International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Instrumentation Mesure Métrologie
Vol. 23, No. 2, April, 2024, pp. 123-139
Journal homepage: http://iieta.org/journals/i2m

Internet of Things (IoT) in Structural Health Monitoring: A Decade of Research Trends

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https://doi.org/10.18280/i2m.230205

Received: 9 January 2024
Revised: 12 April 2024
Accepted: 16 April 2024
Available online: 25 April 2024

Keywords:
bibliometric analysis, scientometric analysis, Internet of Things (IoT), Structural Health Monitoring (SHM), infrastructure

ABSTRACT

Structural Health Monitoring (SHM) is important for the safety and performance of civil infrastructure. With IoT, the SHM paradigm is changing; real-time wireless sensors capture and transfer data directly to data processing centres, eliminating physical wiring. IoT integration enables more effective, continuous, and responsive structural monitoring in real-time. Although there are many publications in this field, few comprehensive surveys have conducted scientific analyses. This paper presents bibliometric and scientometric analysis methods to see how research progress on wireless Internet of Things (IoT) technology is applied in SHM. Over the past ten years, 170 Scopus-based publications have been evaluated to achieve this goal. Annual trends, active journals, top researchers, research hotspots, nation involvement, and keyword emergence were all noted in the review. The data reveals a marked upsurge in research activity trends, with the US playing a prominent role. Clustering visualisation with VOSviewer software was used to classify programs into various clusters and identify the scope of applications and their relationships through link strength. The findings provide a comprehensive picture of the utilisation of the Internet of Things for SHM, highlighting trends and can serve as pointers/knowledge to assist researchers in future research.

1. INTRODUCTION

Civil infrastructure structures and systems, such as bridges, buildings, dams, and pipelines, are complex engineering systems that support economic prosperity and people's quality of life [1, 2]. The structural performance of civil engineering infrastructure degrades over time due to factors such as dynamic loads [1, 3, 4], vibration [5], shrinkage cracking [6], degradation or collapse [7], corrosion [8, 9], as well as environmental factors and various natural disasters [10]. The loss and damage of civil engineering structures due to inadequate Structural Health Monitoring have been documented in several case studies, including the Florida International University pedestrian bridge collapse in 2018 due to over-tightening of cables, which led to crack growth collapse [11], and the Xinjia Express Hotel which experienced structural collapse in 2020 [12]. Such structures can appear in varying degrees, and different types of damage that can cause serious accidents and economic losses. A major challenge in civil engineering is maintaining infrastructure reliability. Therefore, proper inspection, monitoring, and maintenance are becoming increasingly important.

Structural Health Monitoring (SHM) systems have been proven in various critical projects worldwide, demonstrating their effective ability to respond to various structures' health monitoring, inspection, and maintenance needs [13-15]. SHM aims to identify, detect and characterise the degradation and deterioration of all engineering structures [15, 16]. "Structural Health Monitoring" refers to the real-time assessment and evaluation of structural conditions [17, 18]. Real-time SHM for engineering structures is that it can timely identify/detect the cumulative damage of structures, evaluate their performance and service life, and establish corresponding safety early warning mechanisms for early warning of possible disasters, which not only has great scientific significance for the repair, safety, and reliability of structures but also can reduce the operation and maintenance costs of structures. This has become an inevitable need in future engineering and is also a difficult problem that must be solved urgently [19-24].

As technology advances, SHM has moved from traditional cable-based methods to real-time wireless sensor implementations based on Internet of Things (IoT) technology [13, 25]. The new generation of the Industrial Internet of Things transforms the Industrial Age into the Information Age by utilising the opportunities and benefits of Information Age technologies and techniques. Sensor-based IoT devices can collect more data, facilitate more complex analyses and faster reactions, and reduce human error, thus providing more precise and efficient capabilities than previous systems [26]. Sensor network-based Structural Health Monitoring (SHM) systems have the potential to provide real-time and historical sensor-based data. SHM systems can reliably detect, localise, and quantify damage to components in existing and new structural assets. They can also use the identified damage to decide when to remove components or estimate the remaining useful life of components and system performance. Therefore, integrating IoT and wireless technologies further advances SHM, offering continuous and periodic assessments of safety and structural performance [27].

Rapid developments in Internet of Things (IoT) technologies have significantly expanded the capabilities of Structural Health Monitoring (SHM) systems. A number of literatures conclude breakthroughs have mainly occurred in three key areas: more sophisticated sensor advancements, more efficient data processing, and more reliable communication protocols. In 2020, Misra et al. [28] proposed an Internet of Things (IoT)-based building health monitoring (BHM) system consisting of piezoelectric sensors, Wi-Fi Arduino, and ESP8266 modules. The data is processed with the help of a cloud server system due to its advantages in terms of data usability, ease of access, and disaster recovery. Thus, the system can generate all the details related to the structural health of the building and can inform the responsible authorities to take action if repairs are needed. In 2021, Iyer et al. [29] replaced manual human visual inspection with an IoT-based multi-robot system. The system uses ultrasonic sensors and is coupled with image processing using OpenCV. Meanwhile, several studies [30-38] implemented a Structural Health Monitoring System (SHMS) using advanced sensors to collect data from important parameters, such as pressure, humidity, vibration, and tensile forces on bridge structures. These data are then processed and analysed using intelligent algorithms to detect potential problems and damage to the bridge early.

Significantly, gathering, sending, and keeping massive amounts of data may be difficult for systems that use SHM. Numerous sensors are needed to monitor large-scale constructions thoroughly [39]. This exploration aims to uncover the synergistic relationship between Structural Health Monitoring and the Internet of Things in the context of civil engineering infrastructure. By harnessing the power of IoT, engineers can remotely monitor and analyse structural health metrics, anticipate potential problems, and implement timely interventions. This integration improves the efficiency of maintenance practices and contributes to the longevity and resilience of infrastructure. The main objective of this comprehensive review is to critically analyse and synthesise current research trends in Structural Health Monitoring (SHM) for civil engineering structures, with a particular focus on utilizing Internet of Things (IoT) platforms. This review is expected to provide a holistic understanding of the evolving landscape in integrating IoT platforms to enhance structural health monitoring in civil engineering structures through careful examination of existing literature, technological advancements, and methodological approaches. By identifying key challenges, emerging technologies, and best practices, this review seeks to contribute valuable insights that can guide future research efforts, drive innovation, and ultimately improve the efficiency and reliability of structural health monitoring systems in the context of civil engineering structures.

2. RESEARCH SIGNIFICANCE

When looking at current review and survey studies, it is worth noting several points that demonstrate the contribution of this research:

- This research expands the field of IoT studies for structural health monitoring (SHM), especially looking at research trends.
- Since previous review and survey studies could not provide a complete picture of research trends, this research conducted a database search covering the last 10 years using the selected keywords of "Internet of things", "Structural Health Monitoring", and "Infrastructure" in the title, abstract, and keywords search box.
- The publications focused on scientific journal databases managed by the scientific information from Scopus, and non-English publications were excluded.
- The exploration spanned from January 2013 to January 2024, culminating in the compilation of a thorough selection comprising 170 pertinent articles.
- As far as the authors are aware, no review studies discuss the visual relationship of country trends, co-authorship, and title keywords in SHM research with IoT in civil engineering structures. Visualise it using VOSviewer software, which uses the Visualisation of Similarity (VOS) technique, and Tableau software, especially the depiction of the distribution of country participation trends.

This article seeks to contribute a comprehensive review identifying an overview of the trends of scientific development in the last 10 years and provide a clear perspective for future research on Structural Health Monitoring (SHM) of civil engineering structures using the Internet of Things (IoT).

3. AN OVERVIEW OF WHAT ARE SHM BY USING IOT

Structural Health Monitoring (SHM) is an emerging multidisciplinary research field involving many modern engineering materials [10]. SHM is generally characterised by a non-destructive approach that allows continuous and autonomous monitoring thanks to integrated sensors [40]. SHM systems optimise resource utilisation, minimise maintenance time by detecting early damage, and calculate the remaining life of the infrastructure [41]. SHM systems consist of three main parts: sensor systems, data processing systems (including data acquisition, transmission, and storage), and structural identification or health evaluation systems (including diagnostic algorithms and information management) [42].

The Internet of Things (IoT) paradigm is the basis of a new generation of SHM systems, which incorporate intelligent sensors in their architecture, allowing them to collect and transmit measurement signals over the Internet [43, 44]. The Internet of Things paradigm states that a "thing" is the only component complementing existing entities in the Internet domain, such as hosts, terminals, routers, etc. [45]. Objects connected to the Internet can be mobile phones, cameras, household appliances, city infrastructure, medical equipment, and sensor-equipped plants or vehicles. This concept is associated with the Internet of Things (IoT), where objects sense and use IP to communicate with each other and share information about their environment anytime and anywhere. Wireless sensor networks (WSNs) are considered one of the key technologies of IoT [46, 47] and are widely used in various fields such as healthcare systems, environmental monitoring systems, structural health monitoring (SHM) systems, etc. [48]. Numerous studies [49-63] have shown how important wireless sensors and the Internet of Things (IoT) are for SHM.

SHM generally uses an IoT paradigm based on three main aspects of smart objects: (i) identifiable, (ii) communicating, and (iii) interacting. These points must be considered to maintain the connection between objects, end-users, and others [64]. Conceptually, the scheme of Structural Health

Monitoring (SHM) using the Internet of Things (IoT) can be seen in Figure 1. Here are the main components, schematic layout, and steps for SHM using IoT:

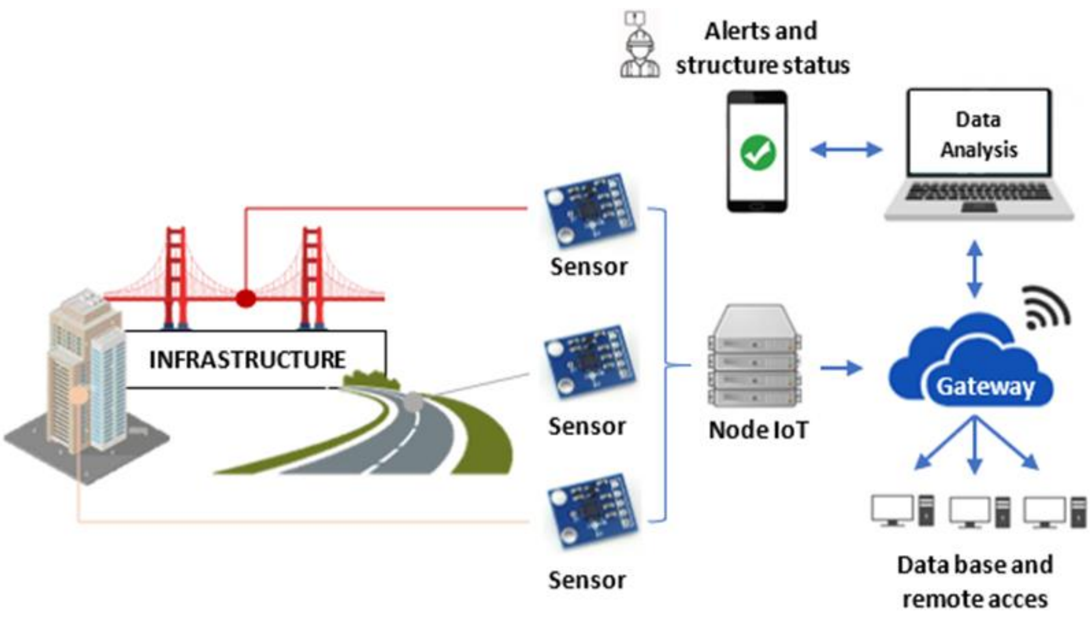

Figure 1. The IoT scheme implemented in SHM

(1) Sensor implementation: Sensors in SHM are key to detecting the structure's condition. They are installed throughout the structure (such as bridges, buildings, dams, etc.) to collect data about the physical condition of the structure. SHM systems use sensors to monitor several physical quantities such as acceleration, tensile and compressive stress, temperature, humidity, and so on [15]. Different types of sensors can be used depending on the specific monitoring needs, and these sensors play an important role in enabling the implementation of IoT-based SHM. Several studies show that sensors used in IoT-based SHM systems include temperature sensors [65-69], accelerometers [61, 70], fibre optic sensors [71], strain gauge [72], displacement sensors [36, 73], piezoelectric sensors [74-77], and vibration sensors [15, 78]. These sensors can help collect real-time data and perform remote monitoring.

(2) Data collection: IoT nodes serve as data collectors from connected sensors, transmit them over wireless networks, and facilitate communication for analysis [79, 80]. These sensors and nodes directly synergise in the efforts of the structure detection and data collection system. Sensors monitor the parameters required for structural assessment/monitoring, and nodes collect structural data from sensors. These nodes can generally be microcontrollers [81, 82], Single-Board Computers, etc.

(3) Gateway system: A Gateway is a device that connects IoT nodes with a larger network or with the internet [15]. It is an intermediate level between the connected devices and the cloud platform. Gateways can instantly collect and transmit data recorded by sensors and nodes to a remote-control room, where the data is in real-time [14]. It enables data transfer from nodes to a central processing system or the cloud. The advantage of storing information in the cloud makes it possible to access remote computers so that other users know the state of the structure or perform analyses on this data [82]. Using a cloud system, data can be accessed from anywhere at any time and integrated with other applications for further analysis.

(4) Data Analysis: The data collected by the nodes is sent to a data processing system, a local server, or a cloud platform and analysed using sophisticated algorithms to detect structural damage or deterioration signs. This analysis can involve machine learning, data mining, and predictive modelling [25]. Analyses can be performed using software. The software receives the processed data and uses it to generate a structural behaviour model. This model can show how the structure reacts to loads, temperature changes, or other environmental factors.

(5) Damage Detection: Based on the analysis, the system can detect damage or potential problems in the structure. This information can be used to initiate repairs or other mitigation measures [25]. IoT in Structural Health Monitoring (SHM) enables the detection of various types of damage and structural abnormalities. Some of the damages detected through SHM using IoT include structural cracks, vibration damage, etc. [13].

(6) Remote Monitoring: IoT nodes can be accessed from anywhere with internet connectivity, allowing users to monitor the structural health of buildings and bridges in real time. This feature enables early detection of potential problems and helps extend the life of structures [15, 41]. Engineers and technicians can access information through a user interface, a dashboard, or a mobile application. This interface displays real-time data and alerts. If anomalies or trends are detected, they indicate a decline in structural health. If the system detects a problem, corrective or preventive actions can be taken. This may include further inspection, repair, or even evacuation of the structure if necessary.

The widespread deployment of sensors on the Internet of Things (IoT) for Structural Health Monitoring (SHM) brings a number of technical challenges and limitations to consider, such as scalability in system development. SHM systems can have many sensors and devices, which require high equipment and proficiency to manage the collected data [83]. Data collection by IoT sensors on civil structures may involve sensitive information, such as location, activities, or usage conditions. Sensors connected to IoT networks are also vulnerable to cyber-attacks. Data leakage or manipulation can threaten the reliability and security of the structure, so it is necessary to pay attention to data privacy protection, including secure data management, data anonymity, data encryption, and continuous security monitoring to maintain data privacy and security [84]. In SHM, the measurement accuracy of sensors is very important. Poorly calibrated sensors can generate incorrect data, leading to misinterpretation and inappropriate actions. Failure of IoT infrastructure or sensors can disrupt general structural health monitoring. To ensure monitoring continuity, the system design must be redundant and fault-tolerant. To ensure the success and sustainability of the implemented monitoring solution, stakeholders should consider the issues and take a holistic and sustainable approach when implementing IoT for SHM structures.

In the context of Structural Health Monitoring (SHM), implementing the Internet of Things (IoT) offers significant practical benefits or impacts. One of them is the potential cost savings through automated and real-time management. Systems capable of automatically controlling and collecting data facilitate identifying and handling issues. This leads to more efficient maintenance and lower costs [85]. Additionally, control and data collection systems can aid in recognizing structural conditions and organizing repairs, ultimately enhancing effectiveness and efficiency in structural lifecycle management. With IoT, infrastructure management and control are more efficacious [86]. Overall, the use of IoT in SHM enables continuous and real-time monitoring of structural health, reducing structural failure risks and enhancing overall safety.

In the perspective of future directions in IoT for Structural Health Monitoring (SHM), developing smarter and multifunctional sensor technologies can enhance structural monitoring capabilities. Additionally, it is crucial to focus on proactive maintenance methods to identify potential structural issues before they become critical. Thus, the use of IoT in SHM will continue to evolve and make significant contributions to improving infrastructure reliability, efficiency, and safety.

4. RESEARCH METHODOLOGY

To obtain a comprehensive overview, it is necessary to identify the appropriate articles in the field under study. The database collected in this research utilizes a single indexing and database provider or journal data center, namely Scopus. The collection of databases used is limited based on the title, objectives, methodology, and significant contributions from the selected databases for the scope of the study. Bibliometric and Scientometric analyses provide in-depth insight into research trends and map the scholarly literature landscape. Figure 2 illustrates the methodological metrics of this paper.

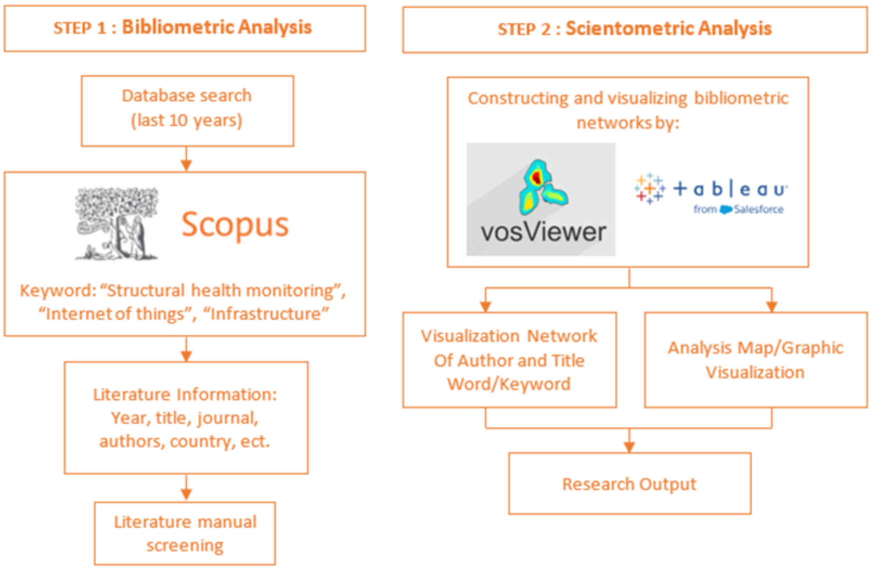

Figure 2. Research methodology

4.1 Bibliometric analysis

Bibliometric analysis is a quantitative method that can identify core research, authorship, and relationships by covering all publications related to a particular topic or field [87-90]. This method adopts a network of analysis based on titles, keywords, and abstract data [91-93]. This bibliometrical analysis is important to understand the articles that impact a particular field most through site analysis and co-citation [94]. The research carried out a database search covering the last 10 years using special keywords such as "Internet of things", "Structural Health Monitoring", and "Infrastructure" in the title, abstract, and publication search keywords. The data collection of this research is focused on the database of scientific journals Scopus alone and does not include non-English publications. The search was conducted from January 2013 to January 2024. Information such as publications by year, quotations, keywords in areas, most journal names, most authors' countries, and most author institutions of relevant articles are used in this analysis.

4.2 Scientometric analysis

At this stage, bibliometric data from articles maps the network and evolution of related topics according to large-scale scientific data sets [95]. A scientometric analysis is a more advanced form of bibliometrical analysis focusing on the relationship between these data points, such as author co-citations, journal co-citations, and document co-citations [96]. This analysis involves using software to create visual data representations, such as quotation networks or bibliometric maps. The VOSviewer and Tableau software are used in this paper to describe bibliometric data. VOSviewer uses common visualization techniques (VOS) that provide facilities for visualizing and mapping fields of knowledge to analyze its intellectual landscape [97]. This feature directs us to use scientometric analysis in this survey. It enables young researchers to gain a global perspective on research trends in SHM infrastructure using IoT and measuring scientific progress.

Thus, the main focus of bibliometric analysis is on bibliographic data and trends in scientific publications. Meanwhile, scientometric analysis includes a broader understanding of the dynamics of relationships, the impact of science and technology in society at large such as identifying scientific collaboration of researchers, understanding scientific cooperation networks and mapping fields of knowledge. Thus, the contribution of these two methods is expected to identify research trends, measure the impact of scientific work, and map collaboration networks between researchers. Analyses were conducted to reveal the following trends: year of publication, country participation, source contributions, authors, and affiliations, citations, co-authorship, title word and keyword cluster networks, and type and subject divisions based on keywords.

5. RESULT AND DISCUSSION

After going through the procedures and filtration steps outlined earlier, as many as 170 publications from Scopus with keywords related to the last 10 years have been carefully selected to be involved in comprehensive surveys in the current field of study. This research excludes non-English publications and focuses on the Scopus database only.

5.1 Annual publications trend

Annual publication trends refer to the pattern or trajectory of publications released each year in a particular field, industry, or domain. Analyzing annual publication trends provides valuable insight into a specific subject's growth, development, and focus areas over time. Figure 3 shows the trend of articles published about SHM using IoT in the last 10 years, from January 2013 to January 2024. In 2013, there were 2 documents. The years 2014 to 2016 show a constant number of documents, namely 1 document per year. There was an increase to 4 documents in 2017 and 11 documents in 2018. In 2019, the number of documents jumped sharply to 57, the highest peak in the graph. The graph depicts a varying pattern until 2019, remaining below 57 articles annually. This trend tends to increase due to the large number of published scientific article documents, which indicates that research on structural health monitoring (SHM) using the Internet of Things (IoT) is very interesting. Publication trends in this area are of interest because they are supported by advances in IoT technology, improved monitoring efficiency, and awareness of IoT's potential to enhance structural performance and safety.

Then, there was a drastic decrease in 2020 to 12 documents. The researchers' search results did not find a specific reason for the decline in publications in Scopus about Structural Health Monitoring (SHM) using the Internet of Things (IoT) in 2020. Several possible causes for the general decrease in publication trends on this topic include the complexity and challenges associated with implementation. IoT-based SHM systems, such as integration, scalability, and cost, may have influenced the rate of new publications in this field. There may also be a particular cause due to the impact of the global COVID-19 pandemic, which may have affected research priorities and funding, thus potentially reducing research activity in certain fields, including SHM, which uses IoT. In 2021, the number of documents will start to rise again to 28 documents, in 2022, there will be 27 documents, in 2023, there will be 26 documents, and in the data planned for 2024, only 1 document will be displayed, and this will continue to increase.

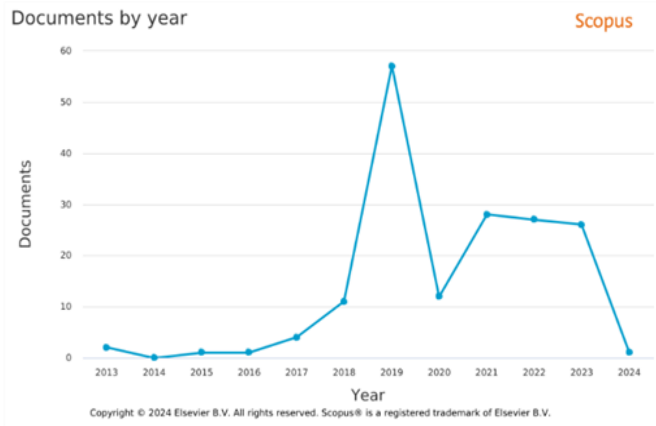

Figure 3. Annual trend of articles published on SHM using IoT platforms
(Source: Scopus.com)

5.2 Distribution of types and subject areas based on keywords

The distribution of subject types and areas underscores the breadth and diversity contained in academic discourse. This distribution, often revealed through the strategic application of keywords, allows researchers to categorize publications according to their thematic content, methodology, and focus areas. There are 5 distributions of publication types, namely articles (42 documents), reviews (10 documents), conference reviews (4 documents), book chapters (3 documents), and conference papers (111 documents), with the percentage distribution of each as in Figure 4. With this, the publication trend seen in SHM using IoT is more of the conference paper type. The dominance of conference papers significantly impacts the dissemination and development of research in the field due to the rapid dissemination of information. As well as forums and discussions that enable the sharing of ideas, the development of innovations, and research collaboration.

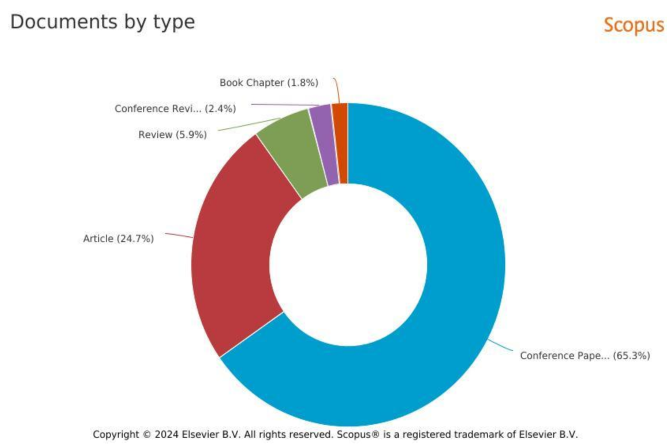

Figure 4. Documents by type
(Source: Scopus.com)

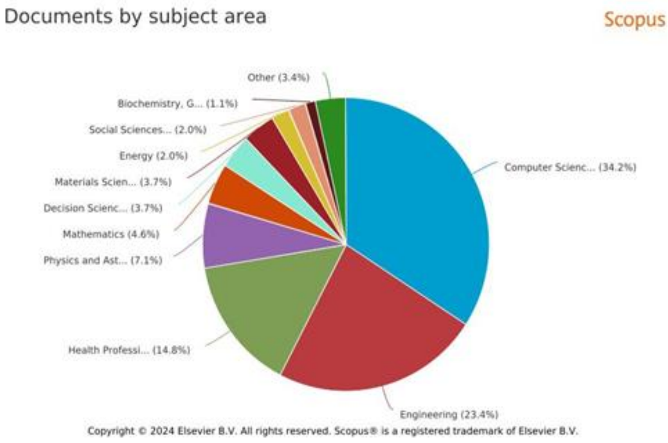

Figure 5. Documents by subject area
(Source: Scopus.com)

The subject areas that are relevant to the keywords "structural health monitoring", "Internet of things", and "infrastructure" in the last 10 years are Computer Science (120 documents); Engineering (82 documents); Health Professions (52 documents); Physics and Astronomy (25 documents); Mathematics (16 documents); Decision Sciences (13 documents); Materials Science (13 documents); Energy (7 documents); Social Sciences (7 documents); Biochemistry, Genetics, and Molecular Biology (4 documents); Chemistry (3 documents); Earth and Planetary Sciences (3 documents); Medicine (3 documents); Business, Management, and Accounting (1 document); Chemical Engineering (1 document); Environmental Science (1 document). Figure 5 depicts the percentage distribution of articles in terms of subject areas based on keywords in this research. Computer science and engineering dominate the subject regions of SHM research using IoT, with contributions of 34.2% and 23.4%. The dominance of the subject area of Computer Science and Engineering reflects aspects of technology and progress, this allows the development of new technology and methods in the field of SHM using IoT technology. By analyzing these distributions, researchers gain valuable insight into existing themes, emerging subfields, and collaborative intersections that characterize the multifaceted nature of research.

5.3 The trend in countries participation

Country participation trends refer to the pattern and degree of developing countries' involvement in various activities, initiatives, or global affairs. In this field of research, it is necessary to know the countries that have contributed the most to this field. Figure 6 illustrates a map of the distribution of author countries in related fields, intending to help readers see the distribution and understand which countries have contributed the most publications or contributed to the progress of research in this field.

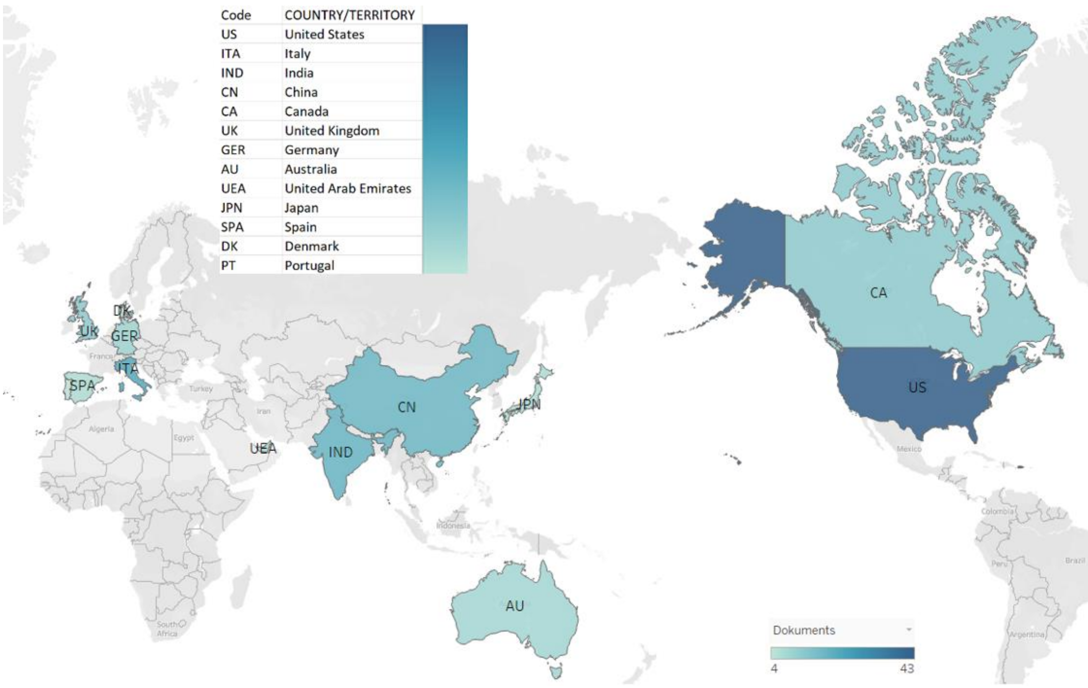

Figure 6. Deployment map of top countries in the SHM sector using IoT in the last 10 years

According to Table 1, the United States leads in research contributions with 43 published articles, accounting for 25.3% of the total. Its contribution surpasses one-third of the research output in this field. Followed by other countries active in this research, including Italy, India, China, Canada, the United Kingdom, Germany, Australia, the United Arab Emirates, and Japan. This information has important implications for understanding the global landscape of SHM research using IoT. In publication trends, countries that lead in publications in this field are influenced by good support from several factors, such as investment and funding, research infrastructure, innovation culture, and government policies that promote research in the field of SHM using IoT. The dominance of countries in SHM research using IoT reflects their proactive approach to driving efficient, real-time solutions to health monitoring, inspection, and maintenance needs across structures. His extensive research shows a strong commitment to exploring the synergistic relationship between structural health monitoring and the Internet of Things in civil engineering infrastructure. The impact of this analysis of participation trends in various countries provides insight into the changing dynamics of the global situation. It offers opportunities to build international research collaborations and exchange new IoT technology ideas for SHM.

Table 1. Top 10 countries in the SHM sector using IoT in the last decade

Code	Country/Territory	Documents	Percentage
US	United States	43	25.3%
ITA	Italy	22	12.9%
IND	India	19	11.2%
CN	China	18	10.6%
CA	Canada	12	7.1%
UK	United Kingdom	12	7.1%
GER	Germany	9	5.3%
AU	Australia	8	4.7%
UEA	United Emirates Arab	7	4.1%
JPN	Japan	6	3.5%

5.4 Most contributing research sources

Refers to important articles and publications that significantly influenced and guided the direction of a particular field or discipline. These sources serve as beacons of insight, shaping intellectual currents and providing a foundation for further exploration and innovation. Figure 7 shows the most contributing research by source over the last 10 years. From the data presented, "Lecture Notes in Civil Engineering" appears to be the most active source during this period, with the number of publications increasing. Meanwhile, the "ACM International Conference Proceedings Series" shows consistency in publication with 1 document every year. Other sources have had little or no activity for several years, suggesting that they may be less likely to be chosen as venues for publication in the context defined by Scopus data. “IEEE Internet Of Things Journal” shows consistency in publication with 2 documents in 2022-2023. Data shows that fields of study or topics related to the Internet of Things at SHM experienced growth or increased interest during that period.

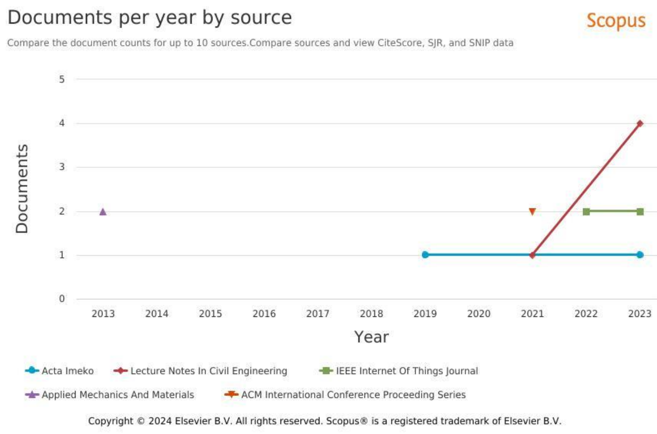

Figure 7. Document per year by source
(Source: Scopus.com)

Examining the most influential research can aid researchers in efficiently identifying pertinent articles and determining suitable journals for future publication endeavors. Table 2 outlines the top sources of scholarly literature that facilitate the advancement and comprehension of Structural Health Monitoring (SHM) employing the Internet of Things (IoT) within the construction sector. By incorporating the SJR ranking, researchers can gauge journals' scientific influence and impact, guiding their selection process. The higher the SJR value of a journal, the better its reputation. It can be seen that the source "IEEE Internet Of Things Journal" has the highest SJR value in the progress of SHM research with IoT in infrastructure.

Table 2. The relevant journals' SCImago Journal Rank (SJR) indicators

Source	Publisher	SJR 2022
IEEE Internet Of Things Journal	Institute of Electrical and Electronics Engineers Inc.	3.747
Acta Imeco	International Measurement Confederation (IMEKO)	0.319
ACM International Conference Proceeding Series	Association for Computing Machinery (ACM)	0.209
Lecture Notes in Civil Engineering	Springer Singapore	0.147
Applied Mechanics and Materials	Trans Tech Publications	0.112

5.5 Most contributing research author

Identifying the research sources to which authors contributed most is a particularly important endeavor, as it offers a unique lens through which researchers can gauge the deep impact and influence each researcher has had on their respective fields. This exploration explores the productive contributions of writers whose work has significantly shaped and defined intellectual currents in a particular field. Figure 8 shows the most contributing research by authors over the last 10 years. With four published pieces, Billie F. Spencer had the most contribution. With three published articles, Luca Benini, Davide Brunelli, Manuel Diaz, Mathew D. Smith, Sebastian Thöns, and Kamyab Zandi followed. In the meanwhile, two documents have been released by Jun Adachi, Cristiano Aguzzi, and Kenro Aihara. Looking at data on the research sources that productive authors contributed most to can reveal the thematic threads, methodological innovations, and lasting impacts that make these authors important contributors to the scientific landscape, thereby enabling collaboration between researchers who understand this field.

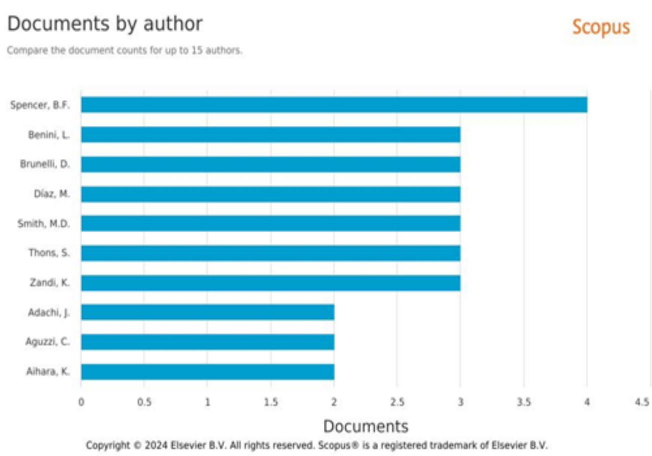

Figure 8. Document by author
(Source: Scopus.com)

5.6 Most contributing research affiliation

Exploration of the research sources that contribute most through affiliation emerges as an exciting endeavor, highlighting the collective impact of an institution, organization, or academic research group. This analysis serves as a lens through which scholars can view the influence and prominence of particular affiliations in shaping and advancing knowledge in a particular field. By examining the output of these affiliations, researchers gain valuable insight into the intellectual currents, thematic concentrations, and collaborative networks that define contemporary research trends. Figure 9 shows the research that has contributed the most by affiliation to SHM research using IoT over the last 10 years.

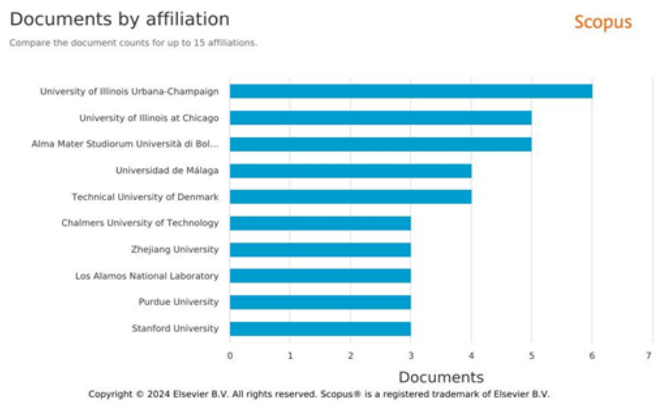

Figure 9. Document by affiliation
(Source: Scopus.com)

The University of Illinois Urbana-Champaign (United States) contributed the most to research in this field in the last 10 years, with 6 published documents related to SHM research using IoT during the last 10 years. Followed in second and third positions, namely the University of Illinois at Chicago (United States) and Alma Mater Studiorum Università di Bologna (Italy) with 5 documents. The next position is occupied by Universidad de Málaga (Spain) with 4 documents and Technical University of Denmark (Denmark) with 4 documents. Then Chalmers University of Technology (Sweden), Zhejiang University (China), Los Alamos National Laboratory (United States), Purdue University (United States), and Stanford University (United States) with all 3 documents published. Knowing these trends in the most contributing research affiliations provides insight into the institutions or research affiliations that contribute most to relevant research. This information can help understand research collaborations, identify centers of excellence, and evaluate the impact of research from various institutions for future research development.

5.7 Highest cited

One of the leading indicators of this impact is the concept of "Most Cited" works, namely articles, papers, or publications that receive much attention and citations from peers and experts in a particular field. Table 3 shows the 10 highest cited publications with the keywords "structural health monitoring", "Internet of things", and "infrastructure" in the last 10 years. As can be seen in Table 3, of the ten most cited articles, the article written by Zhang, J. et al. entitled "A Review of Passive RFID tag antenna-based Sensors and Systems for structural health monitoring applications (2017)", is the article with the highest citations is 278 citations. Knowing the most cited research trends about SHM using IoT can identify influential research, provide insight into new research ideas, and help researchers stay informed about the latest developments in their field. In addition, these trends can reflect advances in knowledge and recent changes in research issues in the field of SHM in real-time, making them representative of the field's current state.

Table 3. List of 10 publications with the highest citations in the last 10 years from Scopus data

No.	Document Title	Type	Authors	Year	Citations	Ref.
1	A review of passive RFID tag antenna-based sensors and systems for structural health monitoring applications	Review	Zhang et al.	2017	278	[98]
2	Hybrid energy harvesting technology: From materials, structural design, system integration to applications	Review	Liu et al.	2021	188	[99]
3	Machine learning algorithms in civil structural health monitoring: A systematic review	Article	Flah et al.	2021	178	[100]
4	Machine learning and structural health monitoring overview with emerging technology and high-dimensional data source highlights	Review	Malekloo et al.	2022	112	[101]
5	Structural health monitoring of civil engineering structures by using the internet of things: A review	Review	Misra et al.	2022	111	[13]
6	Digital Twins: A Survey on Enabling Technologies, Challenges, Trends and Future Prospects	Article	Mihai et al.	2022	105	[102]
7	A digital twin of bridges for structural health monitoring	Conference Paper	Ye et al.	2019	62	[103]
8	Middleware and communication technologies for structural health monitoring of critical infrastructures: A survey	Article	Alonso et al.	2018	50	[104]
9	Cloud-Based Digital Twinning for Structural Health Monitoring Using Deep Learning	Article	Dang et al.	2022	49	[105]
10	Structural Health Monitoring System with Narrowband IoT and MEMS Sensors	Article	Di Nuzzo et al.	2021	43	[106]

5.8 Publications of most relevance

The analysis process is carried out using a search method through the Scopus academic database, which involves sorting steps based on predetermined criteria to evaluate the suitability of a publication with the title, theme, content, and type of publication relevant to the specified research objectives. This process includes searching and using restrictions provided by the Scopus system to filter relevant studies. Table 4 shows 10 publications relevant to structural health monitoring, the Internet of Things, and infrastructure in the last 10 years. The Scopus system highlights the research of Chanv et al. [27] as the most relevant research based on the criteria in the established Scopus system. These most relevant publication trends are important because they can provide insight into the latest developments and emerging topics in the field of SHM, especially those using IoT. With this analysis of the most relevant publications, future researchers can identify gaps in knowledge, potential research opportunities, and areas that require further investigation. In addition, these results can help researchers stay abreast of the latest research developments and advances in the field of SHM in real-time using IoT, which is very important for maintaining the quality and relevance of their research.

Table 4. List of 10 publications with the most relevant publications in the last 10 years from Scopus data

No.	Document Title	Type	Authors	Year	Ref.
1	Structural health monitoring system using IOT and wireless technologies	Conference Paper	Chanv et al.	2017	[27]
2	Structural health monitoring cloud and its applications for large-scale infrastructures	Conference Paper	Lan.and Liu	2013	[107]
3	Structural health monitoring	Book Chapter	Lu and Yang	2017	[108]
4	Validation of an ultra-low-cost wireless structural health monitoring system for civil infrastructure	Conference Paper	Smarsly et al.	2019	[109]
5	Application of IoT for concrete structural health monitoring	Conference Paper	Lim et al.	2018	[110]
6	Synchronization of IoT Layers for Structural Health Monitoring	Conference Paper	Lamonaca et al.	2018	[111]
7	Mortar-diatom composites for smart sensors and buildings	Article	Canning	2021	[112]
8	Energy harvesting for IoT road monitoring systems	Article	Fedele et al.	2018	[113]
9	The industry internet of things (IIoT) as a methodology for autonomous diagnostics, prognostics in aerospace structural health monitoring	Conference Paper	Malik et al.	2019	[114]
10	3D printed vorticella-kirigami inspired sensors for structural health monitoring in Internet-of-Things	Article	Kim et al.	2023	[115]

5.9 Co-authorship analysis

This methodological approach allows us to dissect emerging trends in research by examining patterns of co-authorship relationships among scholars. This signifies the exploration of collaborative efforts that produce scientific outcomes. Figure 10 depicts a Visualization of authorship density along with at least one article published by an author in the field of SHM using IoT in infrastructure. The contrast between colors in Figure 10 is like a visualization of thermographic images, which can indicate significant temperature differences between the areas depicted. Hot spots (red) indicate the number of published articles and authors who actively contribute to the field of SHM using IoT. As can be seen, authors active in this field can be identified. The largest contribution was Billie F. Spencer, who published the largest number of articles, followed by Luca Benini, Kamyab Zandi, and Sebastian Thöns.

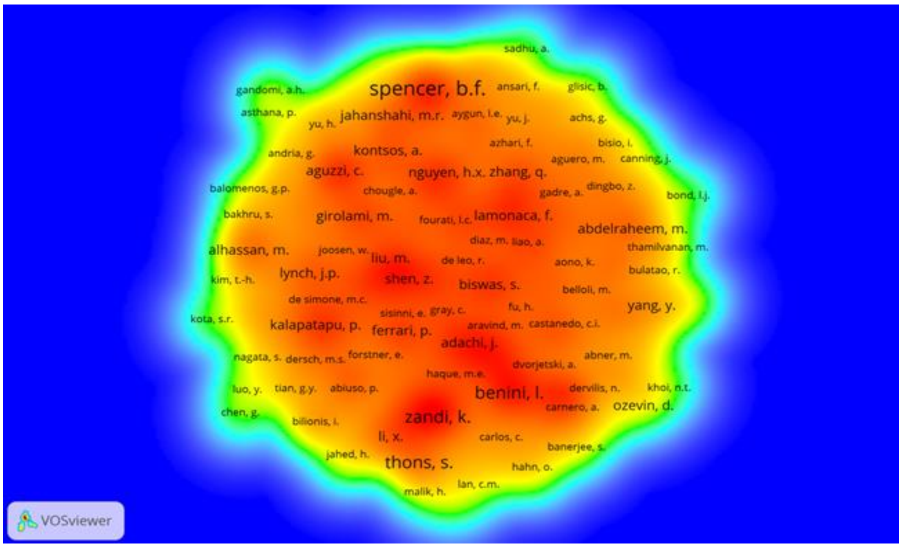

Figure 10. Density visualization of co-authorship
(Source: VOSviewer)

Figure 11 shows each author's publication year and co-authorship linkages to provide further insight. In this image, the color spectrum indicates the year the article was published; therefore, blue indicates the oldest published studies, and yellow indicates the most recently published studies. Additionally, the node size indicates how many articles were published by each author. Figure 11 shows that searches by author are dominated by green and yellow, indicating that many new researchers in the last 5 years are involved, such as Hamed Jahed, Stefano Rinaldi, and Marco

Belloli, who are investigating the field of SHM research using the Internet of Things on structures. Figure 10 shows the network of researchers and authors involved in SHM research using the Internet of Things. Figure 12 shows the node size, which indicates the frequency of the number of connections or links between authors.

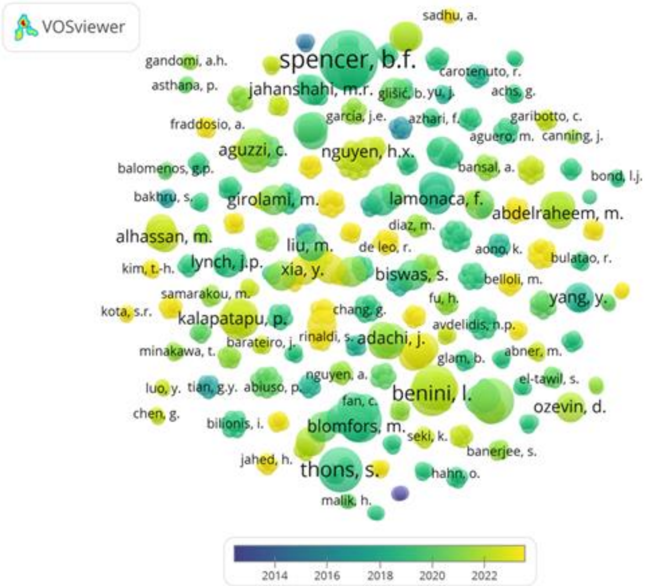

Figure 11. Overlay visualization of co-authorship
(Source: VOSviewer)

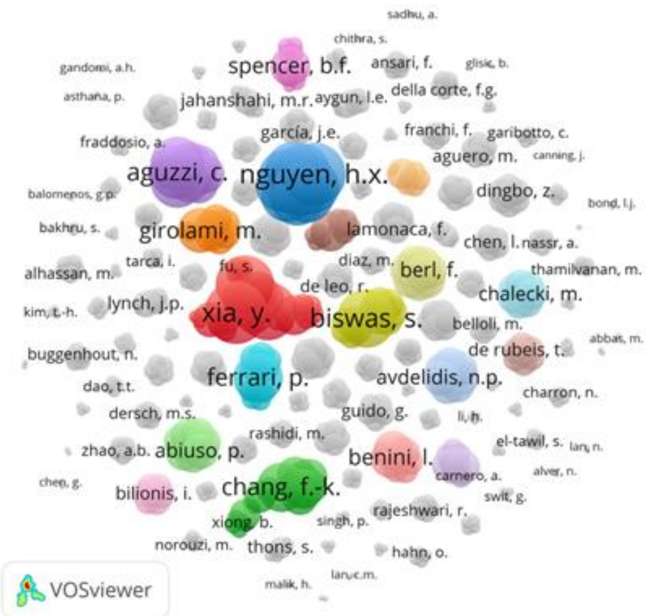

Figure 12. Network visualization of co-authorship
(Source: VOSviewer)

Additionally, different shades of gray indicate authors with more links, such as Huan X. Nguyen, Cristiano Aguzzi, Mark A. Girolami, Luca Benini, Billie F. Spencer, Foukuo Chang, Paolo Ferrari, and Sushas Biswam. This visualization analyzes use the Internet of Things to help identify active and leading SHM researchers. Also, in planning future research, young researchers can gain better insight into their research environment, identify potential collaboration opportunities, and plan more effective research strategies to achieve their goals.

5.10 Clustering trend by keywords

When looking for and interacting with an article, the first thing that springs to mind is the headline. The article's title and keywords may have something to do with the research's central theme. Understanding and categorizing emerging trends is critical for researchers, scholars, and enthusiasts in the complexity of academic research. Clustering trends by keywords, especially through innovative tools like VOSviewer, offers a powerful method for uncovering interconnected themes, visualizing collaborative networks, and distinguishing intellectual currents in the vast sea of scientific literature. The co-occurrence of terms is shown in Figure 13, where each keyword appears at least five times in the 170 articles that VOSviewer gathered. The size of the circle is positively correlated with the amount of research conducted on that keyword: larger circles mean more research on the subject, and vice versa. The keyword co-occurrence map shows that structural health monitoring and the Internet of things have larger nodes than other keywords.

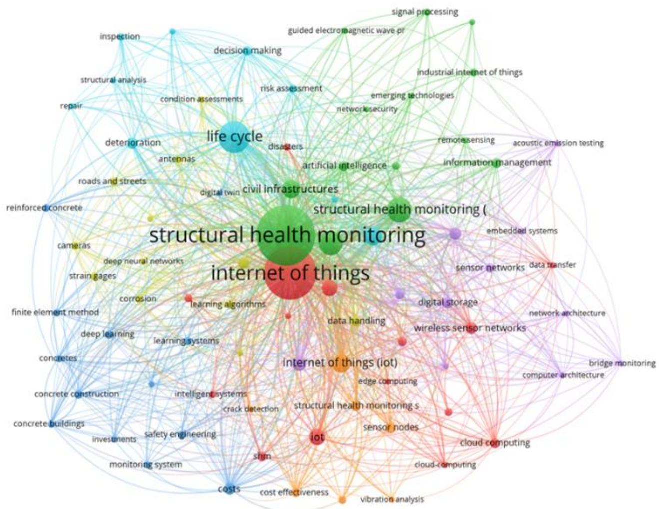

Figure 13. Clustering co-occurrence of keywords
(Source: VOSviewer)

VOSviewer software aids in analysis through the association strength technique, wherein keywords are interconnected via branches of distinct colors. Branches of the same color signify the co-occurrence of title words forming a group. A total of 83 items (7 clusters) are identified, each requiring a minimum of 5 co-occurrences with keywords. Below, we will examine the leading 7 keywords associated with IoT in Structural Health Monitoring (SHM) technology within infrastructure.

(1) Red cluster: Consisting of 15 terms, this red cluster stands out with the most keywords. In particular, the term “Internet of Things (IoT)” has gained significant attention in the red. Artificial neural networks, consisting of several intra-clusters, constitute the largest cluster, connecting it to the broad Internet of Things (IoT) technology field. In the structural health monitoring (SHM) context, the Internet of Things (IoT) transfers data over a network without requiring interaction between humans and computers. The number of occurrences of “Internet of Things” is 132. Figure 14 shows the red cluster network map. This analysis shows that Internet of Things integration focuses on computing network systems such as cloud computing, edge computing, intelligent

systems, data transfer, and wireless sensor networks.

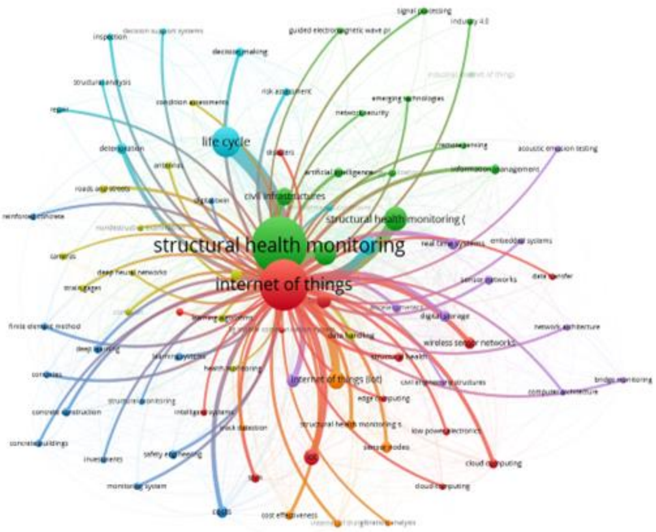

Figure 14. Red clustering network

(2) Green cluster: The green cluster has 14 keywords, almost the same as the red cluster. Figure 15 shows the green cluster network map. The most commonly used keyword in the green cluster is structural health monitoring, abbreviated as “SHM”. The term "structural health monitoring" appears 158 times, which indicates that nearly every article uses it. SHM is a civil engineering field concerned with identifying damage to infrastructure (bridges, roads, tunnels, buildings, etc.). The cluster results show the SHM network with civil infrastructure, information management, and emerging technologies.

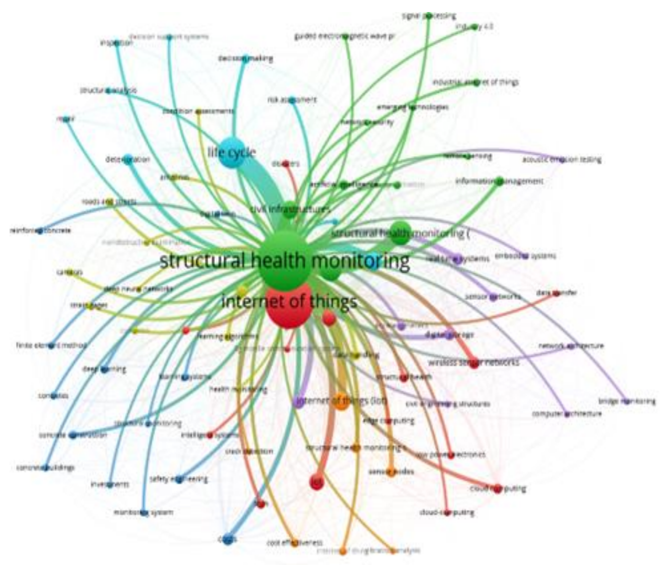

Figure 15. Green clustering network

(3) Blue cluster: This cluster contains information about “Development of Monitoring Systems and Safety Engineering”. It reflects an approach that uses IoT technology to build sophisticated monitoring systems and prioritize safety aspects in structural engineering. There are 14 keywords in the blue cluster. Figure 16 displays the network map of the blue cluster. Some words that appear in this cluster include concrete building (6), deep learning (8), learning system (7), monitoring system (6), cost, and safety engineering (8).

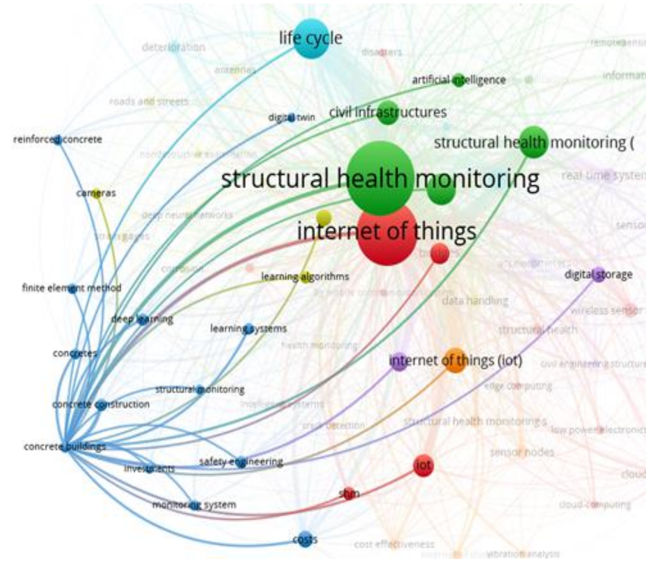

Figure 16. Blue clustering network

(4) Yellow cluster: There are 13 keywords in the yellow cluster network. Figure 17 shows the yellow cluster network map. Several keywords that appear in this cluster still have little research related to this, such as strain gauge (6), deep neural networks (5), cameras (6), and corrosion (6). These terms can be grouped in the "Sensors and Data Analysis for Structural Health Monitoring" cluster. This cluster includes the use of various types of sensors, such as strain gauges and cameras, to detect various parameters related to structural health, such as corrosion, as well as the application of advanced data analysis techniques, such as deep neural networks, to interpret the collected data

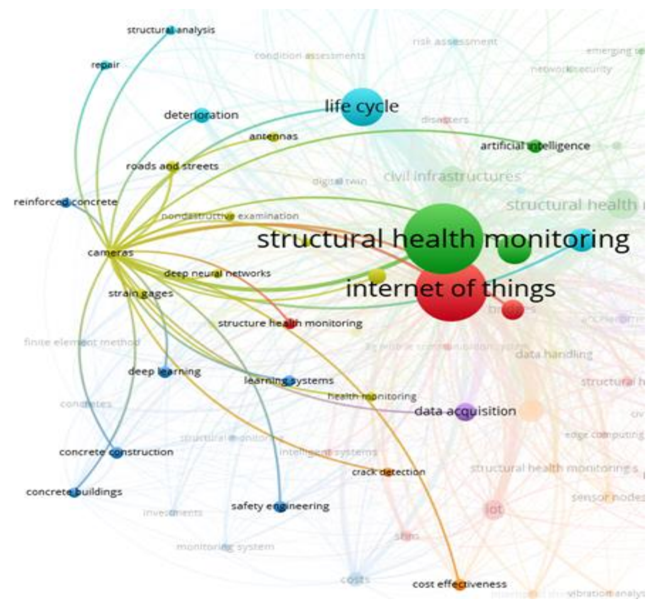

Figure 17. Yellow clustering network

(5) Purple cluster: There are 11 keywords in the purple cluster network. Figure 18 shows the purple cluster network map. These networks can be grouped in the "IoT Infrastructure and System Architecture for Structural Health Monitoring" cluster. This cluster includes elements related to information technology infrastructure that support structural

health monitoring systems, including real-time systems, digital storage, embedded systems, sensor networks, network architecture, and computer architecture.

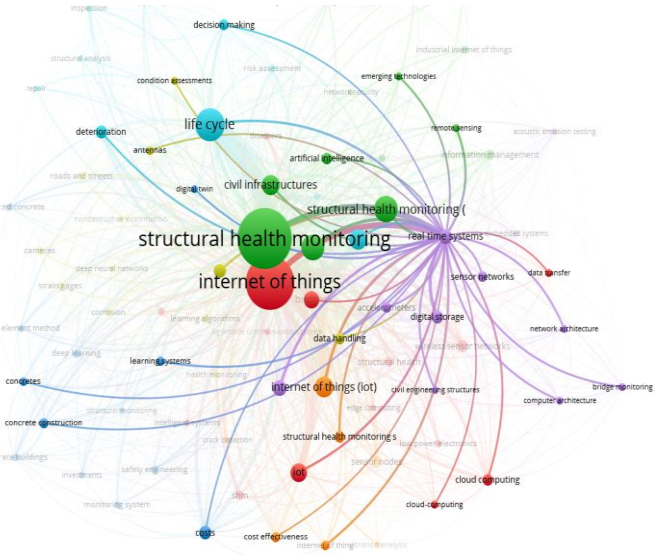

Figure 18. Purple clustering network

(6) Light blue cluster: This light blue cluster has 10 keywords with the "life cycle" grouping network and is the largest occurrence in this cluster of 59. In the context of SHM, this refers to Life Cycle Assessment (LCA), a method for assessing the environmental impact of a cycle stage. Figure 19 shows the light blue cluster network map. Other keywords related to life cycle and SHM are condition assessment, risk assessment, inspection, structural analysis, decision-making, and repair.

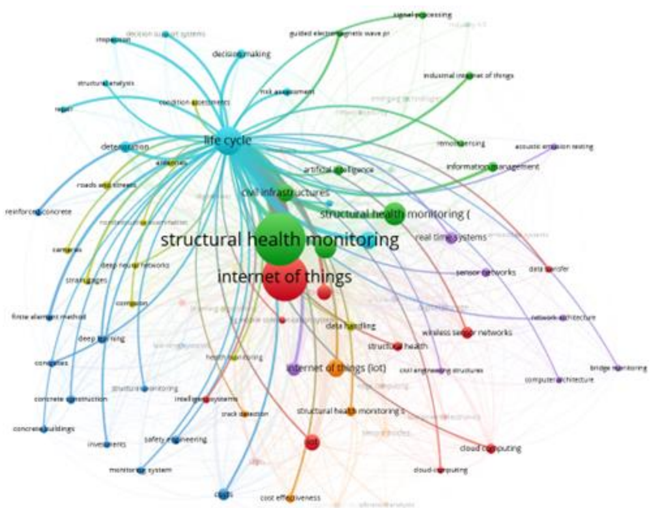

Figure 19. Light blue clustering network

(7) Orange cluster: The orange cluster has 7 keywords. Figure 20 shows the orange cluster network map. The frequently appearing words are Internet of Things (IoT) and sensor node, with 27 and 12 occurrences, respectively. A sensor node is a small device consisting of a physical sensor, a processing unit, and a communication module connected in a wireless sensor network. This group focuses its research on the application of IoT technology in structural health monitoring, with sensor nodes as the main component in the monitoring network.

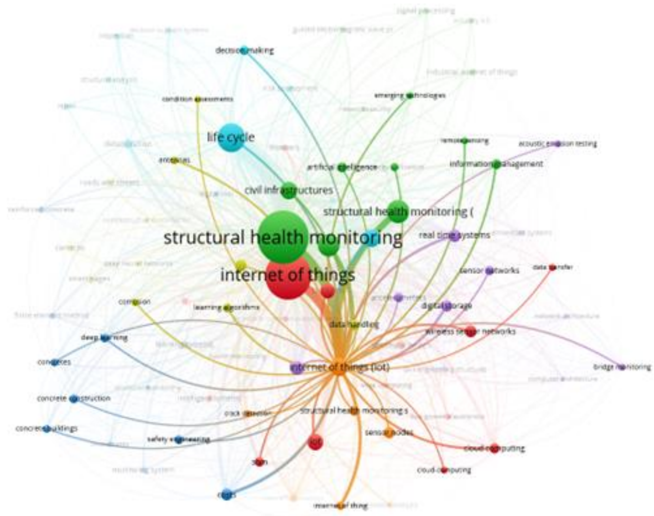

Figure 20. Orange clustering network

The clustering in this study provides an in-depth look at current trends and opens the door to more focused and collaborative future research. With this, researchers can identify patterns and focus on the areas most critical to achieving breakthroughs in structural health monitoring.

6. CONCLUSIONS

In summarizing the findings, it is known that this study has limitations that need to be considered. The data taken or used for analysis only uses data from Scopus, which was accessed in January 2024 and does not include non-English publications. It must be acknowledged that research in this field involves contributions and perspectives from various scientific disciplines, especially in research methods. This study provides a comprehensive overview of the Internet of Things (IoT) application in structural health monitoring (SHM) for infrastructure, highlighting trends in articles published between 2013 and 2023. Annual publication trends show a significant increase in the last 10 years, with a peak in 2019, 57 documents were published. The United States was the most important contributor, with 43 articles indicating extensive international involvement. The majority of research focuses on scientific conferences, especially in the fields of Computer Science and Engineering. This trend marks significant progress in the broad advancement of IoT technology, particularly in the field of structural health monitoring (SHM) systems.

Examining the sources of research reveals that the journal 'Lecture Notes in Civil Engineering' has emerged as the leading publisher, contributing the highest number of articles and making the most substantial impact over the past three years. Among the authors, Billie F. Spencer has recorded dominance with 4 articles. At the same time, the University of Illinois Urbana-Champaign stands out as the top contributor with 6 published documents in research in SHM using IoT in infrastructure. One of the most cited articles in the last decade is "A Review of passive RFID tag antenna-based sensors and systems for structural health monitoring applications," written by Zhang, J. et al. in 2017, with 278 citations. Through this examination, researchers can quickly access articles from various sources and find related journals to disseminate their research. Analysis of co-authorship and grouping similar data through visual representation also makes it easier for researchers to identify active colleagues with potential for future collaboration and sharing innovative ideas.

This presents an aspiration to develop a more sophisticated and responsive IoT structural health monitoring system to provide more accurate and real-time information to support appropriate decision-making in maintaining infrastructure security and reliability. There is an optimistic outlook for increased research activity in this domain in the forthcoming years. Recommendations include integrating insights from diverse fields and critically assessing the strengths and weaknesses of each technique to enhance future research endeavors. Moreover, proposing similar studies in the future can facilitate monitoring the progress of IoT techniques in Structural Health Monitoring (SHM) infrastructure and tracking their evolutionary trajectories.

ACKNOWLEDGMENT

We would like to thank all who have contributed and helped to complete this paper entitled "Internet of Things (IoT) in Structural Health Monitoring: A Decade of Research Trends". This work is required as a value in the technical course of assessment, monitoring, and improvement of the structure of the magister of civil engineering study program at the Universitas Muhammadiyah Yogyakarta (UMY).

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