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Applying Artificial Intelligence in Multi Axis Additive Manufacturing: A Bibliographic Review

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Abstract:- Fused deposition modeling is the most used 3D printing technology, but it has several limitations in the manufactured objects, such as anisotropy and low surface quality. Artificial intelligence can help optimize this manufacturing process, and when complemented with multi axis 3D printing, it can improve the physical properties to be comparable to the final use products.

This study analyzes the scientific production in Scopus and Web of Science databases during 2019-2023 on the application of artificial intelligence in multi axis additive manufacturing processes, defining the projections in this new and multidisciplinary research area. Complementary search techniques are applied using synonyms and permutations with search strings of two keywords. From the results obtained, three spec areas of study have been identified: Artificial Intelligence & Additive Manufacturing, Artificial Intelligence & Multi Axis, and Additive Manufacturing & Multi Axis. Each area is analyzed independently, and then their results are intersected to relate them to the main research area.

The matching results show that artificial intelligence applied to multi axis additive manufacturing has become increasingly important over the last 5 years, as evidenced by the growing number of papers and international collaborations. The scientific output is abundant, especially in Artificial Intelligence & Additive Manufacturing area, where the number of papers continues to grow, reaching 4590 in total. The high quartile journals Additive Manufacturing and IEEE Access are the main sources of dissemination with a total of 192 papers, and the citation analysis shows a strong influence of the authors Zhang Y., Wang Y., and Li Y. Institutions from China, USA and India lead the global scientific production, demonstrating a commitment to academic research and strong international collaboration that provides a global focus on the development of these technologies.

Keywords*:* Additive manufacturing, Artificial intelligence, Multi axis.

1. Introduction

Additive manufacturing, or 3D printing, has several advantages, including the creation of complex and large structures, mass customization, and waste reduction [1]. The most widely used 3D printing technology is Fused Deposition Modeling FDM [2], but its main limitations are the production of objects with anisotropic properties, where the mechanical strength varies according to the direction of applied stress, and low surface quality with high roughness, affecting the appearance and functionality of the part. This is caused by the manufacturing process of stacking flat layers [3]. Multi axis 3D printing, which uses movement in different axes or directions during the printing process, can overcome these difficulties and produce parts with complex curves. It can also improve the surface quality and mechanical performance of printed objects [4].

Similarly, artificial intelligence (AI) is increasingly being applied to 3D printing, where machine learning algorithms are used to determine the printability of 3D objects, accelerate the slicing process, optimize route planning, select the correct process parameters, and improve the ability to produce precise, complex, multifunctional, and customized designs [5]. To enhance these benefits, it is possible to combine the advantages of artificial intelligence with the utility of multi axis motion during the additive manufacturing process, to obtain techniques of semantic segmentation and deep reinforcement learning (DRL) and so achieve adaptive printing with real time error detection and correction, significantly improving efficiency compared to conventional methods [6].

In this paper, we study the scientific production of publications on artificial intelligence assisted multi axis additive manufacturing for the period 2019-2023. However, due to its multidisciplinary nature, searches in Scopus and Web of Science, the two main scientific databases recognized in academic research, yield few results. Therefore, the searches are grouped in to three specific areas of study: Artificial Intelligence & Additive Manufacturing, Artificial Intelligence & Multi Axis, and Additive Manufacturing & Multi Axis, using search strings with two keywords and their synonyms, we find that the Artificial Intelligence & Additive Manufacturing area leads with 4590 publications, followed by Artificial Intelligence & Multi axis area with 2237, and Additive Manufacturing & Multi axis area with 1200. The top journals are Additive Manufacturing and IEEE Access with 146 and 46 publications respectively, reflecting the relevance of the area. Zhang Y., Wang Y. and Li Y. are the most prominent authors, with multidisciplinary collaborations in all three areas of study, especially in Artificial Intelligence & Additive Manufacturing area. The distribution of citations shows a greater interest in Artificial Intelligence & Additive Manufacturing area and in Artificial Intelligence & Multi axis area. China leads in scientific production and international collaboration, followed by the US and India, with China-USA collaboration standing out as a central axis in all three study areas.

2. Methodology

A. Data source.

All information was obtained from the central Internet databases of Web of Science (WOS) and Scopus during the period from January 1, 2019, to December 31, 2023. This timeframe covers the last five years of scientific production and is consistent with the recommendations of Price's index [7], which is an important measure of the obsolescence of scientific information.

B. Data Treatment

To search for scientific production in repositories, it was used the AND operator to combine keywords. It was applying filters to the title, abstract, and keyword areas to obtain more precise results. The search strategy follows these steps:

1. Identifying characteristic keywords or terms that encompass the main title. In this case, there are three keywords: artificial intelligence, additive manufacturing, and multi axis. Then, combining these three keywords, an exhaustive search of all the scientific production generated from year zero to 2023 is conducted. However, no papers were found that meet the established search criteria.

2. To expand the search area, it was identifying suitable synonyms for each keyword, creating three groups of keywords.

Group 1: Artificial intelligence (AI), Machine learning (ML), Intelligent system*(IS).

Group 2: Additive manufacturing (AM), 3D print* (3D), Fused deposition model* (FDM).

Group 3: Multi axis (MA), Curved layer (CL), Non planar (NP).

(*) asterisk expands the search to include variations of a word [8].

3. By combining these three groups of words, 27 three keyword search strings were obtained. These search strings were used to conduct a comprehensive search of all scientific production from year zero to 2023. The search yielded 86 articles in Scopus and 22 in WOS. However, this quantity is still too small to perform a complete bibliometric analysis. Please refer to Table 1 for further details.

Table I. Results from search strings of three terms.

Ord	Search strings			Scopus	WOS
1	AI	AM	MA	0	0
2	AI	AM	CL	0	0
3	AI	AM	NP	0	0
4	AI	3D*	MA	18	4
5	AI	3D*	CL	0	5
6	AI	3D*	NP	4	1
7	AI	FDM*	MA	24	0
8	AI	FDM*	CL	1	0
9	AI	FDM*	NP	1	0
10	ML	AM	MA	0	0
11	ML	AM	CL	0	0
12	ML	AM	NP	0	0
13	ML	3D*	MA	6	2
14	ML	3D*	CL	2	2
15	ML	3D*	NP	7	3
16	ML	FDM*	MA	14	2
17	ML	FDM*	CL	3	1
18	ML	FDM*	NP	3	0
19	IS*	AM	MA	0	0
20	IS*	AM	CL	0	0
21	IS*	AM	NP	0	0
22	IS*	3D*	MA	0	0
23	IS*	3D*	CL	0	1
24	IS*	3D*	NP	1	1
25	IS*	FDM*	MA	1	0
26	IS*	FDM*	CL	1	0
27	IS*	FDM*	NP	0	0
		Total		86	22

4. Using a new search strategy that combines two keywords, we obtained 27 search strings. It was conducted an exhaustive search in the Scopus and WOS databases, which yielded a total of 18,946 papers from year zero to 2023. Out of this number, 15,492 papers correspond to the period 2019-2023, which is 4.46 times greater than the 3,454 papers from the years prior to 2019. The bibliometric analysis will be focused on the last 5 years, as recommended by the Price index.

5. Table II shows that out of the 15,422 papers published between 2019-2023, 9,182 are from the Scopus database and 6,240 are from Web of Science. To ensure accurate metrics, it is not recommended to perform a joint analysis as it would only reflect the results of the search with the most papers. Instead, it is better to categorize the search results by study areas. The terms can be categorized using the first keyword from each group as follows:

- Artificial Intelligence & Additive Manufacturing (AI & AM)
- Artificial Intelligence & Multi axis (AI & MA)
- Additive Manufacturing & Multi axis (AM & MA).

The objective is to perform a bibliometric analysis for each area individually, cross-reference the results, and identify common relationships, trends, and projections.

Table II. Results from search strings of two terms.

Areas	Search strings		Scopus	WOS
Area 1 Groups 1 & 2 (AI & AM)	AI	AM	650	386
	AI	3D*	1126	505
	AI	FDM*	65	31
	ML	AM	1489	1086
	ML	3D*	1826	708
	ML	FDM*	162	109
	IS*	AM	411	167
	IS*	3D*	862	277
	IS*	FDM*	45	15
Area 2 Groups 1 & 3 (AI & MA)	AI	MA	111	45
	AI	CL	8	307
	AI	NP	33	12
	ML	MA	285	161
	ML	CL	23	864
	ML	NP	131	60
	IS*	MA	412	55
	IS*	CL	21	84
	IS*	NP	105	22
Area 3 Groups 2 & 3 (AM&MA)	AM	MA	243	169
	AM	CL	138	336
	AM	NP	168	119
	3D*	MA	306	164
	3D*	CL	174	270
	3D*	NP	271	163
	FDM*	MA	42	31
	FDM*	CL	39	68
	FDM*	NP	36	26
	Subtotal		9182	6240
	Total		15422	

C. Data analysis.

This study is descriptive in nature and presents the existing relationships between the study areas through data representation.

The search results are stored in 9 Bibtex format files for Scopus and 9 Plain Text files for WOS for each area. These files are then merged using the statistical software R, which also removes duplicate papers. This consolidation and purification process is essential to ensure the integrity and quality of the collected data in scientific research. Please refer to Fig. 1.

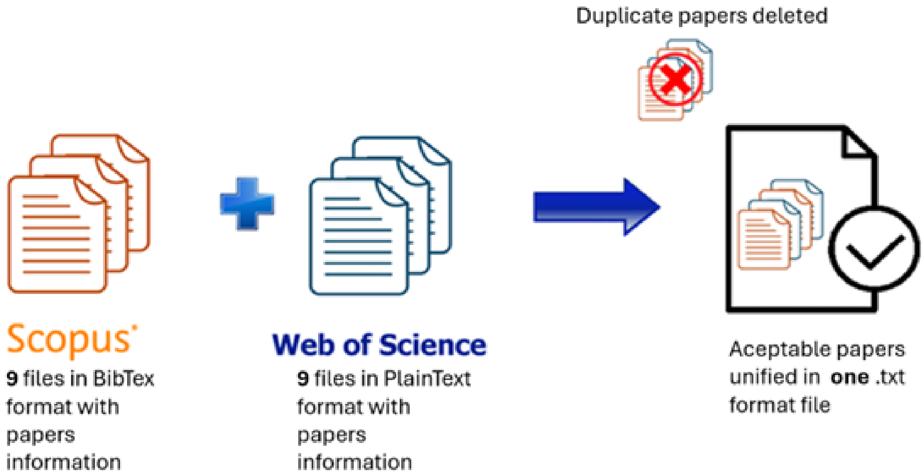

Fig.1. Representation of the file merging process using R software.

Table 3 shows the results of the refinement.

The area with the highest scientific output is AI & AM, with 4590 papers. This is followed by AI & MA area, with 2237 papers. AM & MA area has the least scientific output, with 1200 papers.

Table III. Number of papers processed using R software.

Area	Scopus		WOS		Duplicated		Valid
AI & AM	6636	+	3284	-	5330	=	4590
AI & MA	1129	+	1610	-	502	=	2237
AM & MA	1417	+	1346	-	1563	=	1200

AI & AM area has a significant number of valid papers, reflecting intense research activity. However, it also has a high rate of duplicate papers. In contrast Artificial Intelligence & Multi axis area has a lower number of duplicate papers, indicating that this research area is in a developmental stage and has potential for expansion.

To analyze valid papers, it was using the open-source software Bibliometrix, which is owned by the Massachusetts Institute of Technology (MIT), it operates within the R statistical software environment and is widely used for bibliometric analyses [9].

An analysis is conducted for each study area based on annual production, significant journals, relevant and cited authors, institutions and countries with the highest scientific output, most cited papers, keywords, and networks of collaboration among authors and countries.

3. Result And Discussion

A. Sources of information

Table IV shows the classification of valid papers based on the authors, document types, and level of scientific production for each study area after the refinement process.

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Table IV. Authors and document types.

Area	Author	Co- author	Paper	Book	Book chapter	Conference paper	Other
AI & AM	12090	4,47 per doc.	2238	46	198	1383	663
AI & MA	8135	5,34 per doc.	1584	4	22	420	198
AM & MA	3957	4,91 per doc.	888	0	10	217	75

B. Characteristics of scientific production.

Fig. 2 shows a sustained increase in the number of papers across all three study areas. AI & AM area stands out for the highest growth rate, rising from 471 papers in 2019 to 1356 in 2023, which represents a 187.9% percentage increase. AI & MA area have also shown a considerable increase. Additionally, the AM & MA area has experienced modest growth, but maintains a positive upward trend, albeit of a smaller magnitude.

These data suggest a growing interest and investment in research that combines artificial intelligence with additive manufacturing and multi axis technologies, which may be indicative of future trends in these areas.

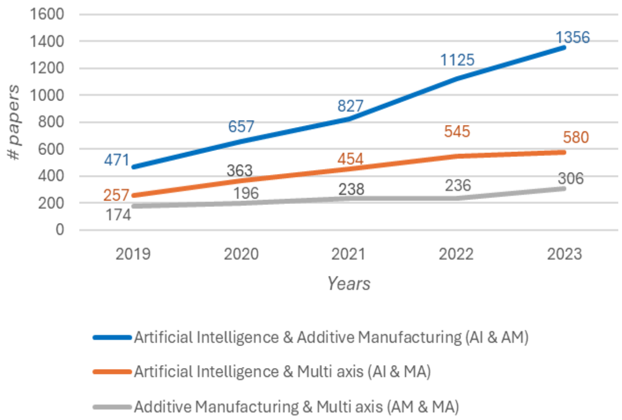

Fig. 2. Scientific production (2019-2023)

C. Top journals.

For the period 2019-2023, the journals with the highest scientific output in each research area are highlighted. The Q1 Journal Additive Manufacturing stands out, with the highest number of papers in Artificial Intelligence & Additive Manufacturing area and Artificial Intelligence & Multi axis area. Similarly, the Q1 Journal IEEE Access dominates production in the Additive Manufacturing & Multi axis area, as shown in Figure 3

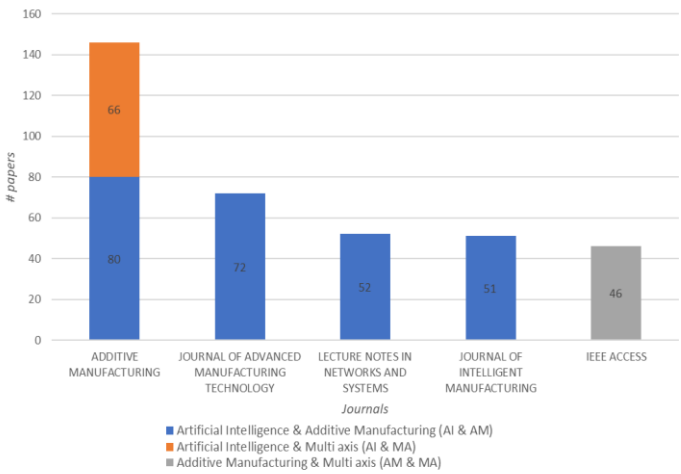

Fig. 3. Journals with most publications.

D. Citation analysis.

Fig. 4 shows a slight decrease in the number of citations until the 2022, the year in which a gradual increase begins. This could be related to the increase in the total number of papers published in AI & AM area, which means that there are more research papers available for citation. Another factor is that the papers published from this year onwards begin to gain importance or have made significant advances in their respective areas of study.

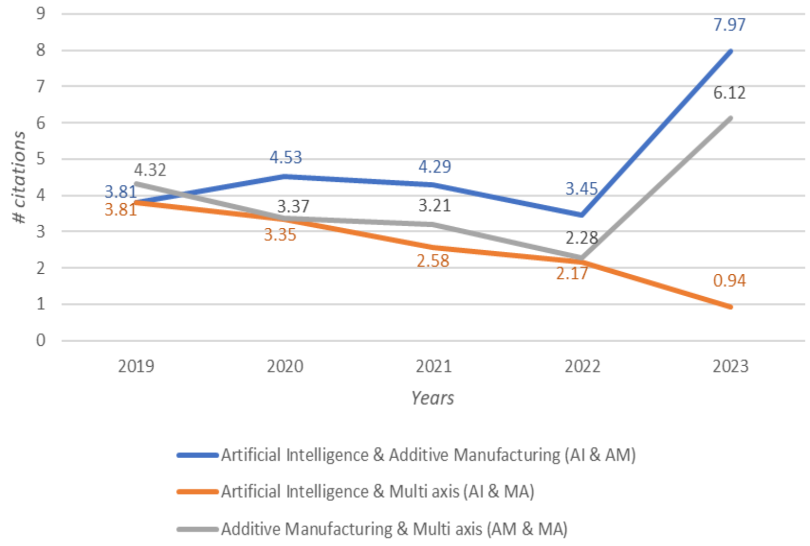

Fig. 4. Annual citation variation

E. Influential authors.

Fig. 5 shows the authors with the most influence and relevance within the study areas. They include Zhang Y., Wang Y., and Li Y., which have the highest total number of papers and actively contribute to all three study areas.

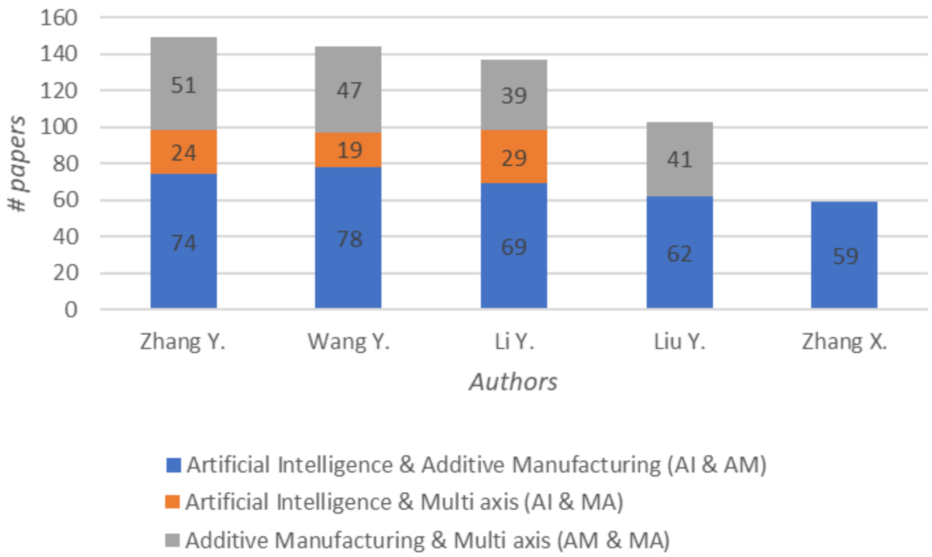

Fig. 5. More publications by authors

Analyzing Table V, we see that there is a diversity of authors in the number of citations. AI & AM area has a higher number of citations compared to other areas, which may reflect a greater interest in research or development in this area of study. For example, Wang C. stands out as the most cited author in AI & AM area, and Chang R. stands out in AM & MA area, indicating a significant influence and contribution in each of their fields. In AI &

MA area, there is a more even distribution of citations among authors, suggesting a fairer competition or a variety of relevant contributions.

Table 5. Most cited authors

Area	Author	Citations
AI & AM	Wang C.	31
	Scime L.	26
	Lim C.	21
	Tan X.	21
	Tor S.	21
AI & MA	Baudis S.	6
	Hofstetter C.	6
	Orman S.	6
	Stampfl J.	6
	Li Y.	4
AM & MA	Chang R.	13
	Cheung C.	11
	Ran A.	11
	Araie M.	10
	Asaoka R.	10

F. Author collaboration networks.

A close collaboration network is established among the authors Wang Y., Zhang Y., and Li Y. across the three research areas. Fig. 6 shows that in the AI & AM area, the three authors have formed a unified collaboration network.

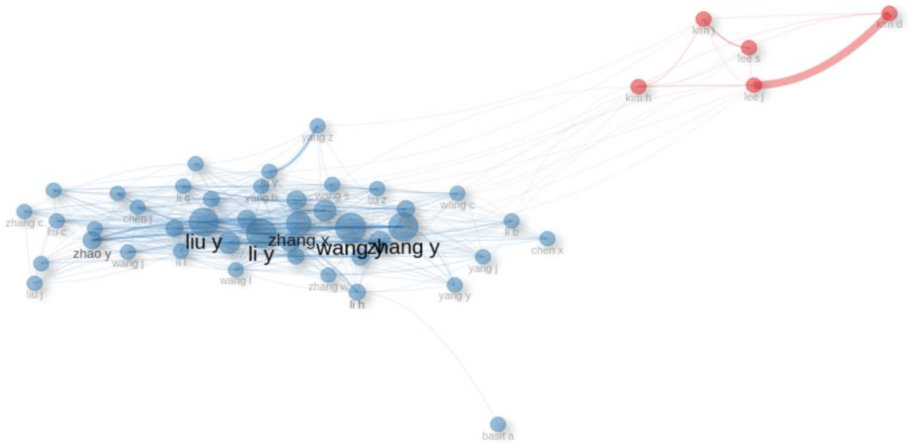

Fig. 6. Author collaboration network in AI & AM area

Fig. 7 shows the collaboration network in AI & MA area. It is evident that authors Wang Y. and Zhang Y. have established a closer collaboration, while Li Y. is positioned in an independent subnet.

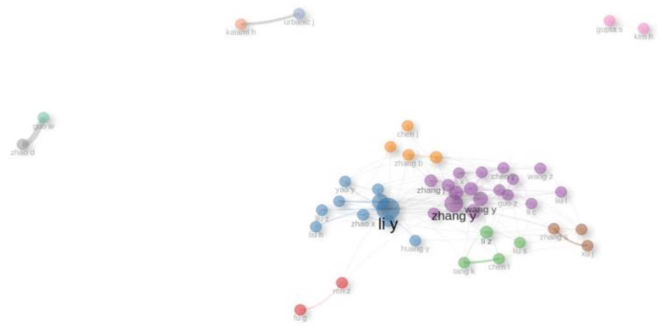

Fig. 7. Author collaboration network in AI & MA area

In AM & MA area, Wang Y. and Li Y. are the main leaders of the network, while Zhang Y. is positioned in a separate subnet, as shown in Fig. 8.

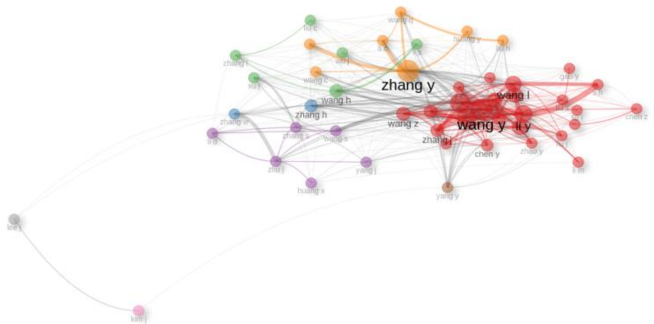

Fig. 8. Author collaboration network in AM & MA area

G. Most cited papers.

After analyzing the most cited papers in the three study areas represented in Table VI, it is notable that Oztemel E.'s paper, 'Literature review of Industry 4.0 and related technologies,' has the highest number of citations with 1050 citations in AI & AM area. In AI & MA area, Schwartz JJ.'s paper, 'Multimaterial actinic spatial control 3D and 4D printing,' has the most citations with 206. Lastly, AM & MA area, the article titled 'Quantum approximate optimization of non-planar graph problems on a planar superconducting processor' by Harrigan M. is the most cited paper with 242 mentions.

Table VI. Most cited papers

Area	Paper	Total citations	Citation Per year
AI & AM	• Oztemel E., 2020, Literature review of Industry 4.0 and related technologies	1050	210
	• Kuang X., 2019, Advances in 4D Printing: Materials and Applications.	624	124.8
	• Klerkx L., 2019, A review of social science on digital agriculture, smart farming, and agriculture 4.0: New contributions and a future research agenda	562	112.4
	• Ahmed A., 2021, 4D printing: Fundamentals, materials, applications and challenges	370	74
	• Wang C., 2020, Machine learning in additive manufacturing: state-of-the-art and perspectives	365	73

Area	Paper	Total citations	Citation Per year
AI & MA	• Schwartz JJ., 2019, Multimaterial actinic spatial control 3D and 4D printing	206	41.2
	• Ho A., 2019, On the origin of microstructural banding in Ti-6Al4V wire-arc based high deposition rate additive manufacturing	164	32.8
	• Urhal P., 2019, Robot assisted additive manufacturing: A review	157	31.4
	• Akhoundi B., 2019, Effect of Filling Pattern on the Tensile and Flexural Mechanical Properties of FDM 3D Printed Products	140	28
	• Panda B., 2019, Synthesis and characterization of one-part geopolymers for extrusion-based 3D concrete printing	127	25.4
AM & MA	• Harrigan MP., 2021, Quantum approximate optimization of non-planar graph problems on a planar superconducting processor	242	48.4
	• Lu H., 2021, Aerial Intelligent Reflecting Surface: Joint Placement and Passive Beamforming Design With 3D Beam Flattening	151	30.2
	• Qin J., 2022, Research and Application of Machine Learning for Additive Manufacturing	103	20.6
	• Alagha AN, 2021, Additive manufacturing of shape memory alloys: A review with emphasis on powder bed systems	85	17
	• Zhou C., 2021, Ferromagnetic soft catheter robots for minimally invasive bioprinting	85	17

H. Institutions with the most scientific production

Based on Fig. 9, it can be concluded that Huazhong University of Science and Technology (HUST) has the highest scientific output with a total of 104 papers and interdisciplinary contributions across all three areas. It is followed by the University of California with 94 papers and participation in two areas of study, and Nanyang Technological University with 58 papers.

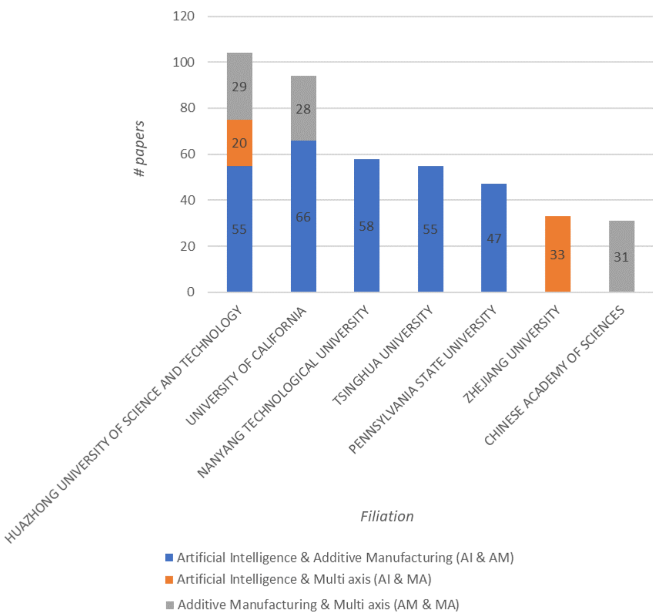

Fig. 9. Scientific production by institutional affiliation

I. Global scientific production by country.

Fig. 10 reflects the global distribution of leadership in research and development of these emerging technologies. China leads in total scientific paper production and international collaborations across all three areas, followed closely by the USA, particularly in AI & AM area. India also makes a significant contribution, albeit to a lesser extent.

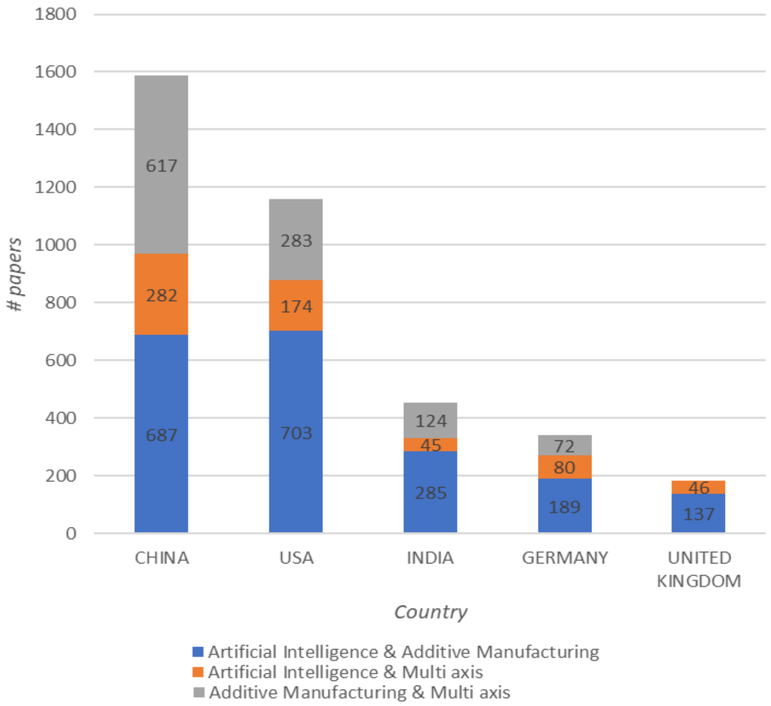

Fig. 10. Ranking of global scientific production

J. Global collaboration networks.

In the Fig. 11 shows the global network collaboration in AI & AM area, highlighting the strong relationship between China and USA. These two countries also engage in secondary cooperation with other nations, such as Singapore, Korea, and the United Kingdom.

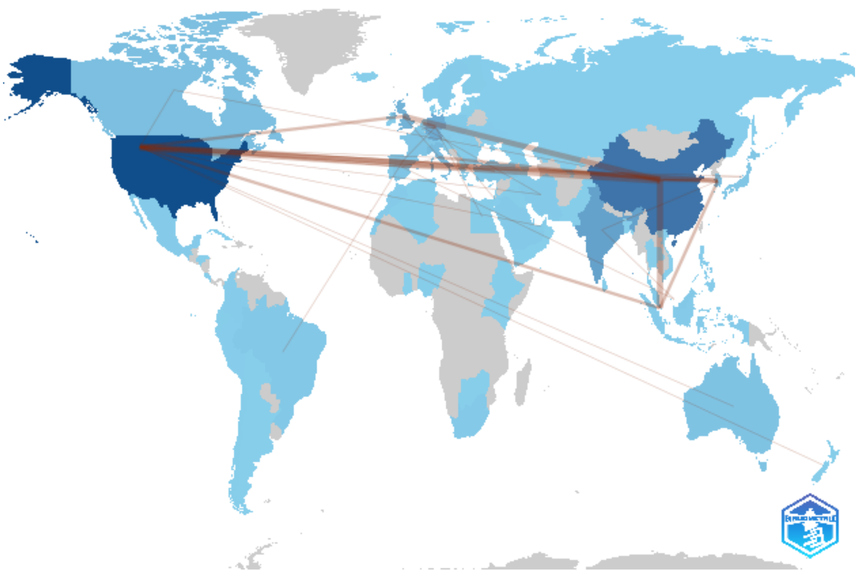

Fig. 11. Global collaboration network in AI & AM area

In AI & MA area, Fig. 12 shows that the primary core of collaboration is between China and USA. This central link enables secondary connections with Singapore and Switzerland and extends the collaborative network to Australia, the United Kingdom, and Germany.

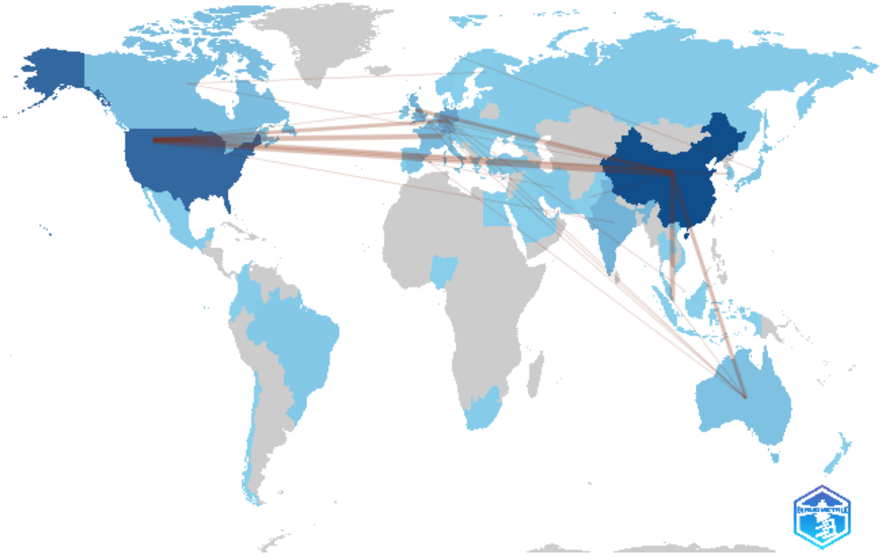

Fig. 12. Global collaboration network in AI & MA area

A broad network of collaborations is shown in Fig. 13 There is a strong focus on AM & MA area collaborations between China and USA. Secondary connections are observed with the United Kingdom, Pakistan, Italy, Saudi Arabia, Germany, and Australia.

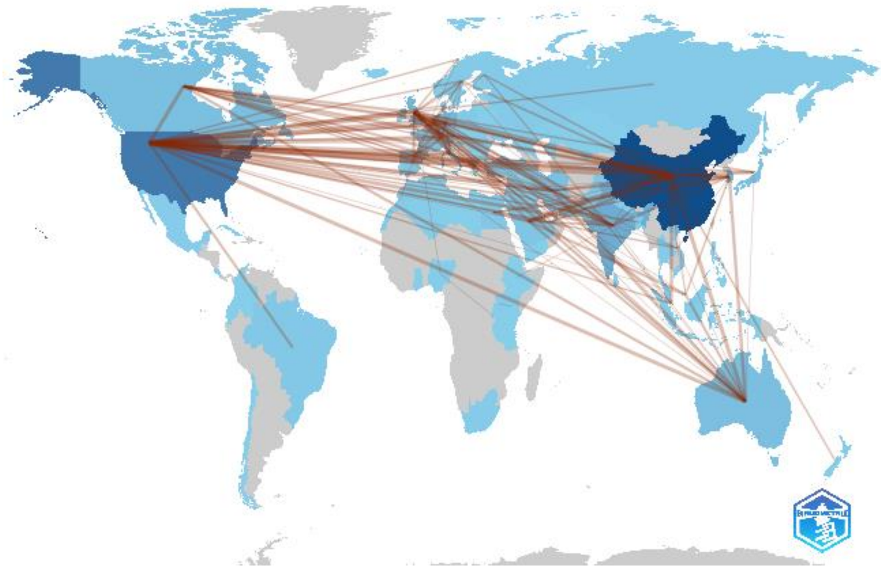

Fig. 13. Global collaboration network in AM & MA area

K. Most used keywords.

In the Fig. 14 shows the frequency of key terms across the three areas of study. The most frequent term in all areas is '3d printers', indicating its central importance at the intersection of these areas. 'Machine learning' and 'additives' are also prominent, suggesting they are key concepts in research and development within these disciplines. The prevalence of 'artificial intelligence' and '3D printing' in the text reflects their importance in current technological innovation and mirrors the current trends and areas of focus in cutting-edge research in these interdisciplinary areas.

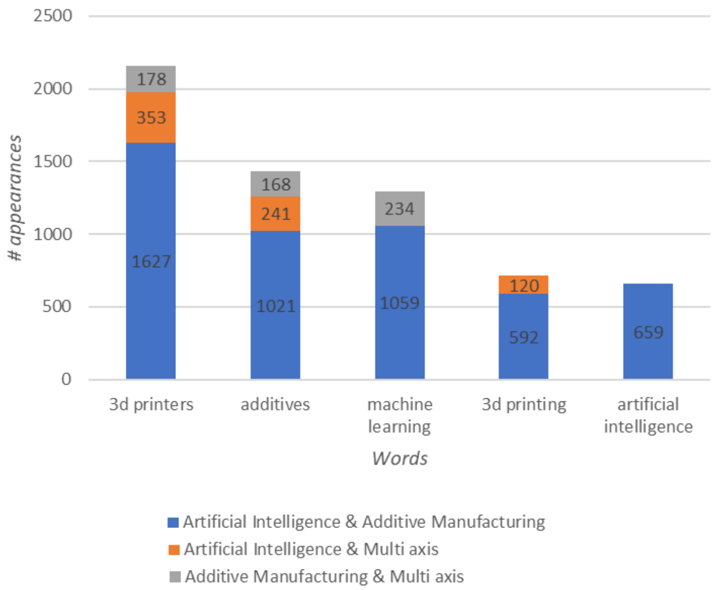

Fig. 14. Most used keywords.

L. Future work

The application of Artificial Intelligence to multi axis Additive Manufacturing poses several multidisciplinary challenges and tasks for future development:

- Models and Simulations Development: The article discusses the development of mathematical models and simulation tools that can be integrated with AI systems to optimize the design for additive manufacturing. The models and simulations will improve movement speed, deposition rate, and print volume, as well as the implementation of support microstructures, topological optimization, and variation in fill patterns.
- Cloud data integration: The next step is to integrate additive manufacturing data into the cloud. This will enable the processing of large volumes of design and production data, facilitating remote access and real-time collaboration among manufacturers. [14]
- File Format Optimization: Research improvements in Standard Triangle Language (STL) files and alternative formats to enhance the accuracy of slicing algorithms.
- Collaborative Additive Manufacturing: Promote the use of collaborative additive manufacturing among multiple robots to increase productivity and enable the construction of large-scale objects. Additionally, develop advanced calibration and control methods for robotic manipulators to improve precision in additive manufacturing processes.
- Hybrid Manufacturing Processes: To improve the efficiency and quality of production, it is recommended to combine additive and subtractive methods in manufacturing processes [15].

4. CONCLUSIONS

The study of artificial intelligence applied to multi axis additive manufacturing is an area of great relevance and scientific appeal, as evidenced by multiple indicators of impact and collaboration.

- The scientific production in this area is prolific, with 4590 papers in Artificial Intelligence & Additive Manufacturing area, followed by 2237 papers in Artificial Intelligence & Multi axis area, and 1200 papers in Additive Manufacturing and Multi axis area. These figures demonstrate a significant focus on integrating different disciplines.

- The number of papers has increased notably, with Artificial Intelligence & Additive Manufacturing area showing the most significant growth rate at 187.9%. This suggests a growing interest in the convergence of these technologies.
- The Q1 Journals Additive Manufacturing and IEEE Access are the main dissemination platforms, with 146 and 46 papers respectively. This highlights their thematic relevance and recognition in the academic community.
- Citation analysis shows a high frequency of references to papers in Artificial Intelligence & Additive Manufacturing area, with authors such as Zhang Y., Wang Y., and Li Y. This highlights their prominent influence and active contribution to the subject.
- In terms of institutional and geographical production, Huazhong University of Science and Technology in China, along with entities from the U.S. and India, lead the way in demonstrating a strong commitment to the research and development of these technologies.
- The international collaboration between China and the U.S., extended to other countries, reflects a globalized approach to the research and development of artificial intelligence applied to multi-axis additive manufacturing.

Overall, these data indicate the significant relevance and promising potential of the topic. There is a growing interest in the artificial intelligence and multi axis additive manufacturing area, which reaffirms its strategic importance for scientific and technological advancement.

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