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Photogrammetry as a New Scientific Tool in Archaeology: Worldwide Research Trends

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Abstract: Archaeology has made significant advances in the last 20 years. This can be seen by the remarkable increase in specialised literature on all archaeology-related disciplines. These advances have made it a science with links to many other sciences, both in the field of experimental sciences and in the use of techniques from other disciplines such as engineering. Within this last issue it is important to highlight the great advance that the use of photogrammetry has brought for archaeology. In this research, through a systematic study with bibliometric techniques, the main institutions and countries that are carrying them out and the main interests of the scientific community in archaeology related to photogrammetry have been identified. The main increase in this field has been observed since 2010, especially the contribution of UAVs that have reduced the cost of photogrammetric flights for reduced areas. The main lines of research in photogrammetry applied to archaeology are close-range photogrammetry, aerial photogrammetry (UAV), cultural heritage, excavation, cameras, GPS, laser scan, and virtual reconstruction including 3D printing.

Keywords: photogrammetry; archaeology; history; surveys; 3D computer graphics; remote sensing; cultural heritage; UAV; bibliometry; Scopus

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1. Introduction

Archaeology is the study of human cultures through the analysis of their material evidence to explain the origin and development of civilizations [1]. So, archaeological sites are a valuable source of historical information [2]. The materials found at these sites are usually studied using both physical and chemical methods, from radiocarbon dating to the study of food remains in the earliest pottery [3]. Within this science, specializations such as archaeometallurgy have meant that iron has been a valuable product since the Iron Age [4]; therefore, the identification and investigation of archaeological evidence related to the production and consumption of iron is a very relevant challenge for archaeology [5]. What is clear is that it is essential to record how and where a certain material was found, and to make a scale map of the excavation for each stratum found [6]. The availability of the most accurate documentation allows in the future to take up where it left off, or even reinterpret it if another hypothesis came up later [7].

Photogrammetry is a technique which was first developed in the early 19th century [8]. The first aerial photograph was taken in 1858 by French colonel Aime Laussedat (1819–1907) [9], although Laussedat had begun his experiments to use images for topographical mapping in early 1851 [10]. Later, Austrian army captain Theodor Scheimpflug (1865–1911) carried out zonal rectification around 1900, thus laying the foundation for the differential rectification used in ortho-photography [11]. Dr Carl Pulfrich (1858–1927) built the first stereocomparator in 1902, which allows a 3D stereoscopic vision of the relief. Thus, the photogrammetry era began with simple terrestrial photogrammetry, based on the principles of perspective intersections, passed through stereoscopic terrestrial photogrammetry, and in its aerial version passed through balloons; an example is the 1907 photographs of Stonehenge as seen from a war balloon [12]. One of the first practical results of aerial photogrammetry (using a balloon), or mapping, was achieved by the Italian captain Cesare Tardivo (1870–1953). In 1911, he made a mosaic of Venice with balloon photographs and, in 1913, he created a 1:4000 scale mosaic of Benghazi in Libya from aerial photographs taken from an aircraft [13].

The acquisition of large-scale information has thus been a permanent feature in the history of the world and photogrammetry has played an important role in achieving this. Moreover, the digital photography associated with the development of image processing and its automation has made these techniques widely attractive for various areas of application [14]. Today, the use of online information in our environment is in great demand for all kinds of social applications and is increasingly used for research purposes. Therefore, mapping platforms such as Google Earth are widely used to provide a clear view of cultural heritage areas [15], elevation data [16], or for the improvement of national-scale land cover classification for ecosystem services improvement [17].

From conventional aircraft flights such as those mentioned above, UAV technology allows to quickly capture significant areas of land in a reasonable time and at low cost [18]. The use of UAVs has led to the widespread use of aerial photogrammetry [19] in significantly more areas than was previously available, including their potential use in archaeological surveys [20,21]. In fact, modern photogrammetric techniques are based on the traditional ones, but the requirements, necessary equipment and the complexity of the tasks are considerably reduced. Therefore, UAV photogrammetry can be understood as a low-cost analytical tool. It has been used in many situations where it was not possible before, such as at archaeological sites [22], or in forestry [23] and agriculture [24]. In summary, traditional surveying only allows to collect discrete data of the feature lines that determine a surface, border, slope change, etc., while the massive capture methods based on photogrammetry allow to collect continuous points of the surfaces [25].

The advance of digital photography, where the contribution of computer sciences allows the use of conventional cameras, reducing the cost of the calibrated metric cameras that were previously mandatory for photogrammetry, cannot go unmentioned. The required parameters to adjust the geometrical distortions of the image are called inherent parameters of the camera. To determine them a procedure called calibration will be performed. There are several methods and algorithms for camera calibration, some of them automatic from photographs of printed patterns, but nowadays there is free software such as the programme called Hugin 2, dedicated to the stitching of images for the construction of panoramas which, indirectly, allows both the calibration of cameras and the correction and rectification of images.

Figure 1 summarises the photogrammetric processes involved in archaeology. Firstly, the 3D object is found, and depending on the proximity to it, the photogrammetric technique is chosen: from the ground, low altitude flight (UAV), traditional flight with aeroplanes, or if it is at a high altitude from satellites (remote sensing). The second step in image acquisition is the choice of the physical sensor or vision system, which can range from a conventional camera, photogrammetric camera, LiDAR (laser imaging detection and ranging), etc. Once the 2D images or information has been obtained, the digital image processing is carried out. Here, a large number of techniques come into play, starting with image filters, since all images have a certain amount of noise; this may be due to the camera or the signal transmission medium. Generally, the noise appears as isolated pixels that take on a different grey level than their neighbours [26]. Other are arithmetic operations with images of the same scene, or combination from different points of view (stereoscopy), to later carry out automatic classification [27], shape recognition [28], or pattern prediction. To find the contours, the image is searched for areas in the image where the pixel intensity changes fast. usually using one of the following criteria: locations where the first derivative (gradient) of the intensity is of a magnitude greater than that of a predefined threshold, or places where the second derivative (Laplacian) of the intensity has a zero crossing. In the first case, large peaks shall be sought and in the second case, changes of sign shall be sought. All of these latter techniques can be understood as belonging to the scientific field of computer science.

Finally, metric quality results can be obtained, in many formats, to make 2D models as maps, or with all the information contained in the photograph as orthophotography, or 3D models for DEM or virtual reconstruction.

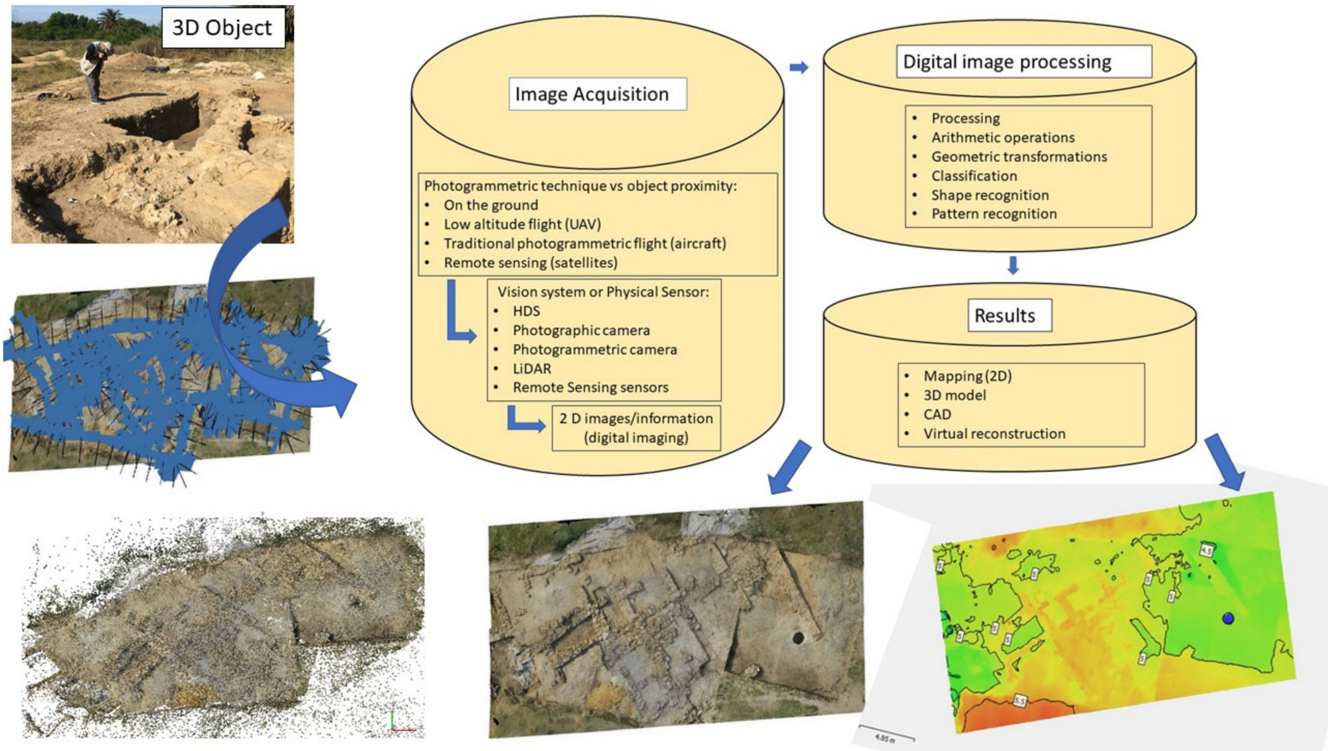

Figure 1. Summary of photogrammetric processes involved in archaeology.

It should be noted that advances in photography itself have been revolutionary milestones for photogrammetry and photointerpretation. It should be remembered that scientific advances take time to be implemented, since for example the first colour photograph by Thomas Sutton was presented by James Clerk Maxwell on 17 May 1861 at King's College, London [29]. The system was based on the discovery of the physicist Clerk Maxwell, who separated colours into magenta, cyan and yellow. Even the most recent digital cameras make use of this separation method to capture light. Colour is formed by combining the three basic colours red, green and blue (RGB). Figure 2 shows how light is separated into its three main directions, RGB, and how the result is the grey scale. A digital image can now be understood as a two-dimensional array of pixels with different luminous intensity (grey scale). Thus, to obtain the desired colour X, the arithmetic sum of the components is carried out: X = R + G + B, graphically represented by a cube—see Figure 2.

It is therefore understood that the development of sensors has benefited archaeological applications using phototogrammetry, such as the use of near-ultraviolet images [30] or aerial thermography [31]. Moreover, multispectral and hyperspectral satellite-based instruments have provided substantial data for the detection, mapping and investigation of archaeological locations all over the world [32]. At the end of the 20th century with the launch of IKONOS, the first commercial very-high-resolution satellite with a spatial resolution of 1 m, a major improvement for archaeological research applications, was achieved [33,34]. In summary, with the digital revolution, images are less expensive, easier to process and the latest algorithms can work with a low-cost or standard camera.

The main objective of this research is to analyse global research trends in the application of photogrammetry to archaeology, as well as future lines of research. To this end, a bibliometric study of all indexed publications in these fields will be analysed and classified by means of a cluster analysis. As secondary objectives in addition, the periods in which significant advances in scientific production related to both fields have taken place, in which scientific categories these contributions can be classified, which are the main countries and institutions working in this field and their possible relationship with each other will also be sought.

Although there are no specific bibliometric studies in the literature on photogrammetry applied to archaeology, it is worth highlighting the works related to cultural heritage, which were searched in WoS (Web of Science), obtaining 535 records for the period from 1987 to 2007, and finding a significant increase in the number of publications since 2012. It is also concluded that tourism is the main driver of the digital transformation of heritage [35] and digital technology tools, such as 3D technology, laser technology, geographic information technology, database modelling, providing important tools for risk management, monitoring, planning and visualisation of cultural heritage [36]. In the analysis of the scientific communities that have been found are applications in archaeology, with related means of detection, such as laser scanning, radar, remote sensing or photogrammetry [37].

Later, a bibliometric study was carried out focusing on remote sensing and archaeology for the years 1999 to 2015, but limited to European countries [38]. They obtained 434 results. In this research, they found an increasing linear trend over time, i.e., they did not find periods of progress in scientific publication in this field. However, what is relevant for our research is that in the analysis of the evolution of the keywords, photogrammetry and digital photogrammetry have stood out since 2010, and in the last years studied, 2015, coastal archaeology and computer vision have appeared.

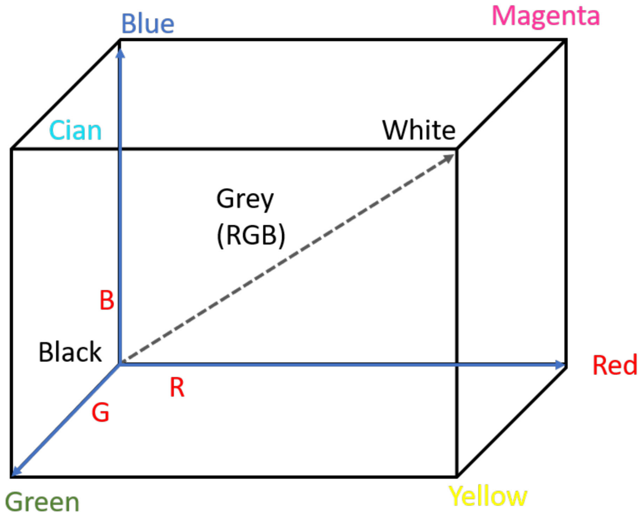

Figure 2. Relationship between greyscale and colors (RGB) of the photography.

2. Materials and Methods

There are two large scientific databases—Scopus, and WoS (Web of Science). Scopus has been proven to overlap in many scientific areas by a large percentage with WoS (Web of Science) [39,40], and has been successfully used for a large variety of bibliometric studies in specific areas such as medicine [41], social sciences [42] or engineering [43]. Therefore, Scopus has been used to conduct this research.

The query was: (TITLE-ABS-KEY (archaeology) AND TITLE-ABS-KEY (photogrammetry)). See Figure 3 for an overview of the methodology followed. The analysis of the scientific communities, both in terms of keywords and the relationship between authors or between countries, was executed with the software VOSviewer [44]. The problem of community detection arises from a common characteristic inherent to all complex systems. This characteristic is the presence of patterns of nodes that are more densely connected to each other than to the rest of the nodes in the network [45]. The nodes that show these connection patterns are called communities. From these, they are expected to share certain properties that will allow the detection of new characteristics or functional relations of the network [46]. The search for these patterns or community structures is known as the problem of community detection. To do so, the optimal community structure that best represents the characteristics of a network has become a scientific challenge. For this purpose, a multitude of algorithms and objective functions have been proposed to solve the problem. Among them, the evolutionary algorithms and the modularity index have stood out as the main solutions accepted by the scientific community [47]. The software tool Vosviewer uses an algorithm for modularity-based community detection in large networks. Modularity functions were introduced by Newman and Girvan, and the idea of using them to detect communities by optimizing a modularity function was proposed by Newman himself [48]. There are many variants of the modularity-based approach to community detection. These variants, for example, deal with targeted or weighted networks, or provide a resolution parameter [49] that allows for customization of the level of granularity at which communities are detected and mitigation of the so-called resolution limit problem [50]. For the case of the date trend, the keywords are associated with the date of publication; based on a date probability density function for a particular keyword, the maximum of the function is chosen to indicate the date where a particular keyword is most accumulated.

Note that as an alternative tool to the software used in this research, there is also a new open-source software tool, SciMAT, which performs scientific mapping analysis [51].

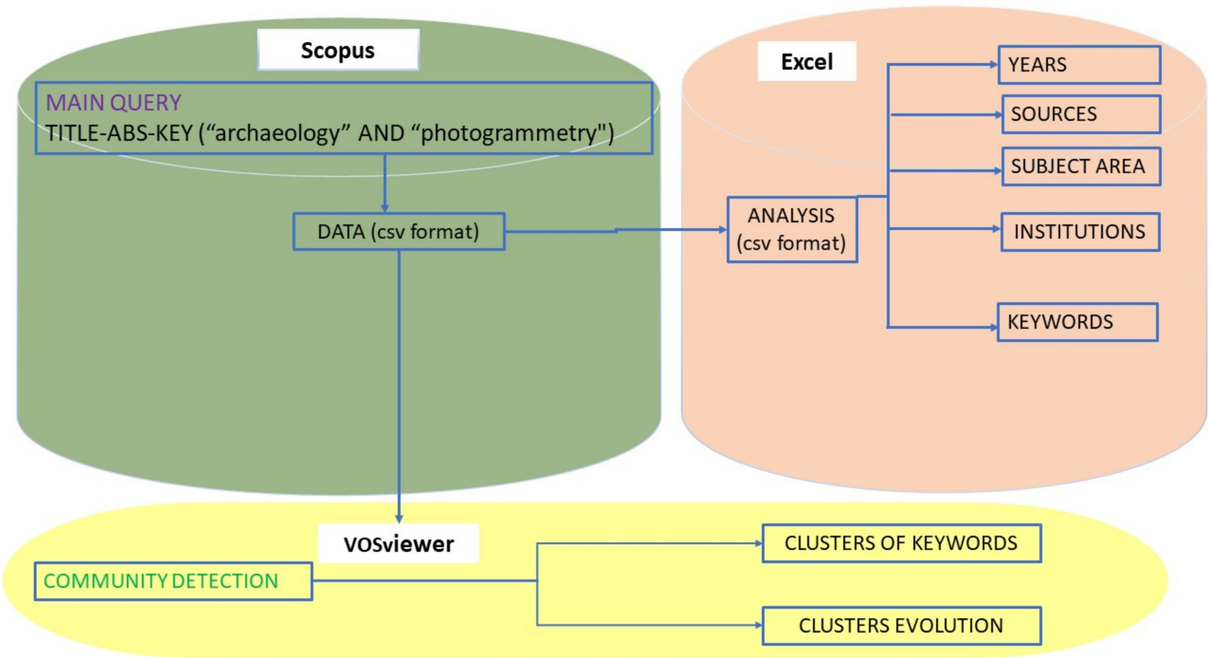

Figure 3. Methodology flow chart.

3. Results

The search yielded just over 700 results in the studied period (1980–2019), of which 52% were in conference paper format, 43% were articles (of which 2.5% were review articles in this field), and just under 2% were books or book chapters. This is an indicator that this field of research is certainly new. The more consolidated the research, the higher the percentage of books, and articles, but when it is dominated by conference papers, the scientific field is still on the rise [52].

3.1. Scientific Categories of Research in Photogrammetry and Archaeology

When analyzing the results obtained by the scientific categories in which they are indexed according to Scopus (see Figure 4) it can be seen, as expected, that it is led by social science (26%), where archaeology studies are partially included. Therein follow, almost at the same level, computer science (24%), then arts and humanities (12%), which is the most significant field of archaeology, and finally, the fields of earth and planetary sciences (9%), which is where geomatics is traditionally included, and engineering (8%). Other categories, as can be seen in Figure 4, are less relevant.

It should be noted that the same research can be indexed in several scientific categories at once. For example, a review on the use of drones (or UAV) to make 3D maps is outstanding [53]. This study deals with archaeology, but also with other sciences such as engineering since they propose that drones or UAVs can be considered as a low-cost alternative to conventional manned aerial photogrammetry.

However, other publications are indexed according to the journal, such as a case study of Mondújar castle (Spain) using UAV photogrammetry surveying for sustainable conservation [54] or the rockfall susceptibility analysis of the western slope of the Cumae Mount in the Cumae Archaeological Site (Phlegraean Fields, Naples, Italy) [55].

The computer science category, for example, includes further advances in image analysis techniques, such as automated reconstruction of 3D scenes from image sequences [56], or specific research on UAV systems and flight modes for photogrammetric applications [57]. This last category, computer science, has considerable overlap with engineering, in the line of research being analyzed. As an anecdote, other categories could be considered, such as energy, medicine, or decision science. This, as mentioned above, is the result of review articles that involve or cover all the fields of study where certain technology can be applied; i.e., the work is also indexed in these categories.

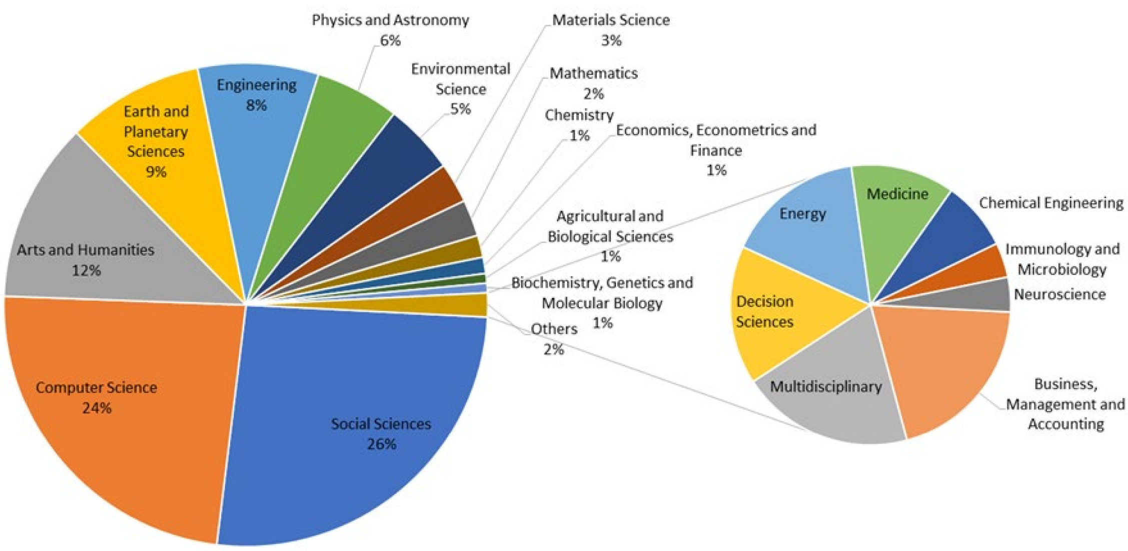

Figure 4. Distribution by scientific categories of research in photogrammetry and archaeology.

3.2. *Temporal Evolution of the Publications*

Over time, the evolution of these works has been discontinuous until 1999 (see Figure 5), which we could describe as an approach of archaeology to photogrammetry. This can be explained by two factors: either the costs or the technology were not appropriate for its implementation or also from the bibliometric point of view, since in the last 20 years they have launched significantly more scientific journals that increase the number of published papers in all sciences.

The figure only shows the studies since 1980, since previously the scientific production of these photogrammetric and archaeological studies was very sparse in time. The first recorded study began in 1962 with "The Teotihuacan Mapping Project" in the Valley of Mexico [58], where the idea was to fly an area of 20 km^2, although it was estimated that the site could more than double the area, about 53 km^2.

This project is still a reference in the early days of photogrammetry for archaeology and is being studied [59,60]. After this work, a gap of almost a decade appears. As early as 1970, the Celtic fields in Himmerland were discovered through vertical photography on a scale of 1:25,000 (Denmark) [61], where an ancient Celtic cultivation pattern was found. This may be considered an example of the so-called aerial archaeology techniques, in which a large area of land is analysed using photogrammetry. Another closer example could be the Phoenician-Punic fortified settlement on the coast of eastern Andalusia called Altos de Reveque [62]. Without intending to enter an in-depth debate on this issue, the need for the use of photogrammetry in archaeological excavations was already established in the 1970s. In the beginning, photography was used in archaeology, instead of photogrammetric techniques, and therefore the results obtained lacked metric accuracy. To cite one author who stated "Archaeologists seem to be generally unaware that if they used a square scale for photographs of their sites, they would increase the value of the photographs as it would be possible to obtain photogrammetrically accurate plans from them" but it was also stated that "if the photograph is taken just for an excavation it can be expensive" [63]. It is this constraint on costs that has undoubtedly limited the widespread use of photogrammetry in archaeology over decades. However, there is clearly a constant and growing trend of documents with the issue of photogrammetry applied to archaeology in the last decade, from 2010 to 2019.

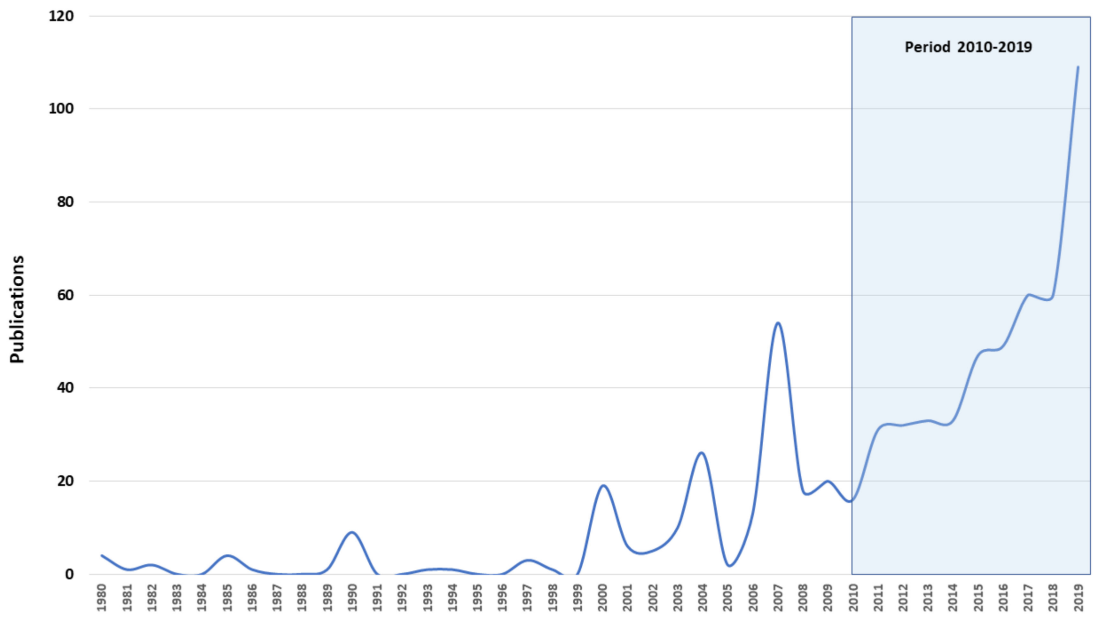

Figure 5. Temporal evolution of research in photogrammetry and archaeology.

3.3. Countries and Research Centres or Affiliations

Publications focussed on photogrammetry and archaeology are mainly produced by central research institutions in France or Italy, see Figure 6. The colours of the figure just intend to highlight the first three positions of this ranking, where the red colour is the one that leads this classification with more than 30 publications, the CNRS Centre National de la Recherche Scientifique, and the yellow colour for the next two, which have more than 20 each, the Consiglio Nazionale delle Ricerche, and a Spanish university, the Universidad de Salamanca. The institutions with more than 20 publication in this field are shown in Figure 4. Regarding these studies, it should be noted that the French institution has an important interest in photogrammetry in underwater archaeology, such as the shipwreck of the Phoenician Xelendi in Malta [64], which is probably the oldest known shipwreck in the western Mediterranean. This line of research involves underwater photogrammetry in extreme conditions, for example, in high turbidity waters, such as the work carried out with the Roman wreck Arles-Rhone XIII in the Rhodano River (France) [65]; or in deep waters such as the ROV -D project which was responsible for the study of the Roman shipwreck Cap Bénat 4, at a depth of 328 m [66].

The Italian Consiglio Nazionale delle Ricerche, for its part, stands out in the virtual reconstruction applied to archaeology, for example in its territory such as that of some building in the city of Pompeii, Insula V 1, whose data were taken with laserscan [67], or international collaborations such as the reconstruction of a typical building called Huaca Arco Iris, located in the complex of the site of Chan, a UNESCO archaeological site in Peru [68].

Spanish research in the field of photogrammetry for archaeological applications, led by the University of Salamanca, is most successful in the use of drones or UAVs as an effective and low-cost tool [22]. One of the first works in this sense was in the archaeological modelling of a Jewish tannery in Avila [69].

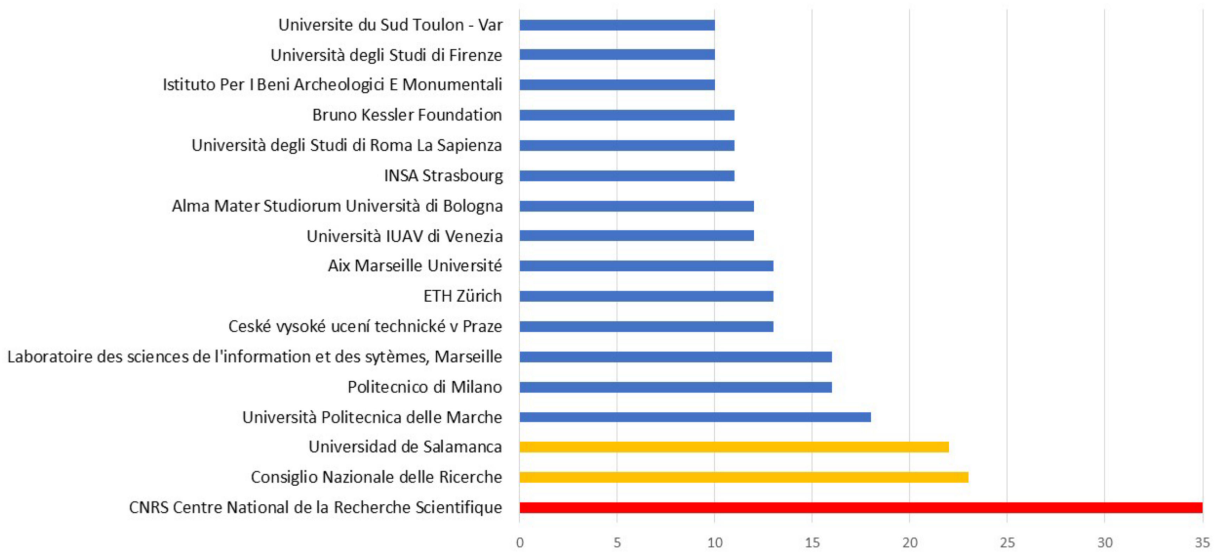

Figure 6. Major research affiliations in photogrammetry and archaeology.

If the publications by country are analysed, in general this line of research, as seen in the affiliations, is led by Italy with more than 180 works. Then there is another group of countries—the United States, Spain, France, and the United Kingdom—with a range of between 50 and 100 papers. The third group of countries, with publications between 21 and 50, would be Germany, Greece, Austria, and the Czech Republic. The geographical distribution of these publications is shown in Figure 7.

As one might expect, the United States has a long tradition in this regard. In fact, the first recorded work is from 1964, the Teotihuacan mapping project by Million [58]. This country stands out in the use of GIS within this line of research [70], innovating with 3D GIS [71] and 4D GIS [72], and recently exploring the possibilities of online platforms such as Google Earth in this field [73].

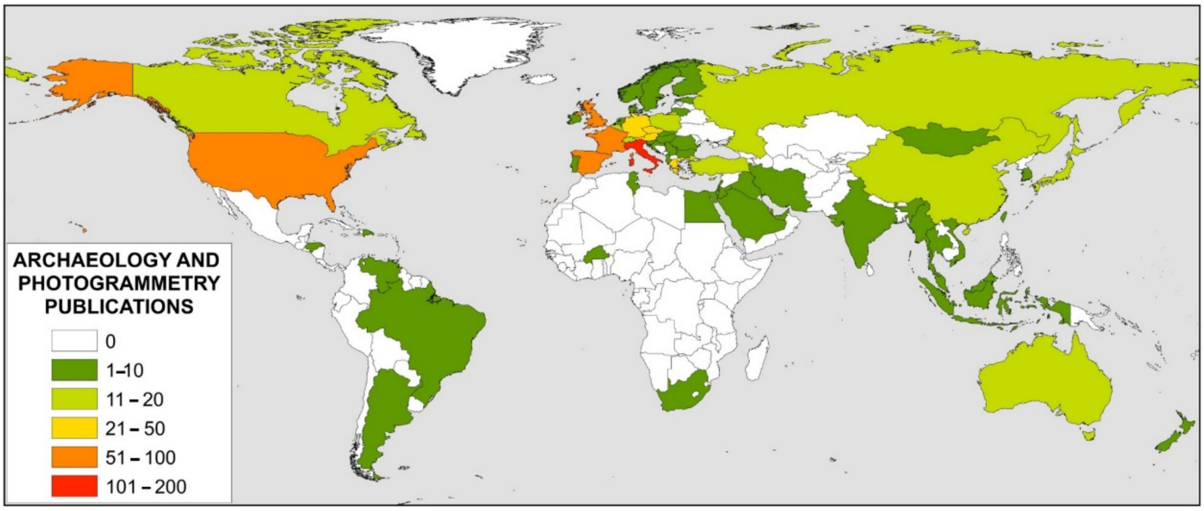

Figure 7. Distribution by country of research in photogrammetry and archaeology.

3.4. Authors

Concerning the main authors who have published in this field, Table 1 provides a detailed list of the top 10 authors with the most publications in this field. In the last column, their degree of specialisation in this subject has been established by comparing the author's total publications to date with those of the research topic.

It can be observed that one author has a high degree of specialisation, but this is due to the low number of total publications. From the list of authors, the first author, Pierre Drap, can be understood as a specialist in this field, since more than a third of his publications are in this field. The second in this ranking of specialisation is Francesco Guerra, with almost 25%. The other authors in this list are around 10%. It is remarkable that 6 of the top 10 authors are from France.

Table 1. Top 10 authors in photogrammetry applied to archaeology.

Author	Affiliation, Country	N_T	$N_{Ph\&A}$	% ($N_{Ph\&A}$ vs N_T)
Drap, Pierre	Aix Marseille Université, France	67	23	34.3
González-Aguilera, Diego	Universidad de Salamanca, Spain	197	12	6.1
Seinturier, Julien	COMEX SA, France	17	12	70.6
Guerra, Francesco	Università IUAV di Venezia, Italy	45	11	24.4
Pavelka, Karel	Ceské vysoké ucení technické v Praze, Czech Republic	86	10	11.6
Grussenmeyer, Pierre	INSA Strasbourg, France	128	9	7.0
Nocerino, Erica	Aix Marseille Université, France	82	9	11.0
Menna, Fabio	COMEX SA, France	69	8	11.6
Merad, Djamal	Aix Marseille Université, France	57	8	14.0
Rodríguez-Gonzálvez, P.	Universidad de León, Spain	108	8	7.4

Figure 8 analyses the scientific collaboration between all the authors who have published in this field, some 167. It can be seen that there are six groups of authors, which are listed in Table 2, where the affiliation of the main author of that cluster has been highlighted in the first column. In the last column, the main lines of research of the cluster have been detailed according to the keywords of their publications. Figure 9 shows the evolution of these scientific collaborations over time. Scientific collaboration in this field has been detected starting in 2008 from the institutions of Politecnico di Torino (Italy) and ETH Zürich, Zurich (Switzerland).

Table 2. Photogrammetry applied to archaeology: Research clusters.

Cluster	Colour	Authors	Main Topics
Università IUAV di Venezia, Venice, Italy	red	Guerra F.; Balleti C.; Beltrame C.; Costa E.; Vernier, P.	photogrammetry; 3d modelling; cultural heritage; maritime archaeology
Politecnico di Milano, Milan, Italy	purple	Adami, A.; Fassi, F.; Rossi, C.	cultural heritages; laser scanner
Aix Marseille Université, Marseille, France	green	Nocerino, E.; Menna, F.; Remondino, F.; Neyer, F.; Gruen, A.	photogrammetry; three dimensional; computer graphics; 3d modelling
Cyprus University of Technology, Limassol, Cyprus	yellow	Skarlatos, D.: Agrafiotis, P.; Demesticha, S.;	archaeological site; three dimensional; computer graphics; underwater photogrammetry
Politecnico di Torino, Turin, Italy	blue	Chiabrando, F.; Bornaz, L.; Nex, F.; Rinaudo, F.; Spanò, A.	archaeology; photogrammetry; image acquisition
ETH Zürich, Zurich ZH, Switzerland	cyan	Eisenbeiss, H.; Sauerbier, M.	photogrammetry; archaeology; archaeological excavations

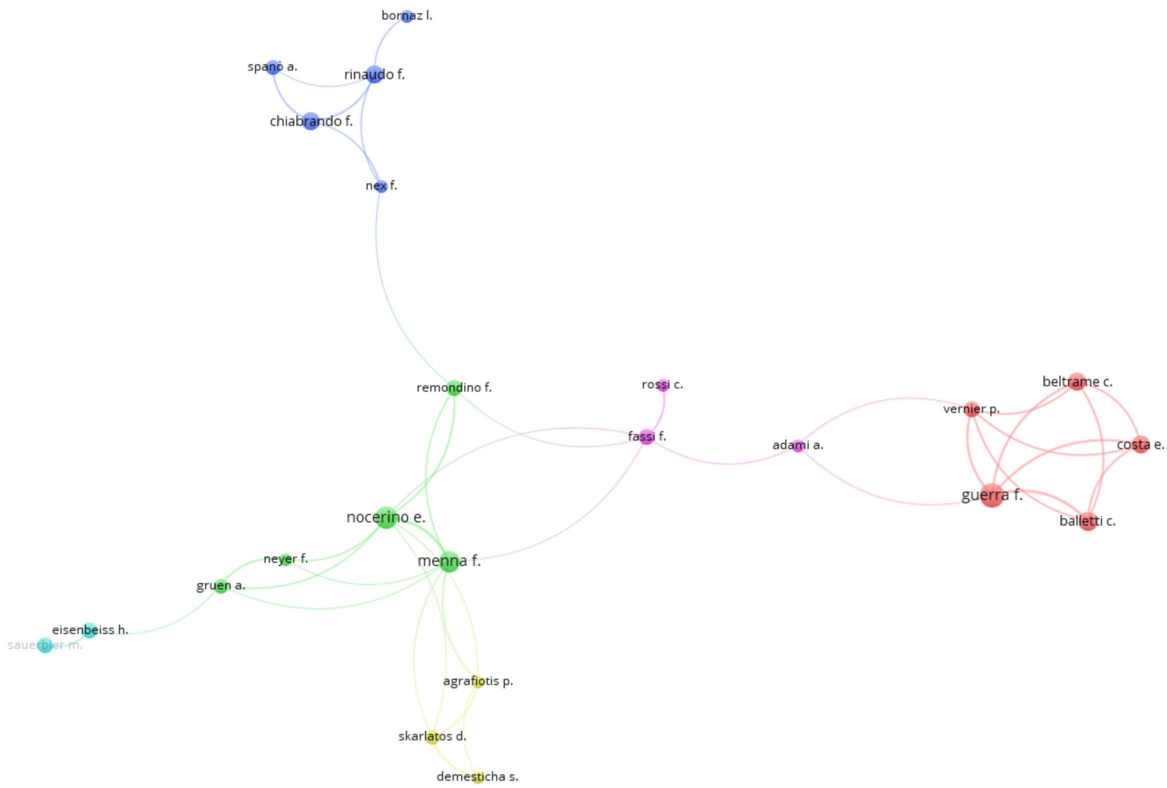

Figure 8. Scientific collaboration between all the authors in photogrammetry and archaeology.

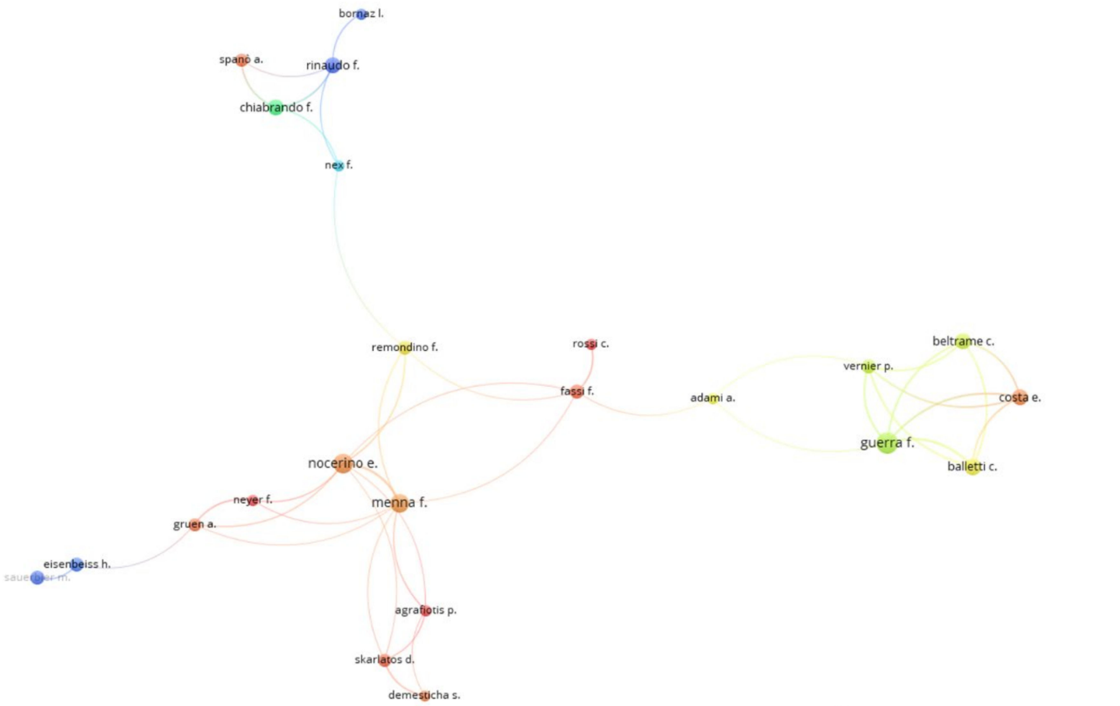

Figure 9. Evolution of Scientific collaboration between all the authors in photogrammetry and archaeology.

3.5. Keyword Analysis

In the publications studied, the lines of research in particular are defined by the indexing keywords. Figure 10 shows a cloud of words with all the key words in these publications, where the size is representative of the frequency of occurrence. If the search terms photogrammetry and archaeology are not taken into account, the most prominent keywords are: history (120 times), surveys (120 times), three dimensional computer graphics (117 times), remote sensing (115 times), cultural heritage (114 times), architecture (80 times), digital photogrammetry (65 times), laser applications (59 times), laser scanning (58 times), close range photogrammetry (56 times), excavation (55 times), 3d modeling (54 times), archaeological site (52 times), image reconstruction (51 times), visualization (51 times), or GIS (50 times).

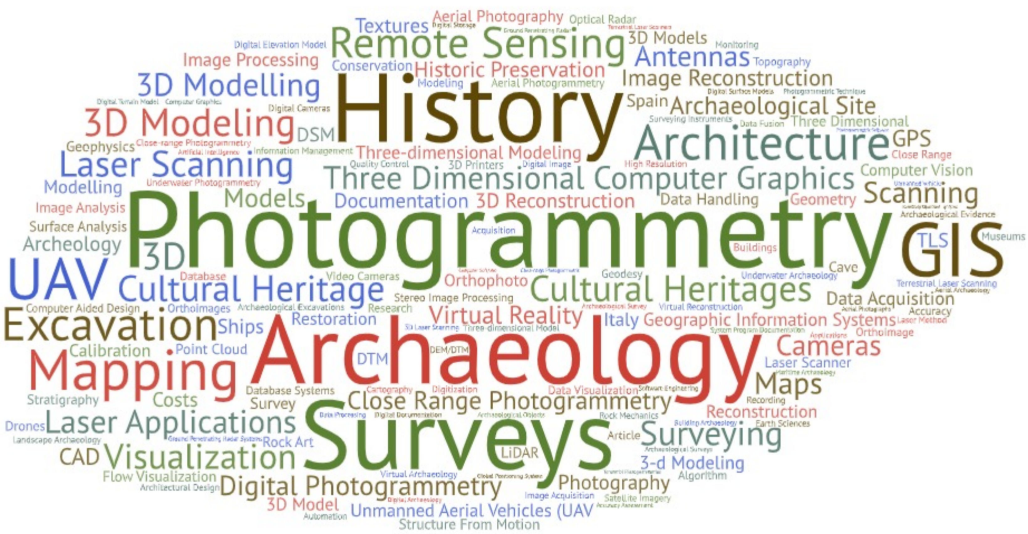

Figure 10. Cloud of words made with the keywords of research in photogrammetry and archaeology.

The evolution of this research from the analysis of its keywords can be seen in Figure 11, and in Table 3. It began by focusing mainly on cartography (maps) and CAD systems in 2008, then in 2010 this information was integrated into GIS, virtual reconstruction was carried out, and it was proposed as a tool for cultural heritage [74]. Later, in 2012, 3D graphics were made, and scanners were used. In 2014, UAV flights and LiDAR systems were combined to make 3D reconstructions. It can be understood that this is where the jump is, i.e., the massive appearance of drones or UAVs. Figure 3 also shows a much higher growth rate than in previous periods. The last period in which they are still in use would be the SfM techniques and their application to what is called virtual archaeology and their application to building archaeology.

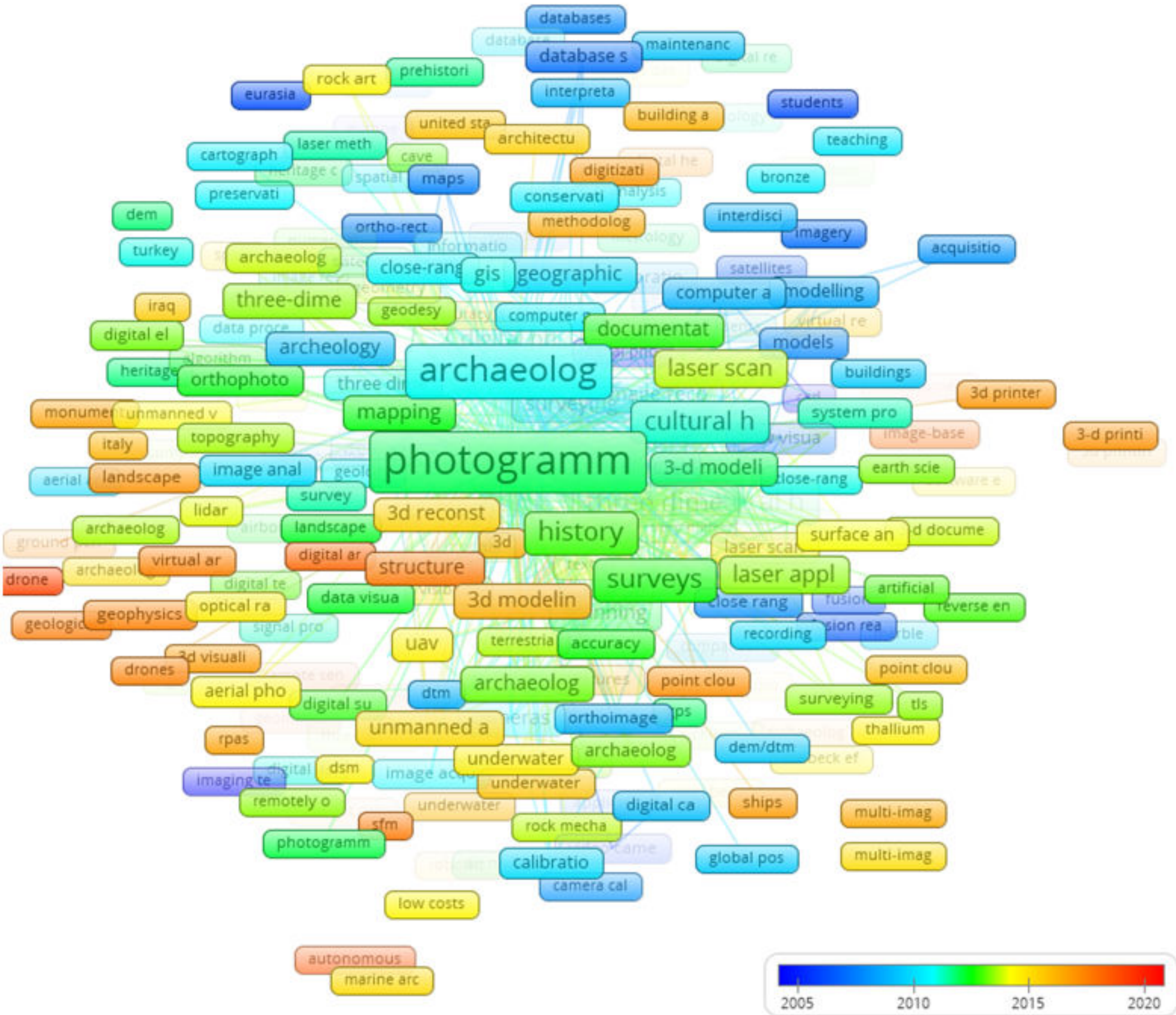

Figure 11. Research evolution in photogrammetry and archaeology in terms of keywords.

Table 3. Evolution of keywords in photogrammetry applied to archaeology.

Year	Keywords
2008	Maps, data base systems, computer aided design modelling
2010	Cultural heritage, image reconstruction, GIS
2012	Three-dimensional computer graph, mapping, scanning
2014	UAV, LiDAR, 3D reconstruction
2016	Structure from Motion, SfM, virtual archaeology, building archaeology

Figure 12 analyses the research relations between these countries and their evolution over time. This evolution or use of photogrammetry in archaeology, Figure 12, seems to have been started by Germany, Greece, and Japan in 2008. In a second period, France and the USA are incorporated in 2013, finally Italy, and more recently, Spain in 2015, as significant countries for the number of scientific contributions in this field. Modern UAVs include a GPS system with RTK on board, making the images already georeferenced. For this reason, a base station is established that retransmits differential corrections to the UAV, and the images are already georeferenced as the center of capture of each photograph has precise coordinates. However, the use of UAVs for professional activities is subject to specific restrictions by law. This issue should therefore be dealt with due caution. In any case, the use of GPS for photogrammetric control points or ground control points (GCP) is fully accepted by the scientific community, both in terms of cost and accuracy [75].

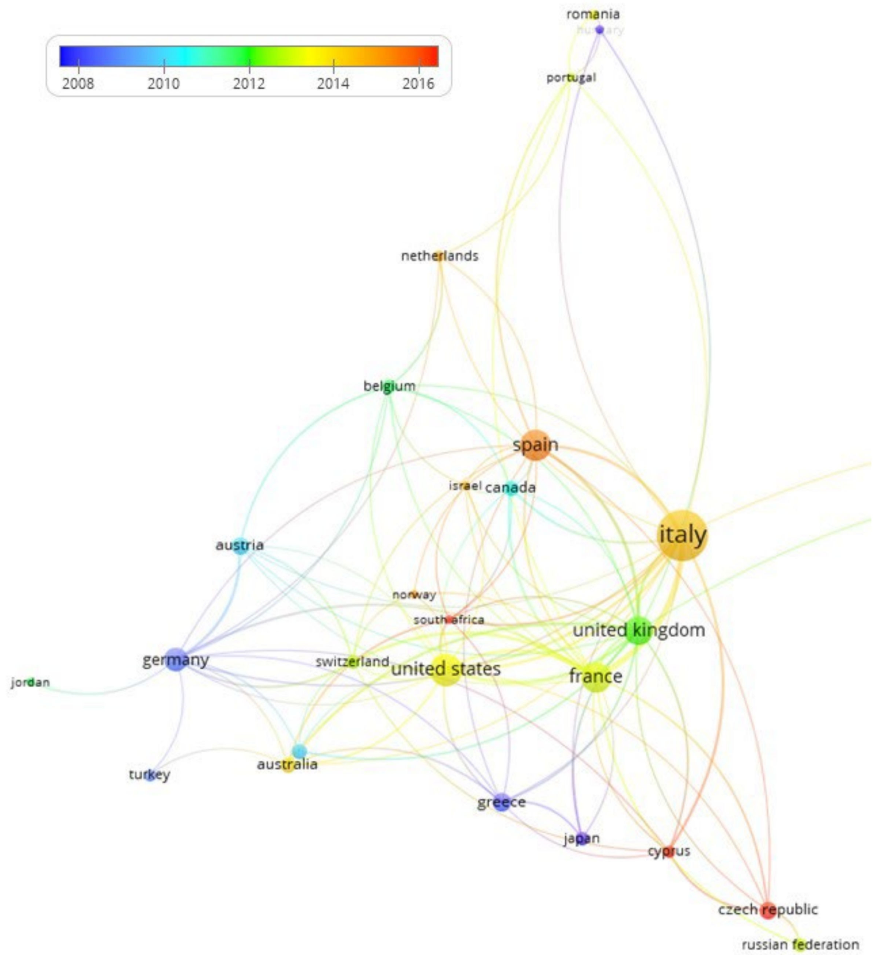

Figure 12. Evolution by country of research in photogrammetry and archaeology in terms of keywords.

4. Discussion: Research Trends in Photogrammetry Applied to Archaeology

Finally, the analysis would not be complete without analyzing the scientific communities or clusters around which the line of research is conducted, which set the global research trends. To this end, the clusters obtained from all these publications are analysed with the free software VosViewer, which has given good returns in many scientific areas [76]. Figure 13 shows the eight clusters obtained, and Table 4 summarises them, naming them according to the main keywords obtained. Thus, the clusters obtained are those related to: terrestrial photogrammetry; aerial photogrammetry; cultural heritage; excavation; cameras; GPS; LaserScan; and virtual reconstruction/3D printers.

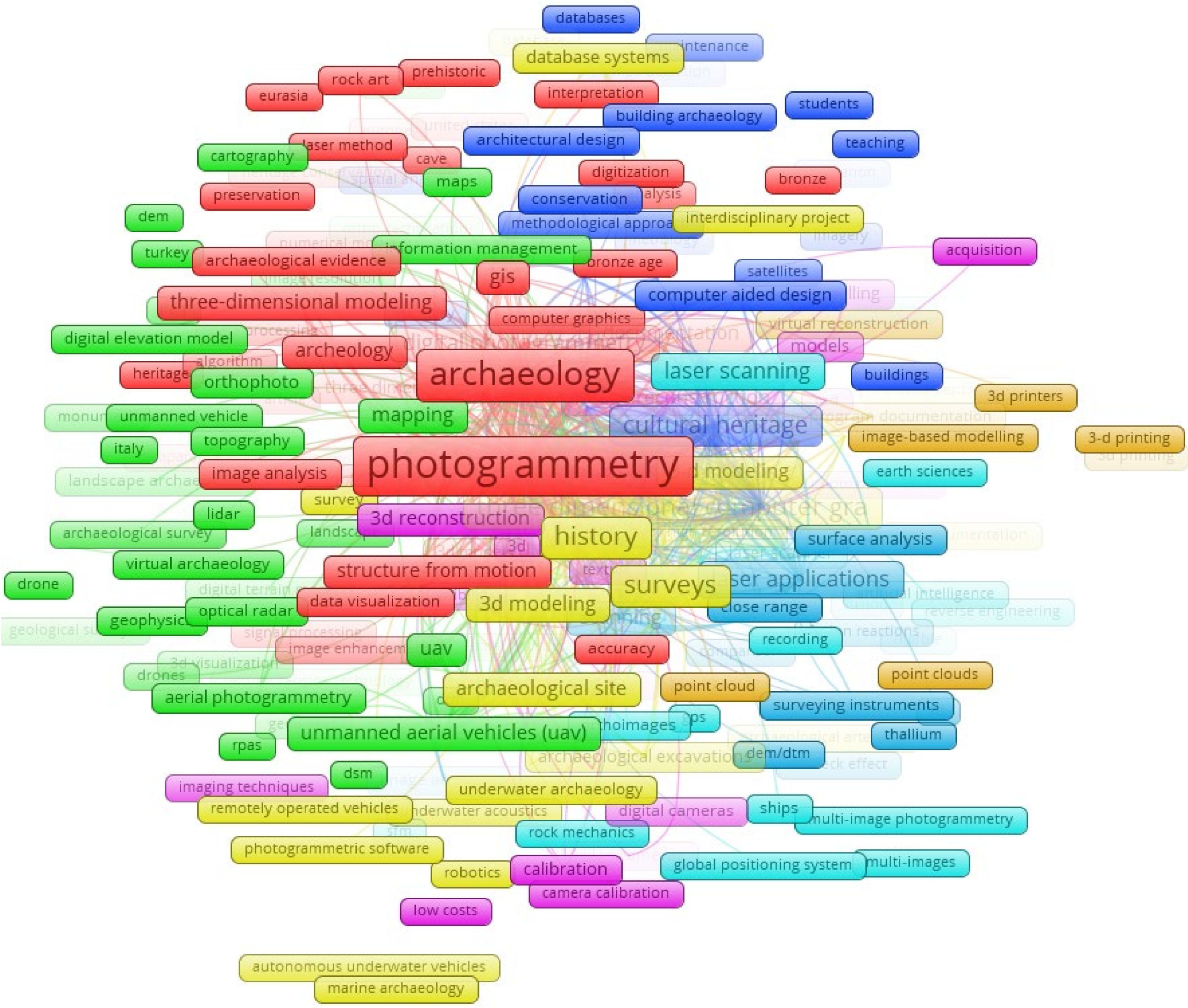

Figure 13. Clusters of research in photogrammetry and archaeology.

Table 4. Photogrammetry applied to archaeology: Research clusters.

Cluster	Weight (%)	Color	Keywords
Close range photogrammetry	22.1	red	digital photogrammetry, three-dimensional modelling, close range photogrammetry, structure from motion, 3D models, GIS
Aerial photogrammetry	20.4	green	orthophoto/orthoimage, LiDAR, UAV, aerial photography, remote sensing, mapping, Digital elevation models
Cultural heritage	13.7	blue	Cultural heritage, architecture, buildings, geographic information systems, computer aided design, historic preservation
Excavation	12.6	yellow	Three-dimensional computer graph, history, excavation, cost effectiveness, surveys, 3D modeling
Cameras	10.9	purple	3D reconstruction, stereo image processing, CAD, camera calibration, cameras
GPS	8.8	cyan	GPS, 3D modelling, reverse engineering, ground control point, SfM, laser scan
Laser scan	7.7	orange	Laser applications, surface analysis, terrestrial laser scanning, TLS, survey instruments
Virtual reconstruction/3D print	3.9	brown	3D printing, 3D printers, image-based modelling, point cloud, virtual reconstruction

Cluster 1 is centered on near or short-range object photogrammetry. Of the first works in this sense, it is worth mentioning the study of the Mausoleum of the Emperor Qin Shi Huang in 1990, where techniques of close-range photogrammetry, low-altitude photogrammetry and remote sensing were combined [77]. However, it was not until years later, in 2000, that the use of close-range photogrammetry proved its use in virtual reality and its integration into archaeology [78]. It was this year that the close-range photogrammetric technique was used for the documentation of Naqsh-I Rustam in the south of Iran [79]. After this, there have been many success reports widely cited in the literature, such as the archaeological site of Ajina Tepa (Tajikistan) [80], the Upper Palaeolithic Cave of Parpalló (Spain) [81], or also the Bronze Age cave "Les Fraux" at Saint-Martin-de-Fressengeas (France) [82]. Figure 14 shows an example of close-range photogrammetry and 3D virtual reconstruction of an amphora from the 8th century BC, which is currently in the Archaeological Museum of Seville (Spain).

Cluster 2 focuses on aerial photogrammetry and the development of UAVs. A remarkable fact that could be considered as the beginning of UAVs is the work of Theodoridou et al., [83], on the use of remote-controlled helicopters for their application in archaeological studies and in the building construction industry. The idea was to create a system for acquiring photogrammetric images at low altitude, using a radio-controlled helicopter, and to develop a specific methodology based on digital photogrammetry, for the rapid and efficient survey of archaeological sites, excavations and/or monuments in general. It is noteworthy that in 2003 the use of hot air balloons (inflated with helium) was still being considered as a solution for the acquisition of images at low cost compared to traditional flights. Here, with 4 Megapixel cameras, an aerial image accuracy of better than 4 cm in position and height was achieved [84]. The first important work with UAVs can be said to have begun with the comparison of the DSM (digital surface model) generated from images of mini-UAVs and terrestrial laser scanners in cultural heritage applications. For example, the studies of Pinchango Alto, an LIP settlement (Late Intermediate Period; 1400 AD), located 400 km south of the capital of Peru (Lima), near the famous Nasca geoglyphs, where they achieved 10 cm resolution with UAV images [85]. A 3D comparison of both elevation models shows an average value of less than 1 cm with a standard deviation of 6 cm. LiDAR (laser imaging detection and ranging) systems have demonstrated a high capacity to rapidly produce digital terrain models (DTMs) even under vegetation. This in archaeology has meant a very important progress in the prospection of large territories scarcely explored due to orographic or vegetation difficulties. As early examples, there are the studies in Ireland on the abandoned medieval settlement of Newtown Jerpoint, the prehistoric port of Dún Ailinne or the archaeological complex of Tara Hill [86]. Another work of interest in this sense was in the archaeological zone of Augusta Bagiennorum, where different surveys have been carried out since 1990. With UAVs flying at an altitude of 200 m with an average speed of 15 m/s, they obtained the accuracy of three-dimensional mapping suitable for determining the suitability of this technique for archaeological purposes [87]. Figure 15 shows a UAV photogrammetric flight of Utica (Tunisia) in the year 2018 under the research started by the Tunisian-Spanish project launched in 2010 [88].

Figure 14. Close range photogrammetry and 3D virtual reconstruction.

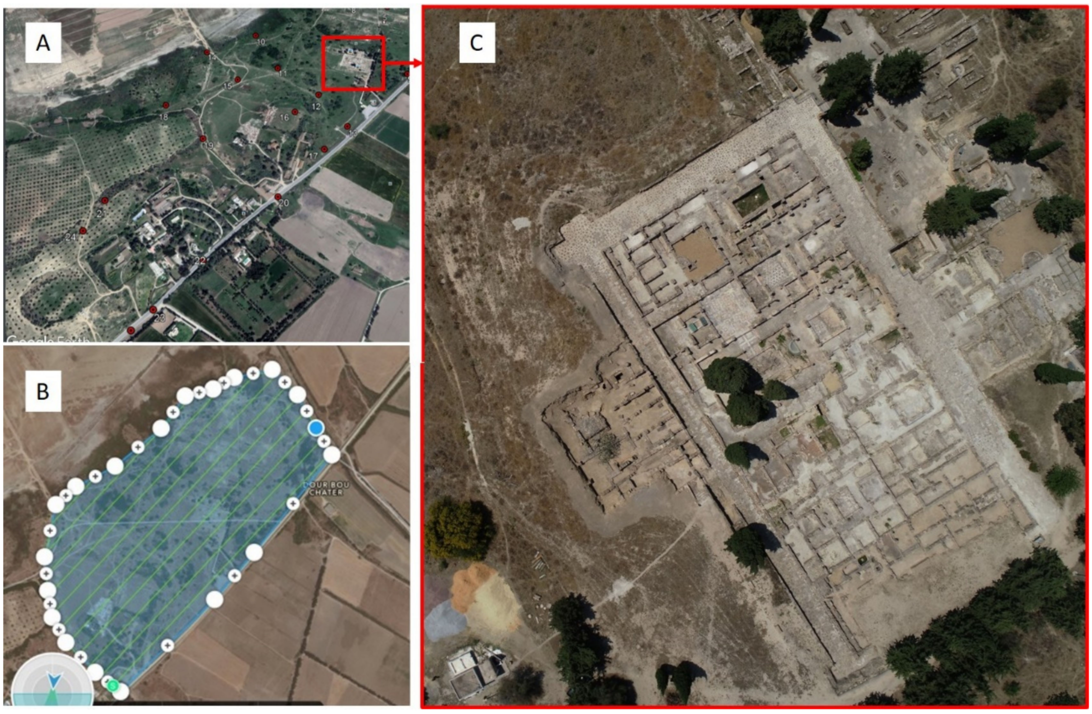

Figure 15. UAV photogrammetric flight of Utica (Tunisia). (**A**) Ground control points. (**B**) Photogrammetric flight paths. (**C**) Example of aerial photography on the restored Roman insula.

Cluster 3, named cultural heritage, is closely linked to virtual reality and 3D modelling [89]. An example is the integration of different topographical and photogrammetric survey methods, together with photographic virtual reality techniques, around the ancient city of Bakchias (Fayyum, Egypt) [90]. The great potential of virtual reality technologies is that they make it possible to study an archaeological site from remote locations using the Internet without the need for people to travel. In addition, the 3D reconstruction allows you to move from a 3D model to a 2D model for your study. An outstanding example is the large hypostyle hall of the Karnak temple [91], where, by means of photogrammetry, they made it possible to study and record the hieroglyphic inscriptions engraved on conical or cylindrical surfaces. This study carried out a three-dimensional reconstitution of a column and a two-dimensional survey of its epigraphy, based on a series of snapshots of the column's surface. Figure 16 shows a 3D image of parts of a temple, city of Utica (Tunisia), from several point of view.

Figure 16. Image 3 D showing parts of a temple, city of Utica (Tunisia).

Cluster 4 has been named the excavation cluster. Here, the aim is to bring together all the techniques—for example, combining various data sources such as 3D tachometric surveys and photogrammetry. An early example is the Finnish mission at Jabal Haroun (Mount Aaron) in Petra, Jordan [92]. Already, many authors suggest that for excavations, UAVs can be a suitable alternative to traditional measuring methods such as tape measures or tachymeters [93]. These authors made three case studies of different lengths: a large archaeological site in Bhutan, the excavation of a smaller site containing ancient tombs in the Nasca region (Peru) and the Mayan site of Copan (Honduras). For example, in Spain, comparative studies have been carried out at the excavation level, between terrestrial laser scanning (TLS) and close-range photogrammetry—for example, in the cave of Can Sadurní (Begues, Barcelona) which is a Neolithic burial episode [94]. Another example is in the urban archaeological site of Plaza Velarde in Santander, which is an area of 450 m^2; to document all the structures that appeared in the archaeological site, it was decided to use photogrammetry techniques from digital camera images taken from a UAV [95]. Figure 17 illustrates the photogrammetry for the archaeological excavation site in the city of Utica. The Figure 18 shows how the 3D reconstruction allows you to rotate to study it from different points of view.

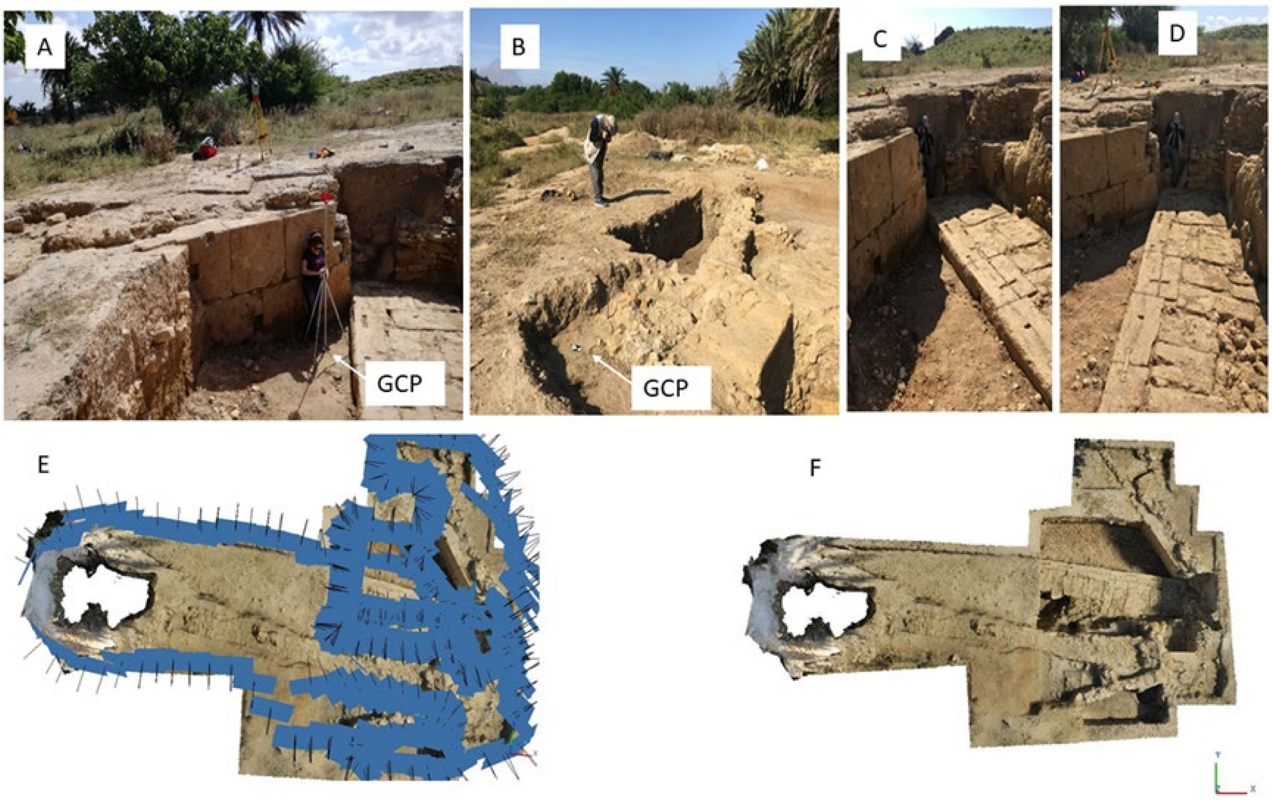

Figure 17. Photogrammetry for the archaeological excavation site in the city of Utica (Tunisia). (**A**) The survey of control points with total station; (**B**–**D**) the recording of photographs with a conventional camera from different points of view; (**E**) the points of view of all the photographs taken; (**F**) the final 3D model obtained.

Figure 18. 3D reconstruction of an archaeological excavation site in the city of Utica (Tunisia).

Cluster 5 is dedicated to cameras, and therefore it is understood that it is more in the field of computer science or engineering than of archaeology itself, although it has a clear application to this field. Photogrammetry usually requires calibrated metric cameras so that the whole process of internal orientation can be carried out, and the alternative steps of external orientation of each data acquisition, and relative and absolute orientation. The three-dimensional reconstruction of scenes from uncalibrated images is one of the most technically difficult problems in computer vision and photogrammetry [96]. So, camera self-calibration is an important research topic in computer vision [97]. Only images taken from different locations and orientations are available to estimate the intrinsic camera parameters. By using only these images, the relationship between pairs of images can be represented algebraically with fundamental matrices. However, the fundamental matrix contains both the intrinsic camera parameters and the relative motion between the two images or cameras. Therefore, a formulation must be defined that does not change due to the relative motion between the two images. Due to this contradictory relationship, there must be a virtual conic that is far enough away from the camera while viewing the locations, and its projection depends only on the intrinsic parameters of the camera. By defining the relationship between this virtual conic and the intrinsic parameters of the camera, the equations for the self-calibration of the camera are defined [98]. The development of these systems or algorithms has made it possible to use unknown camera settings (uncalibrated cameras), and even to change the parameters of this camera, such as zoom or focus during the data acquisition. This line of work then focuses on systems that automatically extract a textured 3D surface model from a sequence of images of the same scene.

Cluster 6 is focused on GPS. Above all, it should be noted that in large extensions of land the establishment of control points for photogrammetric flights with UAVs or the integration of archaeological sections requires georeferenced data (see example in Figure 19), so that all the information can be integrated into a GIS and subsequently analyzed [99].

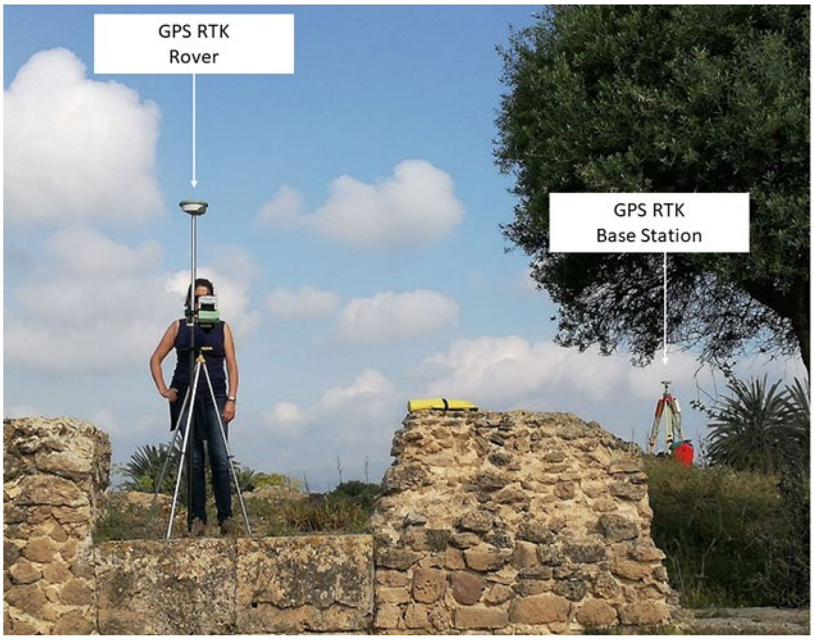

Figure 19. Measurement of control points with GPS RTK for photogrammetric flight in the city of Utica (Tunisia).

Cluster 7 focused on instrumentation, especially terrestrial laser scanners (TLS). Terrestrial laser scanning has become increasingly popular in recent years as it provides very dense 3D points on the surface of an object with high accuracy [100]. These techniques have been combined with others as mentioned above, such as with UAV [101].

As an anecdote, it is worth mentioning that quite a few works from the so-called "industrial archaeology" are included in this cluster. Without intending to make a debate on the question, it results in the indexing of many papers with this search term within archaeology. Industrial archaeology is concerned with questions of industrial culture and the preservation of industrial monuments [102,103] or best-known historical inventions [104]. The concept was introduced in 1955 in England, after the Swiss engineer Conrad Matschoss extended the history of technology to industrial monuments in 1932 [105]. Figure 20 shows the measurement of points by laser scan of a Roman mosaic in Cantillana, Seville (Spain).

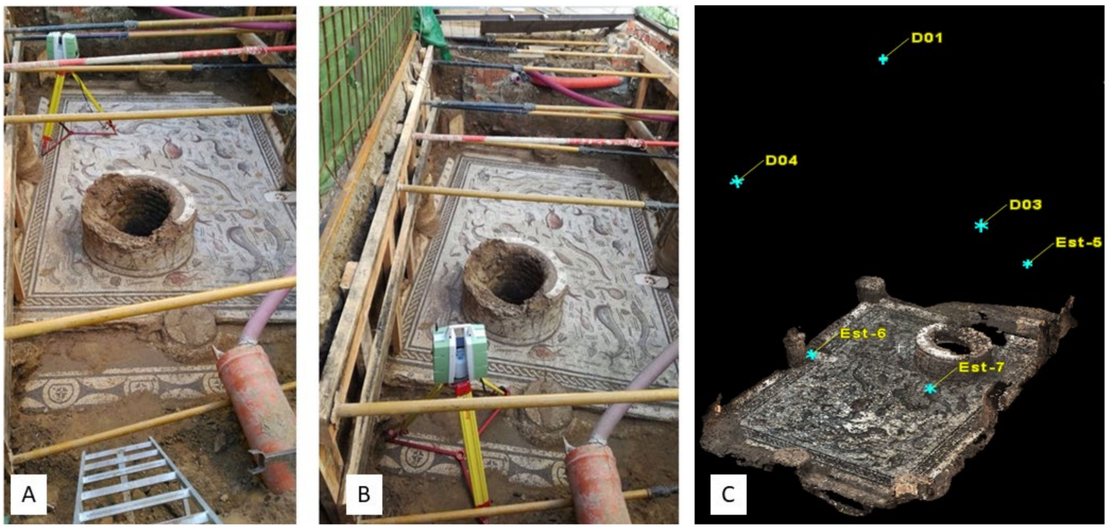

Figure 20. Roman mosaic in Cantillana, Seville (Spain). (**A**,**B**) Measurement of points by laser scan at different positions. (**C**) Result as cloud of points.

The last cluster, cluster 8, is focused on virtual reconstruction, and once the models are generated, even make a 3D print of them as a scientific dissemination, or heritage preservation, because sometimes it is not possible to expose the original and a copy of it is exposed, either at a 1:1 scale, or at another scale so that it can be adapted to the place of exhibition. To cite some examples of 3D reconstruction from image sequences, in order to make photo-realistic digital (and physical) replicas for an exhibition and for 3D visualization in virtual museum applications, there is the exhibition "Treasures of Vietnamese Archaeology and Culture", in which cultural heritage objects from different Vietnamese museums were selected and digitised in September 2015 [106]. The Vietnamese Treasures, which have never been exhibited outside Vietnam, could be shown for the first time in Germany in the context of three exhibitions in the cities of Herne, Chemnitz and Mannheim between October 2016 and February 2018. This certainly allows another dimension to be given to cultural heritage without putting it at risk. A great example in Spain is the replica of the Altamira Cave, the so-called neo-cave that is actually visited, to preserve the original. From 28 pairs of photographs, a very accurate representation in relief was obtained. From the images, the photogrammetry allows to establish a precise cartography of the ceiling, with equidistant contour lines of 2 cm. The superimposition of the photographic coverage made it possible to position each of the cave paintings with great precision [107]. However, the enormous effort and costs that must be invested to obtain realistic models remains a problem [108], which is why the line of low-cost solutions must be worked on [109]. Figure 21 shows the virtual reconstruction of Doña Blanca castle, 8th century B.C., from the archaeological site data and written documentation of the site and other sources of information.

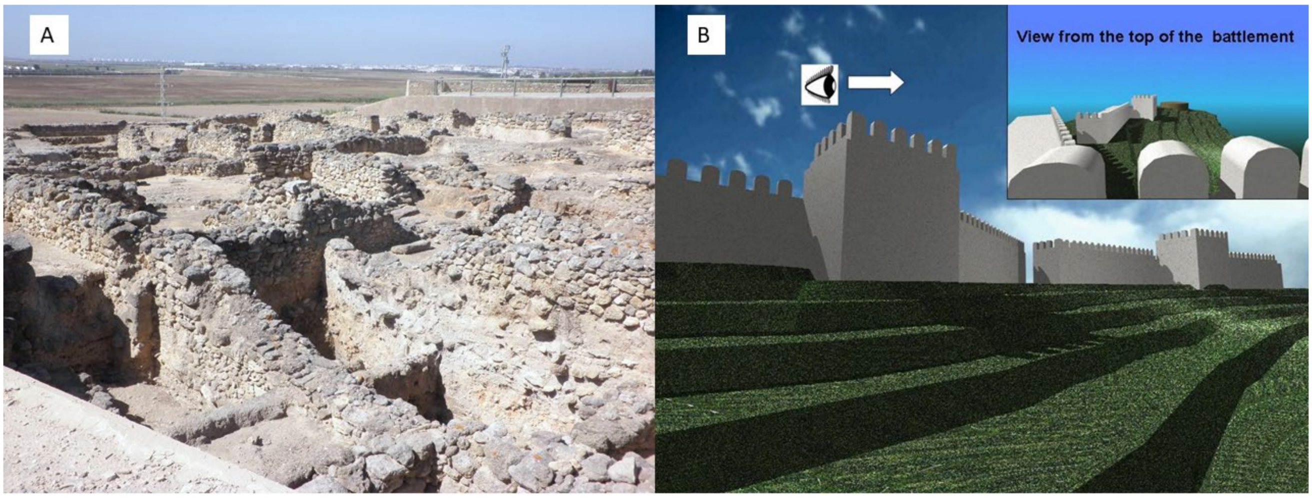

Figure 21. Virtual recreation of the Doña Blanca castle. (**A**) Archaeological site in its current state. (**B**) Virtual reconstruction of the fortification wall.

Geometric survey has traditionally been one of the tasks to be carried out in the analysis of an archaeological site. The preservation of the site's elements requires non-invasive methods that allow the same or a higher degree of precision that can be achieved using traditional surveying and drawing techniques. The main advantage of photogrammetry is, besides being a non-invasive method as with the traditional ones, to be able to extract all the information in 3D and to work on large areas. In this framework, 3D modelling techniques using photogrammetry and laser scanning appear to be an appropriate solution. Finally, it is worth mentioning the importance of using 3D technologies as a tool to improve archaeological research and increase the production of information from archaeological data for analysis and interpretation in 4D [110]. To visualise evolution over longer time periods within archaeology, the three spatial dimensions of virtual space can be extended with time as a fourth dimension, so-called 4D visualisation techniques [111]. An example of this is the work on a "nuraghe", a typical megalithic monument built only in Sardinia during the Bronze Age [112].

In the latter respect, important projects are being developed showing that it is possible to add a multi-temporal and multi-scale perspective to field excavation, as financed by the Swedish Research Council [113].

5. Conclusions

Archaeology should be understood as a multidisciplinary scientific discipline, which uses other scientific fields' technologies to improve the recording and interpretation of data from archaeological surveys. Photogrammetry is playing an essential role in this context by providing visual information from the photograph at the field level, with the information from the photograph and with metric accuracy. In this research, it has been observed that the first uses of photogrammetry in archaeology date back to 1962, but it is not until 2010 that an exponential growth in publications can be noticed. The most prominent scientific categories have been social science (26%), where archaeological studies are partially included, and computer science (24%). This shows both the importance of photogrammetry for archaeology and the interest of computer science in promoting photogrammetric tools for application in archaeology. The leading institutions in this field of research are the central research institutions of France (CNRS Centre National de la Recherche Scientifique) and Italy (Consiglio Nazionale delle Ricerche). In third place, there is a Spanish university, the University of Salamanca. By country, publications in this field are led by Italy, followed by the USA, Spain, France, and the United Kingdom.

Photogrammetry was applied until 2008 for cartography (maps) and as a basic tool for drawing with CAD systems; then, in 2010, this cartographic information was integrated into GIS and virtual reconstructions were carried out; it was also proposed as a tool for cultural heritage. Subsequently, in 2012, HDS was used for data capture and 3D models of objects became popular. In 2014, UAV flights and LiDAR systems were combined to make large-scale 3D reconstructions. The main lines of research in photogrammetry applied to archaeology are close range photogrammetry, aerial photogrammetry (UAV), cultural heritage, excavation, cameras, GPS, laser scan, virtual reconstruction, and 3D printing. Of these trends, underwater archaeology has not yet emerged as a cluster, perhaps because the specific publications on this topic do not yet cover the possibilities of underwater photogrammetry. The reconstruction of archaeological data is a time-consuming and multidisciplinary research process, as archaeologists must deal with large datasets and complex multifaceted archaeological information stored and spread across different types of media and documents. As the use of multimedia data acquisition is rapidly increasing, as seen in this research, archaeological information systems must in the future allow for 3D visualization in the form of virtual reality, and to help understand its evolution the integration of multimedia and visualization of temporally and/or spatially referenced data will lead to the emergence of so-called 4D techniques. In conclusion, it can be said that the development of photogrammetry opens up new perspectives for archaeology.

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