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Review

Photogrammetry, from the Land to the Sea and Beyond: A Unifying Approach to Study Terrestrial and Marine Environments

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Abstract: The series of technological advances that occurred over the past two decades allowed photogrammetry-based approaches to achieve their actual potential, giving birth to one of the most popular and applied procedures: structure from motion (SfM). The technique expanded rapidly to different environments, from the early ground-based and aerial applications in terrestrial scenarios, to underground and underwater surveys. Nevertheless, the transfer through different media required a period of adaptation that could take anything from years to decades. Only recently, thanks to the emergence of low-cost versatile imaging systems, have airborne and underwater photogrammetry became approachable to a wide range of research budgets, resulting in a popular cost-effective solution for many disciplines. Although numerous review efforts have already been made to resume the current knowledge on photogrammetry, this review summarizes the evolution of the technique in both terrestrial and underwater environments, paying special attention to the transfer of methods and techniques between the two environments. The acquired information helped to identify trends during its development and to highlight the urgency to widen the range of its applications in aquatic habitats in order to fill the current gap of knowledge on their structure and species distribution, delaying the design of proper conservation strategies.

Keywords: optical methods; structure from motion; three-dimensional approaches; multidisciplinary; survey

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1. Introduction

The description of habitat complexity is the method we use to define the surrounding environment and to quantify the structural key elements of an ecosystem [1,2]. From the traditional bi-dimensional (2D) survey techniques to the relatively recent three-dimensional (3D) approaches, every method has accomplished its objective in its own historical and technological context. Among the pool of techniques available is photogrammetry, defined as "the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and other phenomena" [3]. Although it has more than 170 years of history, various technological and methodological advancements have allowed for photogrammetry "Renaissance" over the past decades [4]. In fact, since its first documented cartographical applications by Laussedat in 1949, a series of turns of events pushed photogrammetry from its highly parameterized origins towards more optimized procedures, transforming it into the versatile tool it is today [5]. At its start, the rise of stereoscopy and the development of the airplane popularised the technique defining what is now called analogue photogrammetry [6]. In the 1940s, thanks to the arrival of computers and their increasingly widespread availability, fully analytical procedures were developed, leaving graphical solutions outdated and establishing the basis of modern photogrammetry. However, it was not until the appearance of digital imagery, together with the design of state-of-the-art algorithms (e.g., scale-invariant feature transform), that photogrammetry became such a powerful tool [7–11]. The subsequent optimization of pattern recognition algorithms and the exponential increase in computing power since the late 1990s finally allowed the methodology to achieve its actual potential, giving birth to one of the most popular and applied procedures: structure from motion (SfM) photogrammetry. With the appearance of SfM workflow, photogrammetric sampling and processing were facilitated considerably. Even though this procedure is based on stereoscopic principles, its main asset is its highly automated nature: the whole 3D geometry of the scene, including the camera orientation and positions, is solved through the implementation of a series of algorithms over a dataset of overlapping images [12].

The advent of more powerful workstations favoured the development of tailored commercial and open-source software, leading to easier access to the technique. With its increased potential and accessibility, it was only a matter of time before photogrammetry caught the attention of different disciplines, such as paleosciences [13–15], geological sciences [16–18], architecture [19–21], civil and industrial engineering [22–24], cultural heritage [25–27], and life sciences [1,28,29]. Photogrammetry's main purpose was no longer cartography and topography, but instead to record and explore the world from a 3D perspective. Consequently, the technique expanded rapidly to different environments, from the early ground-based and aerial applications in terrestrial habitats [30–32], to underground [33,34] or underwater surveys [35,36], and even outer space [37]. Generally, this transfer through different media required a period of adaptation that could take years to decades, firstly to adapt the existing apparatus to these new environments, and secondly to develop equipment affordable to the different discipline's budget [38,39].

In the case of submerged environments, the first underwater photographs were taken in the 1850s [40], but we had to wait until 1978 for the first major photogrammetric underwater survey [41]. This delay corresponded to the development of tools that allowed for a reliable underwater implementation of the technique, such as the appearance of the diving apparatus and the rise in compact water-proof housing. However, only recently underwater imaging systems became economically affordable to the broad public, making underwater photogrammetry approachable to a wide range of research budgets and resulting in a popular cost-effective solution for many disciplines (e.g., archaeology, marine biology, oceanography, or engineering) [42–44].

Nowadays, similar patterns as the ones described below can be observed in the coupling of photogrammetry with various emerging technologies developed in the first place for terrestrial applications. One clear example is the merging of photogrammetry and laser-scanning data, which, through its combination, allow for overcoming some of the techniques' individual limitations (e.g., increase in accuracy for photogrammetry and include colour information in the case of laser-scanning) [18,26,27]. Although numerous review efforts have already been made to resume the current knowledge on photogrammetry [45–53], the main aim of this work is to summarise the evolution of the technique in both terrestrial and underwater environments, paying special attention to the transfer of methods and techniques between the two environments. The acquired information will help to identify trends during its development and to highlight the urgency needed to widen the range of applications in the aquatic habitats to fill the still current gap of knowledge on their structure and species distribution, delaying the design of proper conservation strategies.

2. Materials and Methods

The review effort was conducted using the search procedure present in Table 1, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement as a guide [54], and limiting it to the cut-off date of 31 January 2022. Documents complying with the inclusion criteria and containing the search term combination in the title, keywords, or abstract were included in the screening. Only publications written in English, Italian, French, or Spanish were considered for eligibility. Publications not containing any information on photogrammetric surveys were excluded. This strategy resulted in 2546 documents being found. To select which papers to include in the analysis, a three-step process was implemented, as follows: (i) duplicates were excluded, (ii) abstract screening was performed to identify potentially relevant manuscripts (Figure 1), and (iii) a full-text screening was conducted. Finally, a total of 1923 publications were retained for the quantitative analysis (Table S1).

Table 1. Research procedure and inclusion and exclusion criteria.

Years	**1950–2021**
Search terms	"Photogrammetry" AND ("mapping" OR "survey") AND ("terrestrial" OR" underwater")
Database	Scopus
Inclusion criteria	Peer reviewed studies, conference papers and books Studies including photogrammetric applications. Published in English, Italian, French, or Spanish
Exclusion criteria	Duplicated manuscripts Studies not including photogrammetric surveys

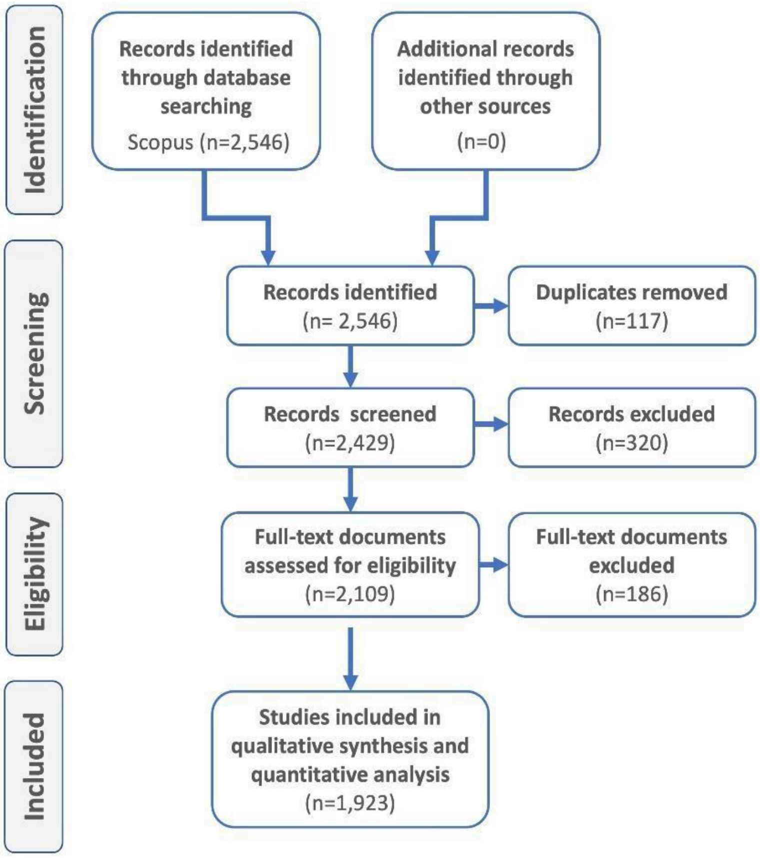

Figure 1. Flow diagram of the method and selection process implemented for this review effort.

From each of the included manuscripts, different information was obtained (Table 2A) and is presented as Supplementary Material Table S1. Regarding the specific details from each of the photogrammetric surveys types, the following details were extracted: (i) the branch of science in which the survey was framed; (ii) the environment in which the technique was applied; (iii) the specific habitat, structure, or object addressed; (iv) the nature of the surveyed item; (v) the type of implemented photogrammetry; (vi) if underwater, the maximum surveyed depth; (vii) the coupled methodology; and (vii) the location system (Table 2B; see Table S1 for categories). In all the analyses conducted on the literature, each publication could be included in one or more categories.

Table 2. Parameters used to classify photogrammetric surveys during the data extraction.

Category	Definition
(A) General features of the manuscript	
Year	Year of publication
Authors	Authors of the publication
Title	Title of the publication
DOI	DOI of the publication
Country	Country who funded the study
(B) Features extracted from each survey	
Branch of science	Discipline in which it is applied the survey
Environment	Environment in which the survey has been performed: (i) terrestrial; (ii) marine; (iii) freshwater; (iv) terrestrial–aquatic; (v) underground
Specific environment	Specific type of environment/structure/object surveyed
Nature scenario	Nature of the surveyed scenario: (i) natural; (ii) artificial
Sampling approach	Type of photogrammetry implemented: (i) airborne; (ii) ground-based; (iii) underwater; (iv) space-borne
Depth	If underwater, maximum depth at which the survey was performed
Coupled techniques	If applicable, complementary approach with which have been coupled the photogrammetry: (i) laser-scan; (ii) multi-spectral imaging; (iii) thermal imaging; (iv) acoustic techniques; (v) tomography; (vi) radiation; (vii) machine learning
Coupled location system	If applicable, location system with which have been coupled the photogrammetry: (i) global positioning system (GPS) and global navigation satellite system (GNSS); (ii) mobile mapping system (MMS); (iii) post-processing kinetics (PPK); (v) real time kinetics (RTK); (vi) simultaneous location and mapping (SLAM)
Vehicles	If applicable, vehicle used for the photogrammetry survey: (i) remote operated vehicle; (ROV); (ii) unmanned aerial vehicle (UAV); (iii) satellite

3. Results and Discussion

3.1. Photogrammetric Surveys through Time

The history of photogrammetry can be seen as a constant process of development and optimization [10], with a continuous widening of its application through time (Figure 2). Before 1960, only three articles were recorded, mainly for cartographical purposes [54–56]; however, since the 1960s the number of publications started to fluctuate until 2000, representing a breakpoint. From this year on, the growth of computing power and the emergence of new technologies [57] allowed for the spread of the technique. Among all types of photogrammetry, ground-based and airborne implementations were the ones that prevailed in the reviewed literature. Conversely, underwater applications started to be noticed just after 2010, with a peak in publications in 2019 (n = 35), likely thanks to the increasingly available low-cost waterproof compact cameras [58]. The general drop observed after this year

(Figure 2) can probably be traced to two main reasons: (i) not all published manuscripts were already added to SCOPUS when the online research took place and (ii) the effects of the 2020 COVID-19 emergency in terms of field-work and mobility restrictions [59].

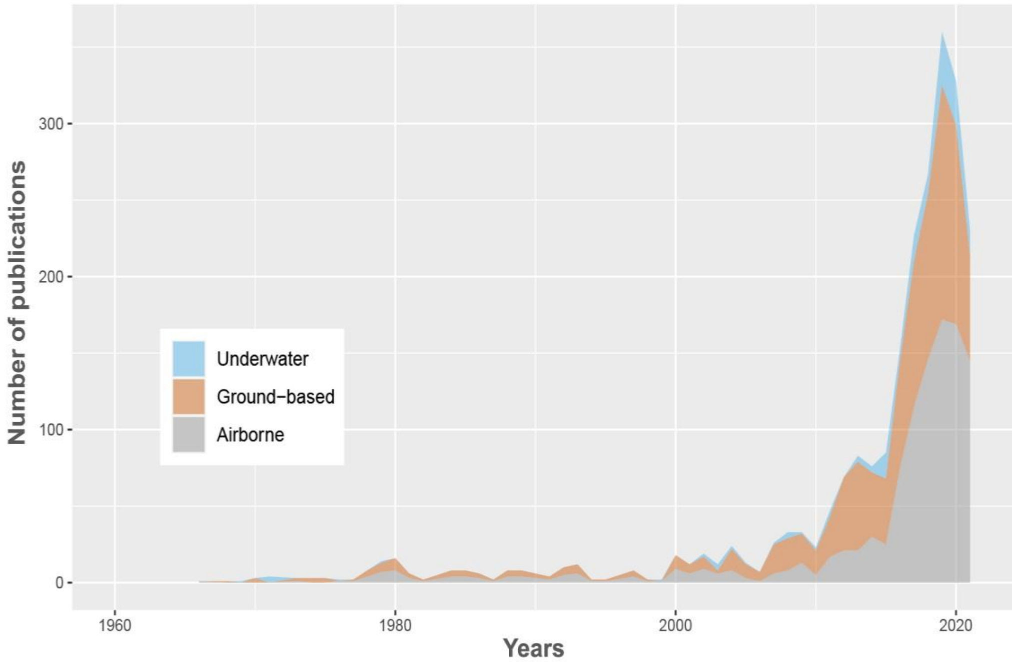

Figure 2. Area plot representing the number of publications per year in the function of the type of photogrammetry applied.

3.2. Worldwide Application of Photogrammetry

In the past, the application of photogrammetry was polarised towards developed countries; however, since 2010, the accessibility and thus use of this technique became increasingly frequent [11]. Considering the total number of publications and the types of photogrammetry considered here, Italy was the country with more research groups focused on photogrammetric approaches (with 454, 296, 231, and 47 publications in general, ground-based, airborne, and underwater applications, respectively) (Figure 3a–d). Other countries highly involved in photogrammetric surveys were the USA, the UK, China, France, Spain, and Germany (Figure 3a–d). While airborne and ground-based studies showed a similar distribution worldwide, underwater implementations still seem to be mainly focused on Europe and the USA (Figure 3d). The almost complete lack of studies in developing countries regarding underwater approaches could be related to the relatively high implementation costs until recent years [58]. However, it may also be explained as an artefact of this analysis, as only the first author's affiliation was recorded to define the geographical distribution of the publications [60]. With the current commercialization of low-budget solutions [58,61], the number of publications in all three photogrammetry types is expected to increase, especially in developing countries.

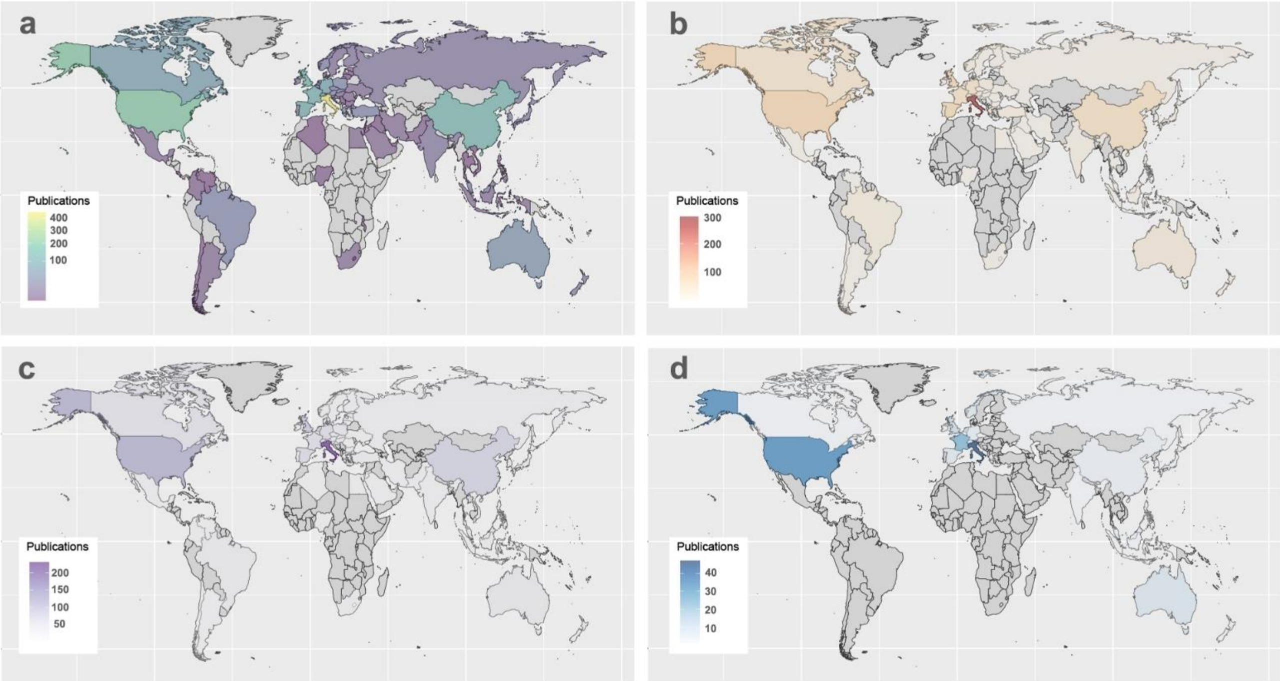

Figure 3. Geographical distribution of the countries who funded the study in the analysed publications: (**a**) total number of publications, (**b**) ground-based applications, (**c**) airborne-photogrammetry applications, and (**d**) underwater applications.

3.3. Photogrammetric Surveys among Disciplines

In agreement with Figures 2 and 4, some of the disciplines have a longer history applying photogrammetry. Taking a close look to the heatmaps, it is possible to identify some of the "pioneer-disciplines", such as photogrammetry/geomatics, geosciences, and cartography/topography, which were already implementing all three photogrammetry types in the 1970s (Figure 4a–c). These early applications are clearly marked by the testing of the technique's accuracy or its potential uses, especially for mapping purposes e.g., [62,63].

Even though it is evident how all three technique typologies benefited from an increase in the number of studies after 2010, airborne approaches showed the most marked growth in this latest period, reaching a wider range of disciplines (Figure 4b). This is directly related with the development and popularisation of small unmanned aerial vehicles (UAVs), which drastically decreased the cost of aerial surveys, previously performed by manned aircrafts [64]. The other two typologies, on the other hand, seemed to have been applied in more specific contexts so far, with a few areas of science monopolising their implementation (Figure 4a,c). In fact, the disciplines showing a predilection for ground-based approaches are cultural heritage/archaeology (164), geosciences (87), and architecture/civil engineering (78) (Figure 4a), which benefited from the opportunity to monitor scenarios from a 3D perspective, a useful approach in terms of structure integrity assessments [65–67]. Concerning cultural heritage, photogrammetry also allowed for the possibility for the development of virtual repositories, an emerging tool in constant evolution thanks to its huge potential in terms of science transfer and education [68,69]. In the matter of underwater applications, Biology/Ecology (46) and Cultural Heritage/Archaeology (28) were the disciplines mostly exploiting the technique (Figure 4c). This fact reflects the increasing interest of Life Sciences in the study and monitoring of underwater habitats' structural complexity and organisms' distributions [1,35,70,71]. Additionally, in terms of underwater cultural heritage, as well as land-based approaches, the popularisation of image-based techniques for the digitalization of historical sites also occurred. In fact, the number of 3D reconstructions and immersive experiences of archaeological sites skyrocketed over the past years [42,72], with a special emphasis on wreck scenarios [73–76].

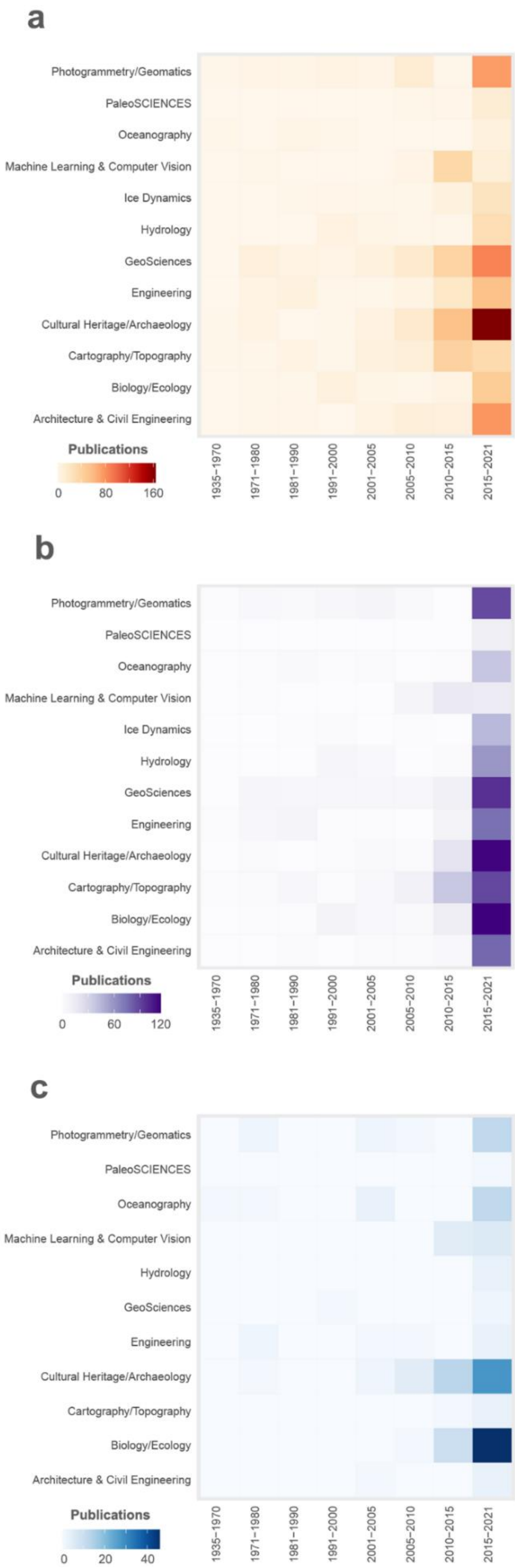

Figure 4. Number of publications per year and the discipline in which the study was framed. (**a**) Ground-based applications, (**b**) airborne-photogrammetry applications, and (**c**) underwater.

3.4. Environments Surveyed by Photogrammetry

As photogrammetry allows for cost-effectively evaluating a wide range of scenarios at different scales, it has rapidly expanded through different environments along history [1,77,78]. To analyse the scenarios covered by photogrammetric surveys, we focussed our analysis during the period containing most of the publications (2000–2021). A clear general dominance on terrestrial environments' surveys have been recorded (Figure 5a). Although after 2012 a promising increase occurred in the number of studies covering aquatic environments, the total number of works is still quite small ($n = 209$) (Figure 5a). Coupled and underground approaches are instead still marginal, a fact possibly linked to the purposes of these studies, which mainly focussed on coastal areas [79,80] and cave systems [81,82], respectively.

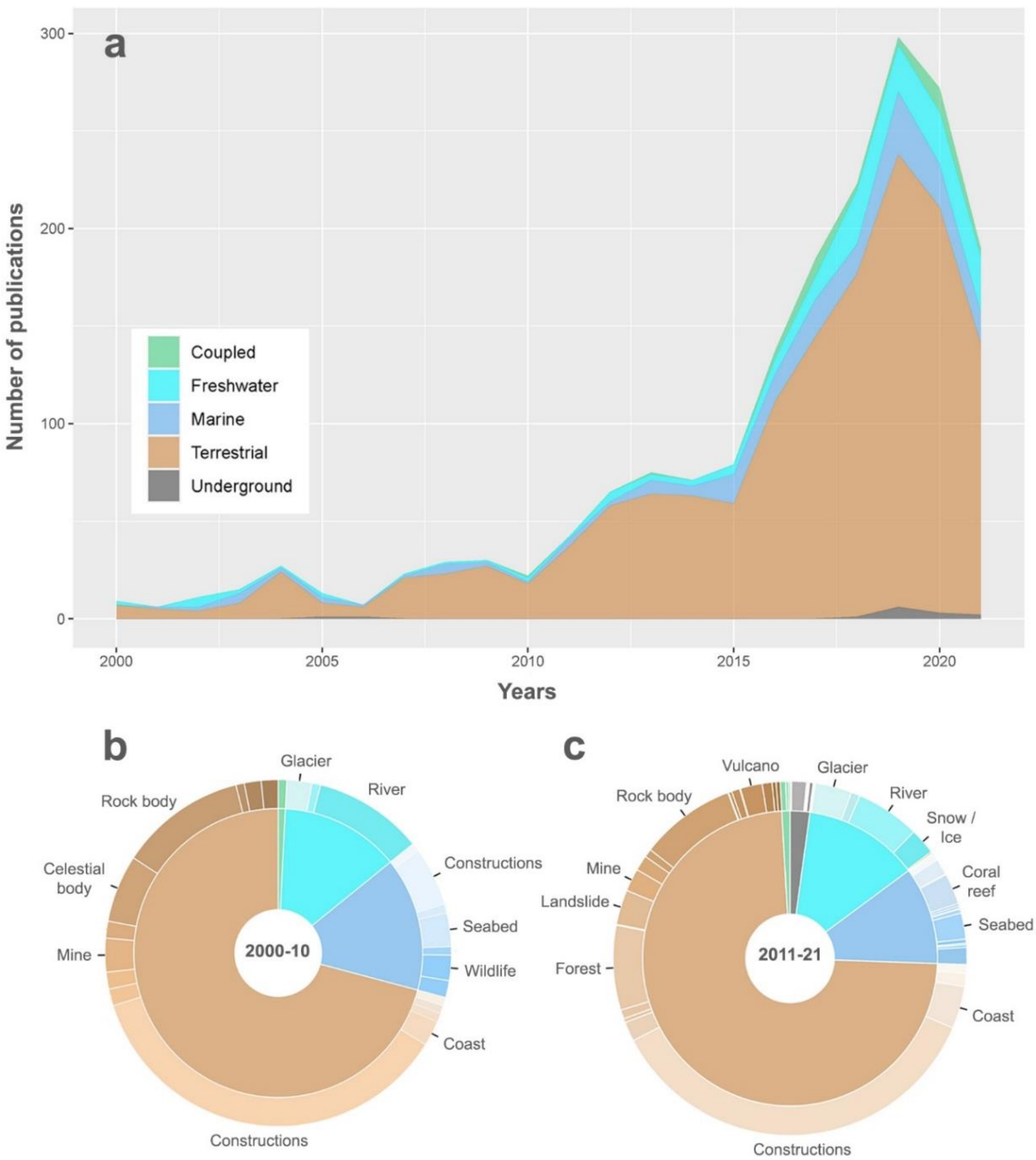

Figure 5. Type of environments addressed during the surveys over the past two decades: (**a**) temporal trend; (**b**) ring chart representing the percentage of surveys performed per environment from 2000 to 2010; (**c**) ring chart representing the percentage of surveys performed per environment from 2011 to 2021.

A deeper analysis was also performed considering the two decades separately, in order to understand which scenarios were assessed (Figure 5b,c). Construction surveys prevailed in terrestrial environments for both decades, driven by its rising application in cultural heritage and architectural studies (Figure 5b,c). Even though the ratio terrestrial–aquatic did not change significantly among the decades, a higher representation of natural scenarios could be detected (Figure 5b,c), with the emergence of forests monitoring activities in land, of ice dynamic research in fresh-water media, and coral reefs in marine habitats (Figure 5c).

Environmental sciences have always acknowledged the importance of 3D complexity as a main driver of ecosystem functionality, but it is only now that we have the tools to properly quantify it [83–85]. The current decade (2021–2030) has been defined by the United Nations as the Decade for Ecosystem Restoration, during which landscape approaches will be promoted to prevent and reverse ecosystem degradation in terrestrial, freshwater, and marine environments [86]. Huge monitoring efforts will be necessary to properly assess their status and the effectiveness of the restoration actions [86].

The marked increase in the number and diversity of photogrammetric approaches in life and environmental sciences suggests the technique as a suitable candidate to cost-effectively survey wide natural areas, monitoring changes from both a 2D and a 3D perspective and assessing features previously oversighted, such as structural complexity.

3.5. Bathymetric Distribution of Underwater Surveys

Most of the studies assessing aquatic systems mainly address depths accessible by recreational diving [87], leaving our oceans largely unexplored, with only a few sparse pieces of information collected about the deep sea [88]. Although huge international efforts are being made to cover these gaps [89], there is still much work to do before we have a complete map of our oceans' floors. Indeed, we observed how most of the underwater surveys were performed between the surface and 40 m depth (78), leaving deeper areas highly underrepresented (Figure 6), with the deepest survey reaching 3659 m [78]. Biological studies (36) were the most abundant from the surface down to 40 m depth, mainly tackling coral reef ecology (see Table S1 for references). Below this bathymetry, archaeological surveys were the ones prevailing in the literature, mostly addressing wreck remains (see Table S1 for references). However, up to 45% of the total documents assessing underwater scenarios could not be considered for the creation of Figure 6 as they did not provide any specific information about the depth range covered by the survey's activities (Table S1). Nonetheless, the highlighted gaps of knowledge are expected to be gradually filled by a combination of: (i) the continuous reduction in the operational costs of remote operated vehicles (ROVs) [90,91]; (ii) the increased frequent involvement of the technical diving community through citizen science projects [87,91–94]; (iii) the international legislations (e.g., Marine Life 2030 and other various Ocean Decade programs) aiming to increase the number of monitoring plans worldwide to create a global network and community of practice for the observation and forecasting of marine life [95]; and (iv) the international effort being performed in the framework of the GEBCO Seabed 2030 project, which aims to map the whole oceans by 2030 [89].

3.6. The Revolution of Unmanned Vehicles

Thanks to the development of powerful micro-computers along with the downsizing of remote sensing devices, the survey costs of remotely control systems have dropped continuously in the past years, persuading more and more disciplines towards the everyday use of these robotic systems [60,90,96]. To analyse this phenomenon, we decided to focus on the period from 2010 to 2021, as our research strategy only included six studies before 2010 (see Table S1 for references). The growing interest in the use of unmanned vehicles is reflected in Figure 7. Unmanned aerial vehicles (UAVs) found rapid popularization and implementation, substituting the more traditional airborne approaches and considerably reducing the sampling costs [97]. The drastic increase after 2015 of aerial drone-based surveys (Figure 7) was related to the relatively rapid commercialization of low-cost systems [63,97], while their underwater equivalent (i.e., ROVs) was still struggling with the development of more accessible systems due to the intrinsic challenges and logistic constraints of underwater robotics [91,98]. For this reason, the total number of ROV surveys found by our review strategy was quite low (n = 59), even though a slight growth in their use was observed in the last few years (Figure 7). In fact, ROVs are mainly used by offshore oil and gas companies for inspection, maintenance, and repair of their infrastructures [98]. Nonetheless, the release of more approachable priced apparatus allowed for predicting a rise in the application of ROVs by the scientific community, and with it, an opportunity to increase the knowledge on deep environments, helping with the implementation of nature-based management and conservation strategies.

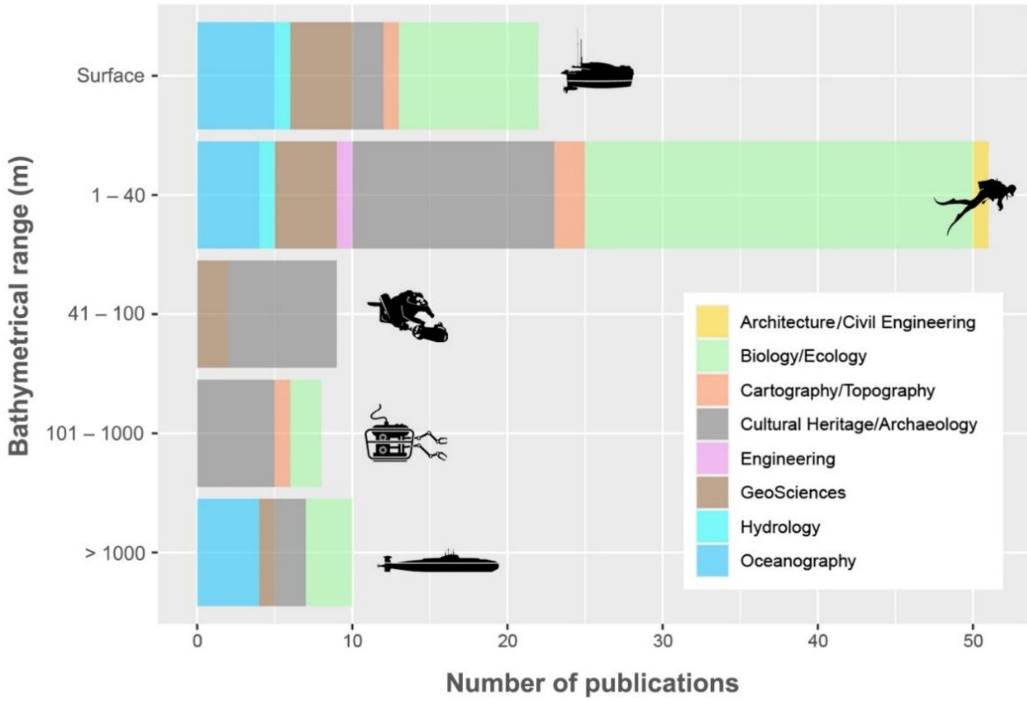

Figure 6. Bathymetric distribution of underwater photogrammetric approaches with the relative disciplines of implementation. Icons indicate the main but not exclusive tools applied at each depth range.

In terms of the type of surveyed scenarios in the last decade, an increase in the number of studies addressing natural environments was observed compared with artificial scenarios, especially when UAVs were used (Figure 7). Nowadays, the coupling of cutting-edge technologies (e.g., multi-spectral imagery, laser-scan, and thermal imagery) with UAVs, have opened new possibilities, becoming the tool of choice for small and medium scale surveys for many different user groups [51,99,100].

Autonomous underwater vehicles (AUVs) were not considered for plotting Figure 7 due to the small number of studies included in this review (5), even though they are now a hot topic in research [46,101], especially for monitoring purposes. It is expected that the same technological advances contributing to the appearance of low-cost ROVs will price down these high-budget pieces of equipment as well [91]. In fact, these systems, together with machine learning approaches and real time photogrammetry, will be a promising research line for the forthcoming years.

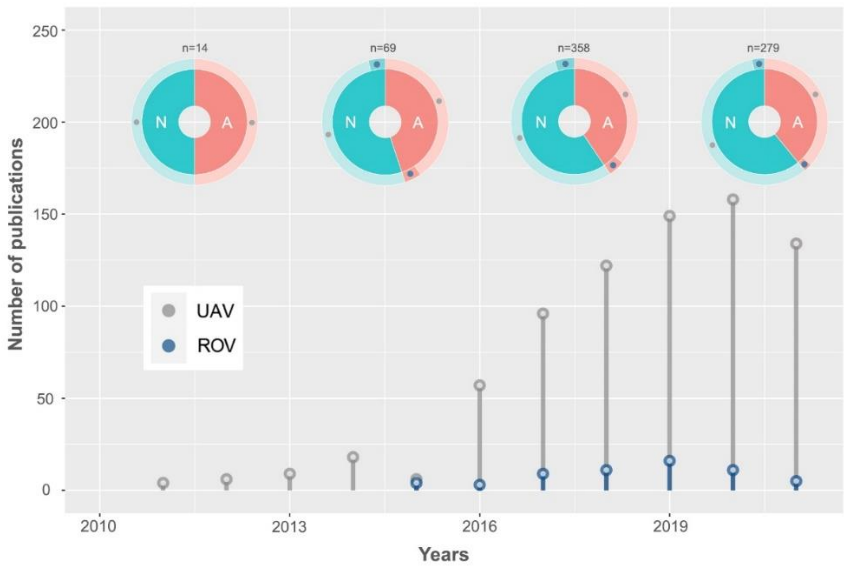

Figure 7. Lolly plot presenting the use of unmanned aerial vehicles (UAVs) and remotely operated vehicles (ROVs) in the past 21 years. The ring plots on the upper part of the figure show the percentage of studies covering natural (N, in bluish) or artificial scenarios (A, in red) for each three-year period. *n* = number of total studies.

3.7. Coupling of Photogrammetry with Other Techniques

Another interesting aspect of photogrammetry is its versatility to be coupled with a wide range of complementary approaches (Figure 8). By analysing the literature, a repeated pattern could be identified (Figure 8), in which the first trials on technique-coupling were often performed to control the accuracy of photogrammetry or to test a possible data merging among techniques [102,103]. Over the years, these combinations raised some interesting approaches, occasionally ending up in the following:

(i) The development of new methodologies, such as multispectral photogrammetry [100,104] or thermal photogrammetry [105];

(ii) The increase in the accuracy and resolution of the technique (such as laser-scanner or real time kinetics) [106–109];

(iii) The approach to new environments through the use of ROVs or AUVs [27,34,110,111].

After 2016, a great increase in the number of surveys using coupled approaches could be identified, with laser-scanning being the most paired technique (Figure 8), reaching great results through merging the textures obtained from the RGB imagery with the depth maps produced by the laser-scanning [112]. Its coupling with location systems (e.g., real time kinetics, simultaneous localization, mapping, and Global Navigation Satellite Systems) also gained some adaptions over time (Figure 8), representing a great improvement in the georeferencing process of digital reconstructions [21,113–116]. Conversely, coupling with other techniques, such as acoustic systems and multispectral or thermal imagery, still nowadays remains low (Figure 8), mainly due to their specificity, thus reducing their application to a few disciplines [99,115].

Regarding the transfer of these coupled approaches to the underwater domain, while some of them are already widely applied (e.g., multibeam, radar, and sonar) [76,117], others are still poorly implemented due to the high costs of the required equipment (e.g., multispectral imagery or underwater location systems) or the limitations of specific techniques (e.g., the fast extinction of near-IR wavelengths in underwater environments for thermal imagery) [118,119]. There are still some challenges to overcome before they can become suitable candidates for low-budget underwater survey plans. Nonetheless, the rapid development of new technologies and the growing interest in aquatic environments create the perfect framework to keep investing in the implementation of non-invasive, low-cost, multi-sensor approaches, thus contributing to the establishment of standardised monitoring techniques in a multidisciplinary scenario.

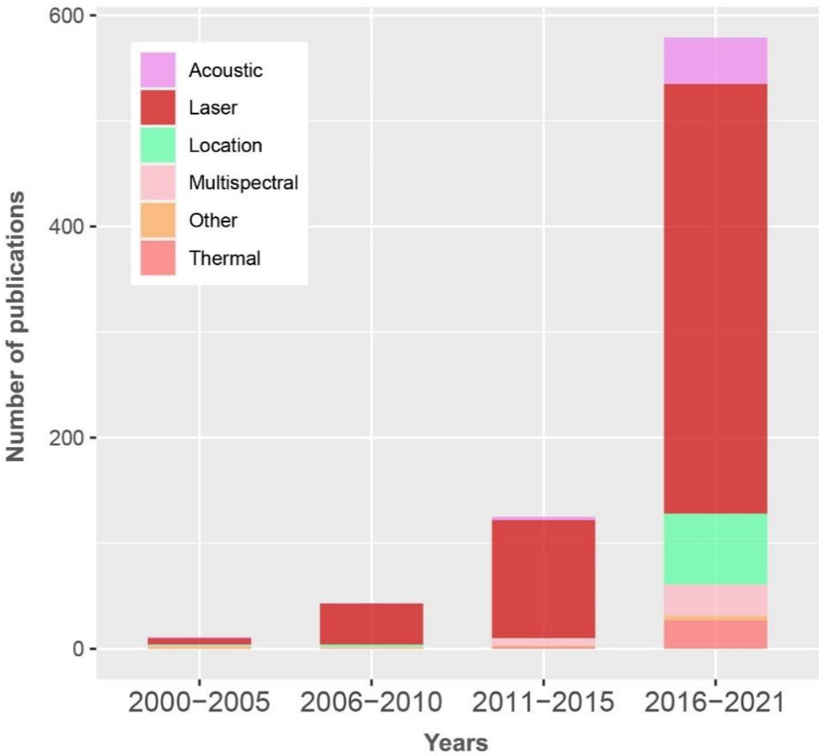

Figure 8. Stacked bar plot showing the number of publications in which photogrammetry was coupled with other techniques during survey activities.

4. Conclusions and Future Perspectives

This study summarises past and current trends in photogrammetry applications in both terrestrial and aquatic environments. Over the past decades, this technique has provided a cost-effective solution for different disciplines to approach a wide range of scenarios that are more and more frequently represented by natural environments. In this context, the inclusion of SfM photogrammetry in monitoring programs should be considered to accurately describe habitats' structural complexity, creating temporal baselines fundamental to understanding and measuring possible changes over time, and thus possibly helping lawmakers in designing ad hoc nature-based conservation and protection plans. The continuous development of new technologies has allowed for couple photogrammetry with other techniques, capturing global complexity as never before. Given the current tendencies, an exponential increase in its application both in terrestrial and aquatic environments can be expected. Advances in the field of machine learning classifiers, cloud computing, and unmanned vehicles will play a key role in upscaling and automatization of the technique.

Underwater photogrammetric approaches still have a long road to go before reaching their full potential. The appearance of more economic underwater location systems and ROVs will contribute to the popularization of photogrammetric surveys for medium and large-scale assessments. Nonetheless, at local scale, the wide-spread use of low-cost compact cameras allows photogrammetry to be included in marine citizen science programs (e.g., protocol 11 of the Interreg MED MPA Engage project, [120]), highlighting the high versatility of the technique and its huge potential in public engagement.

To conclude, there is an urgent need for the implementation of non-invasive, cost-effective techniques, and SfM photogrammetry represents a valuable example that could allow us to look at marine ecosystems from a multiscale integrative perspective, which is fundamental for the exploration of seascapes and the design of effective and tailored conservation measures.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse11040759/s1. Table S1: List of publications, with all articles' details.

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