The Global Publication Output in Augmented Reality Research: A Scientometric Assessment for 1992-2019

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ABSTRACT

This paper describes global research in the field of augmented reality (22078) as indexed in Scopus database during 1992-2019, using a series of bibliometric indicators. The augmented reality (AR) research registered high 54.23% growth, averaged citation impact of 8.90 citations per paper. Nearly 1% of global output in the subject (226 papers) registered high-end citations (100+) per paper. The top 15 countries accounted for 87.05% of global publications output in the subject. The USA is in leadership position for its highest publications productivity (19.25% global share). The U.K. leads the world on relative citation index (2.05). International collaboration has been a major driver of AR research pursuits; between 11.89% and 44.04% of national share of top 15 countries in AR research appeared as international collaborative publications. AR research productivity by application types was the largest across sectors, such as education, industry and medical. Computer science has emerged as the most popular areas in AR research pursuits. Technical University of Munich, Germany and Osaka University, Japan have been the most productive organizations and Nara Institute of S&T, Japan (66.55 and 7.48) and Imperial College, London, U.K. (57.14 and 6.42) have been the most impactful organizations. M. Billinghurst and N. Navab have been the most productive authors and S. Feiner and B. MacIntyre have been the most impactful authors. *IEEE Transactions on Visualization & Computer Graphics, Multimedia Tools & Applications* and *Virtual Reality* topped the list of most productive journals.

1. Introduction

Augmented Reality - (AR) is an emerging artificial intelligence technology that modifies a view of the real physical world environment by superimposing the view in reference with computer-generated images (include perceptual information from multiple sensory modalities including visual, auditory,

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haptic, somatosensory, and olfactory) (Billinghurst, Clark, & Lee, 2015; Gijevsk, 2017; Wikipedia, 2018). The sensory information can be constructive (i.e. adding to the natural environment) or destructive (i.e. masking of the natural environment) and it is seamlessly interwoven with the physical world in such a way that it is perceived as the part of the real environment (Wikipedia, 2018; Collins, 2018). AR has three key characteristics (Azuma, 1997): (i) The technology combines real and virtual content, (ii) The virtual content can be interacted with in real time and (iii) The virtual content is registered or fixed in three-dimensional space.

The main types of AR display hardware are: Head Mounted Displays, Handheld Displays and Spatial Displays. In order to fix virtual content in space, AR tracking technologies are used which exist in different categories, each varying in their objectives and application uses. These include: (i) Marker-based AR tracking which typically uses a camera, computer vision algorithm and some type of visual marker; (ii) Markerless AR uses computer vision techniques to recognize the AR camera position from naturally occurring visual features in the real environment.; (iii) Location-based AR uses GPS, digital compass, inertial measurement unit, accelerometer or other sensors embedded in device to calculate the device location. There is also some AR tracking systems that combine several elements together into a hybrid tracking system (Wagner & Schmalstieg, 2006; Bimber & Raskar, 2005).

There are a number of ways to categorize AR, with Edwards-Stewart, Hoyt, & Reger (2016) identifying two main categories (along with sub-categories include): (i) Triggered Based − Marker-based, Location-based, Dynamic Augmentation and Complex Augmentation and (ii) View-based augmentation - Indirect Augmentation and Non-Specific Digital Augmentation.

AR different types of Applications have the potential to change the way we consume information, communicate, express and share creativity and conduct business. Some of the use cases where AR technology is currently being applied (Bimber & Raskar, 2005) include areas/sectors such as: business, communication, construction, design - architecture and interior home, education, entertainment, gaming, healthcare, surgery, marketing and advertising, manufacturing - inventory management, safety training, maintenance inspection, shopping and therapy (Martin-Erro, A., Espinosa-Escudero, & Dominguez, 2014).

1.1 Literature Review

The bibliometric studies in the field AR including its broader areas is limited to a few publications. Billinghurst (2018) provides an overview of AR research, analyzes the global research output by leading countries, organizations and authors. Dey et al. (2018) reviewed and classified 10-year literature covering AR user studies literature (consisting of 291 papers) from 2005 to 2014. Cipresso et al. (2018) explored the global research output on virtual reality and AR (21,667 and 9944 papers respectively) from 1990 to 2018, using the WoS database. Network and cluster analysis techniques were used to show changes in research productivity over time in the field. Karakus, Ersozlu, and Clark (2019) examined the global publications (437) on the application of augmented reality (AR) in the education sector published during 1999-19. The paper evaluated publication countries, institutions, journals, and authors as well as studied co-occurrences of author keywords. Gupte (2019)

examined research field intersecting augmented reality and health Informatics (7360 publications). The findings are based on analysis of publications as well as social media output on measures such as publication output, top authors, affiliations, subject areas and geographical location. Yung and Khoo-Lattimore (2019) examined the applications of virtual reality and augmented reality (AR) in tourism sector using 46 manuscripts. Choi, Jung, and Noh (2015) analyzed 154 articles relevant to virtual reality's application to manufacturing, exploring the trends in the past and present research and discussed the future of virtual reality research.

Similar kind of bibliometric studies assessing global literature in virtual reality and mixed reality do exist in the literature. Gupta and Dhawan (2019) and Gupta et al. (2019) examined virtual reality research output (91,429) during 1996–2017 and mixed reality research (2415) published during 1994-17 on a series of aspects, such as the growth rate, global share, citation impact, share of international collaborative publications, distribution of publications by broad subjects, productivity and citation profile of top countries, organizations and authors, preferred media of communication and bibliographic characteristics of highly-cited publications.

Although past research studies did evaluate AR research but the data sets covered in such bibliometric studies were rather small, limited to select few publication years. Until now there has been hardly any bibliomeric study that attempted to analyze AR research based on a comprehensive data set. This paper seeks to fill this gap. It will aim to evaluate AR research since its inception in 1992 till 2019 and discuss how growth in its applications overtime shaped the dynamics of research in the subject.

2. Objectives

The study has been undertaken with the intent to analyze the global research in the field of augmented reality, covering data indexed in Scopus international database during 1992-2019. The data has been analyzed on measures such as research growth, citation impact, global publications share, activity index and international collaborative publications share. Besides, the study will profile the research output by broad subject areas, by most productive countries, research organizations and authors, and by their collaborative linkages. The study will also ascertain main modes of research communication. It is hoped that this kind of research study may provide greater insight into global research trends in this fast growing research field.

3. Methodology

The study retrieved and downloaded publications data on AR research from Scopus database (http://www.scopus.com) the period 1992-1999. The search string formulated for the purpose included the keyword term "Augmented Reality", and tagged them to "Keyword" field and "Article Title" field. To limit the global research output to the publication period '1992-19', the date range field was used along with Boolean Operator 'AND'. In the subsequent round of searching, the final

search output was refined by using “subject area tag”, “country tag”, “source title tag”, “journal title name” and “affiliation tag” with a view to obtain statistics on global publications output by subject, collaborating countries, author-wise, organization-wise and journal-wise, etc. Citations for publications were collected from date of publication till 3 January 2020. Since the first publication on AR appeared in 1992 in Scopus database, as a result we decided to cover the entire period from 1992 to 2019.

4. Analysis and Results

4.1 Growth Analysis

Augmented Reality (AR) research conducted across the world accumulated a total of 20, 228 publications during 1992-19. The annual publications output in the subject registered significantly hi,gh 54.23% annual growth, increasing in its annual volume from just 2 in 1992 to 3077 publications in 2019. The global output averaged to 788.5 papers per year. Its 14-year publications output registered 994.05% absolute growth, up from 1,849 in 1992-05 to 20,229 publications in 2006-19 which implies that research growth in the subject was significantly faster in the second-half period of the study compared to the fist-half (Table 1, Fig. 1).

Table 1. Annual & Cumulative Global Publications Output in Augmented Reality Research, 1992-19

Year	TP	TC	CPP	Year	TP	TC	CPP	Year	TP	TC	CPP
1992	2	15	7.50	2003	302	6189	20.49	2014	1522	13858	9.11
1993	8	1327	165.88	2004	312	4805	15.40	2015	1643	10760	6.55
1994	4	1990	497.50	2005	292	5524	18.92	2016	1809	10909	6.03
1995	30	1523	50.77	2006	403	5126	12.72	2017	2377	11432	4.81
1996	28	1004	35.86	2007	427	8100	18.97	2018	3175	6888	2.17
1997	62	7211	116.31	2008	606	8909	14.70	2019	3077	1814	0.59
1998	80	2732	34.15	2009	631	11490	18.21	1992-05	1849	56067	30.32
1999	105	5532	52.69	2010	811	9061	11.17	2006-19	20229	140412	6.94
2000	164	5402	32.94	2011	1003	14559	14.52	1992-19	22078	196479	8.90
2001	211	6479	30.71	2012	1283	12682	9.88				
2002	249	6334	25.44	2013	1462	14824	10.14				

*TP=Total Papers; TC=Total Citations; CPP=Citations Per Paper

Annual Growth=54.23; Cumulative Growth=994.05

The 28-year citation impact of AR research averaged to 8.90 citations per publication (CPP) during 1992-19, although its 14-year citation impact declined from 30.32 CPP in 1992-05 to 6.94 CPP in 2006-19. The citation impact of the research was the highest 497.5 CPP in 1990 (Fig. 2).

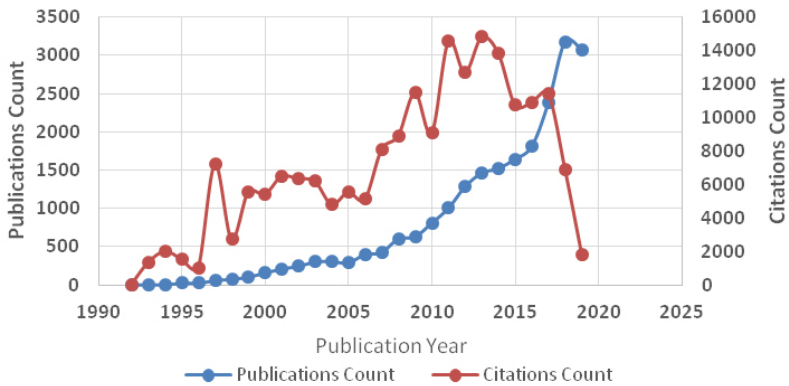

Fig. 1. Augmented Reality Research - Global Growth in Publications Output 1992-2019

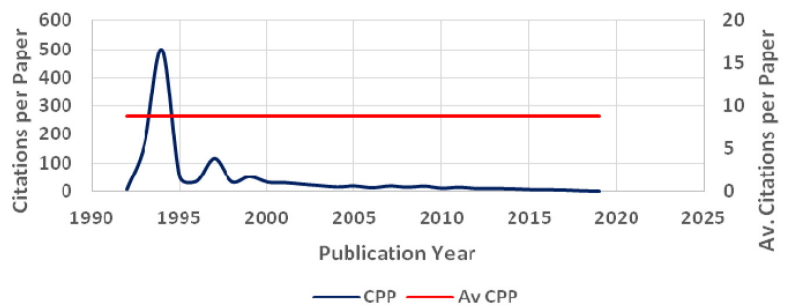

Fig. 2. Augmented Reality Research - Citations per Paper 1992-2019

Of the total global publications in AR, 69.41% (5324) appeared as conference papers, 25.17% (5356) as articles, 2.33% (514) as book chapters, 1.51% (334) as reviews, and others less than 1.0: 0.43% (94) as conference reviews, 0.32% (53) editorials, 0.24% (52) as notes, 0.14% (30) as books, 0.12% (26) as short surveys, 0.09% (19) as letters, etc.

4.2 Top 15 Most Productive Countries in Augmented Reality

Top 15 countries in AR research collectively contributed 87.05% global publications share and accounted for citations impact 10.23 CPP, above the world average 0f 8.90 CPP (Table 2, Fig. 3). Individually their global publication share differs widely from 1.75% to 19.25%. The USA contributed the highest publication share of 19.25%, followed by Germany (9.74%), Japan (9.05%), etc. India and Austria positioned at the bottom end of the tally with contributed 1.75% to 2.19% global publications share. There is some change of ranking order of countries in global share from 1992-05 to 2006-19. Only four countries registered their relative citations index above their group average (1.15): the U.K. (2.05), Austria (2.0), USA (1.81) and Canada (1.64).

Table 2. Global Publication Share of Top 15 Most Productive Countries in Augmented Reality Research during 1992-19

S.No	Name of the country	Total Papers			Share of Papers			1992-19				
		1992-05	2006-19	1992-19	1992-05	2006-19	1992-19	TC	CPP	ICP	%ICP	RCI
1	USA	541	3709	4250	29.26	18.34	19.25	68528	16.12	1082	25.46	1.81
2	Germany	238	1913	2151	12.87	9.46	9.74	19608	9.12	580	26.96	1.02
3	Japan	228	1770	1998	12.33	8.75	9.05	15397	7.71	351	17.57	0.87
4	China	73	1590	1663	3.95	7.86	7.53	6470	3.89	381	22.91	0.44
5	South Korea	43	1252	1295	2.33	6.19	5.87	7658	5.91	240	18.53	0.66
6	U.K.	146	1112	1258	7.90	5.50	5.70	22991	18.28	554	44.04	2.05
7	Italy	36	1041	1077	1.95	5.15	4.88	6403	5.95	267	24.79	0.67
8	France	108	864	972	5.84	4.27	4.40	8418	8.66	333	34.26	0.97
9	Spain	24	864	888	1.30	4.27	4.02	7956	8.96	293	33.00	1.01
10	Taiwan	6	754	760	0.32	3.73	3.44	5336	7.02	117	15.39	0.79
11	Australia	43	699	742	2.33	3.46	3.36	6580	8.87	311	41.91	1.00
12	Canada	75	602	677	4.06	2.98	3.07	9909	14.64	258	38.11	1.64
13	Brazil	6	613	619	0.32	3.03	2.80	1865	3.01	85	13.73	0.34
14	Austria	100	383	483	5.41	1.89	2.19	8585	17.77	188	38.92	2.00
15	India	0	387	387	0.00	1.91	1.75	883	2.28	46	11.89	0.26
		1667	17553	19220	90.16	86.77	87.05	196587	10.23	5086	26.46	1.15
		1849	20229	22078				196479	8.90			

*TP=Total Papers; TC=Total Citations; CPP=Citations Per Paper; ICP=International Collaborative Papers; RCI=Relative Citation Index

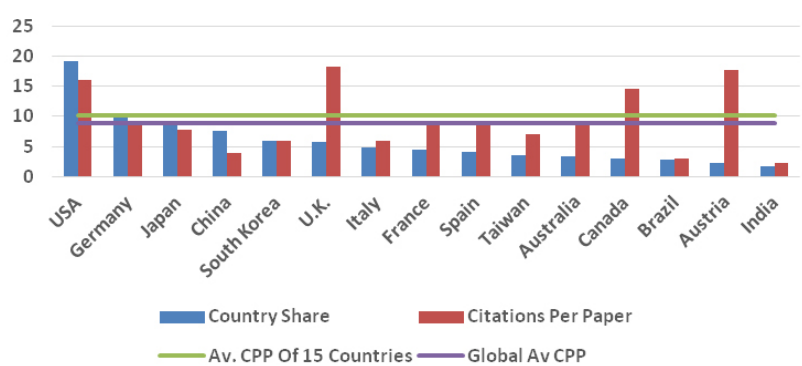

Fig. 3. Augmented Reality Research - Most Productive Countries 1992-19 Global Publications Share Vs Av. Citations per Paper

101 countries contributed to global research in AR during 1992-19. However, the distribution of research output coming from these participating countries is highly skewed. Only a select few countries had contributed to publications productivity above the global average of 788.5 publications per year. Of the 101 countries, 44 produced as low output with 1-10 papers each, 29 countries produced from 11-50 papers each, 9 countries from 51-100 papers each, 25 countries from 101-500

papers each, 7 countries from 501-1000 papers each, 4 countries 1001-1700 papers each, 2 countries 2001-2200 papers each and 1 country, the USA, produced 4254 papers. Table 2 shows the leading countries which have produced the most AR papers (Fig. 3).

4.2.1 Collaboration among Top 10 Most Productive Countries

A closer examination of collaborative linkages across top 10 most productive countries in AR research reveal that the USA leads with highest 786 linkages, followed by Germany (443), U.K. (389), Japan (281), China (280), France (242), Italy (209), Spain (181), South Korea (172) and Taiwan (90). As seen from collaboration network Gephi graph (Fig. 4) in terms of distances between nodes and thickness size of the edges, it is evident that collaborative linkages made by Germany (190), China (133), U.K. (123) and Japan (108) with the USA were relatively greater compared to collaboration linkage between the USA and the remaining countries including South Korea, Italy, France, Spain, and Taiwan (Table 3, Fig. 4).

Table 3. Number of Collaborative Linkages among Top 10 Most Productive Countries in AR during 1992-19

S.No	Country Name	ICP	Number of Collaborative linkages with top 10 countries	TCL
1	USA	1082	2(190), 3(108), 4(133), 5(75), 6(123), 7(49), 8(37), 9(36), 10(35)	786
2	Germany	580	1(190), 3(57), 4(16), 5(17), 6(64), 7(30), 8(44), 9(24), 10(1)	443
3	Japan	351	1(108), 2 (57), 4(27), 5(30), 6(17), 7(3), 8(14), 9(6), 10(7)	281
4	China	381	1(133), 2(16), 3(27), 5(12), 6(37), 7(3), 8(14), 9(2), 10(26)	280
5	South Korea	240	1(75), 2(17), 3(30), 4(12), 6(16), 7(2), 8(9), 9(3), 10(8)	172
6	U.K.	554	1(123), 2(64), 3(17), 4(37), 5(16), 7(50), 8(37), 9(37), 10(8)	389
7	Italy	267	1(49), 2(30), 3(5), 4(3), 5(2), 6(50), 8(39), 9(31), 10(1)	209
8	France	333	1(37), 2(44), 3(24), 4(14), 5(9), 6(37), 7(39), 9(37), 10(1)	242
9	Spain	293	1(36), 2(24), 3(6), 4(2), 5(3), 6(39), 7(31), 8(37), 10(3)	181
10	Taiwan	117	1(35), 2(1), 3(7), 4(26), 5(8), 6(8), 7(1), 8(1), 9(3)	90

ICP=International Collaborative Papers; TCL=Total Collaborative Linkages

Fig. 4. Augmented Reality Research 1992-2019:
Collaboration Network of Top 10 Countries

4.3 Distribution of Research Output by Sub-Fields

The global publication output in AR research distributed across top ten disciplines -- as identified in the Scopus database classification -- revealed that computer Science is the most popular area of research in AR research (74.85% share), followed by engineering (36.26%), mathematics (18.01%), social sciences (9.94%) and other disciplines from 1.75% to 6.93% during 1992-19. The change in research activity across identified disciplines between 1992-05 and 2006-19 was examined. The disciplines that showed increase in their research activity between the periods 1992-05 and 2006-19, from below to above the world average, include: engineering (from 96.79 to 100.29), social sciences (from 27.76 to 106.60), business, accounting & management (from 17.06 to 107.58), decision science (from 78.21 to 101.99) and arts & humanities (from 24.75 to 106.88). The disciplines that showed downfall from above to below average include computer science (from 103.03 to 99.72), mathematics (from 103.31 to 99.70), physics & astronomy (from 105.36 to 99.51), medicine (from 158.98 to 94.61) and materials science (from 125.84 to 97.64) (Table 4).

Table 4. Subject-Wise Breakup of the Global Publications in AR Research during 1992-19

S.No	Subject*	Number of Papers (TP)			Activity Index		%TP
		1992-05	2006-19	1992-19	1992-05	2006-19	
1	Computer science	1426	15100	16526	103.03	99.72	74.85
2	Engineering	649	7357	8006	96.79	100.29	36.26
3	Mathematics	344	3632	3976	103.31	99.70	18.01
4	Social sciences	51	2143	2194	27.76	106.60	9.94
5	Physics & astronomy	135	1395	1530	105.36	99.51	6.93
6	Medicine	190	1237	1427	158.98	94.61	6.46
7	Materials science	129	1095	1224	125.84	97.64	5.54
8	Business, accounting & management	7	483	490	17.06	107.58	2.22
9	Decision science	30	428	458	78.21	101.99	2.07
10	Arts & humanities	8	378	386	24.75	106.88	1.75
	Total	1849	20229	22078			

* There is overlapping of literature covered under various subjects

4.4 Types of Augment Reality (AR) Research

The distribution of AR research by various AR - types reveal that Trigger AR type contributed the largest global publications share 3.96% (874 papers), followed by Markerless AR type 1.58% share (348 papers), Projection-based AR type 0.62% share (136 papers), Superimposition-based AR type 0.27% share (59 papers), Outlining AR type 0.14% share (31 papers) and View-based AR type 0.10% share (22 papers). Within Trigger AR research, Location-based AR contributed the largest share 1.97%, followed by Marker-based AR (1.49%), Dynamic Augmentation (0.29%) and Complex Augmentation (0.27%). Their 14-year cumulative global publication share witnessed marginal to substantial fluctuations during the period between 1992-05 and 2006-19 (Table 5).

Table 5. Classification of Global Output by Types of Augment Reality during 1992-19

S.No	Type of AR	TP			%TP			TC	CPP	% TP
		1992-05	1996-19	1992-19	1992-05	1996-19	1992-19	1992-19		
1	**Triggered AR**	39	835	874	2.11	4.13	3.96	8882	10.16	3.96
1.1	Marker-based AR	19	311	330	1.03	1.54	1.49	2237	6.78	1.49
1.2	Location-based AR	12	423	435	0.65	2.09	1.97	3438	7.90	1.97
1.3	Dynamic Augmentation	3	62	65	0.16	0.31	0.29	2638	40.58	0.29
1.4	Complex Augmentation	7	53	60	0.38	0.26	0.27	743	12.38	0.27
2	**View-based AR**	1	20	21	0.05	0.10	0.10	260	12.38	0.10
2.1	Indirect Augmentation	0	8	8	0.00	0.04	0.04	43	5.38	0.04
2.2	Non-Specific Digital Augmentation	0	1	1	0.00	0.00	0.00	5	5.00	0.00
	Others AR									
3	Marker-less AR	15	333	348	0.81	1.65	1.58	3414	9.81	1.58
4	Projection-based AR	10	126	136	0.54	0.62	0.62	846	6.22	0.62
5	Outlining AR	2	29	31	0.11	0.14	0.14	305	9.84	0.14
6	Superimposition-based AR	10	49	59	0.54	0.24	0.27	688	11.66	0.27
	Total of World	1849	20229	22078	100.00	100.00	100.00			

4.5 AR Application Areas

Global publications share of AR applications vary from sector to sector. In the education sector, it was the largest 15.65% (3456 publications), followed by AR applications in industry including the manufacturing sector 10.78% (2380 papers), medical sector 7.20% (1590 papers), commerce 3.61% (797 papers), industrial and product design 2.86% (631 papers), tourism 2.0% (441 papers), video games 1.56% (345 papers), etc. (Table 6).

Table 6. Classification of Global Output in Augment Reality Research by Type of Application

S.No	Application Area	Number of Papers (TP)			Share of Papers (%TP)			1992-19	
		1992-05	2006-19	1992-19	1992-05	2006-19	1992-19	TC	CPP
1	Education	75	3381	3456	4.06	16.71	15.65	25789	7.46
2	Industry (including manufacturing)	130	2250	2380	7.03	11.12	10.78	20811	8.74
3	Medical Sector	202	1388	1590	10.92	6.86	7.20	16462	10.35
4	Commerce	53	744	797	2.87	3.68	3.61	4914	6.17
5	Industrial or Product Design	25	606	631	1.35	3.00	2.86	4511	7.15
6	Tourism	10	431	441	0.54	2.13	2.00	2744	6.22
7	Videogames	13	332	345	0.70	1.64	1.56	2306	6.68
8	Social Interactions	8	208	216	0.43	1.03	0.98	1434	6.64
9	Architecture	11	120	131	0.59	0.59	0.59	985	7.52
10	Archeology	4	69	73	0.22	0.34	0.33	372	5.10
11	Cultural Heritages	15	353	368	0.81	1.75	1.67	2330	6.33
12	Construction	32	428	460	1.73	2.12	2.08	4965	10.79
13	Defense	2	23	25	0.11	0.11	0.11	128	5.12
		1849	20229	22078					

Global share of AR applications witnessed fluctuations over time. In education sector, it increased significantly from 4.06% to 16.71% during the period between 1992-05 and 2006-19, followed by AR applications in industry sector (from 7.03% to 11.12%), commerce (2.87% to 3.68%), %), industrial and product design (from 1.35% to 3.0%), tourism (from 0.54% to 2.13%), video games (from 0.70% to 1.64%), etc. On the other hand, global publications share of AR applications in medical sector witnessed decline from 10.92% to 6.86% (Table 6).

4.6 Top 50 Most Productive Organizations

During the period under study, a total of 5244 organizations published 22078 publications in AR research with an average of 4.21 publications per organization. The distribution of research publication across participating organizations is highly skewed. Of these 5244 organizations, 4226 contributed 1-10 papers each, 521 organizations 11-20 papers each, 389 organizations 11-50 papers each, 83 organizations 51-100 papers each and 25 organizations 101-342 papers each. The productivity of 50 most productive organizations in global AR research varied from 73 to 342 publications.

Of the top 50 organizations, 13 were from USA, 6 from Japan, 5 from China, 4 from Germany, 3 from South Korea, 2 each from Austria, France, Italy, Singapore and United Kingdom and 1 each from Australia, Brazil, Finland, Italy, Malaysia, New Zealand, Spain, Switzerland and Taiwan. Together the top 10, 20, 30, 40 and 50 organizations accounted for 9.93% (2192 publications), 16.10% (3555), 20.69% (4567), 24.62% (5435) and 28.14% (6213) of global publication share and 18.71% (36769 citations), 34.37% (67539), 44.73% (87883), 50.37% (98966) and 53.92% (105945) global citation share in 28 years during 1992-19. The scientometric profile of the 10 most productive organizations and of the 10 top organizations in terms of citation per paper and relative citation index is presented in Table 7. On further analysis, it was observed that:

- Sixteen organizations registered had a higher publication output than the group average of 124.26: Technical University of Munich, Germany (342 papers), Osaka University, Japan (228 papers), University of South Australia (217 papers), University of Tokyo, Japan (212 papers), National University of Singapore (211 papers), Technical University of Graz, Austria (208 papers), Beijing Institute of Technology, China (200 papers), etc.
- Sixteen organizations registered had a higher citation impact and relative citation impact above the group average of 17.05 citations per publication and 1.92 relative citation impact: Nara Institute of S&T, Japan (66.55 and 7.48), Imperial College, London, U.K. (57.14 and 6.42), Columbia University in the City of New York, USA (50.09 and 5.63), University of Washington, USA (50.03 and 5.62), MIT, USA (42.78 and 4.81), Carnegie Mellon University, USA (37.71 and 4.24), Georgia Institute of Technology, USA (31.36 and 3.52), University of North Carolina at Chapel Hill, USA (29.0 and 3.26), etc.

Table 7. Scientometric Profile of Top 10 Most Productive Global Organizations and Top 10 Most Impactful Organizations in Augmented Reality Research during 1992-2019

S.No	Name of the Organizations	TP	TC	CPP	RCI
1	Nara Institute of S&T, Japan	194	12911	66.55	7.48
2	Imperial College, London, U.K.	104	5943	57.14	6.42
3	Columbia University in the City of New York, USA	116	5811	50.09	5.63
4	University of Washington, Seattle, USA	116	5804	50.03	5.62
5	MIT, USA	147	6288	42.78	4.81
6	Carnegie Mellon University, USA	93	3507	37.71	4.24
7	Georgia Institute of Technology, USA	163	5111	31.36	3.52
8	University of North Carolina at Chapel Hill, USA	95	2755	29.00	3.26
9	Technical University Wien, Austria	106	2759	26.03	2.92
10	National Taiwan University of S&T	78	1694	21.72	2.44
11	University of Canterbury, NZ	188	3982	21.18	2.38
12	Technical University of Graz, Austria	208	4337	20.85	2.34
13	National University of Singapore	211	3676	17.42	1.96
14	Technical University of Munich, Germany	342	4174	12.2	1.37
15	University of South Australia	217	2171	10	1.12
16	University of Tokyo, Japan	212	2112	9.96	1.12
17	Osaka University, Japan	228	1592	6.98	0.78
18	Keio University, Japan	192	1205	6.28	0.71
19	Beijing Institute of Technology, China	200	609	3.05	0.34

*TP=Total Papers; TC=Total Citations; CPP=Citations Per Paper; RCI=Relative Citation Index

4.6.1 Institutional Collaboration among Top 15 Most Productive Organizations

Nara Institute of S&T, Japan (59 linkages), Keio University, Japan (54 linkages) and Osaka University, Japan (50) rank top for registering highest institutional collaboration linkages. On the other hand CNRS Centre National de la Researche Scientifique, France (1 linkage), University of Tokyo, Japan (4 linkages) and MIT, USA (8 linkages) rank at bottom with least collaboration linkages (Table 8).

Table 8. Institutional Collaboration among Top 15 Productive Organizations in AR during 1992-2019

S.No	Name of the Organization	Collaborative Linkages (CL)	TCL
1	Technical University of Munich, Germany	2(5), 3(2), 6(4), 8(8), 10(1), 14(2)	22
2	Osaka University, Japan	1(5), 6(2), 8(27), 9(5), 10(8), 14(2), 15(1)	50
3	University of South Australia	1(2), 2(3), 6(5), 8(7), 9(8), 10(16), 15(3)	44
4	University of Tokyo, Japan	2(4), 5(2), 8(1), 9(18), 12(3)	28

S.No	Name of the Organization	Collaborative Linkages (CL)	TCL
5	National University of Singapore	4(2), 8(1), 9(5), 10(2), 11(1), 14(4)	15
6	Technical University of Graz, Austria	1(4), 2(2), 3(5), 4(2), 7(1), 8(2), 10(8), 11(1), 15(3)	28
7	Beijing Institute of Technology, China	5(3), 6(1)	4
8	Nara Institute of S&T, Japan	1(8), 2(27), 3(7), 4(1), 5(1), 9(7), 10(4), 12(4)	59
9	Keio University, Japan	1(4), 2(5), 3(8), 4(18), 5(5), 6(2), 8(7), 11(2), 12(3)	54
10	University of Canterbury, NZ	1(1), 2(6), 3(16), 5(2), 6(8), 8(4), 12(1), 13(1)	39
11	Georgia Institute of Technology, USA	1(3), 2(3), 5(1), 6(1), 9(2), 10(1), 14(1), 15(3)	14
12	Korea Advanced Institute of S&T, S.Korea	2(1), 3(1), 4(3), 6(1), 8(4), 9(3), 10(1), 15(1)	14
13	CNRS Centre National de la Researche Scientifique, France	10(1)	1
14	MIT, USA	1(2), 5(4), 15(2)	8
15	University of Central Florida, USA	2(1), 3(3), 6(3), 11(3), 12(1), 14(2)	13

TCL=Total Collaborative Linkages; CL=Collaborative Linkages

4.7 Top 50 Most Productive Authors

7537 authors accumulated 22078 publications in AR research with an average of 2.92 publications per author during 1992-19. Their distribution is observed to be highly skewed: 6703 contributed 1-10 papers each, 685 authors 11-20 papers each, 129 authors 11-50 papers each, 16 authors 51-100 papers each and 4 authors 101-250 papers each. The publication productivity of top 50 authors in AR research varied from 35 to 250 publications. Together the top 10, 20, 30, 40 and 50 authors accounted for 5.58% (1232 publications), 8.89% (1963), 11.08% (2446), 12.99% (2868) share of global publications and 14.74% (3255) publication share and 13.68% (26873 citations), 22.18% (43579), 25.31% (49720), 28.47% (55939) and 30.95% (60802) share of global citations in 28 years during 1992-19. The scientometric profile of the top 10 most productive authors and top 10 authors in terms of citation per paper and relative citation index is presented in Table 9. On further analysis, it was observed that:

- Sixteen authors registered had a higher publication output than the group average of 64.30: M. Billinghurst (250 papers), N. Navab (160 papers), D. Schmalstieg (149 papers), H. Kato (111 papers), G. Klinker (99 papers), B.H. Thomas (98 papers), etc; and
- Eighteen authors organizations registered had a higher citation impact and relative citation impact above the group average of 18.91 citations per publication and 2.12 relative citation impact: S. Feiner (71.17 and 8.0), B. MacIntyre (58.22 and 6.54), H. Kato (35.38 and 3.98), H. Fuchs (34.40 and 3.87), T. Hollerer (33.85 and 3.80), G. Reitmayr (32.66 and 3.67), W. Piekarski (32.59 and 3.66), D. Schmalstieg (31.21 and 3.51), M. Billinghurst (29.52 and 3.32), etc.

Table 9. Scientometric Profile of Top 10 Most Productive Global Authors and Top 10 Most Impactful Authors in Augmented Reality Research during 1992-2019

S.No	Name of the authors	Affiliation	TP	TC	CPP	RCI
1	S. Feiner	Columbia University in the City of New York	75	5338	71.17	8
2	B. MacIntyre	Georgia Institute of Technology	64	3726	58.22	6.54
3	H. Kato	Nara Institute of Science and Technology, Japan	111	3927	35.38	3.98
4	H. Fuchs	The University of North Carolina at Chapel Hill	42	1445	34.4	3.87
5	T. Hollerer	University of California, Santa Barbara	88	2979	33.85	3.8
6	G. Reitmayr	Technische Universitat Graz	62	2025	32.66	3.67
7	W. Piekarski	University of South Australia	37	1206	32.59	3.66
8	D. Schmalstieg	Technische Universitat Graz, Austria	149	4651	31.21	3.51
9	M. Billinghurst	University of Canterbury, New Zealand	250	7379	29.52	3.32
10	H. Takemura	Osaka University	39	1041	26.69	3
11	S. K. Ong	National University of Singapore	89	1855	20.84	2.34
12	N. Navab	Technical University of Munich, Germany	160	2588	16.18	1.82
13	G. Klinker	Technical University of Munich, Germany	99	1302	13.15	1.48
14	B. H. Thomas	University of South Australia	98	1111	11.34	1.27
15	W. Woo	Korea Advanced Institute of Science & Technology	93	598	6.43	0.72
16	H. Saito	Keio University, Japan	95	483	5.08	0.57
17	S. Feiner	Columbia University in the City of New York	75	5338	71.17	8

*TP=Total Papers; TC=Total Citations; CPP=Citations Per Paper; RCI=Relative Citation Index

4.7.1 Collaboration among Top 20 Most Productive Authors

S.K. Ong, A.Y.C. Nee and Y. Liu registered the highest collaborative linkages (92, 92 and 78 respectively) and X. Wang, V. Teichrieb and W. Woo registered the least (1, 1 and 4). On the other hand, G. Klinker, S. Feiner and K. Kiyokawa lead the authors list in terms of highest collaborating authors (7 authors each). In terms of author to author collaborative linkages, it was the strongest between S.K. Ong - A.Y.C.Nee (85), Y.Liu - Y.Wang (51), D. Schmalstieg - C. Sandor (36), M.Billinghurst - H. Kato (27) (Table 10).

Table 10. Collaboration Linkages among Top 20 Most Productive Authors in AR during 1992-2019

S.No	Name of the Organization	Total Papers	Affiliation	Collaborative Linkages (CL)	TCL (NCA)
1	M. Billinghurst	250	University of Canterbury, New Zealand	3(5), 4(27), 8(5), 16(1)	37(3)
2	N. Navab	160	Technical University of Munich, Germany	7(2), 13(2), 18(4)	8(3)
3	D. Schmalstieg	149	Technische Universitat Graz, Austria	1(5), 5(3), 7(1), 16(4), 20(25)	39(6)

S.No	Name of the Organization	Total Papers	Affiliation	Collaborative Linkages (CL)	TCL (NCA)
4	H. Kato	111	Nara Institute of Science and Technology, Japan	1(27), 5(1), 10(1), 13(36), 14(2)	67(5)
5	G. Klinker	99	Technical University of Munich, Germany	1(1), 2(1), 3(3), 4(1), 13(10), 15(4), 16(2)	22(7)
6	B. H. Thomas	98	University of South Australia	1(7), 3(1), 4(2), 7(1), 13(4)	15(5)
7	H. Saito	95	Keio University, Japan	2(2), 3(1), 5(1), 6(3), 8(1), 14(1), 16(1)	9(6)
8	W. Woo	93	Korea Advanced Institute of Science & Technology	1(5), 7(1), 16(1), 20(1)	4(4)
9	S. K. Ong	89	National University of Singapore	11(85), 12(1), 18(6)	92(3)
10	Y. Liu	88	Beijing Institute of Technology	12(51)	78(3)
11	A. Y. C. Nee	86	National University of Singapore	9(85), 12(1), 18(6)	92(3)
12	Y. Wang	86	Beijing Institute of Technology	10(71)	72(2)
13	C. Sandor	81	Nara Institute of Science and Technology	1(1), 2(3), 4(36), 5(10), 14(2), 20(3)	55(6)
14	S. Feiner	78	Columbia University in the City of New York	1(1), 3(1), 4(2), 13(2), 15(1), 16(11), 17(8)	26(7)
15	K. Kiyokawa	75	Osaka University	1(6), 4(2), 5(4), 7(1), 14(1), 16(1), 20(2)	12(7)
16	Hollerer, T	88	University of California, Santa Barbara	1(1), 3(4), 7(1), 14(11), 15(1)	
17	B. MacIntyre	72	Georgia Institute of Technology	14(7), 16(2)	9(2)
18	X. Wang	64	The University of Sydney	44(1)	1(1)
19	V. Teichrieb	64	Universidade Federal de Pernambuco, Brazil	2(1)	1(1)
20	G. Reitmayr	63	Technische Universitat Graz	1(1), 3(25), 8(1), 13(3), 15(2)	32(5)

TCL=Total Collaborative Linkages; NCA=Number of Collaborative Authors

4.8 Medium of Research Communication

Of the total research output in the AR field, 70.45% (12571) appeared in conference proceedings, 27.09% (5982) in journals, 1.84% (406) in book series, 0.62% (406) in trade publications and rest undefined. The top 50 journals contributed 16 to 151 papers each in 28 years during 1992-19.

The top 50 journals together accounted for 28.77% (1721) share of the total AR output in journals medium. The top 5 most productive journals include the *IEEE Transactions on Visualization & Computer Graphics* (151 papers), *Multimedia Tools & Applications* (94 papers), *Virtual Reality* (72 papers), *Computers & Graphics Pergamon* (69 papers) and *IEEE Computer Graphics & Applications* (64 papers). The top 5 journals in terms of high citations per paper include *Presence. Teleoperators & Virtual Environment* (41 papers and 115.1 CPP), *IEEE Pervasive Computing* (24 papers and 96.29 CPP), *IEICE Transactions on Information & Systems* (20 papers and 88.55 CPP), *Computers & Education* (37 papers and 85.73 CPP) and *IEEE Computer Graphics & Applications* (64 papers and 59.17 CPP) (Table 11).

Table 11. Top 10 Most Impactful Journals in terms Citation Per Paper in Augmented Reality Research during 1992-19

S.No	Name of the Journal	TP			TC	CPP
		1992-05	2006-19	1992-19	1992-19	
1	Presence. Teleoperators & Virtual Environment	21	20	41	4719	115.1
2	IEEE Pervasive Computing	0	24	24	2311	96.29
3	IEICE Transactions on Information & Systems	3	17	20	1771	88.55
4	Computers & Education	0	37	37	3172	85.73
5	IEEE Computer Graphics & Applications	17	47	64	3787	59.17
6	IEEE Transactions on Medical Imaging	7	16	23	1271	55.26
7	Automation in Construction	2	50	52	2056	39.54
8	Automation in Construction	2	50	52	2056	39.54
9	Personal & Ubiquitous Computing	17	27	44	1729	39.3
10	Computers & Graphics Pergamon	19	50	69	2136	30.96
11	Computers in Human Behavior	0	37	37	1130	30.54
12	IEEE Transactions on Visualization & Computer Graphics	10	141	151	3436	22.75
13	Virtual Reality	13	59	72	1157	16.07
14	International Journal of Computer Assisted Radiology & Surgery	0	59	59	759	12.86
15	Multimedia Tools & Applications	0	94	94	933	9.93
16	IEEE Access	0	55	55	380	6.91
17	Sensors Switzerland	0	52	52	334	6.42

*TP=Total Papers; TC=Total Citations; CPP=Citations Per Paper

4.9 Highly Cited Papers

Of the total 22078 papers that appeared in the field of augmented reality during 1992-19, just 1.02% (226 papers) registered 100 and above citations per paper.

- Of the 226 highly cited papers, 157 received 100-199 citations per paper, 41 had 202-299 citations per paper, 17 had 308-499 citations per paper, 5 had 543-895 citations per paper, 5 had 1214-1968 citations per paper and 2 papers had 2101-3433 citations per paper since their publication.
- These 226 highly cited papers accumulated a total of 59859 citations, with an average of 264.86 citations per paper.
- Of the 226 highly cited papers, 121 were by such organizations that pursued research in their standalone capacity per paper (non-collaborative) and 105 were by others who pursued research in their capacity as collaborative organizations per paper (51 national collaborative and 54 as international collaborative organizations).
- Research participation in the 226 highly cited papers was the largest by USA (106 papers), followed by U.K (30 papers), Japan (18 papers), Canada (13 papers), Germany (12 papers),

Austria (11 papers), France and Spain (10 papers each), Taiwan (9 papers), Switzerland (7 papers), Singapore and Australia (6 papers each), China, South Korea, Finland, New Zealand and Greece (5 papers each), Poland (3 papers), Italy, Portugal, Belgium, Israel and Turkey (2 papers each) and Brazil, Egypt, India, Slovakia and Venezuela (1 papers each).

- A total of 899 authors from 396 organizations contributed to 226 highly cited papers.
- The research organizations that accounted for the largest number of highly cited papers include: Massachusetts Institute of Technology, USA (13 papers), Columbia University, USA and University of Washington, Seattle, USA (12 papers each), University of North Carolina at Chapel Hill, USA (9 papers), Microsoft Research, USA (8 papers), Georgia Institute of Technology, USA (7 papers), Mitsubishi Electric Research Laboratory, USA and Imperial College, London (6 papers each).
- Of the 226 highly cited papers, 124 appeared as articles, 89 as conference papers, 11 as reviews and 1 each as editorial and book.
- These 226 highly cited papers appeared in 73 national and international journals. Twelve papers appeared in the Computer and Education, followed by 7 papers each Communications of the ACM and Personal & Ubiquitous Computing, 5 papers each in ACM Transactions on Graphics, IEEE Trans on Computer Graphics and Applications and IEEE Trans on Medical Imaging, 4 papers each in Computer and Graphics (Pergamon), IEEE Trans on Pattern Analysis & Machine Intelligence and IEEE Trans on Visualization & Computer Graphics, 3 papers each in ACM Trans. on Computer-Human Interactions, Automation in Construction, Journal of Science Education & Technology and Presence, etc.

5. Summary

In this study, we have employed the bibliometric method to analyze augmented reality research from Scopus database. The study provides a quantitative and qualitative description of global research in the field of Augment Reality (AR). AR research, as seen from Scopus database covering 1992-2019 (22078 publications), registered 196479 citations during the study period, averaged 8.90 citations per publication (CPP) and registered 54.23% high growth. A total of 226 papers registered high-end citations (100 or more citations), accumulated 59859 citations, with an average of 264.86 citations per paper.

The distribution of AR research is highly skewed. Of the 101 countries that participated in AR research, 15 contributed 87.05% global publications share. The top three most productive countries are: USA (19.25% share), Germany (9.74% share) and Japan (9.05% share). Four of the top 15 most productive countries registered relative citation index above the group average of 1.15 was: the U.K. (2.05), Austria (2.0), USA (1.81) and Canada (1.64).

In terms of distribution of research by AR technology type, it is seen that ‘Trigger AR’ technology accounted for the highest global publications share 3.96% (874 papers), followed by Markerless AR (348 papers and 1.58% share) and Projection-based AR (136 papers and 0.62% share). The AR applications in the education sector registered the highest publications share (15.65%), followed

by AR applications in manufacturing sector (2380 papers and 10.78% share), medical sector (1590 papers and 7.20% share), commerce (797 papers and 3.61% share), industrial and product design (631 papers and 2.86% share) and tourism (441 papers and 2.0% share).

Computer science is one of the most popular subject areas in research pursuits in the field of augmented reality accounting for the highest subject share (74.85%), followed by engineering (36.26%) and others. Of the 7537 global authors from 5244 global organizations, top 50 organizations contributed 28.14% global publications share and 26.3% global citations share. The top 50 authors contributed 14.74% global publication share and 53.92% global citation share during the period. Nearly 27% of global publications share in the subject appeared in journal literature. The top 50 journals accounted for 2% share of total output in journal medium.

6. Conclusion

Augmented reality research registered significantly high growth 54%. This may be attributed to AR applications in the education sector as it accounts for the highest global publications share (15.65%) in the subject, followed by AR applications in the manufacturing and health sectors. Besides AR applications, International collaboration has also been a major driver of AR research pursuits. Between 11.89% and 44.04% of national share of top 15 countries in AR research appeared as international collaborative publications.

As for countries/territories, the USA is the most productive country and has the highest total citations and accounts for the largest (786) collaborative linkages. But looking at the distribution of global research by continents, it is seen that the Asian countries (Japan, China, South Korea and Taiwan) account for the highest share 25.39%, followed by Europe 24.72% share. At the institution level, Technical University of Munich, Germany and Osaka University, Japan have been the most productive organizations and Nara Institute of S&T, Japan (66.55 and 7.48) and Imperial College, London, U.K. (57.14 and 6.42) have been the most impactful organizations. M. Billinghurst and N. Navab have been the most productive authors and S. Feiner and B. MacIntyre have been the most impactful authors. The collaborative interaction among productive countries/territories, organizations and authors was also analyzed. Academic organizations from Asia and Europe dominate in the list of top 15 most productive organizations, on the other hand academic organizations from the USA the list of top most impactful organizations. It may be concluded that AR research is dominated by the USA along with select few countries from Asia and Europe. Analysis of publications data also suggests that augmented reality research is largely university-centric, and not research institution-centric; nine out of top 10 most productive organizations/most impactful organizations hail from the higher education sector. The analyses reveal emerging research trends as well as influential individuals, institutions, papers, journals and countries in terms of quantitative and qualitative indicators, which may provide useful data to policy-makers to make appropriate decision on the research priorities in their national and international plans on this subject.

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