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ORIGINAL ARTICLE

Mapping the landscape of research on 360-degree videos and images: a network and cluster analysis

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Abstract

The recent emergence of low-cost virtual reality technologies, like 360° videos and images is attracting the attention of researchers suggesting it could be the next significant step in technological innovation. The birth of 360° videos and images is quite young, it goes back to the middle of the nineteenth century and then spread more and more in many areas. In recent years, 360° videos and images have grown in popularity because they provide a great number of advantages compared to traditional virtual reality computer-generated technology. The aim of this research is to map scientific works in the area of 360° technology using advanced scientometric techniques. We collected all the existent articles about 360° contents in the Scopus database, and the resultant dataset contained 3319 records. The bibliographic record encompassed all categories of scientific articles retrieved from Scopus, considering parameters such as countries, institutions, journals, authors, citation counts, and publication years. The network and cluster analysis of the literature showed a composite panorama characterized by changes and evolutions over time of the use of 360° contents. We discuss these aspects in the main areas of application with an emphasis on the future expected 360° capacities, increases, and challenges. As already happened with the advent of virtual reality, the future of 360° technology will be an increasing shift from engineering to clinical use, by improving the use and the development of scientific applications in clinical areas and by modifying social communication and interaction among people.

Keywords 360° Videos and images · Cluster analysis · Virtual reality · Psychometrics · Scientometrics

1 Introduction

360° videos, also known as panoramic, spherical, or omnidirectional videos/images, are a new multimedia type that provides an immersive experience. The content of 360° video/image is on the sphere that covers the whole $360 \times 180°$ viewing range. In other words, unlike traditional 2-dimensional (2D) video/image that only covers a small plane, 360° video/image surrounds the viewer seamlessly and takes up the entire viewer's vision. As a result, viewers are not constrained to only watch a particular segment of the scene chosen by the producers.

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Recent years have witnessed the rapid development of virtual reality (VR) technology. As an essential type of VR content, 360° video/image has been flooding into our daily life and drawing great attention. The viewer can freely move their head to direct the viewport to the desired content with the help of recent commercial head mount displays (HMDs), just like they would in the real world. In this way, immersive and even interactive experiences are provided.

In recent years, 360° videos and images have grown in popularity because they provide a distinctive and immersive viewing experience. With these media formats, viewers can interact with the content and explore an entire environment in ways that were previously not possible with conventional 2D videos and images. In 2016, there was a greater proliferation of 360° videos: more than 8000 new videos on YouTube received more than 250,000 daily views; over 1000 new videos were produced for the Oculus platform; and popular events around the world, including NBA games and the US Open golf tournament, were streamed live using 360° video technology (Mangiante et al. 2017; 360 Degree

Camera Market Size to Reach US$ 4.64 Bn by 2030. n.d.). The adoption of 360° technologies by social media websites like Facebook and YouTube is one factor that has aided in their spread. In 2015, these platforms started to support 360° videos, making it simpler for content producers to distribute their work to a larger audience. This in turn aided in increasing viewer and creator awareness of the technology. The proliferation of cameras that can record 360° video is another factor that has supported the adoption of 360-degree technologies. In addition, these technologies have found use in a range of fields outside of entertainment, such as journalism, tourism, education, and real estate. This has influenced organizations looking to produce more immersive and engaging content for their audiences to adopt the technology. Finally, the adoption of these technologies has been aided by the integration of 360° technologies with VR. 360° videos are increasingly being used to produce immersive VR experiences. However, 360° videos and photos are not brand-new ideas. Indeed, the term "panorama" was first used in London in 1792 to refer to the first example of what would later become a common form of public entertainment: a sizable elevated cylindrical room completely covered in a 360° painting. However, the earliest attempts at panoramic photography were made in the middle of the nineteenth century. The Movie Map represents one of these examples (Lippman 1980) in which the streets of the city of Aspen were filmed at 10-foot intervals. To replicate the effects of walking on the streets, two videodisc players were used to retrieve the appropriate views at playback time. A few years later, digital video interactive (DVI) technology introduced the use of digital videos for exploration. A user could explore Palenque's Mayan ruins using digital video playback from an optical disk thanks to the DVI demonstration (Ripley 1990). Not long after, a 360° "Virtual Museum" was rendered at specific locations within the museum to allow the user to look around. A bi-directional transition movie that contained a frame for each step taken in both directions along the path connecting the two points was used to simulate walking from one of the points to the other (Miller et al. 1992). In 1994, Apple released "QuickTime VR" (Chen 1995) which allowed users to explore a virtual environment by clicking and dragging the mouse in various directions while creating and viewing interactive 360° panoramas. The movie player has been replaced with a real-time image processor, making it different from previous attempts. A walkthrough sequence can be created by connecting several of these images. However, it wasn't until the digital era that panoramic photography began to evolve into 360° videos and images but only in the middle of the 2010s that 360° videos and images were widely available thanks to the development of consumer-grade cameras and the availability of online sharing and viewing services like YouTube and Facebook. It has thus become possible for anyone to produce their own 360° videos and images thanks to the development of accessible and affordable 360° cameras. 360-degree videos and photos started to be used in other industries in the years that followed or in education to give students access to simulations and virtual field trips. For example, they have been used in the tourism industry to show travel destinations and in marketing to make interactive product demonstrations and advertisements. As 360° videos and photos gained popularity, research on their potential uses and effects began to emerge. Researchers started looking into how 360-degree videos affected things like learning outcomes (Blair et al. 2021; Hamilton et al. 2021; Rosendahl and Wagner 2023; Snelson and Hsu 2020), mental health intervention (Ionescu et al. 2021), emotional reactions (Li et al. 2017; Schöne et al. 2021), and attentional processes (Nguyen et al. 2018). In this paper, we conduct a network and cluster analysis of the scientific literature on 360° videos and images. By analyzing the structure of the existing literature, we aim to identify patterns and themes and provide insights into the current state and future directions of research in this field.

1.1 360-degree technology

With 360° videos, viewers can look in any direction from a fixed point while experiencing an immersive video that captures a full circle field of view. They are typically viewed on a computer or mobile device with VR headsets, where the viewer can move the video around to look in different directions. The Oculus Quest 2, HTC Vive, and PlayStation VR are three popular VR headsets. Alternatively, users of computers or mobile devices can view 360° videos using a web browser or specialized app. In this instance, viewers can pan around the video and explore the 360° field of view using a mouse or touch screen.

A camera with multiple lenses is used to record the entire environment around it to capture a 360° video. A seamless 360° video is produced by stitching multiple images simultaneously taken by the camera together using specialized software. The technologies needed to produce and experience 360° videos have advanced over time. Early 360° cameras required specialized tools and technical know-how, were expensive and were challenging to use. However, consumer-grade 360° cameras have gotten more accessible and less expensive as the 360° video market has expanded.

360° cameras come in a wide variety of styles today, from small, portable gadgets to higher-end rigs. Insta360, GoPro, and Ricoh are just a few of the well-known brands. These cameras frequently include software that enables the stitching together of the numerous images taken by the camera to produce a seamless 360° video. Consistently, the size of the global market for 360° cameras was estimated at US$ 0.92 billion in 2021 and is projected to reach over US$ 4.64

billion by 2030, growing at a projected CAGR of 21.3% from 2022 to 2030 (360 Degree Camera Market Size).

1.2 Degrees of separation between 360° and virtual reality technologies

Immersive technologies like 360° videos and VR have grown in popularity across a variety of industries. The ability of both technologies to give viewers an immersive experience is one of their most notable features. While VR offers a fully simulated environment that can be interacted with, 360° videos give viewers the feeling that they are physically present in the environment being portrayed. The high level of interactivity provided by both technologies enables users to discover the environment on their own terms.

Despite their similarities, the two technologies also have some glaring distinctions. While 360° videos focus on real, capturing real-world settings, VR focuses more on simulation, creating entirely artificial environments.

However, both technologies offer immersive, interactive experiences that can grab and hold viewers' attention. In fact, they demonstrated similar promise in achieving “spatial presence” (i.e. the extent to which the immersive environment feels real) (Barreda-Ángeles et al. 2020). Users can “immerse” themselves in a user-controlled training simulation or setting using immersive 360° videos and HMDs, giving the impression that they are physically present there. They are not limited to a single point of view when viewing immersive 360° video content because specialized cameras have made it possible to simultaneously capture and record the entire environment from a fixed point. When using an HMD, the viewer can move their head or use a touch or mouse to adjust the viewing angle at any time (if displayed on a screen). 360° videos and VR have thus a lot in common, including the use of an HMD and audio-visual productions with 360° × 180° navigation.

Furthermore, VR permits a higher level of interactivity, allowing users to interact with objects and characters in the virtual environment. In contrast to VR, 360° videos are notorious for lacking interactivity. However, even though they are not intended to be interacted with properly, by connecting them, it might be possible to create this illusion. For instance, using specific software, interaction and navigation in any environment can be made possible. By placing a link or hotspot on a door, the environment can be changed, giving the impression that there are changing rooms for example. Numerous applications are possible for this feature (Borghesi et al. 2022; Pedroli et al. 2020, 2022; Riva et al. 2020).

VR and 360° videos have some technical requirements in common and some in contrast. For proper operation, both technologies need strong hardware and software. For instance, 360° videos can be viewed on most current smartphones and computers, whereas VR headsets need a powerful computer or gaming console to function. A significant amount of storage space is also needed for both technologies, with VR applications requiring the most space due to their more complex design. In terms of cost, there are significant differences. While VR requires pricey equipment, such as a headset and a potent computer or gaming console, 360° videos can be produced with relatively inexpensive tools, such as a 360° camera. VR content is therefore much more expensive to produce and consume than 360° videos. Finally, when contrasting 360° videos and VR, accessibility is yet another crucial factor. 360° videos can be viewed on a variety of devices and are widely available on websites like YouTube, Facebook, and Vimeo. VR, on the other hand, necessitates specialized hardware and software, which may restrict accessibility. Furthermore, some people may feel uncomfortable or queasy while using VR headsets, which can also affect accessibility.

Although the advantages are clear, we haven’t yet seen widespread use of immersive 360° videos. This omission may be at least partially attributable to the paucity of convincing research data demonstrating the "added value" of this technology over and above VR. The numerosity of studies that employ VR technologies serves as evidence for this (Cipresso et al. 2018).

2 Aim

Within the domain of scientific investigation, the current study conducts an examination of 360° videos through the application of network and cluster analysis techniques. These methodologies are rooted in the principles of science mapping and bibliometrics. Science maps are visual representations that show the connections between different disciplines, fields, specialties, documents, and authors. These maps have various uses in academic discussions (Bales et al. 2020; Small 1999) and encompass various functions such as offering a comprehensive depiction of the cognitive structure within a specific field (Bales et al. 2009), identifying key contributors (Buter and Noyons 2004), pinpointing centers of innovation, aiding in science policy development (Buter et al. 2006) and evaluating the evolutionary paths of scientific disciplines (Bales et al. 2011; Noyons et al. 2006; Polanco et al. 2001; Zitt and Bassecoulard 1994).

Bibliometric maps, which are an essential component of this investigative framework, are created using citation data, common terminologies, or other bibliometric factors (Buter et al. 2006). The bibliometric representations discussed in this context have been appropriately referred to as “landscapes of science” (Noyons et al. 2006, 17–20), drawing an analogy with geographical maps. One notable aspect of these tools is their ability to provide a comprehensive representation of the scientific information landscape, allowing users to further explore specific sections by zooming in, similar to the exploration of geographic terrains.

The triad of bibliometric analyses relevant to the practice of science mapping comprises citation analysis, co-authorship analysis, and co-citation analysis. The analysis of co-citation, which refers to the frequency with which two documents are cited together, provides valuable insights into the intellectual associations within the scholarly domain. In the field of scholarly research, the analysis of co-authorship serves to examine the connections between authors and their affiliations, thereby revealing the complex social structures that exist within collaborative networks (Bales et al. 2020; Buter et al. 2006; Noyons et al. 2006). This comprehensive methodology holds the potential to provide a deeper understanding of the complex network of relationships within the domain of 360° video research, presenting nuanced viewpoints on the collaborative dynamics and intellectual terrain of this emerging discipline.

3 Materials and methods

3.1 Data collection

The scientific database Scopus provided the initial data for the analyses (Falagas et al. 2008). including also Web of Science core collection, with the following query:

"360° video" or "360° videos" or "360 video" or "360 videos" or "360° images" or "360 images" or "360° image" or "360 image" or "equirectangular images" or "equirectangular image" or "equirectangular videos" or "equirectangular video" or "360-degree video" or "360-degree videos" or "360 degree video" or "360-degree images" or "360-degree image" or "360 degree images" or "360 degree image" or "sphering videos" or "sphering video" or "spherical videos" or "spherical video" or "360 videoing" or "360° technology" or "360-degree technology" or "360 technology" or "360 degree technology" or "360° technologies" or "360-degree technologies" or "spheric video" or "spheric videos" or "immersive video" or "immersive videos" or "immersive hypervideo" or "immersive hypervideos" or "360 hypervideo" or "360 hypervideos" or "360 degree hypervideo" or "360 degree hypervideos" or "spheric hypervideo" or "spheric hypervideos" or "spherical hypervideo" or "spherical hypervideos" or "360 media" or "360 medium" or "360 degree media" or "360 degree medium" or "360-degree media" or "360-degree medium".

WoS core collection is composed of: Citation Indexes, Science Citation Index Expanded (SCI-EXPANDED)—1970-present, Social Sciences Citation Index (SSCI)—1970-present, Arts and Humanities Citation Index (A&HCI)—1975-present, Conference Proceedings Citation Index-Science (CPCI-S)—1990-present, Conference Proceedings Citation Index-Social Science & Humanities (CPCI-SSH)—1990-present, Book Citation Index—Science (BKCI-S)—2009-present, Book Citation Index—Social Sciences & Humanities (BKCI-SSH)—2009-present, Emerging Sources Citation Index (ESCI)—2015-present, Chemical Indexes, Current Chemical Reactions (CCR-EXPANDED)—2009-present (Includes Institute National de la Propriete Industrielle structure data back to 1840), Index Chemicus (IC)—2009-present.

The Scopus' resultant dataset contained a total of 3319 records. Numerous fields, including author, title, abstract, and all references, were included in the bibliographic record needed for the citation analysis. Cite space 6.1.R3 Advanced, running on Java Runtime v.8 update 91 (build 1.8.0 91-b15), was the research tool used to visualize the networks (Chen 2006). Utilizing Stata MP-Parallel Edition, Release 14.0, StataCorp LP, statistical analyses were performed. Supplementary material contains additional details. The betweenness centrality of a node in a network measures the extent to which the node is part of paths that connect an arbitrary pair of nodes in the network (Brandes 2001; Chen 2006; Freeman 1977). Betweenness centrality, modularity, and silhouette are examples of structural metrics. Citation burstiness and novelty are included in temporal and hybrid metrics. Each algorithm is described in detail (Chen et al. 2010).

4 Results

The results of the investigation have been subjected to a cluster and network analysis, thorough an analysis across multiple dimensions, such as subject category, country, journals and publishers, document type, authors, and co-citations. It is important to emphasize that the analyses regarding publishers and document types were specifically carried out on a subset of documents that were available through the Web of Science database, comprising a total of 1969 documents. The need for selective focus arises due to the lack of information pertaining to the subject in the Scopus database.

The analysis of subject countries, journals, authors, and citations encompasses the entire dataset of 3319 records.

4.1 Subject category

Regarding the subject category, all the articles' "Category" fields from the WoS are used to calculate nodes and edges as co-occurring subject categories.

According to the subject category statistics, the top five categories with the most records are Engineering Electrical Electronic in Cluster #2, with citation counts of 669, Computer Science Information Systems in Cluster #0, with citation counts of 403, Computer Science Software Engineering in Cluster #0, with citation counts of 369, Computer Science Theory Methods in Cluster #0, with citation counts of 355, and Telecommunications in Cluster #0, with citation counts of 315. Clusters are shown in Table 1 with labels from the LSI, LLR and MI algorithms.

The examination of subject categories within the clusters provides insight into the interdisciplinary character of the research landscape in 360° technology. The five categories with the highest number of records, as determined by Web of Science subject category statistics, offer valuable insights into the prevailing domains that influence the field.

The network consists of 9 clusters. The largest cluster (#0) has 30 members and a silhouette value of 0.812. It is labeled as degree video by LLR, 360-degree video by LSI, and pedagogical activities (6.65) by MI. The major citing article of the cluster is "*Panomobi: panoramic mobile entertainment system"* (Takacs 2007). Significantly, the members with the highest number of citations in this cluster correspond to the primary areas of focus in Computer Science, such as Information Systems, Software Engineering, and Theory & Methods. There is a clear correlation between research on degree video and fundamental computer science fields, highlighting the technical principles and approaches that support progress in 360° technology.

The second largest cluster (#1), labeled as radial arrayed echoendoscope by both LLR and LSI, and as pedagogical activities (0.04) by MI, has 28 members and a silhouette value of 0.88. It consists of a varied group of highly cited members from the fields of Psychology (Multidisciplinary and Experimentla) and Biomedical Engineering. The presence of this interdisciplinary network within the cluster demonstrates the wider significance of 360-degree technology, reaching beyond conventional computer science domains to areas such as psychology and biomedical engineering, where the applications and consequences of this technology are investigated. The most cited article here is "Does looking at a 360° video elicit stress-related psychophysiological activation? a case in emergency professions"(Cosoli et al. 2023).

Cluster #2, labeled as *degree video* by LLR, *360-degree video* by LSI, and *pedagogical activities* by MI, has 22 members and a silhouette value of 0.881. The most cited article in this cluster is "Challenging multi-sensor data models and use of 360 images. The twelve months fountain of valentino park in turin" (Teppati Losè et al. 2020). The most cited categories here exhibits a fusion of engineering, optics, and educational disciplines. This implies a comprehensive examination of 360? technology, which includes not just technical elements but also educational uses and the incorporation of optical technologies. The clusters and their nodes are shown in Fig. 1.

Given the technical nature of 360-degree imaging technology, it is not surprising that most clusters pertain to technological fields, such as engineering, computer science, and telecommunications. However, it is intriguing to note that several clusters, including "Psychology," "Medicine," and "Education & Educational Research," are related to human factors. This implies that the application of 360-degree videos and images goes beyond technical uses and is being investigated in industries like education and healthcare. Overall, a variety of fields are being studied and applied for 360-degree videos and images, with both technical and

Table 1 Summary of the largest 9 clusters

ClusterID	Size	Silhouette	Label (LSI)	Label (LLR)	Label (MI)	Average year
0	30	0.812	360-Degree video	Degree video (1091.96, 1.0E−4)	Pedagogical activities (6.65)	2011
1	28	0.88	Radial arrayed echoendoscope	Radial arrayed echoendoscope (337.58, 1.0E−4)	Pedagogical activities (0.04)	2013
2	22	0.881	360-Degree video	Degree video (816.03, 1.0E−4)	Pedagogical activities (2.89)	2010
3	18	0.881	360-Degree video coding	Panoramic camera (478.24, 1.0E−4)	Subjective quality assessment (0.53)	2013
4	9	0.981	Feasibility pilot study	Internet-based treatment (343.38, 1.0E−4)	360-Degree video (0.04)	2019
5	4	1	Using expert computer technology	Worldwide identification (38.05, 1.0E−4)	360-Degree video (0.05)	2006
6	3	1	Clustering and synchrony in laying hens: the effect of environmental resources on social dynamics	Laying hen (20.41, 1.0E−4)	360-Degree video (0.05)	2011
7	2	1	Qchromosomevisualizer: a new tool for 3d visualization of long simulations of polymer-like chromosome models	Qchromosomevisualizer (20.92. 1.0E−4)	360-Degree video (0.05)	2018

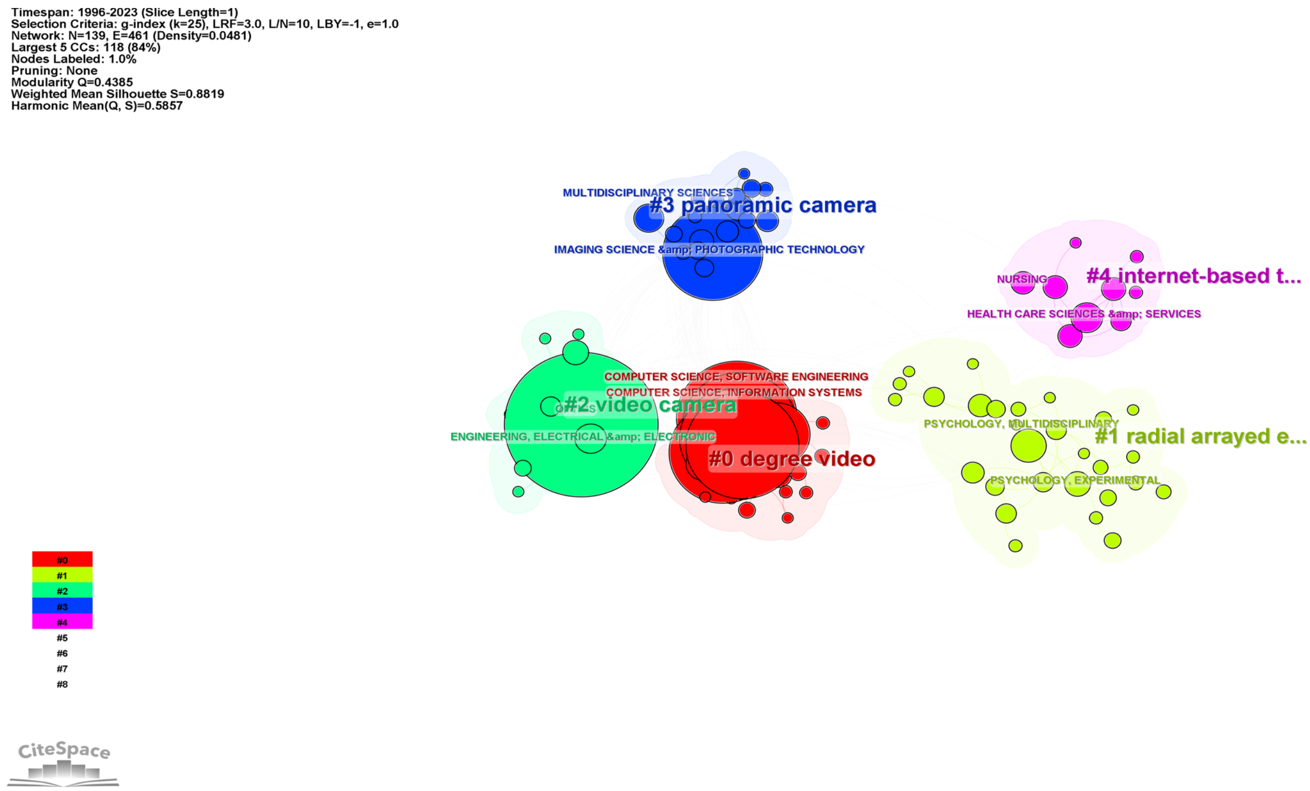

Fig. 1 Clusters from the WoS

human-centered aspects being explored, according to cluster analysis.

4.2 Country

In relation to the countries, nodes and edges are computed as networks of co-authors' countries. A country's multiple occurrences in the same paper are counted just once.

Of the 3319 articles, the United States, China, Japan, and United Kingdom published 680, 487, 224, and 223 articles, respectively. However, contributions also came from all over the globe, especially from Europe, with Germany, Italy, and France, taking positions of prominence, as shown in Fig. 2 along with South Korea and Taiwan.

Figure 3 displays the 12 institutions that have experienced the most significant increases in citations, highlighting notable trends of active research within the academic network. An especially compelling observation in this graphic representation is the presence of Adobe Systems alongside these establishments. This discovery highlights the importance of partnerships between academic institutions and technology companies in promoting research efforts. The collaboration between research initiatives and industry players is crucial, particularly in fields that involve the development and application of cutting-edge technologies and patents. The participation of corporations such as Adobe Systems implies a mutually advantageous collaboration where technological advancements and intellectual property are intertwined with scholarly contributions. The symbiotic relationship between academia and industry highlights the changing nature of research, where collaborative endeavors with industry entities contribute to the creation of knowledge that not only undergoes rigorous academic evaluation but is also documented and indexed for broader distribution.

4.3 Journals and publishers

Regarding the journals, nodes, and edges are calculated as journal co-citation networks between each journal in the relevant field.

The top journal item by citation counts is Lecture Notes in Computer Science (2010) in Cluster #1, with citation counts of 402. The second one is IEEE Transactions on Circuits and Systems for Video Technology (2002) in Cluster #0, with citation counts of 385. The third is Conference on Computer Vision and Pattern Recognition (2004) in Cluster #1, with citation counts of 380. The 4th is IEEE Transactions on Image Processing (2002) in Cluster #1, with citation counts of 305. The 5th is IEEE Transactions on Pattern Analysis and Machine Intelligence (2003) in Cluster #1, with citation counts of 289. The 6th is IEEE Transactions on Multimedia (2011) in Cluster #0, with citation counts of 284. The 7th is

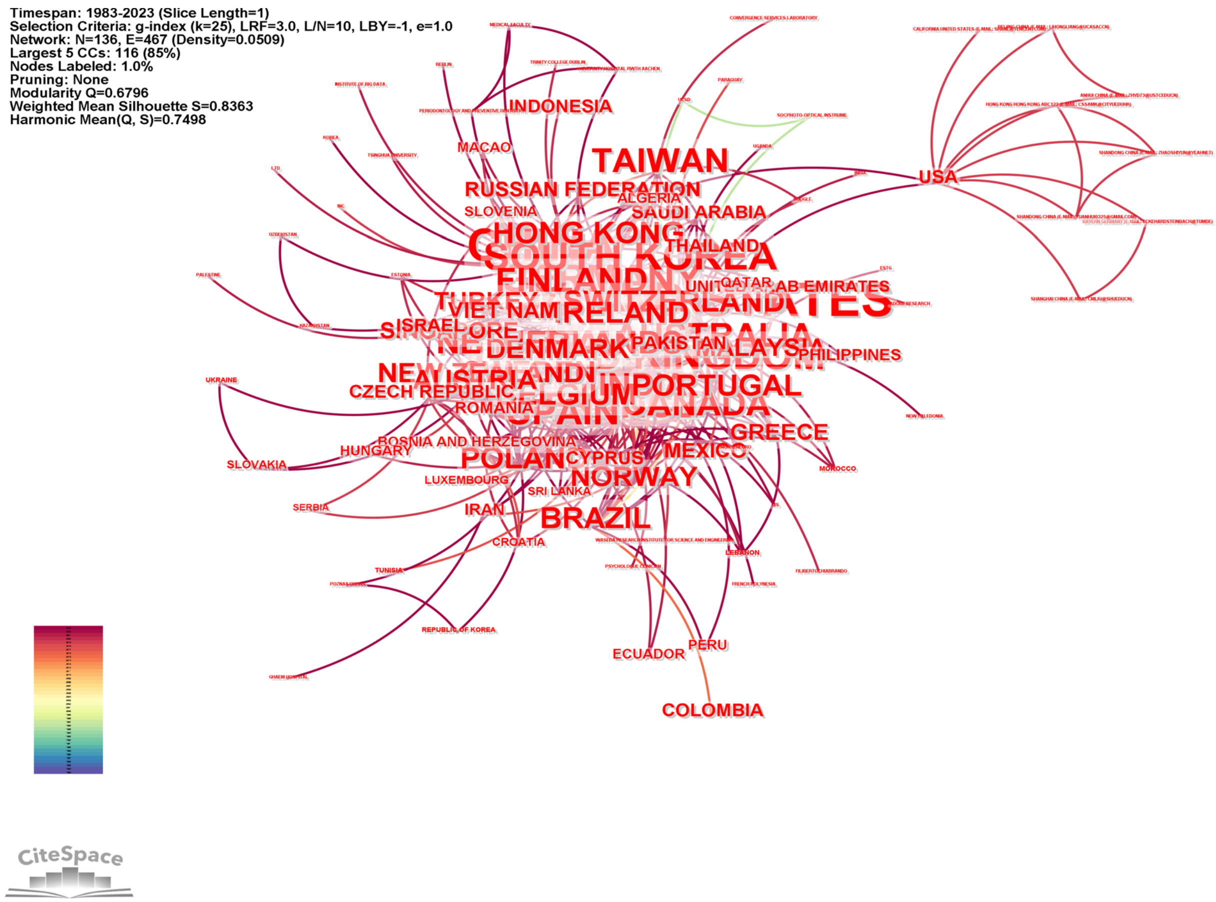

Fig. 2 Country network

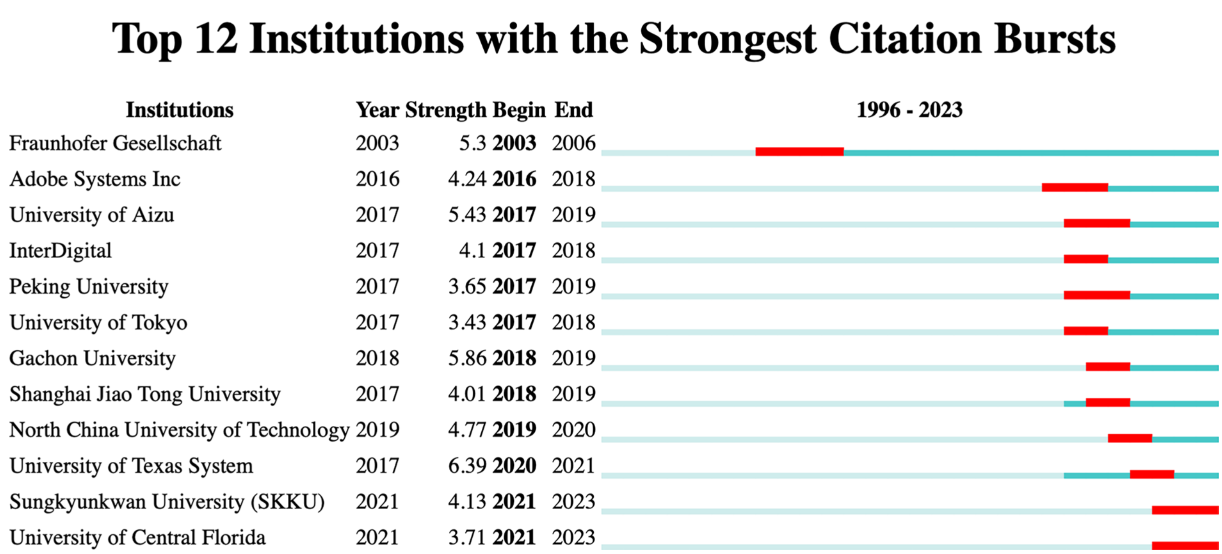

Fig. 3 The top 12 Institutions with the strongest citation bursts

IEEE Transactions on Image Processing (2005) in Cluster #0, with citation counts of 272. The 8th is Proceedings of the 8th ACM on Multimedia Systems Conference (2017) in Cluster #0, with citation counts of 254. The 9th is ACM Transactions on Graphics (2004) in Cluster #1, with citation counts of 209. The 10th is IEEE Transactions on Visualization and Computer Graphics (2016) in Cluster #1, with citation counts of 209 (Fig. 4).

The analysis of the network has identified the existence of 16 separate clusters, as depicted in Fig. 5. The supplementary materials contain detailed labels that have been generated using the LSI, LLR, and MI algorithms. These labels offer a higher level of granularity to the cluster categorizations. Significantly, this analysis has yielded intriguing insights pertaining to human factors, wherein specific clusters demonstrate distinct characteristics.

One noteworthy cluster, referred to as Cluster 1, stands out due to its highly cited article authored by Farmer et al. (2021) entitled "Did you observe what I observed? A comparison of attentional synchrony during 360° video viewing on head-mounted displays and tablets" (Farmer et al. 2021), which was published in the Journal of Experimental Psychology-Applied. Cluster 3, designated as "Virtual Reality", primarily focuses on the theme of "From fomo to jomo: investigating the emotions of fear and joy associated with the fear of missing out and the sense of presence in a 360° video viewing experience" (Aitamurto et al. 2021). Notably, the cluster is characterized by the high citation counts of certain journals, namely Presence-Teleoperators and Virtual Environments (citation = 184), Frontiers in Psychology (citation = 178), and PLOS ONE (citation = 153).

This comprehensive investigation reveals the changing dynamics between Virtual Reality and 360° videos. Over the course of its development, there has been a noticeable convergence between the domains of virtual reality and 360° videos, with the latter showing potential to encompass the entire range of functionalities inherent to VR. The various clusters, each characterized by its distinct emphasis, collectively contribute to the progressive narrative surrounding the gradual expansion of 360° videos beyond their conventional limitations.

Figure 6 instead shows the major publishers in the field of 360-degree video. The data showed that IEEE, which accounts for 45% of all publications, has the highest record count with 886 publications. With contributions of 11.80% and 9.44% each, Springer Nature and the Association for Computing Machinery came in second and third, respectively. Elsevier (5.74%), MDPI (4.01%), Taylor & Francis (3.35%), and Wiley (2.74%), were some of the other important publishers.

4.4 Document type

Notably, the analysis of the existing scientific literature has indicated that most of the publications (1049) are conference proceedings, followed by 894 articles. This outcome

Fig. 4 Networks of journals

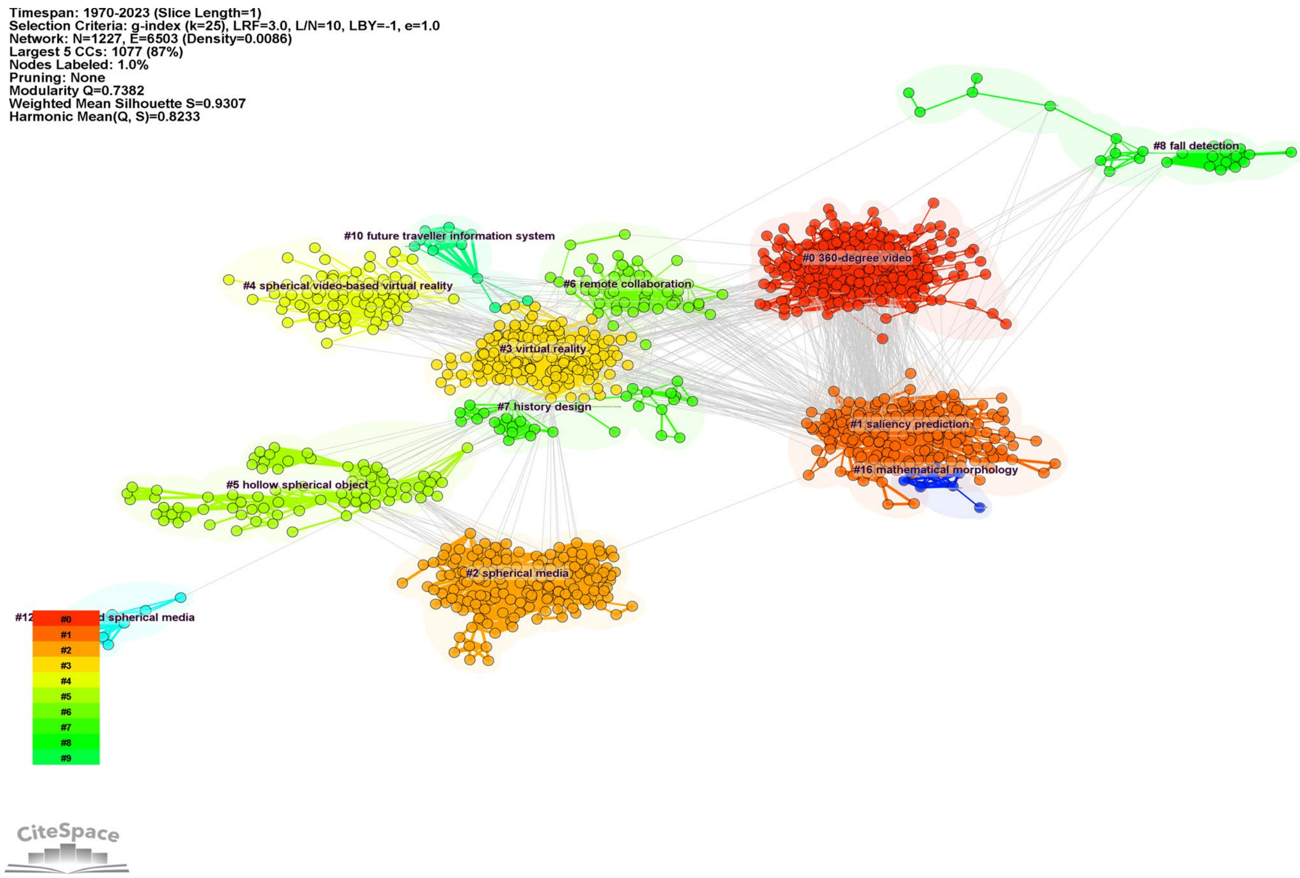

Fig. 5 Co-citation network of journals: the dimensions of the nodes represent centrality according to LLR algorithm

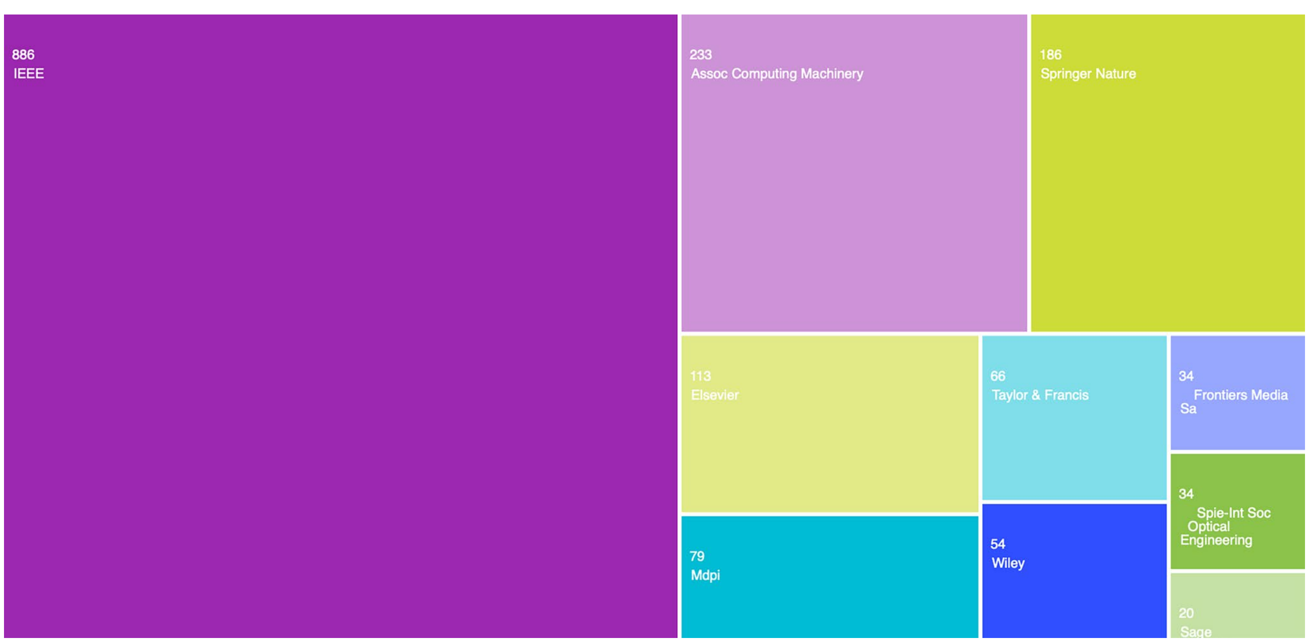

Fig. 6 Distribution of major publishers

suggests that the research community is actively exploring this topic and that the field is still in its infancy. It is plausible that the increased publication of proceedings over articles is due to the fact that conference proceedings serve as the main vehicle for disseminating cutting-edge scientific concepts and innovations. Because of this, the proliferation of proceedings in this field may be an indication of the research community's eagerness to share and disseminate its findings in the form of preliminary results or work in progress. Additionally, the rise in proceedings may be a sign that the field is developing, and that additional study is required to fully realize the potential of 360-degree videos in research (See Fig. 7).

4.5 The faces of 360° research

Authors are the heart and mind of research, and it is up to them to define the direction of these fields as well as to make important discoveries that spark the development of novel theories. It is important to note that the purpose of highlighting the researchers who have contributed significantly to the field of 360° technology is not to create a ranking or hierarchy but rather to recognize the active researchers in this area. While the research on 360° technology is still in its early stages, many researchers have made important contributions that have advanced our understanding and application of this technology. By acknowledging the contributions of these researchers, we can gain a better appreciation of the current state of 360° technology research and the potential for future advancements.

The top ranked author by citation counts is Corbillon (2017) in Cluster #0, with citation counts of 282 and with bursts of 10.72. The second one is Qian et al. (2016) in Cluster #0, with citation counts of 268. The third is Slater (2013) in Cluster #1, with citation counts of 238. The 4th is Yu (2017) in Cluster #2, with citation counts of 196 and the higher bursts of 22.86. The 5th is Zhang (2017) in Cluster #0, with citation counts of 193. The 6th is Sun (2017) in Cluster #2, with citation counts of 190. The 7th is Hosseini (2017) in Cluster #0, with citation counts of 187. The 8th is Xu (2018) in Cluster #2, with citation counts of 166. The 9th is Wang (2010) in Cluster #2, with citation counts of 165. The 10th is Xie (2018) in Cluster #0, with citation counts of 155 (Fig. 8).

The supplementary material provides a detailed explanation of how authors are organized into clusters. This elucidation enhances transparency and offers valuable insights into the organizational structure of the network analysis. This organization functions as a valuable reference for comprehending the affiliations and associations of authors within the identified clusters. By referring to this additional material, readers can enhance their understanding of the collaborative networks and thematic affiliations that form the basis of the contributions made by different authors in the field of 360° video research.

In the domain of network analysis, author citation analysis and co-citation analysis are two discrete methodologies. Author citation analysis evaluates the influence and impact of specific authors through the examination of the frequency with which their works are referenced by others. This approach provides valuable perspectives on the

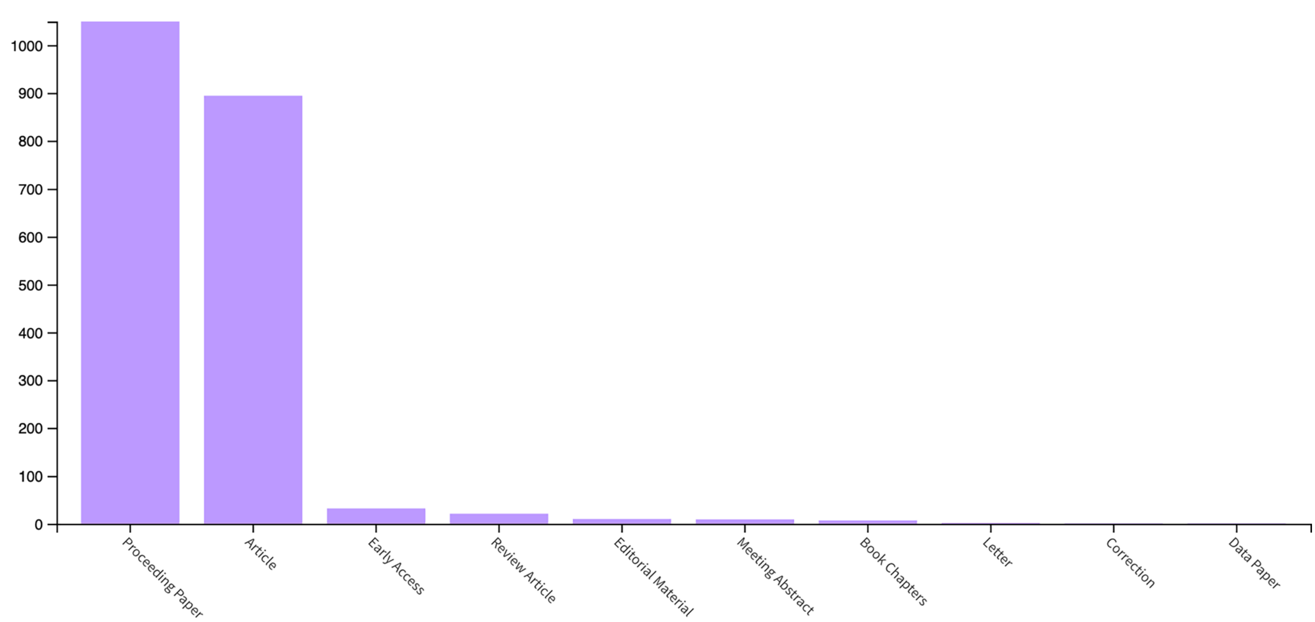

Fig. 7 Documents' type diffusion

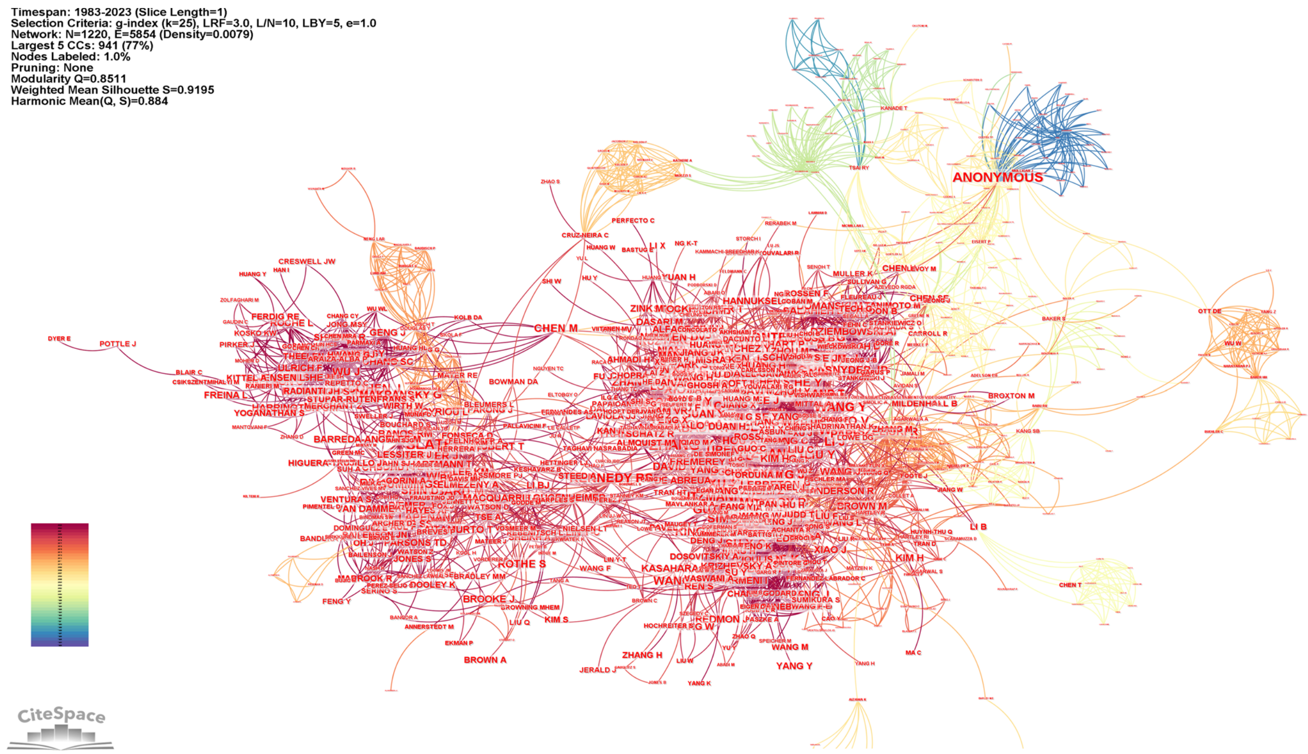

Fig. 8 The dimensions of the nodes represent the centrality index, and the dimensions of the characters represent the author's rank in a network of authors' numbers of publications

eminence of particular scholars in a particular discipline, illuminating their contributions and impact on the academic dialogue. Conversely, co-citation analysis redirects attention away from specific authors and towards the interconnections among pairs of documents, encompassing journals, articles, or authors, predicated on their mutual citation patterns. Instead of identifying specific contributors, co-citation analysis uncovers thematic or conceptual linkages among frequently cited documents. This approach offers a more comprehensive viewpoint on the intellectual framework of a particular discipline, revealing collections of closely related works and revealing the fundamental thematic connections that run throughout the academic literature. Author citation analysis places emphasis on the impact of specific individuals, whereas co-citation analysis provides a more comprehensive comprehension of the interrelationships and thematic clusters that define the wider domain of academic knowledge (Chen et al. 2010).

4.6 Citation network and cluster analyses for all the published articles

Another analysis that can be used is the analysis of co-citations between documents, which enables us to concentrate on the highly cited documents that are typically also the most influential in the domain (Small 1973; González-Teruel et al. 2015; Orosz et al. 2016).

The top-ranked article by citation counts is “Next-generation video encoding techniques for 360 video and VR” of Kuzyakov and Pio (2016) in Cluster #0, with citation counts of 39. The second one is “Optimizing 360 video delivery over cellular networks” of Qian et al. (2016) in Cluster #0, with a citation counts of 36 (Qian et al. 2016). The third is “Developing reflective trainee teacher practice with 360-degree video” of Walshe and Driver (2019) in Cluster #1, with citation counts of 30 (Walshe and Driver 2019). The 4th is “Tiled-based adaptive streaming using MPEG-DASH” of Le Feuvre and Concolato (2016) in Cluster #0, with citation counts of 28 (Le Feuvre and Concolato 2016). The 5th is “Weighted-to-Spherically-Uniform Quality Evaluation for Omnidirectional Video” of Sun (2017) in Cluster #2, with a citation counts of 26. The 6th is “Investigating learning outcomes and subjective experiences in 360-degree videos” of Rupp et al. (2019) in Cluster #1, with a citation counts of 26 (Rupp et al. 2019). The 7th is “View-aware tile-based adaptations in 360 virtual reality video streaming” of Hosseini (2017) in Cluster #0, with a citation counts of 24 (Hosseini 2017). The 8th is “A Framework to Evaluate Omnidirectional Video Coding Schemes” of Yu et al. (2015) in Cluster #0, with citation counts of 22 (Yu et al. 2015). The 9th is “Streaming Virtual Reality Content” of

El-Ganainy and Hefeeda (2016) in Cluster #0, with citation counts of 21 (El-Ganainy and Hefeeda 2016). The 10th is "Saliency in VR: How Do People Explore Virtual Environments?" of Sitzmann et al. (2018) in Cluster #3, with citation counts of 21 (Sitzmann et al. 2018).

Deep comprehension of the topic requires the ability to identify the potential knowledge conglomerate in the area, and this is why the network of document co-citations is so significant. Consequently, a cluster analysis was performed for this purpose (Chen et al. 2010; González-Teruel et al. 2015; Boyack and Klavans 2015). Figure 9 shows the clusters, which are identified with the three algorithms in Table 2.

Figure 10 portrays the changing research landscape in the context of 360° technology over the period from 1996 to 2023. The emergence and development of the main categories in the five clusters offer valuable insights into the growth and diversification of scholarly contributions over time. During the early years, up until the early 2000s, the main nodes and higher centrality were mainly linked to fundamental categories like Computer Science, Cybernetics, and Software Engineering. This observation is consistent with the inherent progression of technological advancements, wherein initial research primarily concentrates on the development of hardware and fundamental technical elements. In this phase, the initial stages of research on 360° technology mainly focused on its hardware components, which laid the necessary foundation for future multidisciplinary applications. Nevertheless, the image also depicts a subtle shift that occurred in the early 2000s, characterized by the appearance of new interconnected points associated with the field of medicine. The inclusion of categories such as Medical Imaging, Surgery, Physiology, Cardiac, Neuroimaging, Neuroscience, Psychology, Sport Science, Obstetrics, and Neurology represents a significant expansion of research in the medical and healthcare fields. The evolution of 360° technology has shifted from a primary focus on hardware to a wide range of applications in the fields of medicine and psychology. The consequences of this chronological advancement are significant. The increasing adoption of medical and psychological classifications demonstrates a growing acknowledgment of the diverse uses of 360° technology beyond its original technical boundaries. The incorporation of 360° technology in medical imaging, surgery, and neuroscience showcases its ability to make substantial contributions to healthcare practices, diagnostics, and behavioral studies. This diversification demonstrates the technology's changing role in tackling interdisciplinary challenges and advancing knowledge in different scientific fields. Moreover, the rising prominence of categories associated with psychology and sport science indicates a growing recognition of the influence of immersive technologies on human perception, cognition, and performance. The convergence of 360° technology with these fields presents potential for groundbreaking applications, spanning from therapeutic interventions to advanced training methodologies.

This figure represents thus the progressive path of 360° technology research, showcasing its development from

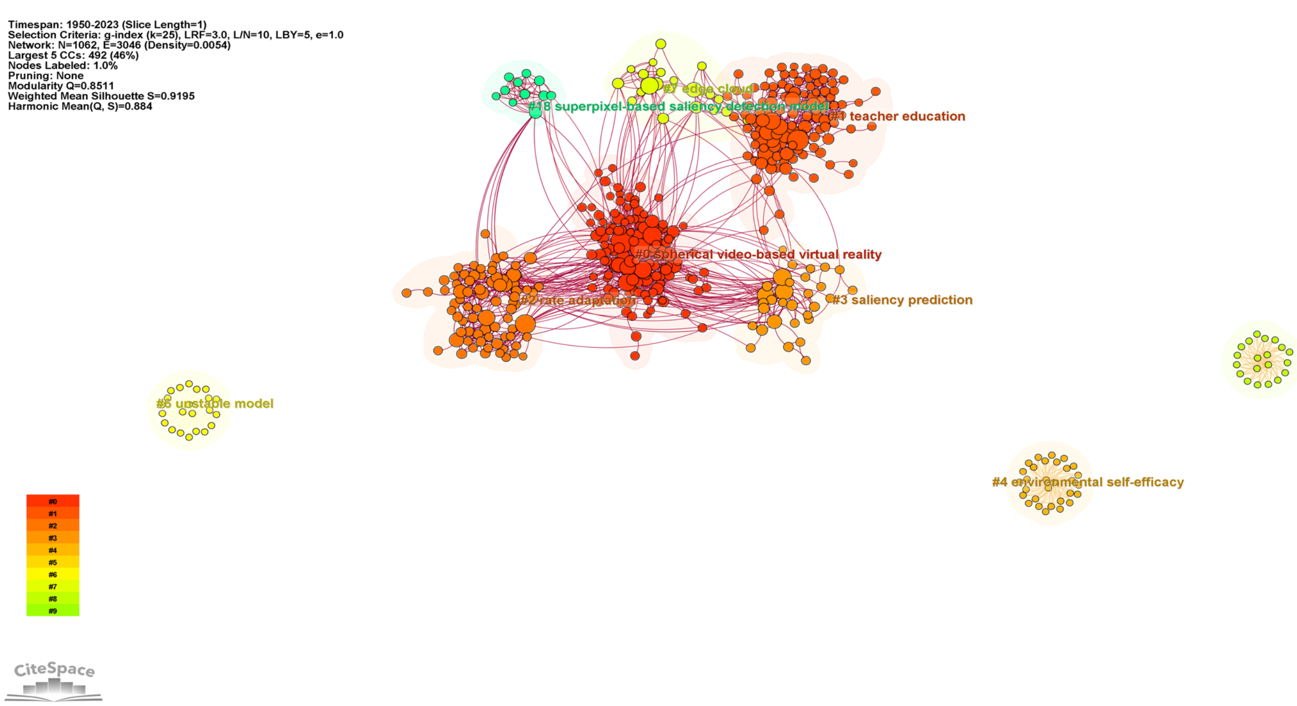

Fig. 9 Document co-citation network by cluster

Table 2 Cluster ID and silhouettes as identified with two algorithms, Latent semantic indexing and LLR (Chen et al. 2010)

ClusterID	Size	Silhouette	Label (LSI)	Label (LLR)	Label (MI)	Average year
0	137	0.83	360-Degree video	Spherical video-based virtual reality (289.31, 1.0E−4)	Tile-based 360-degree video (3.91)	2016
1	114	0.938	360-Degree video	Spherical video-based virtual reality (519.29, 1.0E–4)	Mediating role (2.44)	2018
2	78	0.918	360-Degree video	Rate adaptation (261.64, 1.0E−4)	Vr experience (0.99)	2018
3	31	0.931	Saliency prediction	Saliency prediction (226.76, 1.0E−4)	Graph-based detection (0.18)	2017
4	30	1	Towards video-based immersive environments	Environmental self-efficacy (NaN, 1.0)	360-Degree video (0.08)	1994
5	22	1	Progress in video immersion using panospheric imaging	Progress (21.37, 1.0E−4)	360-Degree video (0.08)	1996
6	22	1	The saturnian ribbon feature-a baroclinically unstable model	Unstable model (18.59, 1.0E−4)	360-Degree video (0.08)	1982
7	21	0.97	Mobile vr	Edge cloud (145.15, 1.0E−4)	Viewport-driven rate-distortion (0.14)	2017
8	20	1	Three-dimensional imaging in aortic disease by lighthouse transesophageal echocardiography using intravascular ultrasound catheters: comparison to three-dimensional transesophageal echocardiography and three- dimensional intra-aortic ultrasound imaging	Lighthouse transesophageal echocardiography (16.87, 1.0E-4)	360-Degree video (0.08)	1994
18	11	0.993	Superpixel-based saliency detection model	Superpixel-based saliency detection model (49.19, 1.0E−4)	360-Degree video (0.08)	2017
28	6	1	Self-supervised learning	Non-local dense prediction transformer (45.29, 1.0E−4)	360-Degree video (0.08)	2018

initial technical investigation to widespread use in various scientific fields. The collaborative efforts shaping the future of 360° technology are underscored by the multidisciplinary nature of the emerging nodes. This highlights the potential of 360° technology to redefine the boundaries of research and application across the scientific spectrum.

5 Discussion

This research's objective was to perform a cluster and network analysis on scientific works in the area of 360° technology. This analysis is significant for several factors. In the first place, it enables to pinpoint the primary areas of study in this area as well as the subtopics that are most and least investigated. Researchers who want to create new studies or projects that build on existing knowledge and fill in current gaps in the literature may find this information to be helpful. Second, the cluster and network analysis can aid in our comprehension of the connections between various 360° technology-related topics and how those relationships have changed over time. Visualizing these relationships allows to gain insights into the fundamental dynamics and organizational framework of this research and to identify potential areas for interdisciplinary collaboration or innovation. Finally, by highlighting connections and common themes among various areas of research, a cluster, and network analysis can assist in bridging the gap between researchers in various sub-disciplines of the field.

The analysis we performed encompassed all categories of scientific articles retrieved from Scopus, considering parameters such as categories, countries, institutions, journals, authors, and co-citation counts. From the data gathered it becomes evident that the most heavily researched areas are related to engineering, computer science, and information systems. These results are not surprising. In fact, they can be attributed to the interdisciplinary nature of 360° video and image technology, which heavily relies on engineering principles to develop hardware and systems that can record and process these immersive visuals. The design and construction of the hardware needed for capturing and rendering this kind of media are based on

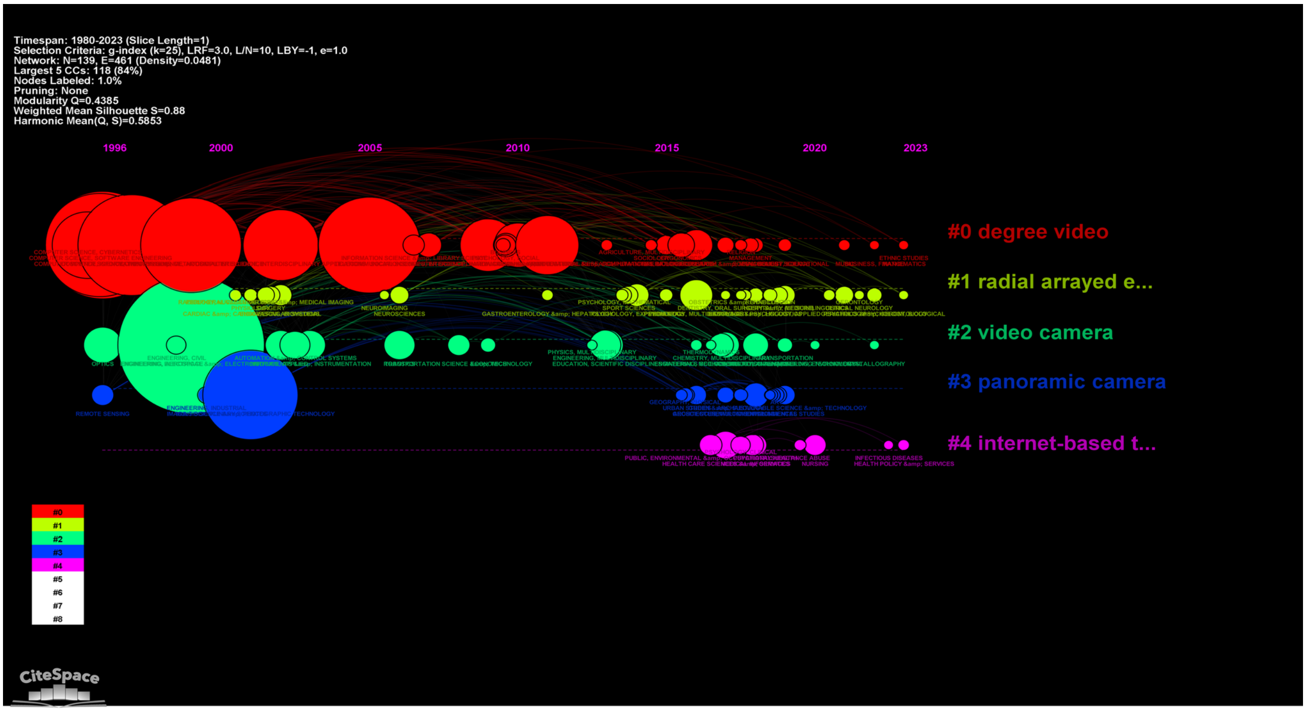

Fig. 10 Network of categories over years

engineering principles. To effectively handle high-resolution images and videos, computer science is essential in the development of algorithms, software frameworks, and data processing methods. Furthermore, understanding the integration of various software and hardware components to achieve seamless functionality in 360° media platforms requires system information. Therefore, the intersection of these fields illustrates how they work together to advance the field of 360-degree videos and imaging.

However, there is a growing trend toward investigating human factors as well. Given the typical process of new technology development and market adoption, the results of our analysis are in line with expectations. In general, innovators first concentrate on obtaining patents for their ideas before putting them on the market. Once a patent application has been submitted and granted, the workable technology can be used commercially and subsequently become the focus of academic publications (Wu et al. 2023).

It is thus not surprising that human factors have started to appear in 360° video and image research only in recent years. This can be attributed to the quick technological advancements and improved accessibility of such immersive media, which have led to wider use in a variety of applications. Researchers and developers have realized the significance of comprehending how people perceive and interact with this technology to enhance the user experience as more and more people engage with 360-degree content.

Likewise, since its inception, VR has adhered to the same pattern (Cipresso et al. 2018). In fact, the focus of VR research has shifted significantly in the new millennium toward what has been called as the clinical-VR era, which places a strong emphasis on rehabilitation, neurosurgery, a new stage of therapy, and laparoscopic skills. The number of applications and articles that have been published over the last years is consistent with the new technological advances visible at both the hardware and software levels, such as the proliferation of HMDs and the growth of VR communities. VR, which was initially primarily concerned with engineering issues like hardware and software development, has gradually developed into a multidisciplinary field that takes into account the needs of its users. VR technology started to be integrated into clinical fields as it advanced and grew beyond its initial application. In fact, the use of VR technology began to go beyond the gaming and entertainment sectors as it developed and became more sophisticated, highlighting the need for a human-centered approach in creating VR experiences for a variety of user groups.

This growth trend is further supported by the introduction of VR in the medical field. These days, medical professionals use technology for things like patient rehabilitation and surgical training (Hodgson et al. 1989). This shift from engineering to clinical use emphasizes how crucial it is to take human factors into account when using elements like 360-degree videos and imaging. In general, the emergence of human factors in the scientific literature on 360-degree videos, imaging, and VR points to a growing understanding of user-centered design and the growing importance of these technologies in a variety of industries. Additionally, it emphasizes how interdisciplinary these fields have become because of their continued growth and development.

In both cases—360-degree videos and VR—the shift towards incorporating human factors highlights a growing recognition of the need to improve interactions with cutting-edge technologies. This integration has created new opportunities for research and development. Researchers can make sure that these immersive technologies continue to be available, interesting, and enjoyable for a variety of users by being aware of and accommodating human needs and limitations.

Figure 9 shows that there has been a significant increase in scientific publications about 360-degree videos and images since 2015. This occurred precisely at the same time as the new economic era, during which significant investments in information technology were made. 360° technologies are now more widely available to a larger audience thanks to the development of 360° cameras and VR headsets that are suitable for consumers. Due to this, more industries, including entertainment, education, tourism, and marketing, as well as research, are using 360-degree technologies.

Despite its growing popularity, 360° videos have not, however, enjoyed the same level of success as VR. One reason is that a particular kind of viewer or headset is necessary to fully experience 360° videos. Even though VR headsets are becoming more readily available and affordable, many people still lack access to the required technology. The audience for 360-degree video content is thus restricted. Additionally, while 360° videos let viewers look around a scene to explore it, they are unable to fully engage with the environment or interact with characters and objects as they can in a fully rendered VR experience. Users of 360-degree videos, on the other hand, were only able to adjust their viewing angle; they were not able to actively participate in or change the environment they were experiencing. Another factor might be that the 360°video content's quality was insufficient to have a significant effect on viewers. These videos frequently had issues with poor image quality, uneven camera stitching, and a dearth of interesting or captivating content. Finally, organizations like Oculus and HTC have made significant investments in and advancements to VR technology recently. As a result, there has been an explosion in the creation of top-notch VR experiences and applications, overshadowing the less dynamic nature of 360° videos.

Overall, the field of 360° technologies faces numerous challenges, but also holds a promising future that requires thoughtful consideration. An important unresolved matter concerns the level of interactivity and user involvement in 360° experiences. At present, 360° videos have fewer options for interaction compared to VR experiences, highlighting the necessity to create inventive techniques for actively involving users in these environments (Mancuso et al. 2020).

Another notable obstacle involves guaranteeing a consistently elevated level of Quality of Experience (QoE) for users. The challenges of stitching artifacts, resolution limitations, and ensuring a high QoE across various platforms and devices remain unresolved. Content creation continues to be intricate, necessitating the development of more user-friendly tools and workflows for content creators. The difficulty lies in resolving problems associated with narrative construction and focus control in 360° settings, requiring inventive and user-centric remedies. Enhancing accessibility is a pertinent concern, necessitating the expansion of the reach of 360° content to a wider audience. This can be achieved by reducing hardware prerequisites or creating novel display technologies. Furthermore, the absence of uniformity and compatibility across platforms poses challenges for integration. Establishing industry standards is crucial to guarantee a smooth and consistent experience across different platforms and devices. Anticipated in the future is a rise in interactivity by incorporating cutting-edge technologies like tactile feedback and gesture control. Artificial intelligence (AI) has the potential to completely transform the creation of 360° content by implementing algorithms that automatically compose scenes, enable adaptive storytelling, and generate personalized content.

One important direction is the incorporation of 360° technologies with other extended reality (XR) components. This allows for the combination of augmented reality (AR) and virtual reality (VR) elements to create hybrid and enhanced experiences.

However, 360° videos have many advantages over VR, especially when it comes to striking a balance between realistic and computer-generated environments. Virtual reality can offer immersive experiences, but it frequently relies on computer-generated graphics that don't always have the same authenticity as 360-degree videos. In contrast, 360-degree videos give viewers a more realistic experience by capturing real-world environments from all sides (Borghesi et al. 2022).

360-degree videos' increased realism has important ramifications for a variety of applications, especially in the healthcare, education, and entertainment sectors. This makes it possible to relate to the material more deeply and can elicit more intense emotional reactions (Calogiuri et al. 2018; Chirico et al. 2017; Chirico and Gaggioli 2019; Jun et al. 2020; Quesnel and Riecke 2018).

The non-immersive nature of 360° videos is another benefit. For instance, 360° videos can be played with ease on tablets and smartphones, while VR frequently requires specialized equipment, which may be burdensome for some users.

In fact, for some groups, like patients in healthcare settings, these specialized headsets might not be practical. 360° videos, on the other hand, are a more practical option for these patients because they can be easily accessed and viewed on a variety of devices, such as tablets, without causing them any discomfort or disruption (Borghesi et al. 2022; Mancuso et al. 2020; Pedroli et al. 2020, 2022; Stramba-Badiale et al. 2020). Due to lower initial investments and ongoing maintenance costs, being able to interact with 360° content without the need for complicated equipment or cumbersome setups also increases profitability. In comparison to VR, using 360° videos can offer immersive experiences to a variety of audiences at a lower cost and with greater effectiveness. 360-degree videos are thus suitable for a wide range of applications because of the authentic environment they offer and their flexible implementation options. These experiences have advantages over more conventional VR ones in that they encourage accessibility, engagement, and the possibility of benefits in a variety of industries.

Thinking about future directions of this technology, the increasing utilization of 360° technologies in education and training is anticipated to be a progressive trend, offering opportunities to develop virtual classrooms, immersive training simulations, and enhanced learning experiences using 360° content.

Industries like healthcare and therapy will witness a rise in the adoption of 360° technologies for virtual therapies, immersive patient encounters, and therapeutic interventions that leverage 360° videos for mental health and rehabilitation purposes. The advancement of live streaming and social interaction in 360° environments is expected to provide real-time collaborative experiences, interactive live events, and social platforms specifically designed for sharing 360° content. The utilization of 360° technologies will make a substantial impact by documenting and preserving cultural heritage and natural environments. This will be achieved through virtual tours of historical sites, immersive documentation of endangered ecosystems, and interactive experiences that contribute to cultural preservation.

These findings demonstrate how crucial interdisciplinary research is to the creation and application of 360° video and image technologies. It is critical to recognize the impact of human factors in determining how users interact with these new media formats even as engineering and computer science continue to play dominant roles. A more thorough understanding of how 360° videos and images can best serve various purposes across various sectors will result from bridging the gap between technology-driven disciplines and human-centered studies.

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Data availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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