern, and the projected pattern itself (Palomer et al., 2019). These tools allow to obtain accurate and high-resolution 3D reconstructions, but results are influenced by visibility conditions and acquisition distance (Figure 1). Passive techniques (photogrammetry) are based on multiple views of a scene and take advantage of structure from motion (SfM) and Multi View Stereo (MVS) algorithms (Burns et al., 2015). Natural or artificial light can be used to illuminate the scene. The triangulation is done by intersecting the optic rays that pass through a pixel in each image where the same feature is automatically identified and allows the generation of an accurate, dense 3D reconstruction (Westoby et al., 2012). Underwater photogrammetry has long been used because of its flexibility and low cost, potentially providing high-resolution imagery in the underwater context under well planned protocols of data collection (Nocerino et al., 2019). RGB sensors are the most used in underwater applications because they allow achieving measurable and photorealistic products. Other sensors may offer new opportunities to visualize the internal and external morphology of bioconstructions, such as multispectral acquisitions (Nocerino et al., 2017) and high-resolution x-ray computed tomography, which can be applied to collected samples (Farber et al., 2016). For shallow water applications, surface autonomous vehicles equipped with acoustic and optical sensors (Stanghellini et al., 2020), and low altitude Unmanned Aerial Vehicle (UAV)-based photogrammetry (Agrafiotis et al., 2020; Casella et al., 2017) can provide important information outlining bathymetric profile, filling the gap between satellite and underwater imagery. In the latter case, compensation for water refraction is required (Agrafiotis et al., 2020). In addition, underwater multispectral and hyperspectral imagery is an emerging technique for applications in shallow and deep-sea environments. It is a passive technique in shallow waters; instead, at high depth, when solar illumination is not available, an active light source is necessary. Anyway, this technique works properly at an acquisition distance of 1-5 m, because of the strong absorption caused by the water column (Liu et al., 2020)

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Simultaneous localization and mapping (SLAM) methodologies have proved to be effective for underwater explorations and subsea metrology applications. SLAM relies on data integration from navigation sensors (e.g., global positioning system - GPS, inertial measurements unit - IMU) and remote sensing or perception (e.g., camera, lidar, sonar) systems; it comprises a wide range of algorithms designed to provide an autonomous vehicle with the ability to move in an uncharted environment while producing a map (or model) of the scene (Menna et al., 2019).

3D animal forest formations can occur in flat and gently sloping seabeds, or even in vertical slopes, often with crevices, terraces and overhangs. This poses major difficulties in surveying from the surface and require complex acquisition paths from ROVs/AUVs/divers to collect images for proper 3D reconstruction. When utilizing underwater photogrammetry (or other optical methodologies) to survey marine animal forests, there is an important trade-off, as well as specific drawbacks and limitations that need to be considered. The spatial resolution of final maps depends on the quality of input images: underwater images suffer from wavelength-specific attenuation and scattering, which cause image degradation to increase significantly with distance. Thus, the distance to the object has a strong effect on the quality of the obtained images and consequently the 3D reconstruction. Additionally, in very shallow waters, rippling caustic are adversely affecting SfM and MVS methods, leading to less accurate matches (Agrafiotis et al., 2018) and causing issues in the SLAM based navigation of the ROVs and AUVs on shallow waters (Trabes et al., 2017). A full reconstruction of the 3D complexity of underwater animal forests is challenging, occlusions can occur, and different view angles must be designed. Additionally, high data redundancy is required. Accurately designed acquisition paths (Vidal et al., 2020) and/or omnidirectional cameras (Bosch et al., 2019) could be used as well as forward-looking cameras and modular survey designs, adaptable in real-time. This requires serious navigation abilities from the AUV and is substantially unenforceable with human divers. New navigation technologies are needed, including visibility enhancement (Berman et al., 2020) for visual SLAM and obstacle avoidance to enable close-range photogrammetry of specific features. Neural networks might offer a solution to improve the AUV capabilities in terms of obstacle avoidance and real time decision-making. Computer simulations may help in training the neural networks and achieve such improvement. The photogrammetric approach has been successfully applied to hard corals, while gorgonians, soft corals and erect sponges pose important challenges due to their passive movement with water flow. However, a SfM technique has recently been tested on images from a gorgonian forest (Palma et al., 2018).

2.2 Image and data analysis

The collection of underwater imagery for the monitoring of marine animal forests became a widespread resource, leading to the accumulation of millions of images each year. However, the rate of image acquisition and the amount of the produced 2D orthophotos dramatically outpaces the human ability to extract information from them (Beijbom et al., 2015). The most commonly required data are the organisms' size and abundance, the spatial distribution of populations on a broader landscape, and their evolution in relation to the changes of the underwater environment. Detailed information about 2D statistical methods for assessing these parameters, but also to evaluate growth and mortalities using ortho-mosaics are summarized in Edwards et al., 2017; Pedersen et al., 2019, Sandin et al., 2020. These large data collections consisting of images can also be coupled with previous experimental or field work observations and quantifications in single species or communities, enabling a validation of ex-situ analysis and a large scale investigations. For example: crossing the numbers of carbon input and output of a single organism together with its distribution, density, population structure and biomass in large spatial approaches, may be the key to understand the role of the organism as a carbon immobilizer (Coppari et al., 2019). Terrestrial tools (used to

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study land communities acting as carbon immobilizers for example) in marine systems are in implementation thanks to the advances in 3D-image analysis and quantification. Acquired digital data (images and 3D models) are also perfectly suited for the sharing within the scientific community and the public. This could enhance a multidisciplinary and shared research, in accordance with FAIR principles.

Regardless of the biological purpose, spatial analysis, such as detecting changes in organisms, implies the need to segment target species with a high degree of accuracy. Manual 2D segmentation, e.g., a per-pixel classification, is an extremely time-consuming process, that can be accelerated using deep learning-based methodologies (Pavoni et al., 2020).

The information on the depth axis is fundamental to evaluate the volumetric change caused by the structural growth or erosion. Additionally, many of the sessile organisms that constitute marine animal forests are hardly recognizable from a simple orthographic top-down view. The main prospect is to extend the semantic segmentation from images to height fields (2.5D) or 3D models. Open source segmentation software specifically targeted to marine species that handling 2.5D data have been already developed and distributed.

For example, TagLab (https://github.com/cnr-isti-vclab/TagLab) enables assisted and automatic annotation, leveraging a human-in-the-loop approach to improve the accuracy of automatic predictions. Besides, it supports the comparison of multi-temporal surveys, automatically extracting useful historical information from segmented regions.

3D automatic semantic segmentation is the open challenge yet to face. As highlighted by a comprehensive survey paper (Han et al., 2019), available deep learning architectures might fail in producing segmentation that meets the standards of ecological analysis. Moreover, the limits of architectures working on point clouds, such as the PointNet++ (Qi et al. 2017) and the one by Cicek et al. 2016, that is a variant of the U-Net architecture originally developed for biomedical data analysis, are not clearly assessed in this application field due to lack of benchmark dataset. Multi-modal learning approaches, combining oriented images, RGB and depth information, might help to fill this gap and solve the task (Dai and Nießner 2018).

3 Discussion

In the context of animal forests mapping and 3D structural complexity analysis, the integration of different technologies could support multi-resolution and multi-scale surveying and monitoring. AUVs have the potential to efficiently investigate vast unexplored underwater regions, while ROVs allow for a higher resolution and more detailed mapping of smaller areas of interest that exceed scuba-diving depth range.

Even if the scientific community is developing new approaches for improving “low” cost surveying and monitoring of the marine environment, their adoption is still not widespread since further testing and optimization of methodologies are needed. In addition, the limited funding for research , and the low interest of the general public in the seabed, slow these developments. Broad scale 3D reconstructions could improve the communication about the importance and diversity of marine environment and increase the public interest.

The main needs and gaps regarding the study of the 3D complexity of underwater animal forests are related to data collection and analysis (Figure 2), with concern to the improvement of diver-based or mobile robots (ROV/AUVs) methods in terms of positioning, guidance, and communication towards

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the surface. Adequate surveying performances of data collection platforms should be improved, depending on the level of robotic and further developments on real time decision capabilities (e.g. real time evaluation of the quality of the data gathered). Likewise, rigorous modeling of sensors, evaluation of metric accuracies and other methodological errors along with the standardization of data formats and analysis tools will be crucial focuses.

The efficiency and quality of collected data, including multiple sensors, data acquisition at multiple scales, and data fusion from multiple platforms and times, need to be supported by the development of machine learning algorithms and methods for biodiversity classification/segmentation and 3D models definition of underwater changing objects. Indeed, benthic populations display 3D behaviours in time whose accurate analysis on the high-resolution 3D representation of these habitats is still beyond modern solutions based either on geometry processing or on deep learning. Fully automated solutions dramatically reduce the human effort in 2D/3D analysis; however, the accuracy of deep learning-based methodologies in the recognition/segmentation of benthic organisms is still lower than human experts, and the dense marine animal forests with a large 3D development pose even more difficulties in the discrimination of organisms. An efficient analysis tool must consider a human in the loop approach, leaving the experts the chance to edit the automatic results thus improving the overall accuracy. In addition, the analysis of large image sets can directly or indirectly benefit from public engagement, through citizen science programs, as was the case with plankton (Robinson et al., 2017). Citizen science data need to be carefully pre-analysed in terms of accuracy and reliability to evaluate their effective use for mapping and 3D reconstruction applications.

Finally, the development of an information system to better retrieve and manage information on 3D complexity from collected data through time should be addressed. The integration of data belonging to various expeditions, methodologies and purposes is an important need too. The integration of all the existing habitat mapping data in a common and open information system could provide a more accurate, spatially representative assessment of habitat degradation and a proper design and management of restoration actions (Gerovasileiou et al., 2019). Ecological data are highly heterogeneous and complex to manage, therefore providing a shared and common understanding of data and processes will improve data accessibility and analysis. Ontologies (a knowledge graph-based Web tool, see Guarino et al., 2009) have a meaningful role in supporting knowledge sharing expectations. A common understanding facilitates communication between people and information systems (machines) and enhances the ability to search for information across different knowledge repositories, in light of meeting the FAIR (i.e., findability, accessibility, interoperability and reusability) data principles (Wilkinson et al., 2016).

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4 Conflict of Interest

Author Marco Palma was employed by the company Habitats Edge Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

5 Author Contributions

A.C., C.Ca., M.Po, and P.R. contributed to the conception of the study.

P.R. wrote the first draft of the manuscript and collects contributions and experiences of all the authors.

A.C., C.Ca., F.Ma., M.Po., P.R., R.S., S.Ri. contributed to the revision of the first draft.

All authors contributed to manuscript revision, read, and approved the submitted version.

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Figure 1 Ecological key aspects of marine animal forests and different technological approaches that can be applied at different spatial scales, depth, and 3D complexity of investigated area. In the table at the bottom, SLAM stands for Simultaneous Localization And Mapping. Illustrations modified from Montero-Serra 2018, and NOAA. Source: IAN Symbols Library, University of Maryland.

Figure 2 Main needs and gaps for 3D complexity investigations of underwater marine animal forests. The generation of exchangeable knowledge (information system) starts from standardized data.

In review

This is a provisional file, not the final typeset article

Figure 1.TIF

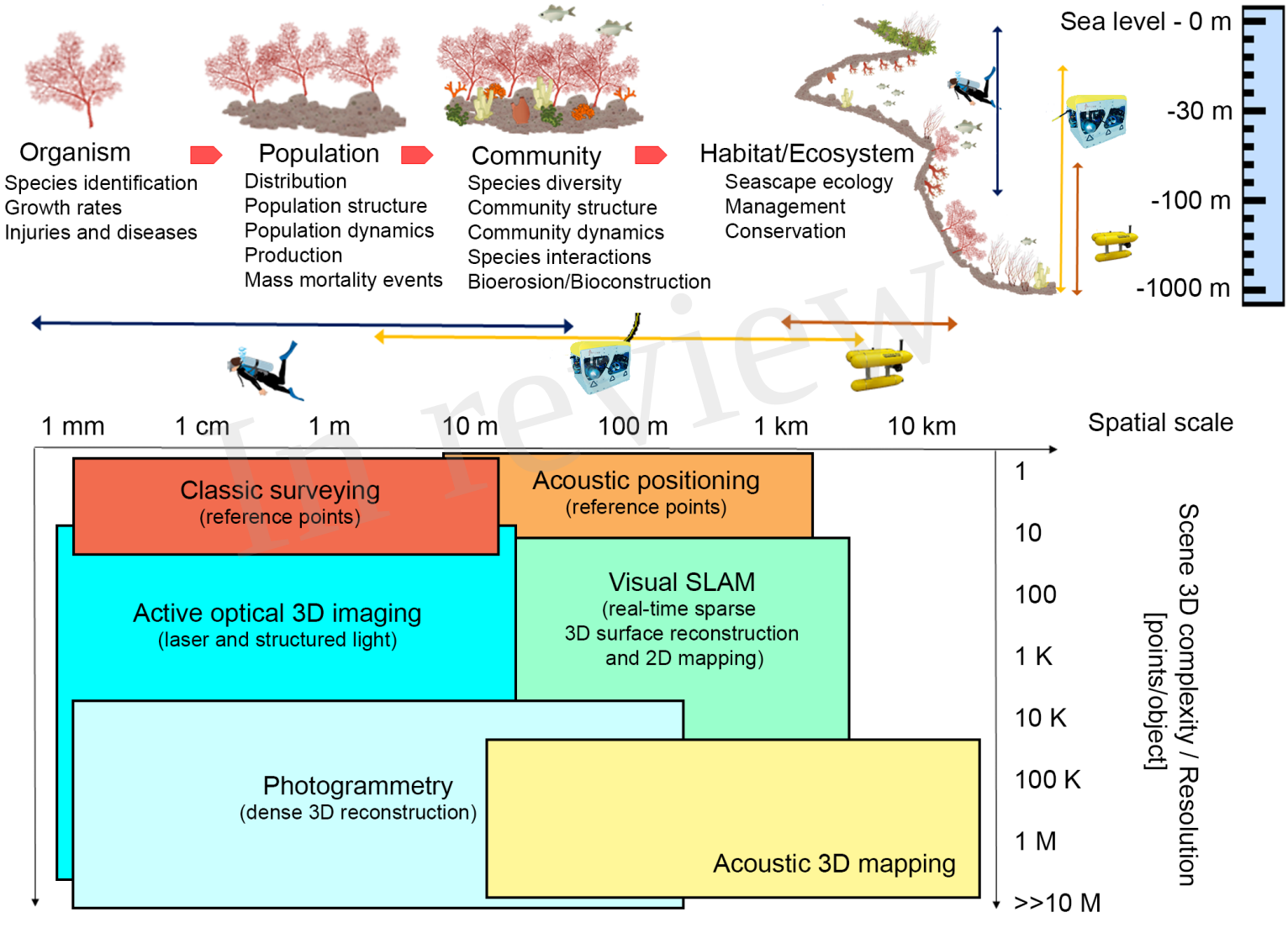

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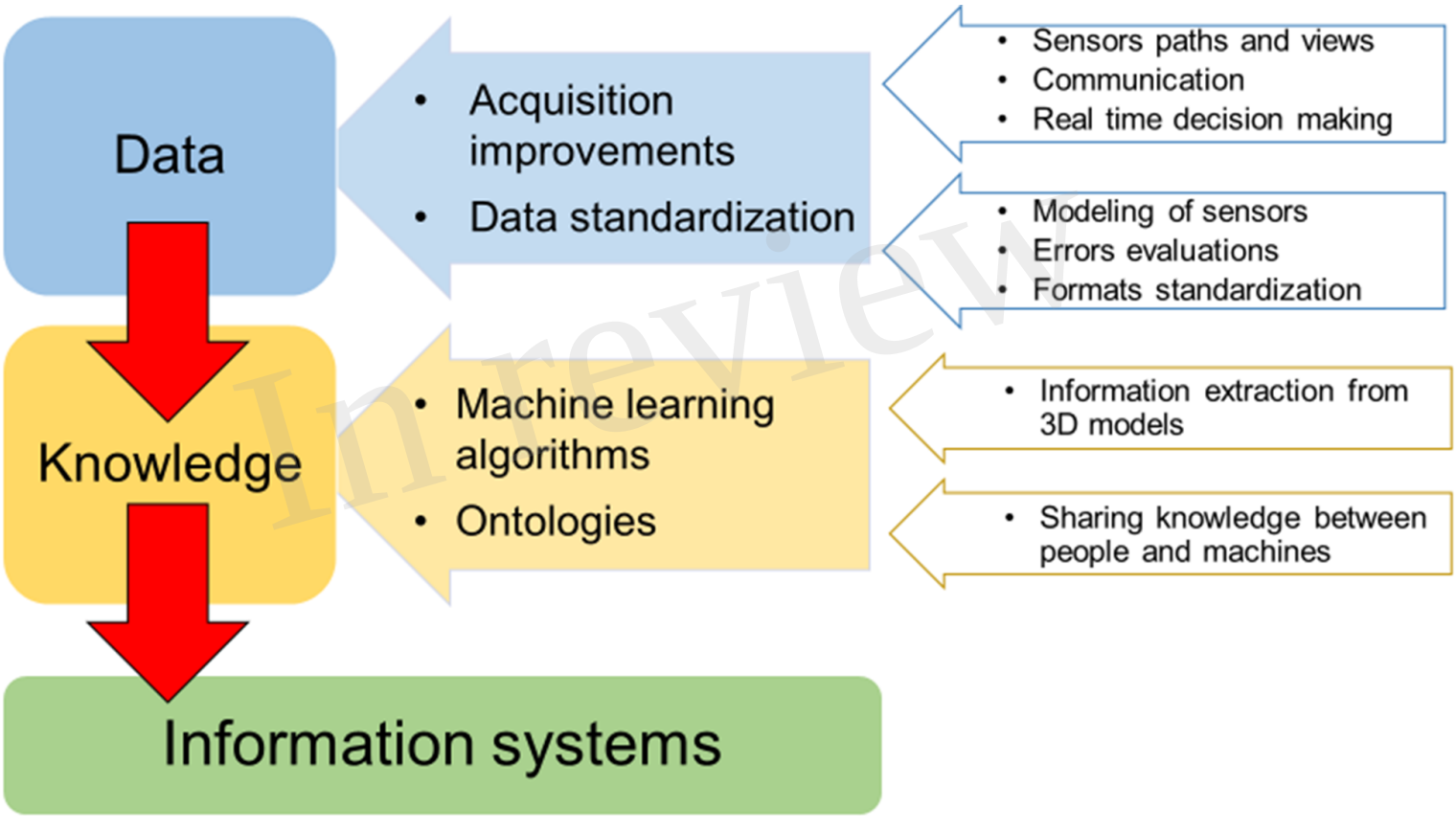
Figure 2.TIF



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