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Robotics in Industry 4.0: A Bibliometric Analysis (2011-2022)

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***Abstract*—Robotics forms an integral part of industry 4.0, the industrial revolution of the 21st century. This paper presents a bibliometric analysis of Web of Science (WoS) indexed publications addressing this emerging field from 2011 till June 2022. WoS research publications were firstly analysed along multiple verticals such as annual counts, types, publishing sources, research directions, researchers, organizations, and countries. Next, co-authorship collaborations among authors, organizations, and countries were discovered. This was followed by an analysis of co-occurring keywords related to robotics in industry 4.0. Finally, a detailed citation analysis was carried out to unearth citation linkages among authors, institutions, documents, nations, and journals. Latest trends, under-investigated topics, and future directions are also discussed. Primary results indicate that more than 3000 articles are being published annually in this emerging field, with a total of 18,893 documents published in WoS during the last decade. The 'IEEE Access', Chinese Academy of Science, Wang Y. (USA), and the USA emerged as the topmost productive journal, institution, author, and nation. Porpiglia Francesco (Italy), Chinese Academy Science and USA obtained the highest co-authorship total link strength (TLS); whereas Lee Chengkuo (Singapore), China, Chinese Academy Science, and the IEEE Access scored the highest citation TLS among authors, countries, organizations, and sources respectively. Machine learning (ML) emerged as the highest co-occurring keyword, followed by artificial intelligence (AI). Computer Science emerged as the most trending research domain, followed by general applications. In the future, ML and AI will advance more sophisticated robots in industry 4.0 systems.**

***Keywords*—Bibliometry; Robotics; Industry 4.0; Co-authorship; Co-occurrence; Citation analysis.**

I. Introduction

Robots have been inseparable in modern manufacturing units for the last few decades. Various kinds of robotic implements have helped industries increase their productivity, minimize losses and achieve the flexibility to cope with the ever-demanding market dynamics and competition. Manufacturing in developed countries is characterized by the dominant presence of robotic arms, automated guided vehicles, automated storage and retrieval systems, and more. Even the service industry is swamped by multiple robotic applications such as drones, unmanned aerial vehicles, chatbots, and more. Most of these robots have been extensively used in military services and now are finding their way in diverse fields such as agriculture, medicine, arts, education, mining, space exploration, and much more.

There are multiple device-level applications and high-level architectures enabling factory, office, and even home automation. The advancement of digital technologies and robotics in various areas will profoundly impact how humans work and live. Researchers worldwide have contributed to and followed the technological advancements in this exciting new field. Extensive investigations have been carried out to incorporate automated architectures in diverse fields such as bolted joints [1], lean manufacturing [2], bio-fuelled engines [3], flexible robotic arms [4], Covid therapy robots [5], industrial DC motors [6], machining of exotic materials [7]–[18], ball nose end milling [19] and many more [20]–[34]. Many of these investigations included applications of various heuristic algorithms to attain optimal solutions to the automation/control problems [35]–[46]. The following subsections give details of some of the latest literature reviews and bibliometric research investigations in this field.

A. Related Reviews

This subsection throws light on some of the recent review studies conducted in the field of robotics and industry 4.0. Vaisi [47] reviewed research articles investigating various optimization techniques in robotic systems with an industry 4.0 implementation perspective. Ribeiro et al [48] conducted a detailed literature survey on the evolution of artificial intelligence, machine learning techniques, and robotic process automation in industry 4.0. Robledo et al. [49] focused their review on literature addressing augmented reality, mixed reality, and virtual reality applications in industry 4.0. Segura et al. [50] surveyed articles highlighting the safety concerns in human-robot systems in the smart manufacturing industries. Rad et al. [51] reviewed the core technologies of industry 4.0

from the perspective of enhancing supply chain performance. Aravindaraj and Chinna [52] reviewed literature about advanced warehouse management in industry 4.0, with an emphasis on sustainability. On the other hand, Grybauskas et al. [53] reviewed the social implications of digitalization in the era of industry 4.0. Abbasi et al. [54] reviewed digitalization in agriculture with the advent of industry 4.0. Duong et al. [55] reviewed industry 4.0 and robotic implements in the food industry supply chains. Bartos et al. [56] presented an interesting review of robotics in automotive manufacturing and assembly units. Unhelkar et al. [57] reviewed literature published on industry 4.0-led enhancement of supply chains, particularly in RFID technology. Taddei et al. [58] presented a detailed review of circular supply chains amid the adoption of the internet of things, cloud, and big data analytics in industry 4.0. Ching et al. [59] directed their literature review on sustainability aspects of industry 4.0-led new manufacturing paradigms. Fraske [60] provided an interesting review of the geographical expanse of industry 4.0 technologies, including value chains, labor markets, industrial districts, and more. Silvestri et al. [61] reviewed literature to unearth the tools required for lean manufacturing implementation using industry 4.0 principles and technologies. Javaid et al. [62] reviewed blockchain technologies in industry 4.0, including data security and privacy aspects. Piccarozzi et al. [63] presented a literature review of articles exploring new age production, taking sustainability and industry 4.0 together. Liu et al. [64] reviewed robot learning in smart manufacturing, including machine learning and training tools to promote human-robot interactions. Moosavi et al. [65] reviewed literature and presented a case study demonstrating the effectiveness of industry 4.0 technologies during the pandemic outbreak. Gualtieri et al. [66] reviewed ergonomics and safety aspects of industrial robotics, especially when using collaborative robots. Lee et al. [67] applied unsupervised machine learning techniques to review various aspects of industry 4.0 practices. Pace et al. [68] reviewed literature addressing augmented reality applications in handling collaborative robots in modern manufacturing units. Morenilla et al. [69] reviewed how the traditional manufacturing sector can be transformed into smart industries through industry 4.0 technological disruptions. Yadav et al. [70] also explored the efficacy of industry 4.0 technologies integrated with the food supply chains originating from agricultural lands. Silvestri et al. [71] reviewed maintenance aspects of industry 4.0 implementations, including self and remote maintenance solutions. Govindan et al. [72] reviewed the performance of the modern supply chain 4.0 networks. Castagnoli et al. [73] reviewed the role of industry 4.0 technologies in reshaping the international business landscape, inclusive of competitiveness and organizational impacts. Gallo et al. [74] reviewed lean production achievement through industry 4.0 tools and techniques. Reiman et al. [75] also reviewed the ergonomics and other human factors in the context of the growing prevalence of industry 4.0 systems. Mitchell et al. [76] reviewed the applications of robotics and artificial intelligence in wind infrastructure lifecycle management with special emphasis on offshore platforms. Forcina et al. [77] reviewed how industry 4.0 technologies make modern factories safer for humans. Aoun et al. [78] conducted a review to explore how blockchain technologies can help improve the security and efficacy of industry 4.0-enabled manufacturing. Resende et al. [79] reviewed the multifarious decision models used by researchers to select optimal suppliers in the era of digital manufacturing and industry 4.0.

B. Related Bibliometric Studies

This subsection throws light on some of the recent review studies conducted in the field of robotics and industry 4.0. Bibliometric analysis is a popular methodology to used by researchers to reveal hidden insights, trends and performers in a particular topic of interest [80]. Atzeni et al. [81] conducted a bibliometric study of collaborative robots in industry 4.0 in logistic applications. Rejeb et al. [82] conducted an bibliometric review of drone applications in agriculture 4.0, including remote sensing, internet of things (IoT) and precision agriculture. Longo et al. [83] conducted a bibliometric analysis of the effect of ergonomics and human factors on implementation of industry 4.0 in the oil and gas sector. Ante [84] carried out a bibliometric study of digital twin technological research to enable industry 4.0 and smart manufacturing. This study included cyber physical coordination between humans and collaborative robots in the context of manufacturing and industrial automation. David et al. [85] used bibliometry to analyse the sustainable security achieved in water, food and energy sectors due to the integration of industry 4.0 technologies such as IoT and big data analytics. The study concluded that industry 4.0 promises to bring clean production processes and strategies for sustainable growth in the long term scenario. Muhuri et al. [86] conducted a detailed bibliometric study of all aspects of industry 4.0, including machine learning, automation, and digital integration of data analytics with physical manufacturing. Fatma [87] conducted a focused bibliometric study of industry 4.0 research to modernize electronic accounting processes in Turkey. Mariani and Borghi [88] conducted a bibliometric study of management structures in service industries implementing industry 4.0 practices. Katoch [89] used bibliometry to analyse research investigations addressing IoT applications in logistics and supply chain including wireless sensor networks and blockchain. Cobo et al. [90] created a co-word analytics of industry 4.0 research documents based on bibliometry. The authors found 'cloud computing' and 'cyber physical systems' as the most important themes investigated during 2013-2017. Miguel et al. [91] presented a bibliometric analytical coverage of research investigations addressing the role supply chains in industry 4.0 implementation. Ahsan and Siddique [92] reviewed research literature focussing on healthcare applications of industry 4.0. Janmaijaya et al. [93] applied bibliometry to analyse various industry 4.0 research along various verticals such as publications, citations, authors and more. The authors also applied latent dirichlet allocation and K-means based clustering to identify emerging industry 4.0 research topics. Said and Barka [94] investigated the impact of industry 4.0 technologies in plastics sector using bibliometric research tools. Dino et al. [95] reviewed the nursing aspects for healthcare robotic applications for elderly people.

C. Research Gap in Literature and Goal of the Present Study

The review of literature in the previous section indicates that most bibliometric researchers have focused on very narrow, niche areas within industry 4.0, and few have explored the overall research trends in industry 4.0 over the past few years. However, there is a bibliometric research gap in the application and proliferation of robotics in industry 4.0. Hence, there is a need and an open scope for conducting a detailed bibliometric analysis of the role of robotics in industry 4.0. The present study aims to bridge this gap and provide an innovative and holistic view of the top-notch research conducted over the past decade in this field along various verticals such as trending topics, authors, organizations, countries, publishing sources, documents, co-authorship, citations and more.

D. Data collection

The present study is based on the research documents collected from the Web of Science (WoS) repository. WoS is a scholarly and reputed database highly regarded as the world's most prestigious publishing source's premium collection. This collection holds articles published in world-class journals since 1990. It includes various database categories for journals, such as the science citation index (SCI), science citation index expanded (SCIE), emerging science citation index (ESCI), social sciences citation index (SSCI), and the arts and humanities citation index (AHCI). Other WoS database categories include the book citation index for science (BCI-S) and conference proceedings citation index for science (CPCI-S). Similar book and conference proceedings indices exist and for social sciences and humanities as well (BCI-SSH and CPCI-SSH).

All the above-mentioned WoS categories were searched for the following keywords for the period of 2011 to 4 July 2022: (((Robotics) OR (Robot) OR (Unmanned aerial vehicle) OR (Drone) OR (automated guided vehicle) OR (Cobots) OR (Remote operational vehicle) OR (Robot operating system) OR (Manipulators) OR (multi-robot) OR (Cognitive Robotics) OR (Swarm Robotics) OR (Manufacturing Robotics)) AND ((Industry 4.0) OR (Industrial Internet of Things) OR (Smart factories) OR (Internet of Things) OR (Augment Reality) OR (cyber security) OR (cloud computing) OR (Cyber Physical Systems) OR (Sustainable Industry) OR (smart manufacturing) OR (Artificial Intelligent) OR (Machine learning) OR (Big data analytics) OR (Internet of Robotic Things))). This keyword search yielded a total of 18,893 documents from the WoS databases. The following sections present the results of bibliometric analyses conducted along various verticals to unearth the most important research performers and indicators during the last decade.

Fig. 1 depicts the step-wise data collection and analysis procedure followed in the present study. The above-mentioned search query was used to extract a corpus of relevant documents from the WoS core collection database, inclusive of all indices mentioned above. Firstly, this corpus was analysed for year-on-year publication counts, publication types, sources, research directions, publishing countries, organizations, and researchers in WoS itself. All these results have been presented in section II. Thereafter, the document corpus was exported in plain text file format, which was imported to VOSviewer software for further analyses, viz. co-authorship, co-occurrence, and citations along different verticals. The type of analysis, counting method (full or fractional) as well as the data threshold limit and exclusion criteria were selected in the VOSviewer. After verifying the mapped entries, network maps as well as the corresponding network files were exported for presentation in the article. These results have been presented and discussed in sections III, IV and V, respectively.

II. Publication Structure Analysis

This section presents bibliometric details of annual publications, top publishing sources, and trends of prominent research directions, followed by the lists of the most productive nations, organizations, and researchers in the field of robotics in industry 4.0.

A. Year on Year Vertical

Fig. 2 shows the year-on-year publication counts in this emerging field of robotics in industry 4.0. The number of publications has been rising almost exponentially, with only 302 papers published in WoS in 2011 up to almost 4000 papers published in 2021 alone! In fact, the number of publications during 2020 more than tripled the annual count just four years ago (2016)! The current year (2022) has already recorded more than 1600 WoS articles published in this area, with many more publications expected by the end of this year.

B. Publication Type

Fig. 3 shows the distribution of the total WoS publications into various subcategories. It is evident that the maximum WoS publications in this field belong to the category of journal articles (9,965). Proceedings papers form the second most dominant group with 7,807 publications, followed by review papers (1,032), early access publications (371), book chapters (222), and editorials (159). The remaining categories such as meeting abstracts (44), data papers (18), books (4), and corrections (4) were represented by very low counts of instances.

C. Publication Sources

Fig. 4 shows the top WoS sources publishing in the field of robotics in industry 4.0. The list is topped by the journal 'IEEE Access' with 522 publications, followed by 'Sensors' with 457

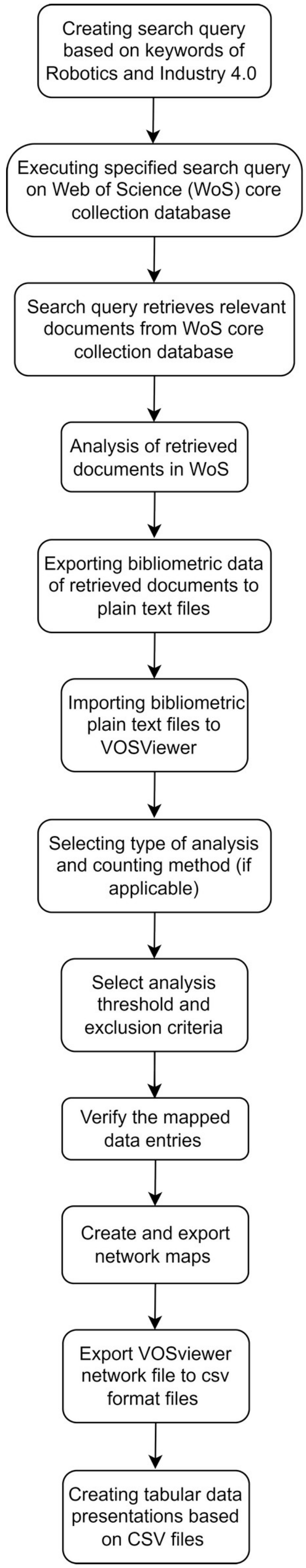

Fig. 1. Flowchart of research methodology

papers. The journals 'Lecture Notes in Computer Science', 'IEEE Internet of Things' and 'Remote Sensing' arrived third, fourth, and fifth with 291, 236 and 231 publications respectively. These were followed by 'Proceedings of SPIE', 'IEEE International Conference on Intelligent Robots and Systems', 'IEEE Robotics and Automation Letters', 'IEEE International Conference on Robotics and Automation ICRA', and 'Applied Sciences' with 230, 220, 216, 197 and 186 publications during the last decade.

D. Research Directions

Fig. 5 shows the top ten subject/application areas that have received the maximum attention from the research community working on robotics in industry 4.0 over the past decade. It is evident that the maximum WoS publications in this field belonged to 'computer science' and 'engineering' domains with 8,412 and 8,355 articles respectively. The next most important subject areas were 'robotics', 'telecommunications', and 'automatic control systems' with 3075,2430 and 2244 publications respectively. It is interesting to note that subject areas such as 'chemistry', 'materials science' and 'physics' also attracted WoS publications related to industry 4.0 and robotics with 926, 901, and 710 articles respectively. Other prominent application domains included 'instruments instrumentation' and 'science technology other topics' with 852 and 763 documents respectively.

E. Productive Countries

Fig. 6 shows the top ten nations contributing to robotics research with industry 4.0 perspectives. The list is topped by the USA with 4,007 publications in the WoS, followed by the People's Republic of China with 3,656 articles. Authors of Germany, England, Italy, and India contributed a similar range of publications: 1364, 1262, 1174, and 1038 respectively. On the other hand, researchers hailing from Japan, South Korea, Canada, and Spain contributed to the third level of publication ranges: 886, 788, 761, and 737 respectively.

F. Productive Organizations

Fig. 7 shows the top ten most productive organizations publishing WoS articles in the field of robotics and industry 4.0. This list is topped by the Chinese Academy of Sciences with 389 publications, followed by the institutes affiliated with the University of California with 325 papers and the Centre National De La Recherche Scientifique CNRS with 223 articles. These are followed by the Udice French Research Universities in fourth place, institutions of the University of Georgia in fifth place, Tsinghua University in sixth place, institutions of the State University of Florida in seventh place, the University of Texas in the eighth place, the University of London at the ninth place and the Nanyang Technological University at the tenth place with 214, 184, 179, 170, 162, 158 and 154 WoS articles respectively.

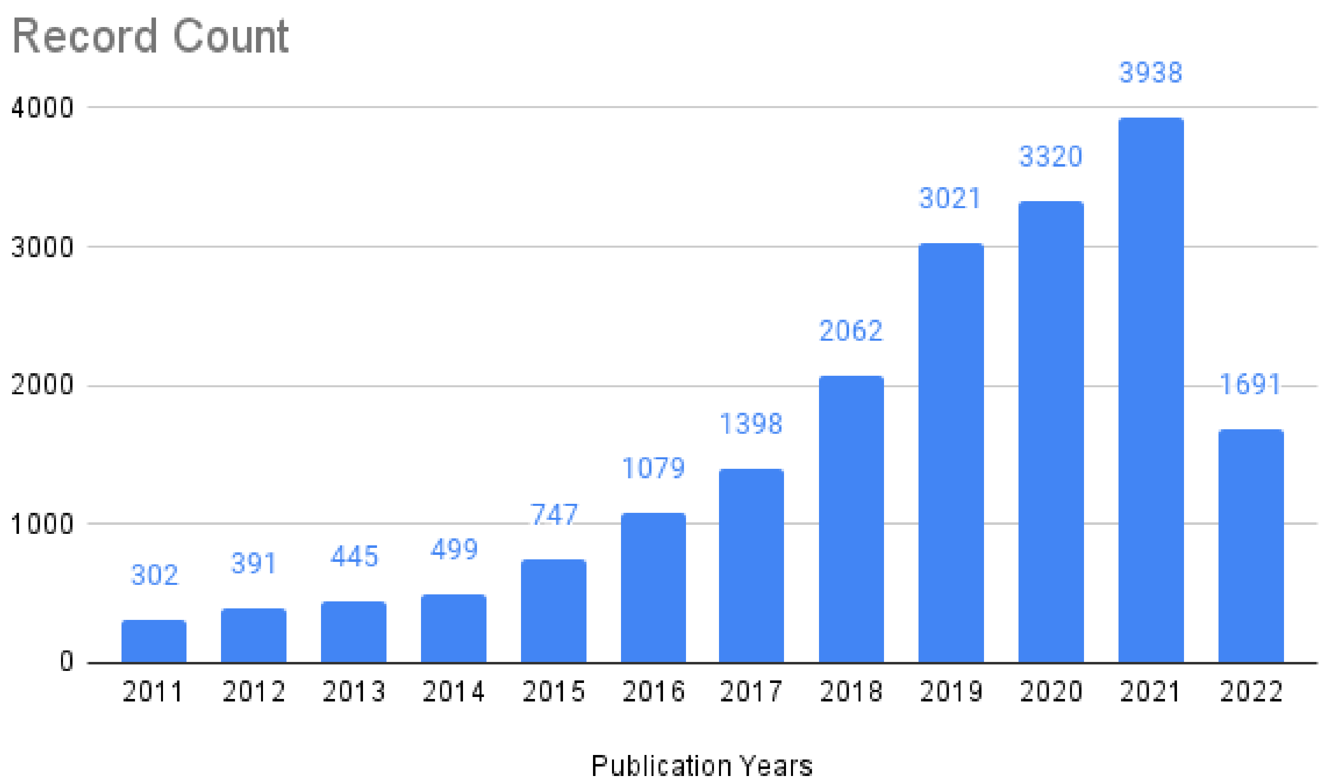

Fig. 2. Annual publication from 2011 to 2022

G. Productive Researchers

Table I indicates the top eleven productive first authors in the selected field of study. This list is dominated by researchers affiliated with Chinese institutions, with four representations. There are three authors from the USA and South Korea each. There is one author from England. This table also shows the number of articles published as first authors by each of these top productive researchers in the field of robotics and industry 4.0. The table also depicts the actual percentage contribution of such papers to the total WoS corpus during the last decade. The list is topped by Wang Y from North Carolina State University, the USA having 88 WoS records as the first author.

III. Co-authorship Analyses

Collaboration is the root of inter-departmental, inter-institutional, and international linkages that facilitate quality research outputs. This section focuses on the top co-authorship linkages among researchers, institutions, and nations in the field of robotics and industry 4.0. VOS viewer software was employed in the current work to present these results.

A. Co-authorship Analysis Based on Authors

This subsection presents the co-authorship-based linkages among authors from different organizations and countries. The VOS search yielded a total of 57,294 authors having contributed to the selected field of research. The co-authorship linkages among these authors were analyzed using the fractional counting method with thresholds of minimum of 5 publications and 10 citations per author. Moreover, this analysis did not consider documents with 25 or more authors. Fractional counting is well regarded and widely acknowledged as a dependable methodology that lays equal emphasis on low-cited papers as it does on the highly cited documents appearing in the references of a citing article [96]. In the current analysis, only 1206 authors were found to satisfy the above-mentioned threshold limits. Of these, only 786 were found to be interconnected in the largest network of co-authors. From this set of connected authors, the top ten researchers with the maximum links strengths are depicted in Table II. This table is dominated by Italian researchers, with as many as five representations. The second highest representation is from the USA, with two researchers. There is one author each from China, Singapore, and Greece. In this table, 'P' indicates the number of WoS publications of

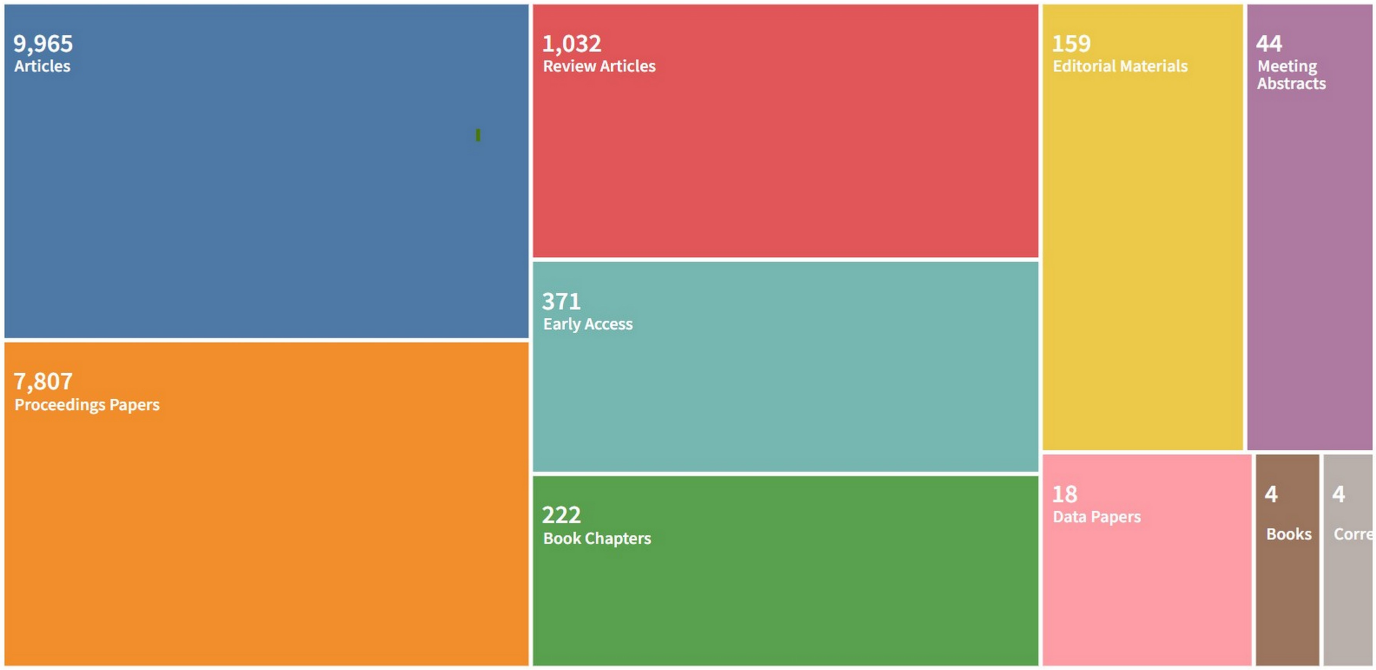

Fig. 3. The detail of publications in top 10 type

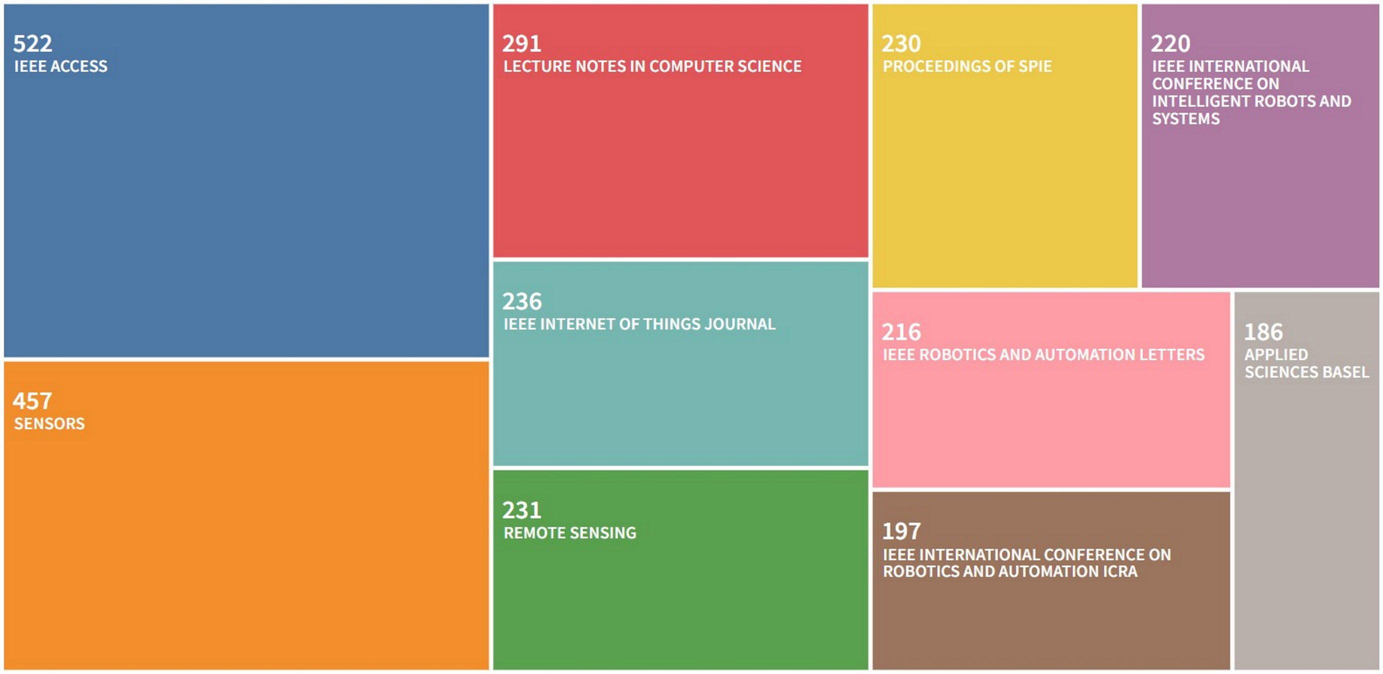

Fig. 4. The top 10 source title of the publications

each author. 'Links' are the number of individual co-authors with whom the particular researcher has published 'P' articles. 'TLS' represents the total link strength, i.e., the sum of strengths of all co-author linkages for a particular researcher. Under the fractional counting method, if an article includes 'n' co-authors, then the co-author link strength among any two of them would

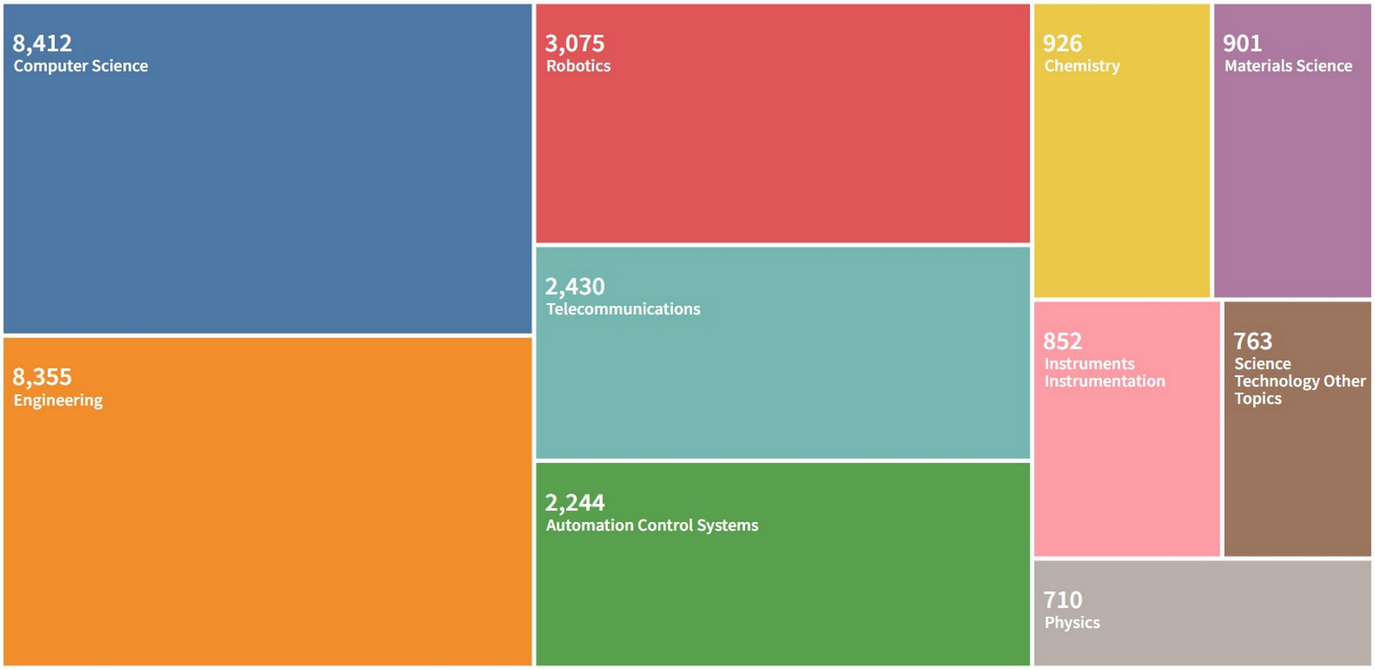

Fig. 5. The top 10 Research areas

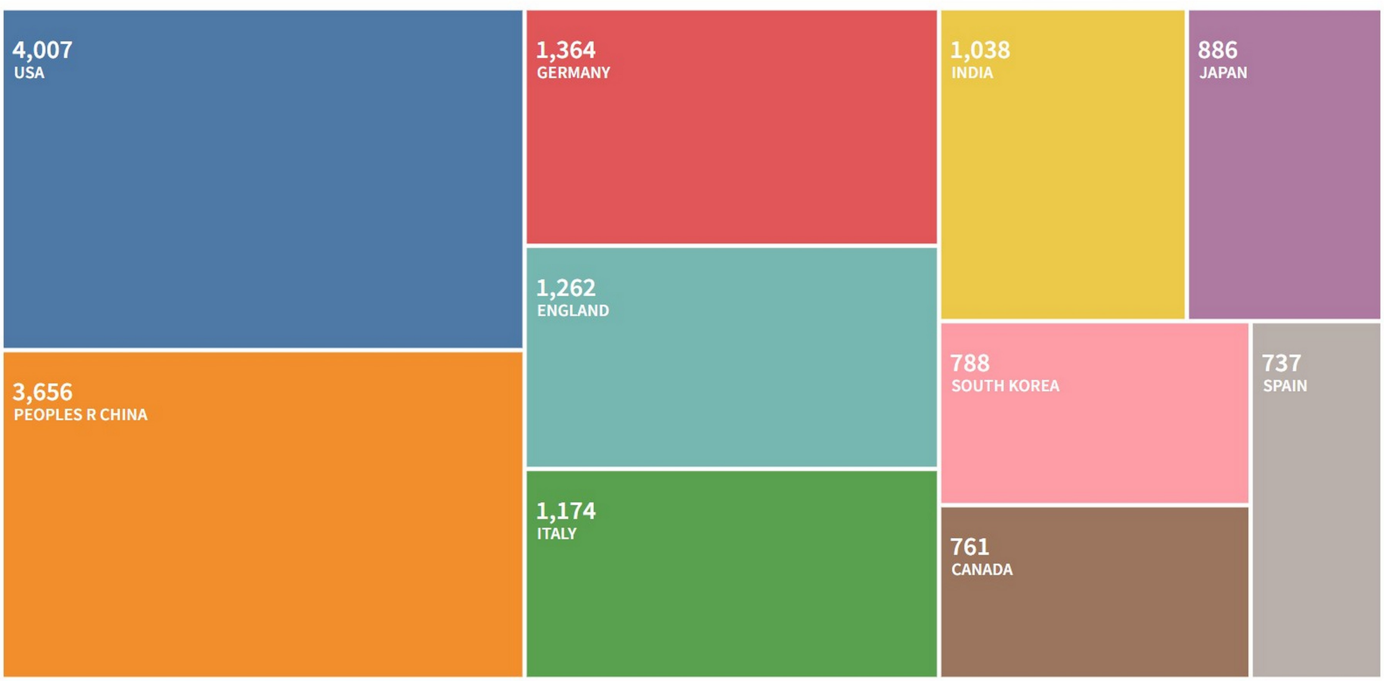

Fig. 6. The top 10 Countries

be 1/n. Hence, the sum of co-author linkages for a particular researcher with all other co-authors in a paper would equal one. That is why the number of links is equal to TLS in the case of some of the researchers listed in Table II: Porpiglia Francesco, Xu Wenjun, Amparore Daniele, Checcucci Enrico, Fiori Cristian, Makris Sotiris and Piazzolla Pietro having ranks

Fig. 7. The top 10 organizations of the publications

TABLE I
THE 10 PRODUCTIVE AUTHORS

Authors	**Organization**	**Country**	**Record Count**	**% of total corpus (18,893)**
Wang Y	North Carolina State University	USA	88	0.466
Zhang Y	Chongqing University of Posts & Telecommunications	China	78	0.413
Liu Y	Nanjing Agricultural University	China	67	0.355
Li J	Hebei University of Technology	China	66	0.349
Kim J	Korea Elect Technol Inst	South Korea	58	0.307
Kim S	Yonsei University	South Korea	50	0.265
Chen J	University of Pennsylvania	USA	47	0.249
Chen Y	Newcastle University - UK	England	44	0.233
Lee J	Indiana University System	USA	44	0.233
Li Y	University of Electronic Science & Technology of China	China	44	0.233
Lee S	Sungkyunkwan University	South Korea	42	0.222

1, 2, 3, 4, 5, 8 and 9 respectively. It may be observed that TLS is lower than the number of co-author links in the case of the rest of the top-ranked authors, i.e. Lee (rank 7) and Han (rank 10). This phenomenon indicates that these scientists published some papers either without any co-authors or included such co-authors which were omitted from the current analysis. Such omissions could have occurred due to such co-authors not meeting the threshold criteria set in the current study and/or not being interconnected in the largest network of co-authors. The results also show that having more co-author linkages does not necessarily translate into higher TLS. For instance, Xu Wenjun has higher links (21) than Porpiglia Francesco (15 links), still, the latter has higher TLS (32) as compared to that of the former (29). This occurrence is because Xu Wenjun has 29 publications, and the sum total of all co-author linkages from all 29 articles cannot be more than 29, as per the fractional counting method described above. On the other hand, Han Zhu has a higher number of publications as well as co-author links as compared to Piazzolla Pietro but still has lesser TLS than the latter. This could be due to some publications of Han Zhu either not having any co-authors at all or due to some papers having co-authors not considered in the current analysis due to not fulfilling the threshold criteria or not occurring in the largest network of connected authors.

Fig. 8 shows the collaborative networks among the various co-authors working in the field of robotics in industry 4.0. The figure depicts the top TLS author, Porpiglia Francesco located as a prominent node of the grey-colored co-author network; whereas Xu Wenjun is situated in the light blue-colored network.

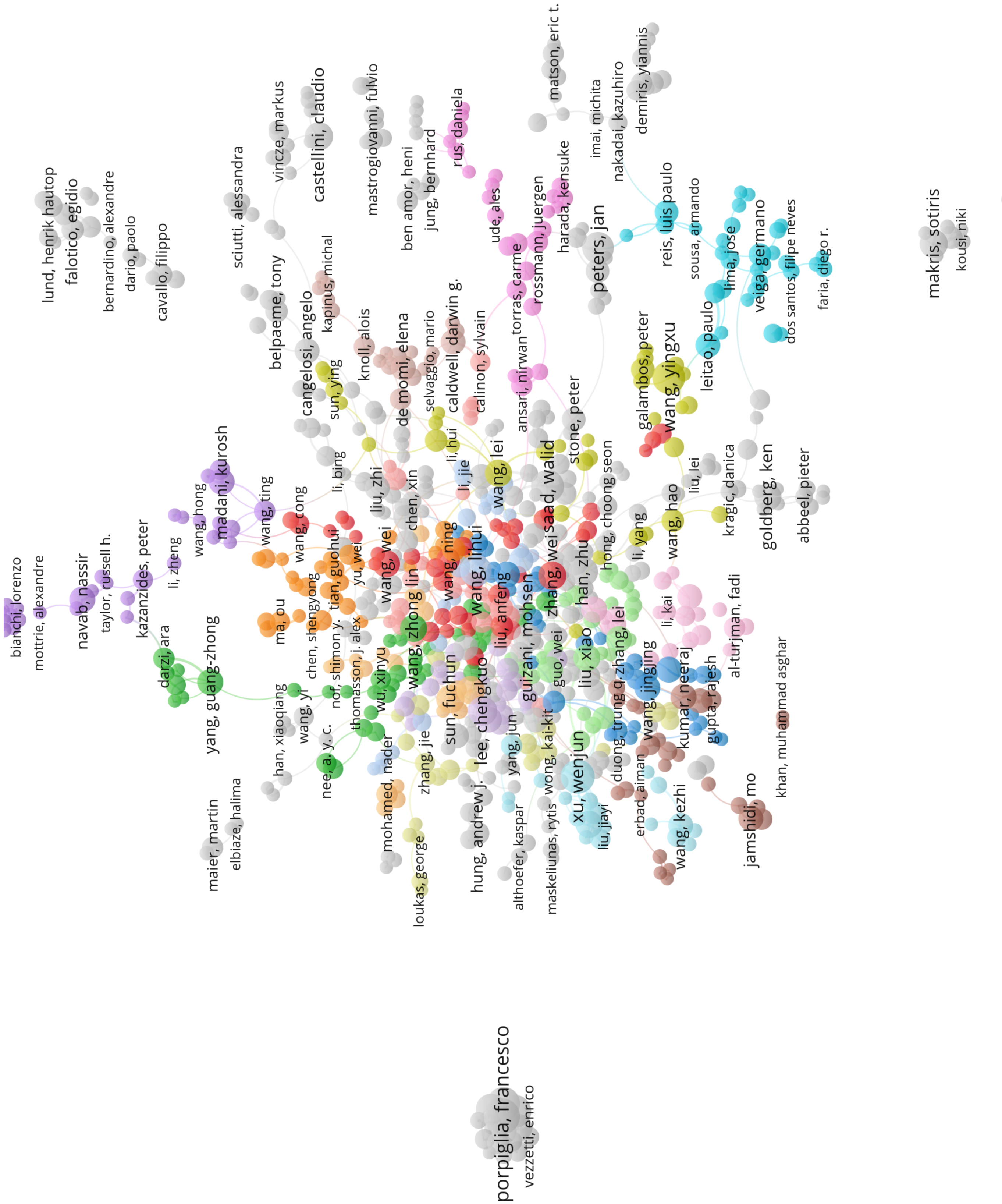

Fig. 8. Co-authorship network based on authors

TABLE II
THE TOP 10 RESEARCHERS WITH MAXIMUM CO-AUTHORSHIP TLS VALUES

Rank	Author	Country	P	Links	TLS
1	Porpiglia, Francesco	Italy	32	15	32.00
2	Xu, Wenjun	China	29	21	29.00
3	Amparore, Daniele	Italy	26	15	26.00
4	Checcucci, Enrico	Italy	26	15	26.00
5	Fiori, Cristian	Italy	24	15	24.00
6	Saad, Walid	USA	27	9	22.00
7	Lee, Chengkuo	Singapore	22	11	21.00
8	Makris, Sotiris	Greece	20	12	20.00
9	Piazzolla, Pietro	Italy	19	14	19.00
10	Han, Zhu	USA	21	21	18.00

B. Co-authorship Analysis Based on Organizations

This subsection presents the co-authorship-based linkages among organizations from different countries. The VOS search yielded a total of 11,137 organizations having contributed to the selected field of research. The co-authorship linkages among these organizations were analysed using the fractional counting method with a minimum of 5 publications and 10 citations per organization. Moreover, this analysis did not consider documents with authors affiliated with 25 or more institutions. In the current analysis, only 1451 organizations were found to satisfy the above-mentioned threshold limits. Of these, only 1350 were found to be interconnected in the largest network of co-authorship. From this set of connected organizations, the top thirteen institutions with the maximum links strengths are depicted in Table III. This table is dominated by Chinese organizations, with as many as six representations. The second highest representation is from the USA, with three organizations, followed by two from Singapore. There is one organization each from Germany and Bangladesh. Hence, the top thirteen TLS nations list comprises just five countries! In this table, 'P' indicates the number of WoS publications of each organization. 'Links' are the number of individual organizations with whom the particular institution has published 'P' articles. 'TLS' represents the total link strength, i.e., the sum of strengths of all co-author linkages for a particular organization. Under the fractional counting method, if an article includes co-authors from 'n' organizations, then the co-author link strength among any two of them would be 1/n. Hence, the sum of co-author linkages for a particular organization with all other co-authored institutions in a paper would equal one. Hence, TLS must be equal to P for every organization. However, the same is not observed in Table III wherein TLS is lesser than P for all institutions. This phenomenon indicates that these institutions published some papers either without any co-authoring organizations, or included such co-authored organizations which were omitted from the current analysis. Such omissions could have occurred due to such co-authored institutions not meeting the threshold criteria set in the current study and/or not being interconnected in the largest network of co-authoring institutions. The results also show that having greater number of co-author institutional linkages does not necessarily translate into higher TLS. For instance, Tsinghua University has higher links (124) than University of Chinese Academy of Sciences (84 links), still the latter has higher TLS (135) as compared to that of the former (132). This occurrence is due to the reason that Tsinghua University has more publications either not having any co-authoring institutions at all, or due to some papers having only such co-authored organizations that were not considered in the current analysis due to their not fulfilling the threshold criteria or not occurring in the largest network of connected organizations. On the other hand, Han Zhu has higher number of publications and co-author links as compared to Piazzolla Pietro, but still has lesser TLS than the latter. This is due to Piazzolla Pietro having lesser co-author linkages in relatively greater number of published articles. It is interesting to note that Southeast University, Bangladesh has higher co-authored institutional linkages and TLS over Beijing University of Posts and Telecommunications (China), the Carnegie Mellon University (USA) and the Shanghai Jiao Tong University (China) despite having lesser published documents in WoS as compared to these three premier organizations. This shows that the researchers of Southeast University, Bangladesh have really done well in terms of co-authored linkages with other institutions in the field of robotics in industry 4.0.

Fig. 9 shows the collaborative networks among the various co-authored institutions working in the field of robotics in industry 4.0. The figure depicts the top TLS organizations such as the Chinese Academy of Sciences and the Nanyang Technological University located as the prominent nodes of the grey colored co-authored network; whereas the Massachusetts Institute of Technology, University of Alberta and Auburn University situated in the red colored collaboration network. Similarly, the Purdue University, Seoul National University and the Sungkyunkwan University are shown connected in the dark blue colored network, whereas University of Tokyo, Osaka University and Tokyo Metropolitan University are connected in the sea blue colored network. The Russian Academy of Sciences, University of Melbourne and the National Taipei University of Technology form the prominent nodes of the purple, green and the sky blue colored networks.

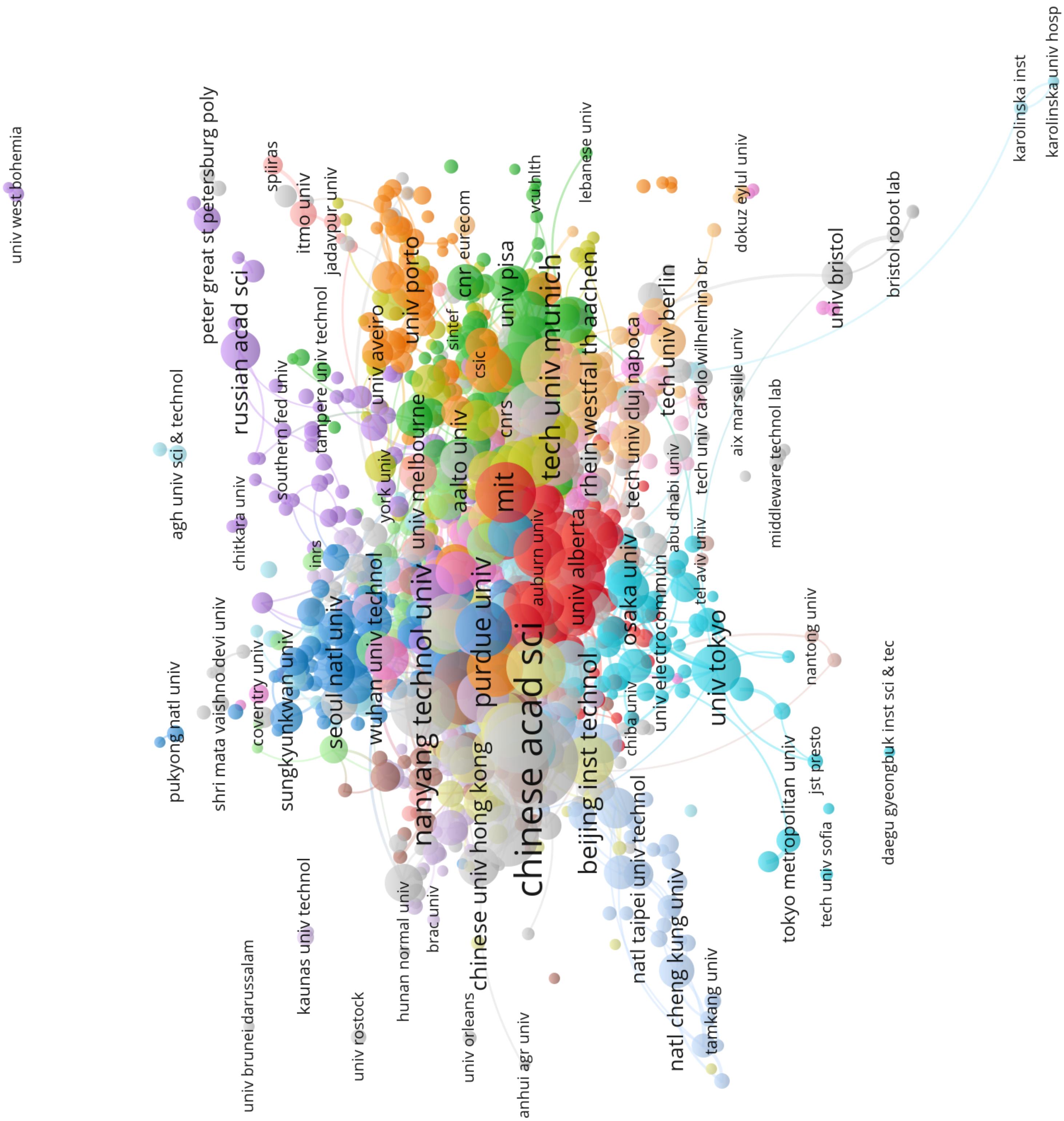

Fig. 9. Co-authorship network based on organizations

TABLE III
THE TOP 13 ORGANIZATIONS WITH THE MAXIMUM CO-AUTHORSHIP TLS

Rank	Organization	Country	P	Links	TLS
1	Chinese Academy of Sciences	China	331	214	293.00
2	University of Chinese Academy of Sciences	China	138	84	135.00
3	Tsinghua University	China	179	124	132.00
4	Nanyang Technological University	Singapore	150	115	104.00
5	Technical University of Munich	Germany	134	97	83.00
6	Massachusetts Institute of Technology	USA	133	125	82.00
7	Georgia Institute of Technology	USA	131	103	76.00
8	Beihang University	China	126	92	75.00
9	National University of Singapore	Singapore	114	75	72.00
10	Southeast University	Bangladesh	89	111	70.00
11	Beijing University of Posts and Telecommunications	China	106	69	68.00
12	Carnegie Mellon University	USA	114	108	68.00
13	Shanghai Jiao Tong University	China	112	83	68.00

C. Co-authorship Analysis Based on Countries

This subsection presents the co-authorship based linkages among organizations from different countries. The VOS search yielded a total of 135 countries having contributed to the selected field of research. The co-authorship linkages among these countries were analysed using the fractional counting method with thresholds of minimum 5 publications and 10 citations per nation. Moreover, documents with authors affiliated to 25 or more nations were not considered in this analysis. In the current analsis, only 95 countries were found to satisfy the above mentioned threshold limits. From this set of 95 connected countries, the top thirteen institutions with the maximum links strengths are depicted in Table III. This table is topped by the USA with 4006 WoS publications; followed by China, England, Germany and Italy with 3656, 1262, 1363 and 1173 WoS articles in the selected field of research. As in the case of the results presented in the preceding subsections, 'P', 'links' and TLS stand for the number of WoS publications of each nation, number of individual nations with whom the particular country has published 'P' articles and the sum of strengths of all international co-author linkages for a particular country, respectively. Under fractional counting method, if an article includes co-authors from 'n' countries, then the co-author link strength among any two of them would be 1/n. Hence, the sum of co-author linkages for a particular country with all other co-authored nations in a paper would be equal to one. Hence, TLS must be equal to P for every country. However, the same is not observed in Table III wherein TLS is much lesser than P for all countries. This phenomenon indicates that these nations published some papers either without any international co-authors, or included co-authors from such nations which were omitted from the current analysis. Such omissions could have occurred due to such co-authored countries not meeting the threshold criteria set in the current study. Table III clearly indicates that greater the number of international co-author linkages of a nation, greater is the total links strength of that country as well. However, having more publications does not necessitate higher international co-author linkages. This is substantiated by the case of India, which has more WoS publications than Canada, France and Australia, but has lesser number of international co-author linkages as compared to the authors of these three nations. Similar case may be observed with regards to Japan-Spain, Germany-England and Australia-France as well.

TABLE IV
THE TOP 13 COUNTRIES WITH THE MAXIMUM CO-AUTHORSHIP TLS

Rank	Country	P	Links	TLS
1	USA	4006	83	1495.00
2	China	3656	71	1337.00
3	England	1262	75	836.00
4	Germany	1363	73	557.00
5	Italy	1173	72	526.00
6	Canada	761	67	461.00
7	France	701	69	427.00
8	Australia	709	64	404.00
9	India	1038	69	323.00
10	Spain	737	61	320.00
11	Japan	886	55	301.00
12	South Korea	788	51	288.00
13	Saudi Arabia	316	56	254.00

Figure 10 shows the collaborative networks among the various co-authored countries working in the field of robotics in industry 4.0. The figure depicts the top TLS nation, the USA located as the prominent node of the pink colored international co-author network; whereas the People's Republic of China, Japan, Indonesia and Singapore are situated in the dark blue colored collaboration network. Similarly, Germany, Italy, Russia, Austria, Poland and others are shown connected in the red colored network, whereas Spain, Brazil, Mexico and Colombia are connected together in the yellow colored network. France, Sweden and Switzerland form the prominent nodes of the purple colored network, whereas Qatar, Pakistan and United Arab Emirates form the important nodes of the green colored network.

IV. CO-OCCURRENCE ANALYSIS

This section gives details of the bibliometric analyses carried out on the co-occurrences of various keywords mentioned in the

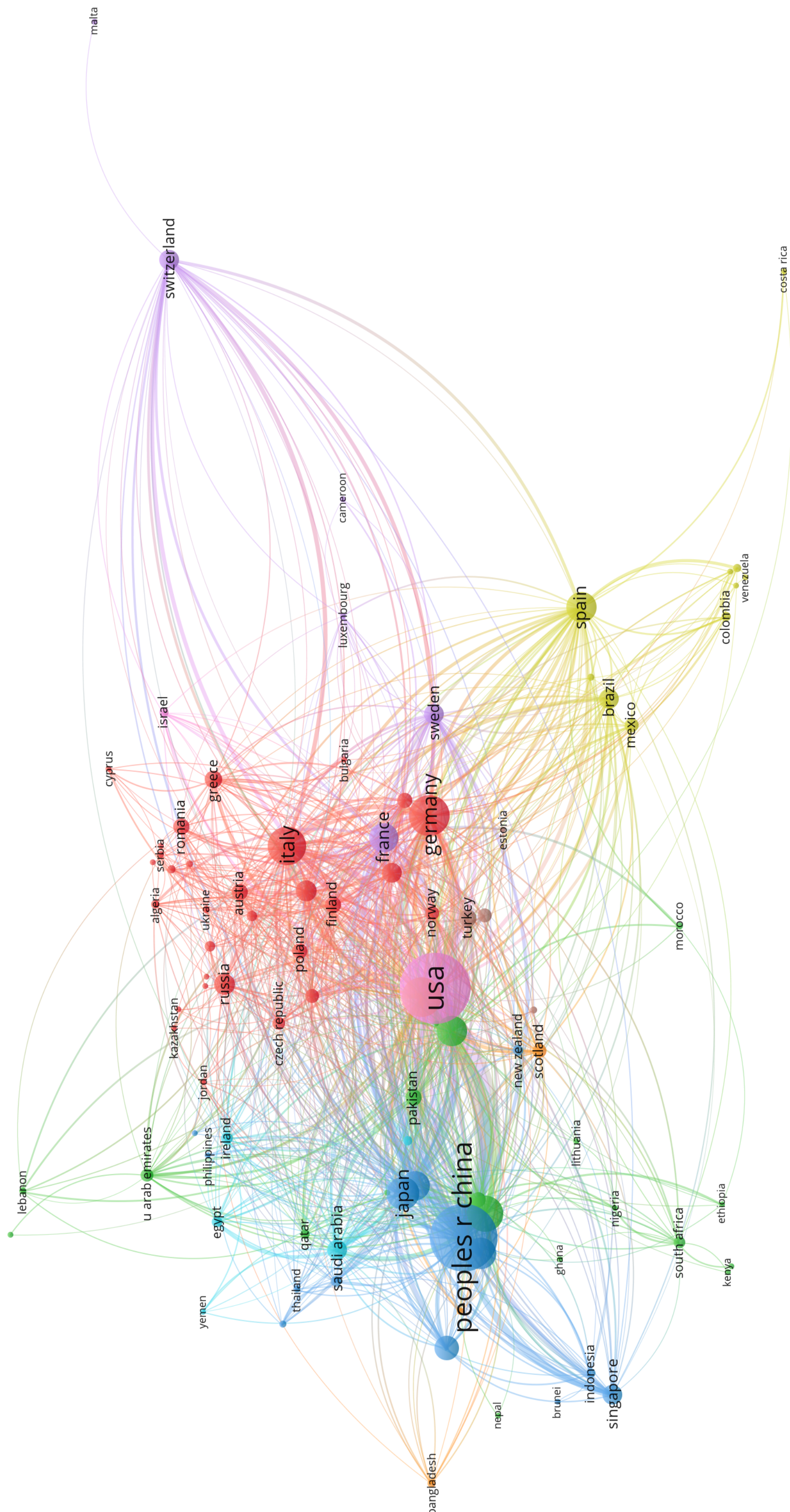

Fig. 10. Co-authorship network based on countries

robotics in industry 4.0 articles published in the WoS during the last decade.

A. Co-occurrence Analysis Based on Author Keywords

This subsection presents a co-occurrence analysis of the keywords quoted by authors in WoS research publications during the past decade. VoS search yielded a total of 36090 such keywords. The co-occurrences among these keywords were analysed using fractional counting method with a threshold of minimum 10 occurrences per keyword. Only 1007 keywords were found to satisfy this criterion. Of these, the top ten c-occurring keywords with highest TLS values are listed in Table V. This table showcases the top thirteen keywords mentioned by researchers in their robotics and industry 4.0 related research articles published in the WoS. The list shows that the keyword 'machine learning' appeared in 2519 published articles (P). 'Machine learning' co-occurred with 842 other author-keywords in these articles. The TLS of 'machine learning' is 2228, which is the sum of the number of times 'machine learning' has co-occurred with each of the 842 other keywords (having minimum 10 occurrences). Herein, if 'n' author-keywords co-occurred an article, then the strength of link among each pair of co-occurred keywords was computed as 1/n (due to the citing article). For instance, if ten keywords co-occurred in an article, then the link strengths among each of them would be 1/10. TLS indicates the sum of such link strengths of a keyword with all other co-occurring keywords over all published papers. The co-occurrence based TLS of keywords is always a whole number (not a fraction) because the sum of fractional link strengths of a keyword in any published article will always be one. Hence, the total co-occurrence link strength of a keyword over all published articles will be equal to the number of such published articles (P). However, this phenomenon is not evident in Table V, wherein the TLS is always a whole number but is always lesser than the actual number of publications (P). This observation indicates that there are some published articles wherein no other robotics and industry 4.0 keyword has been mentioned by the authors. It may also mean that in some published articles only such keywords co-occurred that had less than 10 occurrences themselves, thus getting omitted from the current analysis and not getting counted as co-occurred keywords. For instance, in case of the topmost TLS keyword 'machine learning', publications are 2519 whereas TLS is 2228. Hence, there are 291 articles that mentioned this keyword and, either did not include any other robotics/industry 4.0 WoS keyword or mentioned such keywords that had less than a total of 10 occurrences themselves (individually). Similar observation may be made in case of other author keywords as well. It may be noted in Table V that the fourth ('robotics') and the tenth ('robots') keywords are similar. Seventh ('UAV') and ninth ('unmanned aerial vehicles') are also different instances of the same keyword. The top author defined keywords indicate the focus of most researchers - application of robotics/augmented reality/UAV in industry 4.0/internet of things using artificial intelligence and machine/deep learning. It may be observed from this list that generally, higher number of occurrences correspond with higher TLS of the keywords. However, 'UAV' has higher links (405) and TLS (467) despite appearing in lesser publications (494) as compared to 'industry 4.0' (occurrences 500, links 328 and TLS 440). This implies that the authors have quoted the keyword 'UAV' along with many more co-occurring keywords as compared to that in case of 'industry 4.0'.

TABLE V
THE TOP 13 KEYWORDS WITH THE MAXIMUM CO-OCCURRENCE TLS VALUES FOR AUTHOR KEYWORDS

Rank	Keyword	P	Links	TLS
1	Machine Learning	2519	842	2228.00
2	Artificial Intelligence	1117	617	1004.00
3	Internet of Things	929	587	849.00
4	Robotics	830	557	794.00
5	Deep Learning	825	568	762.00
6	Augmented Reality	665	393	572.00
7	UAV	494	405	467.00
8	Industry 4.0	500	328	440.00
9	Unmanned Aerial Vehicles	465	385	438.00
10	Robots	360	478	347.00
11	Reinforcement Learning	387	346	335.00
12	Cloud Computing	352	368	333.00
13	Human-robot Interaction	364	300	325.00

Fig. 11 shows the co-occurrence network of author defined keywords in the field of robotics and industry 4.0. Keywords such as 'machine learning', 'UAV', 'computer vision', 'object detection', 'remote sensing', 'ensemble learning', 'regression', 'random forest' and 'yolo' co-occur together, with their co-occurrence networks depicted in green color in figure 11. Similarly, the keywords 'internet of things', 'unmanned aerial vehicles', 'robots', 'iot', 'energy efficiency', 'industries', 'routing', 'satellites', 'security' and 'block chain' form important nodes of the red colored co-occurrence network. The blue colored co-occurrence network is composed of author-keywords such as 'industry 4.0', 'smart factory', 'digitalization', 'data analytics', 'collaborative robot', 'digital technologies', 'sustainable development' and more. 'Augmented reality' and 'robotic surgery' belong to the pink colored network whereas 'human-robot interaction', 'mixed reality', 'facial expression' and 'brain-robot interface' co-occur together and shown in the yellow colored network.

B. Co-occurrence Analysis Based on all Keywords

This subsection presents co-occurrence analysis of the all keywords identified by WoS in robotics and industry 4.0 research publications during the past decade. VoS search yielded a total of 43,798 such keywords. The co-occurrences among these keywords were analysed using fractional counting method with a threshold of minimum 10 occurrences per keyword. Only 1678 keywords were found to satisfy this criterion. Of these, the top ten c-occurring keywords with highest TLS values are listed in Table VI. This table showcases the top thirteen keywords

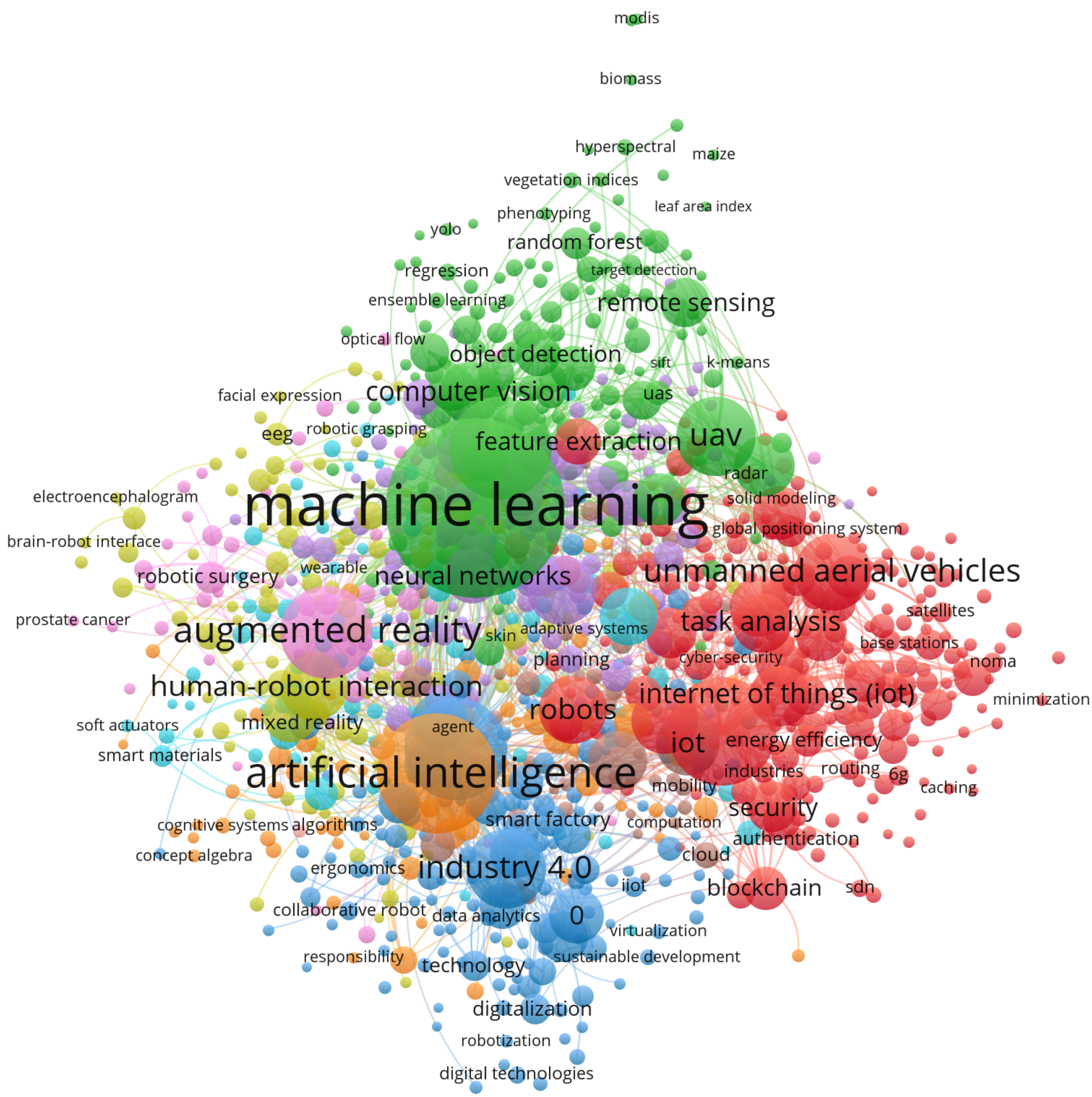

Fig. 11. Co-occurrence network based on author keywords

indexed by the WoS database in the area of robotics and industry 4.0. The list shows that the keyword 'machine learning' appeared in 2519 published articles (P). 'Machine learning' co-occurred with 1433 other WoS-indexed keywords in these articles. The TLS of 'machine learning' is 2406, which is the sum of the number of times 'machine learning' has co-occurred with each of the 1433 other keywords (having minimum 10 occurrences). As in case of author defined keywords, the co-occurrence based TLS of WoS indexed 'all keywords' is always a whole number (not a fraction) because the sum of fractional link strengths of a keyword in any published article will always be one. Hence, the total co-occurrence link strength of a keyword over all published articles will be equal to the number of such published articles (P). However, this phenomenon is not evident in Table VI, wherein the TLS is always a whole number but is always lesser than the actual number of publications (P). This observation indicates that there are some published articles wherein no other robotics and industry 4.0 keyword has been mentioned by the authors. It may also mean that in some published articles only such keywords co-occurred that had less than 10 occurrences themselves, thus getting omitted from the current analysis and not getting counted as co-occurred keywords. For instance, in case of the topmost TLS keyword 'machine learning', publications are 2519 whereas TLS is 2406. Hence, there are 113 articles that mentioned this keyword and, either did not include any other robotics/industry 4.0 WoS keyword or mentioned such keywords that had less than a total of 10 occurrences themselves (individually). Similar observation may be made in case of other author keywords as well. It may be noted in Table VI that the fifth ('robotics') and the thirteenth ('robots') keywords are similar. No other pair of keywords are very similar to each other. Interestingly, 'industry 4.0' does not figure at all in the list of the top thirteen WoS indexed keywords! These top WoS indexed keywords indicate the overall focus of most research articles - application of artificial intelligence/machine learning/deep learning/optimization for system design of internet of things including robotics and UAVs. It may be observed from this list that generally, higher number of occurrences (P) correspond with higher TLS of the keywords. 'Design' has higher links (1179) despite appearing in lesser publications (494) and having lesser TLS (968) as compared to 'artificial intelligence' (occurrences 1117, links 1061 and TLS 1068). This implies that WoS has indexed keyword 'design' along with many more co-occurring keywords as compared to 'artificial intelligence'. However, occurrences in more publications has increased TLS of 'artificial intelligence' over that of 'design'.

Fig. 12 shows the co-occurrence network of author defined keywords in the field of robotics and industry 4.0. Keywords such as 'machine learning', 'deep learning', 'uav', 'object detection', 'drone', 'remote sensing', 'random forest' and 'cnn' co-occur together, with their co-occurrence networks depicted in yellow color. Similarly, the keywords 'internet of things', 'unmanned aerial vehicles', 'drones', 'wireless communication', 'energy efficiency', 'internet', 'servers', 'privacy', 'protocol' and 'mobile cloud computing' form important nodes of the red colored co-occurrence network. The dark blue colored co-occurrence network is composed of WoS indexed keywords such as 'robot', 'recognition', 'network', 'rehabilitation', 'virtual reality', 'social robotics' and more. 'Artificial intelligence', 'robots', 'smart manufacturing', 'management', 'supply chain', 'digitalization', 'ethics' and 'machine ethics' belong to the green colored network whereas 'design', 'perception', 'manipulation', 'fabrication', 'soft robotics', 'electronics', '4d printing', 'gripper', 'strain sensors', 'drug discovery and 'circuits' co-occur together and shown in the light blue colored network.

TABLE VI
THE TOP 13 KEYWORDS WITH THE MAXIMUM CO-OCCURRENCE TLS VALUES FOR ALL KEYWORDS

Rank	Keyword	P	Links	TLS
1	Machine Learning	2519	1433	2406.00
2	Artificial Intelligence	1117	1061	1068.00
3	Design	996	1179	968.00
4	Internet of Things	929	916	898.00
5	Robotics	911	974	892.00
6	Augmented Reality	856	795	802.00
7	Deep Learning	825	951	798.00
8	System	784	1140	754.00
9	Internet	631	780	625.00
10	Classification	636	829	620.00
11	UAV	609	755	598.00
12	Optimization	581	839	570.00
13	Robot	596	847	569.00

V. CITATION ANALYSIS

This section showcases the citations based networks among authors, countries, organizations, published documents and sources in the field of robotics in industry 4.0 in the past one decade.

A. *Citation Analysis Based on Authors*

This subsection presents citation analysis of robotics and industry 4.0 research publishing authors during the past decade. VoS search yielded a total of 57,294 such authors. The citations of these authors were analysed using a threshold of minimum 5 publications and 10 citations per author. Documents co-authored by more than 25 authors were not considered. Only 1206 authors were found to satisfy these criteria. Of these, only 1136 were found to compose the largest set of connected authors. The top thirteen cited authors (from the connected set) with highest TLS values are listed in Table VII. This table also shows the number of citation links of each author, i.e. the number of unique researchers who cited a particular author's articles published in WoS. For instance, Lee Chengkuo (Singapore) published 22 robotics and industry 4.0 articles in WoS during the last decade. These publications received 949 citations from the published documents of 62 unique researchers (each having minimum 5 publications and 10 citations). In this way, each

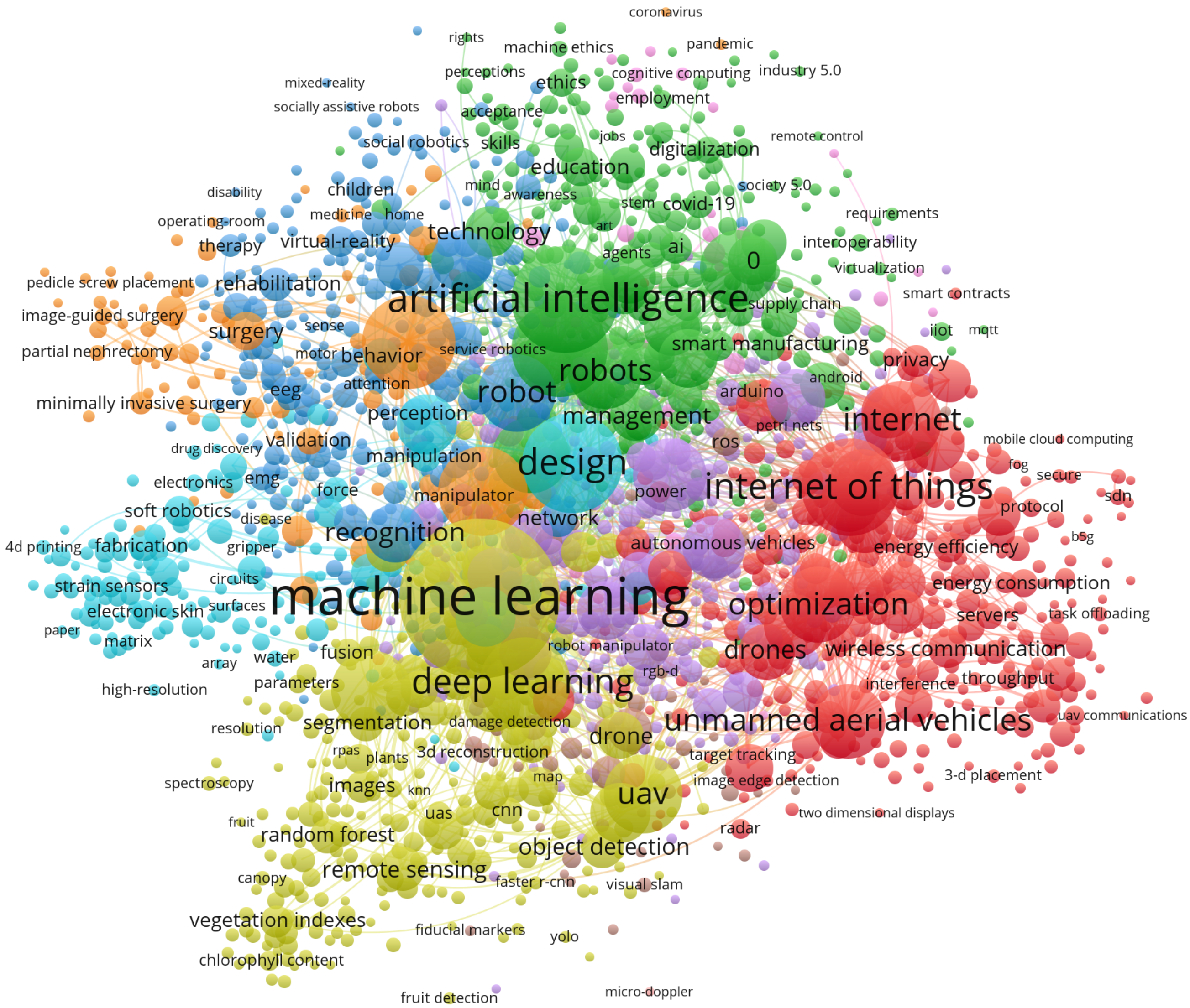

Fig. 12. Co-occurrence network based on all keywords

of these researchers established a citation based link with Lee Chengkuo. The number of citations contained in such a link is its link strength. TLS of the cited author is the sum of strengths of all such citations based links. Table VII is dominated by researchers affiliated to Singapore and Italy, with four authors each. USA, UAE, Australia and Finland are represented by one author each. Interestingly, Saad Walid (USA) is placed second as per the citation TLS (683) despite having the maximum citations (2577) and citation linkages (184) in just 27 papers! In contrast, Lee Chengkuo is placed first with the highest TLS of 687 despite having lesser publications, citations and citation links than Saad Walid. This shows that Lee Chengkuo received many more citations from shortlisted (as per the threshold criteria) linkages (citing authors) as compared to those received by Saad Walid. Similar case may be observed with Debbah Merouane (UAE), who has 2443 citations and 183 citation linkages from just 11 WoS articles! Still, Poropiglia Francesco is ranked higher in terms of TLS despite having much lesser citations (376) and linkages (47) than Debbah Merouane.

Fig. 13 shows the citations based networks among the international robotics and industry 4.0 research community. Different citation networks are depicted in distinct colors viz. For instance, the author Saad Walid is located in the green colored citation network with Tang Jie, Li Wei, Li Bin, Wang

Ying and others. The top TLS author Lee Chengkuo is located in the purple colored citation network with Chen Tao, Wu Fan, Wang Zhong and others. Similarly, Peters Jan, Zhang Yan, Xu Wenjun, Navab Nassir and Porpiglia Francesco are shown as prominent nodes of the red, pink, light green, brown and light purple colored citation networks respectively.

B. Citation Analysis Based on Countries

This subsection presents citation analysis of robotics and indutry 4.0 research publishing countries during the past decade. VoS search yielded a total of 135 such nations. The citations of these nations were analysed using a threshold of minimum 5 published documents and 10 citations per nation. Documents co-authored by more than 25 nations were not considered. Only 94 countries were found to satisfy these criteria. From this set of 94, the top ten cited nations with highest TLS values are listed in Table VIII. This table shows the top thirteen countries with the maximum citations based TLS values. This list shows the number of WoS papers published by the respective countries, the number of citations received by such documents, the number of other unique countries from which these citations have originated (links) and the total strengths of all such citation based links (TLS of the cited country). This list is topped by China with 87 international citing linkages having a total link strength of 12,896. The Chinese affiliated authors have published 3,656 WoS papers in robotics and industry 4.0, obtaining 43,737 citations for them. These papers were cited by authors of 87 nations (citation links) shortlisted as per the threshold criteria mentioned above (minimum 5 published documents and 10 citations per nation). USA has a similar number of international citing linkages (87) and TLS (12,828) despite having much higher citations (63,435) as compared to that of China. Similarly, India has higher TLS (3,809) as compared to that of South Korea (citations 11063, TLS 33593) despite having lesser citations (6766). It is notable that South Korea has 11,063 citations from just 788 papers as compared to India's 6766 citations from 1038 publications. Germany also has a good number of citations (16,081) from 1363 papers with good number of international citing linkages (83). However, its TLS is relatively lower (3234) as compared to that of South Korea and France with similar citations and co-citation linkages. This observation implies that the number of German authored papers cited per individual international citation linkage is relatively lower than that of South Korean and French authored papers. Another interesting observation is regarding Saudi Arabia, which has an impressive number of international citing linkages (76) with comparatively lower number of papers (316) and citations (2562).

Fig. 14 shows the citation networks of the robotics and industry 4.0 publishing nations. This figure shows international citation networks depicted in different colored nodes and linkages. USA forms a prominent node of the brown colored citation network, which has other countries such as Lebanon, North Ireland, Thailand, Vietnam and Luxembourg. The red colored network is composed of England, Australia, Switzerland, Netherlands and others. On the other hand, green colored network is made up of nations such as India, South Korea, Russia, Pakistan, Ireland, Sri Lanka, Qatar and others. Italy, Germany and Austria form the prominent nodes of the purple colored network, whereas Canada, Spain, Portugal, Brazil and the UAE are interconnected and depicted in the yellow colored citation network. Similarly, Singapore, Turkey, Scotland and Egypt form the pink colored network; Malaysia, Croatia, Serbia, Greece and other in dark blue network; and Iran, South Africa and Cyprus are connected in the light/sea blue colored citation network.

C. Citation Analysis Based on Documents

This subsection presents a citation analysis of robotics and industry 4.0 research publications during the past decade. VoS search yielded a total of 18,893 such publications. The citations of these documents were analyzed using a threshold of 10 citations per document. Only 4234 articles were found to satisfy this criterion. Of these, 2421 were found to compose the largest set of connected documents. From this set of 2421 connected sources, the top ten cited documents are listed in Table IX. This table also lists the number of citations based links of these articles i.e., the number of robotics and industry 4.0 articles published in WoS and citing these articles. For instance, the paper titled 'Efficient Processing of Deep Neural Networks: A Tutorial and Survey' [97] obtained 1211 citations in total, of which only eight belonged to the robotics and industry 4.0 articles published in the WoS, having minimum ten citations each and featuring in the largest citation network of connected documents. On the other hand, the article titled 'A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems' [98] attracted a total of 701 citations, 48 of them from WoS literature satisfying the shortlisting criteria specified above. Interestingly, the ninth [99] and tenth [100] ranked documents are connected to only one shortlisted WoS citing document in this field.

Fig. 15 shows the citation-based networks of robotics in industry 4.0 documents published in WoS, depicted in different colored nodes and linkages as per respective citations. For instance, the top cited documents by Sze et al. [97], Zhou et al. [101], Mozaffari et al. [98], Ghahramani et al. [102], Natekin et al. [99] and Qian et al. [100] are located in the light grey, dark grey, yellow, peach, green and brown colored citation networks respectively. The top cited documents by Gao Huang et al. [103] and Garrido-Jurado et al. [104] are also located in the light grey colored citation network. The third highest cited document by Wang et al. [105] forms the most prominent node of the red-colored citation network.

D. Citation Analysis Based on Organizations

This subsection presents a citation analysis of robotics research publishing organizations during the past decade. VoS

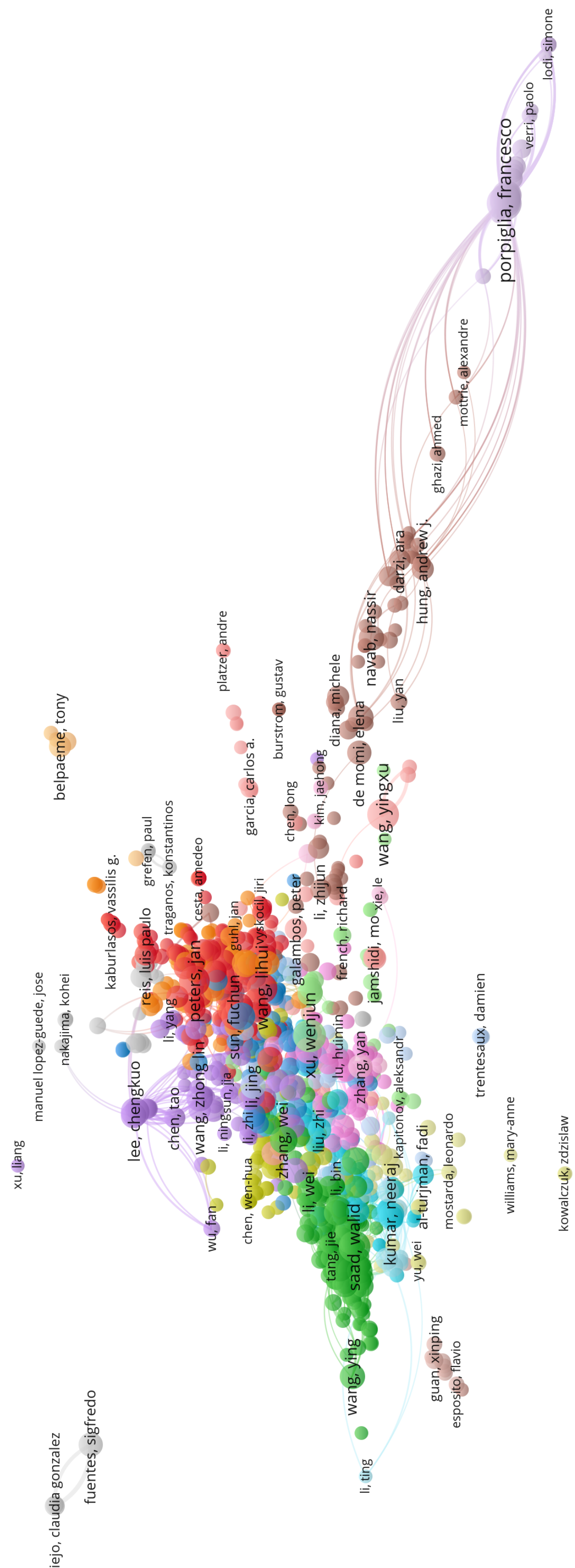

Fig. 13. Citation network based on authors

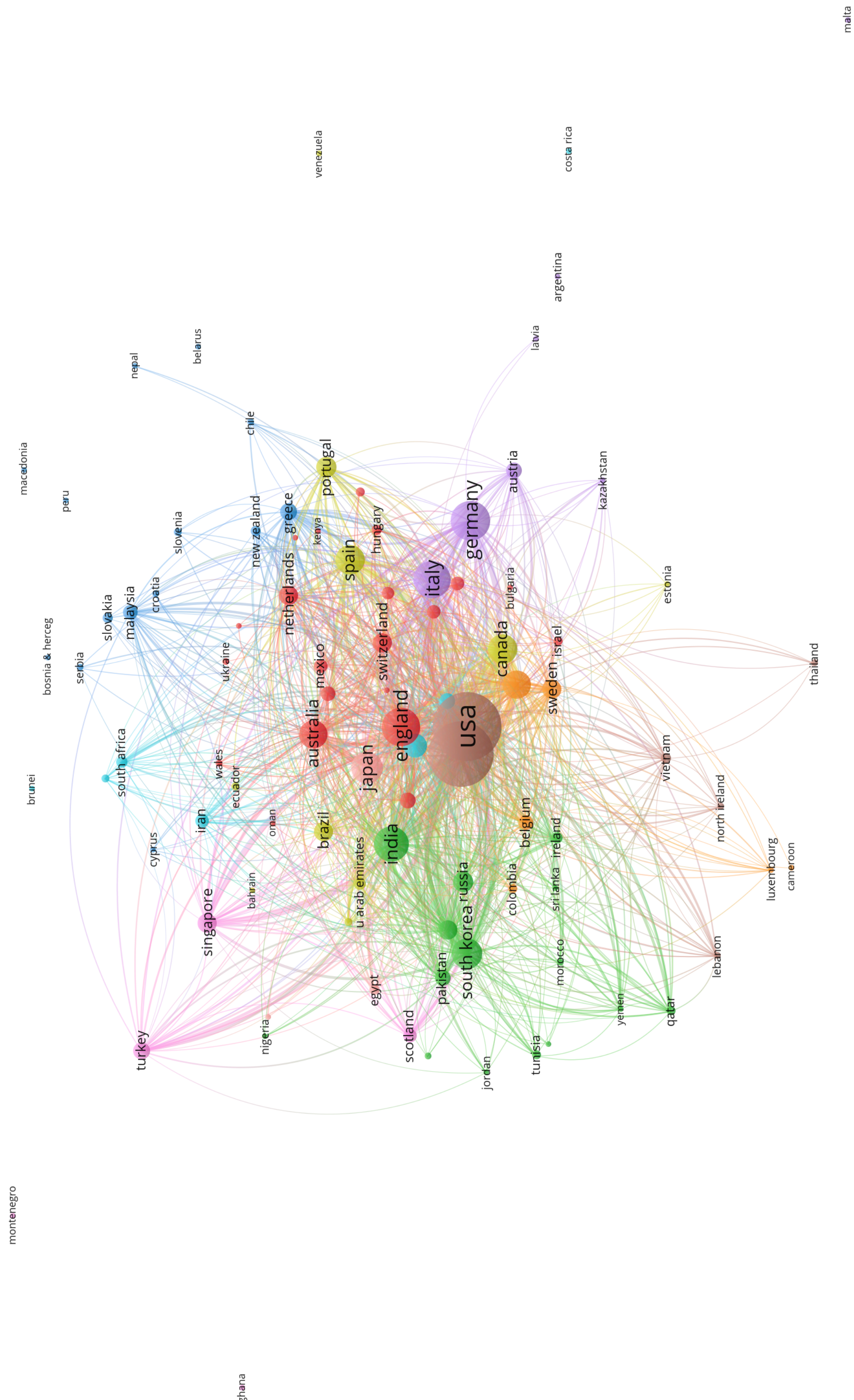

Fig. 14. Citation network based on countries

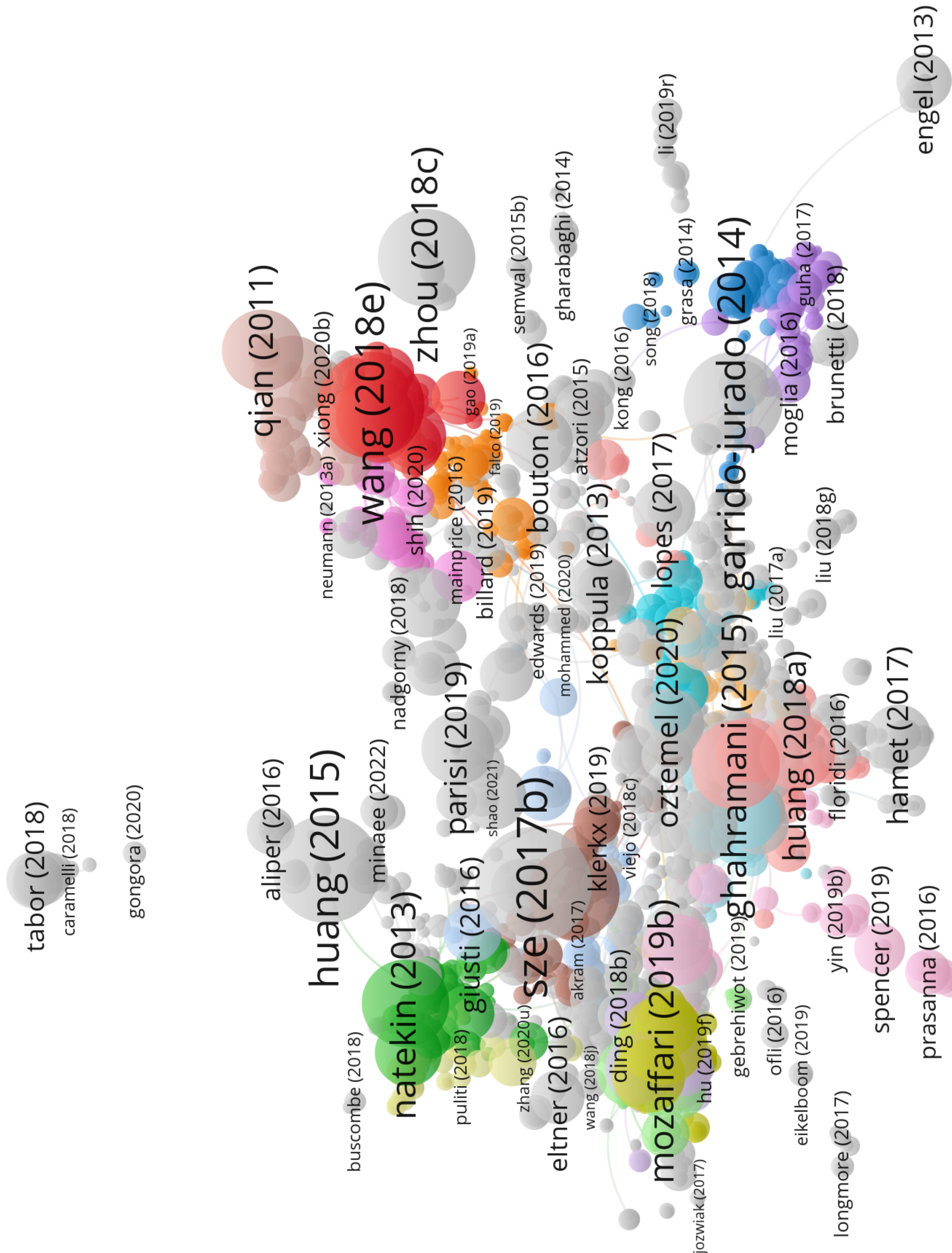

Fig. 15. Citation network based on documents

TABLE VII
THE TOP 13 RESEARCHERS WITH THE HIGHEST CITATION TLS VALUES

Rank	Author	Country	P	Citations	Links	TLS
1	Lee, Chengkuo	Singapore	22	949	62	687
2	Saad, Walid	USA	27	2577	184	683
3	Porpiglia, Francesco	Italy	32	376	47	620
4	Debbah, Merouane	UAE	11	2443	183	571
5	Shi, Qiongfeng	Australia	17	884	53	567
6	Checcucci, Enrico	Italy	26	327	46	526
7	Amparore, Daniele	Italy	26	338	47	522
8	Mozaffari, Mohammad	Netherlands	8	1958	169	509
9	Fiori, Cristian	Italy	24	315	46	502
10	Zhang, Zixuan	Singapore	11	578	62	448
11	Sun, Zhongda	Singapore	11	576	62	440
12	He, Tianyiyi	Singapore	10	608	58	413
13	Bennis, Mehdi	Finland	16	1737	161	410

TABLE VIII
THE TOP 13 COUNTRIES WITH THE MAXIMUM CITATION TLS VALUES

Rank	Country	P	Citations	Links	TLS
1	China	3656	43737	87	12896
2	USA	4006	63435	87	12828
3	England	1262	19971	85	5733
4	Italy	1173	13537	84	4477
5	Canada	761	11668	83	4285
6	India	1038	6766	85	3809
7	South Korea	788	11063	79	3593
8	France	701	11166	84	3452
9	Germany	1363	16081	83	3234
10	Australia	709	10052	79	2905
11	Spain	737	9892	84	2678
12	Saudi Arabia	316	3582	76	2562
13	Singapore	330	8511	73	2208

search yielded a total of 11,137 such organizations. The citations of these organizations were analysed using a threshold of a minimum of 5 published documents and 10 citations per organization. Documents co-authored by more than 25 organizations were not considered. Only 1451 sources were found to satisfy these criteria. Of these, 1362 were found to compose the largest set of connected sources. From this set of 1362 connected sources, the top ten cited sources with the highest TLS values are listed in Table X. This table lists thirteen organizations worldwide with the maximum citations based TLS in the field of robotics and industry 4.0. The list shows the number of publications (P), citations, number of unique citing organizations (links), and the total strengths of all such links (TLS) for an institution. This list is composed of six Chinese institutions, two from Singapore and one each from the USA, France, Bangladesh, and Canada. The Chinese Academy Science tops the list with 331 papers, 7935 citations, 514 inter-institutional citation linkages and TLS 1785. This organization received citations from various organizations, of which only 514 were shortlisted in the current study as per the above-mentioned criteria (minimum 5 published documents and 10 citations per organization). The TLS of 1785 is due to these 514 shortlisted organizations citing the works of the Chinese Academy Science. The Beijing University of Posts and Telecommunications achieved the second highest position with a TLS of 1462 from just 106 publications and 2029 citations; owing to comparatively higher inter-institutional citation linkages (345) per publication. The Tsinghua University published more papers (179) and attracted more citations (3398) than the Beijing University of Posts and Telecommunications, still, it attained a relatively lower rank with TLS 1427. This observation indicates that the articles of Tsinghua University were cited by a lesser number of shortlisted linkages (citing authors) as compared to those of the Beijing University of Posts and Telecommunications. In another observation, the Nanyang University of Singapore has higher WoS publications and citations, but lower institutional citation linkages and TLS as compared to the Xidian University (China), and Virginia Tech (USA). It is notable that the Xidian University (China), and Virginia Tech (USA) have quite high citations, institutional linkages and TLS as compared to their relatively lower WoS publications: 72 and 68 respectively. This indicates a very high number of their organizational citation linkages being included in the current analysis as per the threshold criteria. On the other hand, the South China University of Technology has higher WoS publications, citations, and institutional linkages as well, but still has lower TLS as compared to the Southeast University (Bangladesh) and the Kyung Hee University (South Korea); primarily due to lesser citing organizations shortlisted for the South China University of Technology.

Fig. 16 shows various worldwide institutional citation-based linkages in the field of robotics and industry 4.0. Different citation networks are depicted in distinct colors. It may be observed that some of the topmost citation-TLS universities are connected together in the faint blue-colored network such as the Chinese Academy Science and the Nanyang Technological University, Singapore. Xidian University is located in the brown-colored network with the University of Houston, Cent South University, Kwangwoon University, Deakin University, and the Ho Chi Minh City University of Technology, among others. The citation network demarcated by yellow-

TABLE IX
THE TOP 10 DOCUMENTS WITH MAXIMUM CITATION LINKS

Rank	Title of Article	Authors	Year	Journal	Citations	Links
1	Efficient Processing of Deep Neural Networks: A Tutorial and Survey [97]	Sze, Vivienne and Chen, Yu-Hsin and Yang, Tien-Ju and Emer, Joel S.	2017	Proceedings of the IEEE	1211	8
2	Trends in extreme learning machines: A review [103]	Gao Huang and Guang-Bin Huang and Shiji Song and Keyou You	2015	Neural Networks	1051	12
3	Skin electronics from scalable fabrication of an intrinsically stretchable transistor array [105]	Wang, Sihong and Xu, Jie and Wang, Weichen and Wang, Ging-Ji Nathan and Rastak et al.	2018	Nature	1027	26
4	Automatic generation and detection of highly reliable fiducial markers under occlusion [104]	S. Garrido-Jurado and R. Muñoz-Salinas and F.J. Madrid-Cuevas and M.J. Marín-Jiménez	2014	Pattern Recognition	886	21
5	VoxelNet: End-to-End Learning for Point Cloud Based 3D Object Detection [101]	Zhou, Yin and Tuzel, Oncel	2018	2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition	864	5
6	Big Data in Smart Farming – A review [106]	Sjaak Wolfert and Lan Ge and Cor Verdouw and Marc-Jeroen Bogaardt	2017	Agricultural Systems	766	36
7	A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems [98]	Mozaffari, Mohammad and Saad, Walid and Bennis, Mehdi and Nam, Young-Han and Debbah, Mérouane	2019	IEEE Communications Surveys & Tutorials	701	48
8	Probabilistic machine learning and artificial intelligence [102]	Ghahramani, Zoubin	2015	Nature	700	2
9	Gradient boosting machines, a tutorial [99]	Natekin, Alexey and Knoll, Alois	2013	Frontiers in neurorobotics	682	1
10	Neural network computation with DNA strand displacement cascades [100]	Qian, Lulu and Winfree, Erik and Bruck, Jehoshua	2011	Nature	607	1

colored nodes is populated by institutions such as the King Saud University, Nirma University, Oklahoma State University, and the University Teknologi Petronas, Malaysia. The peach-colored citation network includes the Massachusetts Institute of Technology (MIT), the New York University (NYU), the University of California Berkeley, the University of Toronto, and the University of Tennessee among others. The University of Calgary and the University of Oxford are situated in the light purple colored network. The University of Texas A&M and the University of Queensland are in the red-colored network. The Technological University Munich and the Osaka University form prominent nodes of the green and sea blue colored networks respectively.

E. Citation Analysis Based on Sources

This subsection presents a citation analysis of robotics and industry research publishing sources during the past decade. VoS search yielded a total of 6677 such sources. The citations of these sources were analyzed using a threshold of a minimum of 5 published documents and 10 citations per source. Only 647 sources were found to satisfy these criteria. Of these, 501 were found to compose the largest set of connected sources. From this set of 501 connected sources, the top ten cited sources with the highest TLS values are listed in Table XI. This table shows the top thirteen WoS publishing sources with the highest citations based on TLS values. Similar to the TLS lists described in the previous subsections, this list also shows the number of publications (P), citations, citation-based links (unique number of WoS sources citing articles of a particular journal), and the total strengths of all such links (TLS). This list is topped by IEEE Access, which has published 522 articles related to robotics and industry 4.0. These articles have received 5847 citations from other WoS journals also publishing in this field. Of these citing sources, only a few satisfy the shortlisting criteria set in the current study (minimum 5 published documents and 10 citations per source). Thus, the sum of total citations received by IEEE Access from such 246 linked and shortlisted journals is 1496 (TLS). The IEEE Internet of Things Journal has the second-best TLS of 1138, followed by Sensors with TLS 1048. The remaining sources in the list have a TLS of less than 1000. It is notable that the IEEE Communications Surveys and Tutorials has the sixth highest TLS of 380 with just 21 published articles in this area. These 21 articles have received 3069 citations from 89 other WoS journals qualifying the above-mentioned threshold criteria. The IEEE Transaction on Wireless Communications is a similar instance with just 30 articles highly cited (1400) by 62 unique WoS journals and TLS 348. The IEEE Access is depicted as the biggest node in the source citation network map (Fig. 17). Other top TLS journals depicted in this figure include Remote Sensing, IEEE Internet of Things Journal, and Applied Sciences-Basel as prominent nodes of the purple, pink and blue colored citation networks respectively. Other important sources such as the Frontiers in Neurorobotics and Scientific Reports are shown in the green and yellow colored networks respectively.

VI. Main Findings of the Present Study

The current study presents an in-depth bibliometric analysis of the various aspects of robotics and industry 4.0 research published over the past decade. This study firstly presented an analysis of yearly publications, types of publications, sources, organizations, researchers, countries, and trending topics. Secondly, the above-mentioned detailed analysis was carried out from co-authorship, keyword co-occurrences and citation, and perspectives. The fractional counting method was followed for co-authorship and co-occurrence analyses. The primary findings of the current study are listed as follows -

1) More than 3000 robotics and industry 4.0 related WoS articles were published annually during 2019-2021, highlighting the growing importance of this research field
2) Majority of these publications is composed of journal publications (9,965)
3) The journal IEEE Access published the most WoS articles (522) during the last decade
4) Chinese Academy of Science published maximum articles (389)
5) Wang, Y (USA) published the maximum papers (88) in robotics and industry 4.0 as the first author
6) Researchers from the USA published maximum articles in WoS (4007), followed by Chinese researchers with 3656 publications
7) 'Computer science' is the most popular research area with maximum WoS publications (8412), closely followed by 'engineering' with 8355 WoS articles
8) Porpiglia Francesco (Italy) has the highest co-authorship-based TLS of 32 with 15 co-author linkages
9) Chinese Academy Science has the highest co-authorship based TLS of 293 having co-author linkages with 214 other organizations
10) USA has the highest co-authorship based TLS of 1495 having co-author linkages with 83 other nations
11) Machine learning has the highest co-occurrence based TLS of 2228 having linkages with 842 other author-defined robotics and industry 4.0 keywords
12) Machine learning also has the highest co-occurrence based TLS of 2406 having linkages with 1433 other WoS indexed keywords
13) Lee Chengkuo (Singapore) has the highest citation-based TLS of 687 having citation linkages with 62 robotics and industry 4.0 researchers
14) China has the highest citation-based TLS of 12,896 having citation linkages with 87 countries
15) Chinese Academy Science has the highest citation-based TLS of 1785 having citation linkages with 514 institutions
16) IEEE Access has the highest citation-based TLS of 1496 having citation linkages with 246 journals

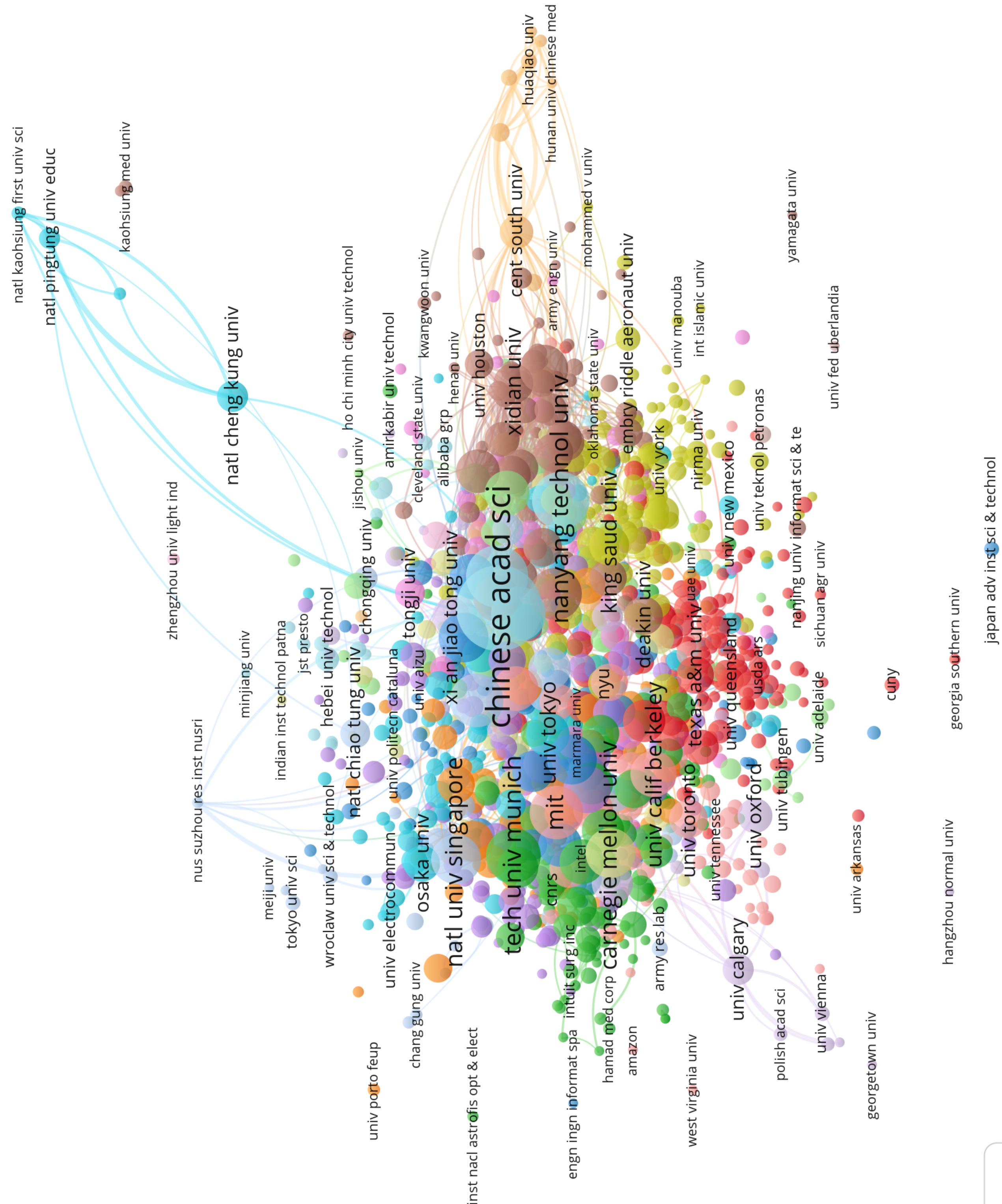

Fig. 16. Citation network based on organizations

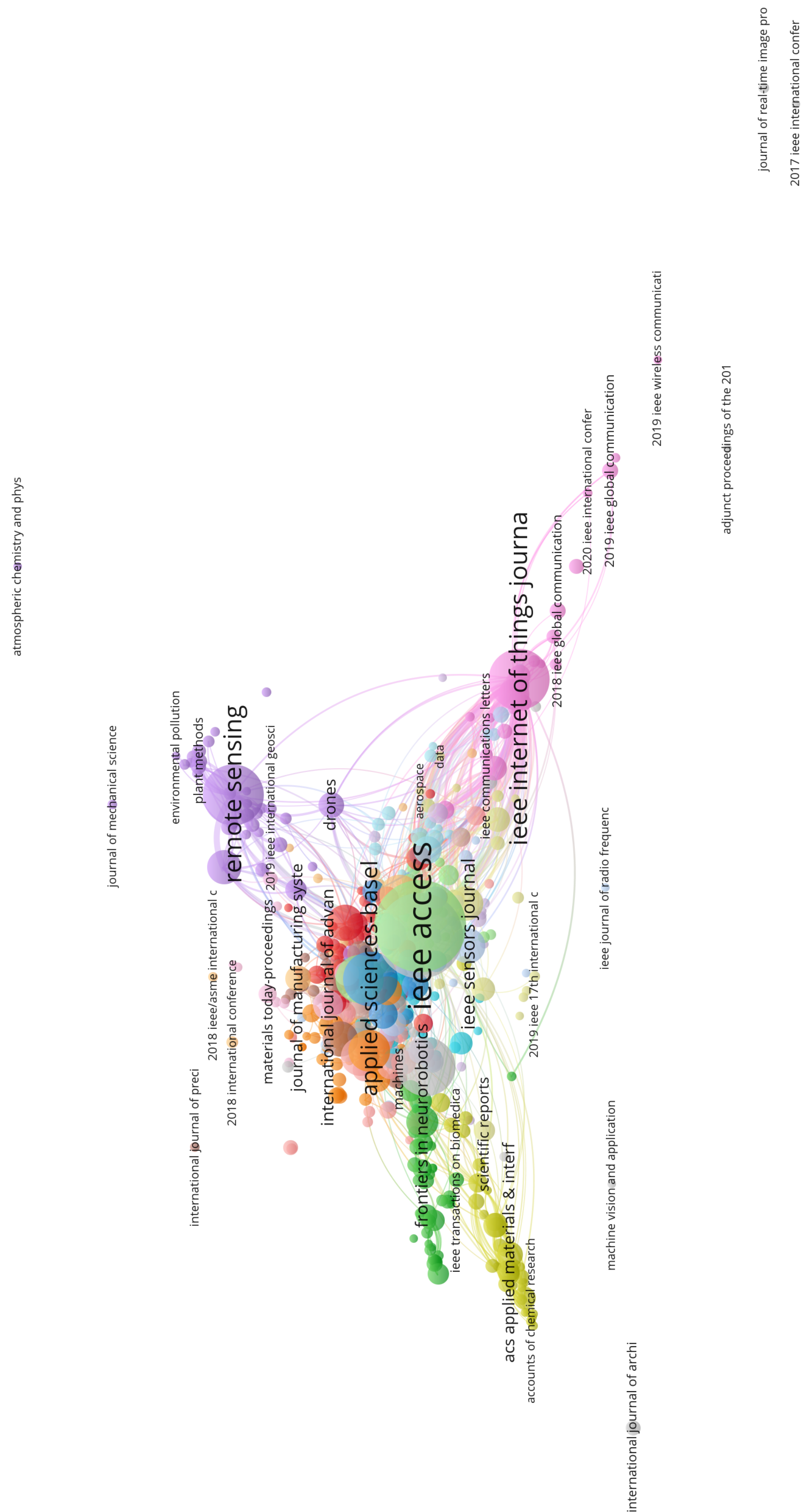

Fig. 17. Citation network based on sources

TABLE X
THE TOP 13 ORGANIZATIONS WITH THE HIGHEST CITATION TLS VALUES

Rank	Organization	Country	P	Citations	Links	TLS
1	Chinese Academy Science	China	331	7935	514	1785
2	Beijing University of Posts and Telecommunications	China	106	2029	345	1462
3	Tsinghua University	China	179	3398	455	1427
4	Nanyang Technological University	Singapore	150	4869	472	1287
5	Xidian University	China	72	1628	301	1202
6	Virginia Tech	USA	68	2644	372	1200
7	National University of Singapore	Singapore	114	3163	298	1072
8	University of Paris-Saclay	France	27	2186	338	1037
9	Southeast University	Bangladesh	89	1845	310	895
10	Kyung Hee University	South Korea	57	1461	306	873
11	South China University of Technology	China	94	2144	366	845
12	Central South University	China	53	910	182	837
13	University of Waterloo	Canada	59	1374	291	804

TABLE XI
THE TOP 13 SOURCES WITH THE MAXIMUM TLS VALUES

Rank	Source	P	Citations	Links	TLS
1	IEEE Access	522	5847	246	1496
2	IEEE Internet of Things Journal	236	4538	130	1138
3	Sensors	457	4185	228	1048
4	Remote Sensing	231	3016	79	569
5	IEEE Transactions on Vehicular Technology	62	1427	75	453
6	IEEE Communications Surveys and Tutorials	21	3069	89	380
7	Robotics and Computer-Integrated Manufacturing	79	1549	107	360
8	Applied Sciences-Basel	186	743	142	355
9	IEEE Transactions on Wireless Communications	30	1400	62	348
10	IEEE Transactions on Industrial Informatics	75	1979	97	291
11	IEEE Robotics and Automation Letters	216	1772	115	278
12	Computer Communications	39	864	79	273
13	IEEE Transactions on Automation Science and Engineering	56	1488	111	265

17) The article published by Sze et al. [97] obtained the maximum citations (1211) in this field during the past decade

VII. COMPARISONS WITH OTHER STUDIES

The present study presented a detailed bibliometric analysis of WoS research focusing on robotics and industry 4.0. In comparison, most of the other similar studies found in published literature focused only on certain niche areas related to robotics and industry 4.0 such as logistics [81], [89], [91], agriculture [82], plastics manufacturing [94], human aspects/ergonomics [83], [84], healthcare/nursing [92], [95], food/water/energy security [85], nation-specific accounting applications [87] and management practices in service sector [88].

The present study found that 'machine learning' was the most common keyword used by researchers as well as by indexing databases (during 2011-June 2022) followed by 'artificial intelligence'. The most trending domain was 'computer science' followed by 'engineering'. However, 'cloud computing' and 'cyber physical systems' were determined to be the most important investigated themes by a bibliometric study carried out on industry 4.0 research by Cobo et al. [90]. However, these authors did not consider robotics as a focus area along with industry 4.0 as is the case in the present study.

The present study determined that the journal IEEE Access published the most articles on industry 4.0 and robotics in the past decade. This result is supported by similar analyses carried out by Muhuri et al. [86] and Janmaijaya et al. [93] on industry 4.0 research. Similarly, both studies - the present work and the studies by Muhuri et al. [86], Janmaijaya et al. [93] agree that the most important and trending research topics are engineering and computer science. On the other hand, the current study found USA and China as the most productive nations in robotics and industry 4.0 publications, whereas Muhuri et al. [86] found Germany and China as the most prominent contributors to industry 4.0 research. Similar to Cobo et al. [90], Muhuri et al. [86] also concluded that 'cybersecurity', 'smart manufacturing' and 'internet of things' were the most important keywords in industry 4.0 research. Janmaijaya et al. [93] reported 'big data' and 'smart manufacturing' as the top keywords in the industry 4.0 domain. Here the difference of these studies from the present work becomes evident. The present study shows 'machine learning' and 'artificial intelligence' as the most prominent keywords owing to its focus on robotics in industry 4.0, as compared to only industry 4.0 considered by the referenced works.

VIII. Implication and Explanation of Findings

The main findings of the present study firstly imply that there is an almost exponentially growing interest in the research community in the field of robotics in industry 4.0. Secondly, the maximum WoS publications being constituted by journal articles implies that most research in this field is in-depth and elaborate. Most researchers in this field do not prefer to publish their initial results in conference proceedings. Thirdly, the Chinese Academy of Science is the most productive organization and has the highest co-authorship-based TLS in the world. This observation implies that higher co-authorship linkages result in greater publication outputs. Such co-author linkages result in citation linkages as well. Thus, the Chinese Academy of Science has the highest citation-based TLS also. Similarly, the researchers affiliated with the USA published maximum articles owing to the highest co-authorship-based TLS of the USA in this field. The Chinese-affiliated authors scored the second highest co-authorship TLS in the world, but obtained the highest citation-based TLS value, seconding the USA. This observation indicates a healthy and close competition among the researchers of China and the USA, with both performing almost equally well in this field. The predominance of 'computer science' indicates that majority of research pertaining to robotics in industry 4.0 is carried out in 'computer science' domain. This observation is corroborated by the emergence of 'machine learning' and 'artificial intelligence' as the topmost keywords. This implies that the driving force behind the integration and prevalence of robotics in industry 4.0 has been and will be computer science domain research.

IX. Strengths and Limitations

The strengths of the current study lie in its unique scope: robotics in industry 4.0, which is an open and emerging area. Bibliometric analysis of robotics in industry 4.0 fulfills a research gap evident in recent literature full of bibliometric studies on niche aspects of industry 4.0 applications. Few studies have addressed industry 4.0 as a whole, and hardly any article has addressed bibliometric analyses of robotics in/and industry 4.0 research in the last decade. Moreover, the current study presents an almost overarching analysis including top contributing authors, organizations, nations, sources, and popular research directions over the last ten years. This was followed up co-authorship, co-occurrence, and citation linkage analyses along various verticals mentioned above. The key findings of this manuscript provide ample pointers to budding researchers interested in conducting further investigations into this ever-growing field of study. The limitations of this study lie in its scope: focus on robotics in industry 4.0 and not industry 4.0 as a whole, consideration of research conducted only during the last decade, selection of only high-quality research databases (WoS core collection) and, of course, in-depth discussions based only on bibliometric results and not the topic-wise discussion of robotics in industry 4.0 research as is found in regular literature review (non-bibliometry) articles. However, a good number of articles have been included in the subsections titled related reviews and related bibliometric studies.

X. Conclusions, Recommendations and Future Direction

Based on the extensive bibliometric analysis of robotics in industry 4.0 research over the past decade, future investigations may be directed toward exploring newer machine learning, artificial intelligence, deep learning, reinforcement, and transfer learning architectures toward improved robotics applications in automated industrial control systems, network communications, human-robot interactions, and cloud integration. There is a lot of scope to conduct robotics and industry 4.0 research in sciences such as physics, chemistry, materials, and instrumentation. Augmented reality, industrial internet of things, and applications of advanced optimization heuristics require more attention regarding robotics implementation in industry 4.0. Researchers may also conduct extensive bibliometric analyses of specific areas of robotics and industry 4.0-related research such as UAVs, AGVs (automated guided vehicles), ASRS (automated storage and retrieval systems), and cloud-based networks in smart manufacturing to reveal underlying trends influencing the current industry 4.0 efforts and shaping the future of modern factories and supply chains as a whole.

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