buildings

Review

Science Mapping for Recent Research Regarding Urban Underground Infrastructure

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Abstract: The presented research conducted a bibliometric analysis regarding academic publications, especially journal publications, in the area of urban underground infrastructure (UI) systems (which include sewer pipes, drinking water pipes, cables, tunnels, etc.). In total, 547 journal papers published from 2002 to July 2022 (around 20 years period) were retrieved from Scopus using the proposed data collection method. Bibliometric analysis was conducted to extract and map the hidden information from retrieved papers. As a result, networks regarding co-citation, co-authorship, and keywords co-occurrence were generated to visualise and analyse the knowledge domain, patterns, and relationships. The eight most investigated topics in the UI research are identified and discussed, which provides an overview of the research history and focuses. Further, five potential research directions are suggested for researchers in the UI research area. The main contribution of this research is on revealing the knowledge domain of UI research in a quantitative manner as well as identifying the possible research directions.

Keywords: underground infrastructure; underground construction; literature review; bibliometric analysis; science mapping

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1. Introduction

Urban underground infrastructure (UI) system is a general term that refers to different types of infrastructures such as sewer pipes, drinking water pipes, cables, tunnels, etc. that are buried underground to provide services for citizens (see Figure 1 as an example of UI system). The UI systems are key components of modern city infrastructure systems, and their functionality and level of service also have significant impacts on the sustainability of the urban built environment in terms of environment, society, and economy [1,2]. UI system's unique characteristics (i.e., mainly buried underground) make them valuable to cities in terms of saving space and providing essential services, but also make their construction and maintenance operations challenging compared with that of aboveground infrastructure. Over the years, many efforts have been devoted to this area trying to reveal the knowledge domain of the research area and identify potential research opportunities. Recent literature review studies in the field of UI are tabulated in Table 1 to summarise their main focus in chronological order. It shows that recent research mainly focused on a special perspective of UI-related research. For instance, Metje et al. investigated the locating technologies for UI [3]; Malek Mohammadi et al. explored the research that focused on factors that affect the deterioration of underground sewer pipes over the 2001 to 2019 period [4];Wang and Yin reviewed recent research on digital technologies for construction and maintenance of UI systems [5]. However, none of the previous research provided a comprehensive view of the knowledge domain of UI-related research in a quantitative way. Bibliometric analysis is a quantitative method in which mathematical or statistical analysis is performed on bibliometric data to reveal internal patterns and relationships for publications in a given research field [6,7]. Therefore, in this research, we conducted a bibliometric analysis to fill this research gap. The purpose of the research is to present the recent advancement of UI-related research in a quantitative manner. To be more specific, science maps of the targeted knowledge domain are constructed by conducting bibliometric analysis. The main outcomes of the research are (1) science maps that reveal the state-of-the-art for UI research, and (2) insights drawn from science maps to unveil the most influencing (or the most productive) journal sources, publications, scholars, topics, etc. in the field of UI-related research, and to identify future research directions. More importantly, the research community could potentially have a better understanding of state-of-the-art UI research and be inspired to initiate innovative UI research topics in the future.

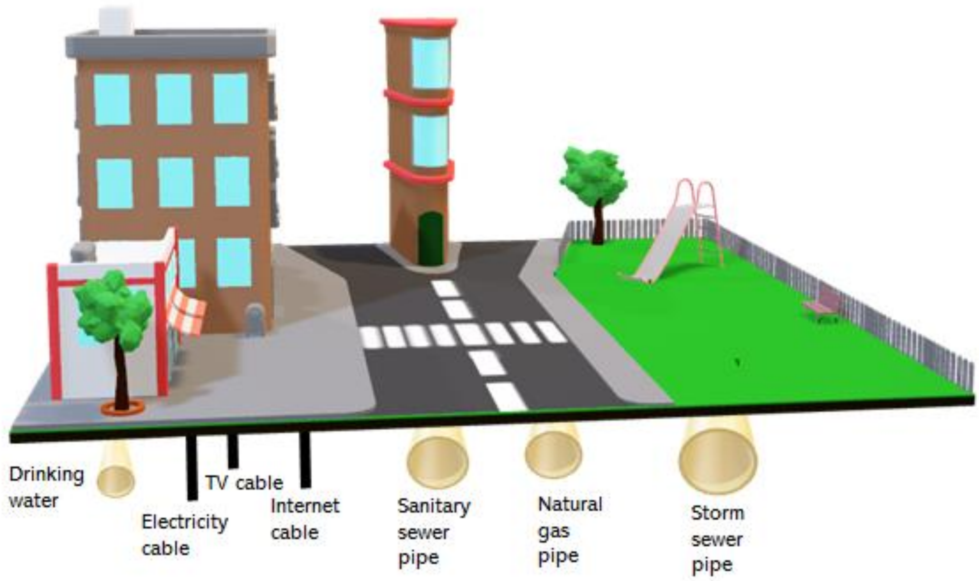

Figure 1. Urban underground infrastructure.

Table 1. Related literature review research in the field of UI.

Reference	Title	Source	Publication Year	Review Topic
[3]	Mapping the underworld—state-of-the-art review	Tunnelling and Underground Space Technology	2007	Locating technologies for UI
[8]	Modeling the structural deterioration of urban drainage pipes: The state-of-the-art in statistical methods	Urban Water Journal	2010	Deterioration modeling for UI
[9]	Condition assessment of the buried utility service infrastructure	Tunnelling and Underground Space Technology	2012	Inspection and assessment for UI
[10]	State-of-the-art review of inspection technologies for condition assessment of water pipes	Measurement	2013	Inspection technologies for UI
[11]	A review on computer vision-based defect detection and condition assessment of concrete and asphalt civil infrastructure	Advanced Engineering Informatics	2015	Computer vision technologies
[12]	Sewer pipes condition prediction models: a state-of-the-art review	Infrastructures	2019	condition prediction for sewer pipes

Table 1. *Cont.*

Reference	Title	Source	Publication Year	Review Topic
[4]	Factors influencing the condition of sewer pipes: state-of-the-art review	Journal of Pipeline Systems Engineering and Practice	2020	Deterioration modelling for UI
[13]	A survey on image-based automation of CCTV and SSET sewer inspections	Automation in Construction	2020	Vision-based method for UI condition assessment
[14]	Artificial intelligence for the modelling of water pipes deterioration mechanisms	Automation in Construction	2020	AI for deterioration modelling for UI
[15]	Automated vision systems for condition assessment of sewer and water pipelines	IEEE Transactions on Automation Science and Engineering	2021	Vision-based method for sewer and water pipeline
[5]	Construction and maintenance of urban underground infrastructure with digital technologies	Automation in Construction	2022	Digital technologies for UI construction and maintenance

The remainder of this paper is organised as follows: Section 2 introduces the review methodology used in this research. Section 3 presents the results of the bibliometric analysis. Research challenges and future trends are discussed in Section 4. Section 5 concludes the paper and summarises the contributions.

2. Methodology

The presented research employs a bibliometric analysis to map the knowledge domain of UI-related research (the overview of the methodology is presented in Figure 2). Bibliometric analysis is applied in this research as it has been used in many previous literature reviews in construction management and engineering field, such as [16–19] and is effective to extract insightful information, patterns, and relationships from a large number of publications. The details of the methodology are discussed in the following sections.

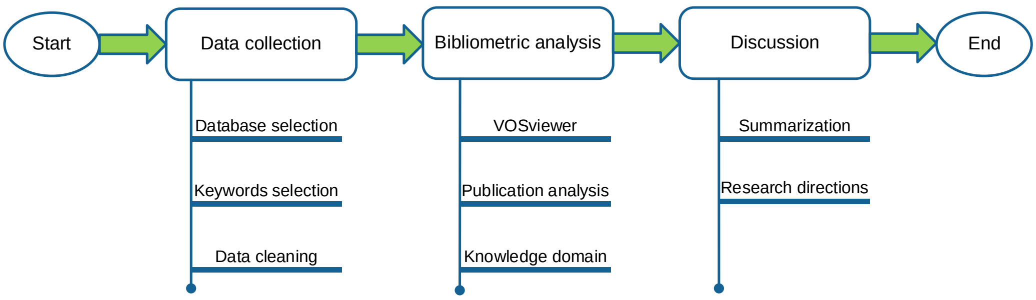

Figure 2. Overview of the methodology.

2.1. Data Collection

As depicted in Figure 2, the research starts with data collection to retrieve the related literature in a comprehensive and systematic manner. In this step, developing a rigorous searching strategy (which includes database selection, keywords selection, and data cleaning process) is important for collecting high-quality data for bibliometric analysis. In this research, among several well-known academic databases (such as Google Scholar, Web of Science, and Scopus), Scopus was selected as the database to collect related literature. The reasons for choosing Scopus are two-fold: (1) Scopus has been used in past civil engineering-related literature review research and its effectiveness has been proven, some examples are [17,20], (2) Scopus has a wider coverage of literature, especially for engineering-related topics [21].

The scope of the research is framed within the UI, especially focusing on utility infrastructures, such as underground water/sewer pipes, underground cables, etc. The keyword selection takes into consideration of previous research (e.g., [9,22,23] as well as the authors' experience and knowledge. After several prior experiments, keywords for searching the related literature are determined as follows: ("underground utility" or "subsurface utility" or "underground assets" or "subsurface assets" or "utility tunnel" or "sewer pipe" or "sewer line" or "water pipe" or "wastewater pipe" or "underground cable" or "subsurface cable" or "buried cable" or "underground infrastructure" or "subsurface infrastructure") and ("underground" or "subsurface" or "buried") and ("design" or "construction" or "maintenance" or "inspection" or "condition assessment") and not ("subway" or "railway" or "metro" or "parking").

Keywords in the first bracket include terms representing UIs (e.g., underground utility, subsurface utility, underground assets), and the categories such as sewer pipe, water pipe, and underground cable using the logical operators or. Underground, subsurface, and buried are a set of synonyms used in the second bracket to make sure that the retrieved papers are related to UI instead of other types of civil infrastructure. In addition, the retrieved papers should be related to engineering issues within the whole life cycle of infrastructures, thus, design, construction, maintenance, inspection, and condition assessment are also used as keywords. The above keywords within each bracket are connected using the logical operator and which means that the retrieved literature should conform to the set conditions at the same time. Finally, subway, railway, metro, and parking in the last bracket are connected with the previous keywords by and not, which means that papers with these keywords are excluded from the search results. This strategy is to limit our research scope to the urban utility infrastructure, while infrastructures such as subway and underground parking spaces are not the focus of this research.

The search period was set as 2002 to the present time (i.e., 3 July 2022), which is around a 20-year period. Journal papers are selected as the main source in the presented searching strategy since the journal papers are often more informative and have a higher impact than conference papers [16]. After retrieving the original data from Scopus, a data cleaning process was conducted to filter out the unrelated literature. Literature from unrelated subjects, such as "physics and astronomy", "agricultural and biological sciences" and "arts and humanities", are excluded. Finally, an inspection of publication titles for retrieved publications is performed to filter out unrelated journal papers. All the remaining papers after the data cleaning process will serve as inputs for the analysis processes in the later stage.

2.2. Bibliometric Analysis

Bibliometric analysis is employed to construct a science map for the targeted research field. For this purpose, VOSviewer [24] is used in this study to analyse the retrieved bibliometric data, as it has been widely used in the previous literature review research, such as [19,25], and has proved to be effective in constructing science maps for various research topics. VOSviewer is able to generate distance-based maps, in which the distance between nodes (that can represent different keywords, journals, authors, or publications) reflects the strength of the relation between them. A shorter distance means a stronger relationship. The nodes in the figure generated by VOSviewer are automatically assigned different colours, which indicates the results of the cluster analysis conducted by the software. Nodes in the same colour belong to the same cluster. Interested readers may consult the VOSviewer Manual [26] for more detailed information. In this research, several analyses were performed using VOSviewer such as publication citation analysis, co-authorship analysis, and keywords co-occurrence analysis to investigate the knowledge domain of the targeted research field.

2.3. Discussion

Finally, a discussion of the major findings of the bibliometric analysis was conducted. Promising research directions are proposed to facilitate researchers in this field to better formulate their research focus. The discussion section complements the bibliometric analysis by revealing the synergies among key research topics, which ultimately helps to identify the challenges of current research and proposes directions for future research [17].

3. Findings

3.1. Overview

Initially, 764 Journal papers are retrieved from the Scopus database. After that, a round of filtering processes was conducted following the method presented in the methodology section. Finally, 547 journal papers are left that met all the criteria set in the methodology section. The publication number for each year between 2002 and July 2022 are depicted in Figure 3. Overall, the figure shows an increasing research trend, especially after 2017, the growing trend became more significant. Note that the publication number in 2022 is lower since only partial data are available at the moment when we were conducting the research. Overall, Figure 3 indicates a growing research interest in the topic of UI.

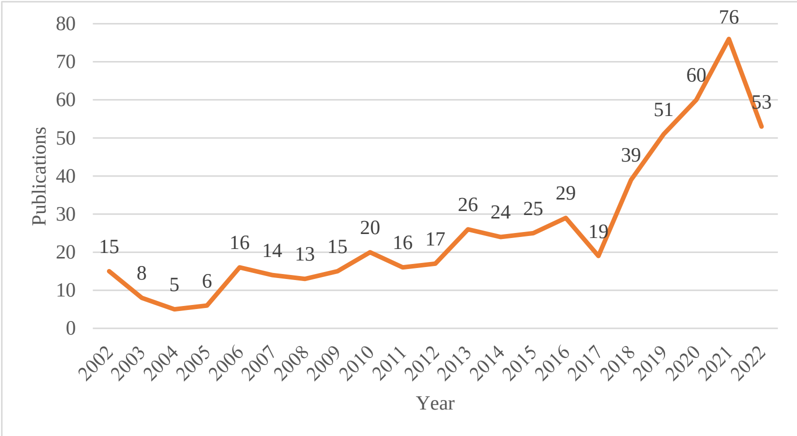

Figure 3. The number of selected journal papers published each year.

Further, these obtained publications are categorised by country or region, and the results are plotted in Figure 4. It is clear that, in the last 20 years, researchers in the United States published the most papers (110 journal papers) in the UI research field, followed by researchers in China with 91 journal papers. The two countries comprise the first leading group. After that, countries including Canada, the United Kingdom, South Korea, Australia, and Italy, are also very productive in terms of publications in the UI research field, publishing more than 30 papers over the last 20 years. Other countries/regions that published more than 10 journal papers in this field are also listed in the figure. More in-depth findings from the bibliometric analysis of publications in the UI research field are described in the following sections.

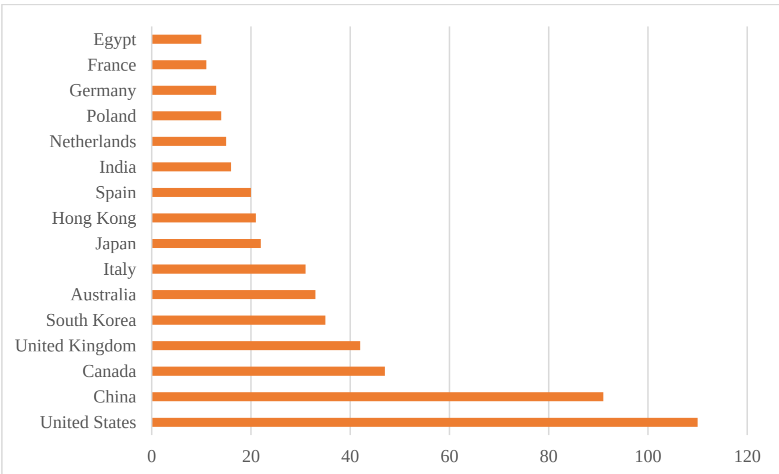

Figure 4. The number of UI-related journal papers published by different countries or regions.

3.2. Publication vs. Citation

This section presents findings regarding the most productive authors, important publications, and the leading journals in the field of UI research. Among the retrieved papers, the most productive authors (who have published more than 4 papers in this area) are plotted in Figure 5. Ariaratnam, S.T. published 11 papers, which makes him the most productive author in the field. Other productive authors include Rogers, C.D.F., Sinha, S.K., Vallati, A., etc. Meanwhile, the top 10 most cited papers among those retrieved papers are tabulated in Table 2. The most cited paper is a review paper namely Recent developments in the direct-current geoelectrical imaging method published by Loke, M.H. in 2013 [27], which garnered 575 citations until mid-2022. The rest of the papers in the table have close citations of around 100. It is worth noting that [28] have been cited 115 times with the shortest publication period (around 4 years) compared with others.

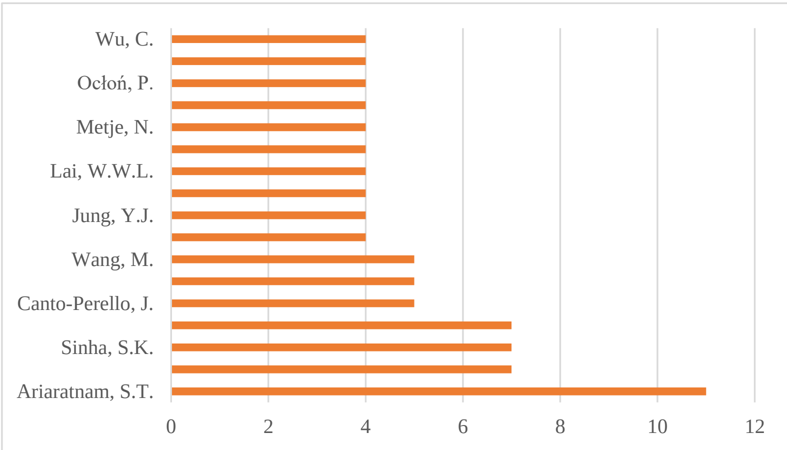

Figure 5. The number of published UI-related articles by different authors.

Table 2. Top 10 most cited publications.

Reference	Title	Publication Year	Source	Citations
[27]	Recent developments in the direct-current geoelectrical imaging method	2013	Journal of Applied Geophysics	575
[29]	Handheld Augmented Reality for underground infrastructure visualisation	2009	Personal and Ubiquitous Computing	156
[30]	Condition rating model for underground infrastructure sustainable water mains	2006	Journal of Performance of Constructed Facilities	118
[28]	Automated defect classification in sewer closed circuit television inspections using deep convolutional neural networks	2018	Automation in Construction	115
[31]	Underground asset location and condition assessment technologies	2007	Tunnelling and Underground Space Technology	113
[32]	Robotic devices for water main in-pipe inspection: A survey	2010	Journal of Field Robotics	95
[33]	Sustainable utility placement via Multi-Utility Tunnels	2014	Tunnelling and Underground Space Technology	94
[34]	Effect of stator winding connection on performance of five-phase induction machines	2014	IEEE Transactions on Industrial Electronics	94
[35]	Segmentation of buried concrete pipe images	2006	Automation in Construction	88
[36]	Implications of bioretention basin spatial arrangements on stormwater recharge and groundwater mounding	2009	Ecological Engineering	86

3.3. Co-Citation Analysis

Co-citation analysis is widely used for investigating the most influential papers, authors, or publication sources for a certain research topic, and some examples in the construction industry of using co-citation analysis for the literature review are [37,38].

When two papers are cited by a third document at the same time, then these two papers are defined as co-cited. When papers are co-cited by other research repeatedly, the co-cited papers often contain the key concepts, key methods, or key experiments in a specific research field [39] that could serve as a basis for other research. Therefore, in this section, the most frequently co-cited journal sources and papers are investigated by the co-citation analysis function of VOSviewer.

Figure 6 shows the co-citation map for journal sources in the UI research domain. In the figure, four major clusters can be identified, which are the red cluster in the top left corner, the green cluster in the middle left, the yellow cluster in the lower-left corner, and the blue cluster on the right side. The red cluster is mainly composed of journals in the construction management domain with a focus on information technology. Represented journals are Automation in Construction, Journal of Computing in Civil Engineering, Computer-aided Civil and Infrastructure Engineering, Journal of Infrastructure systems, etc. The green cluster includes journals that cover underground civil engineering-related topics, and Tunnelling and Underground Space Technology is the most co-cited journal among them, which indicates the high influence of the journal on the UI research topic as well. The yellow cluster is a small cluster in the figure and includes two high-impact journals, which are Construction and Building Materials, and Cement and Concrete Research. They are journals in the domain of material science in civil engineering. Finally, the blue cluster locates in the furthest position from the previous clusters in the figure, and this cluster is composed of journals focusing on the electrical engineering domain, such as IEEE Transactions on Power Delivery and IEEE Transactions on Industry Applications, and they are co-cited in research related to the underground power transmission system. In summary, all the journals presented in the figure are high-impact journals in the UI research domain, while the journals with a bigger circle have a higher impact than others. Further, the most co-cited literature is also identified in Table 3. These papers (or reports) are frequently co-cited by papers in the UI research domain, which indicates the significance of these papers in UI-related research.

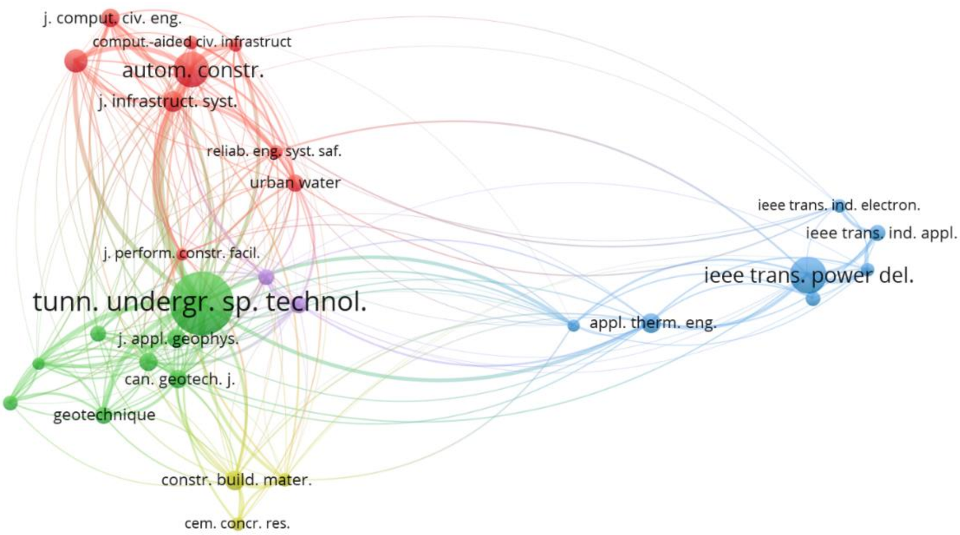

Figure 6. Co-citation analysis of journal sources.

Co-citation analysis results regarding key papers in the research domain are tabulated in Table 3. The minimum number of co-citations for one paper was set as 6, and 11 papers met the threshold out of 16,279 cited references. (Note that, the threshold selection considered the previous practice and suggestions from other literature review research (such as [16,40]) as well as the objective of optimising the visibility of the presented network. The threshold selections presented later follow the same logic). Those papers are the most frequently co-cited papers in the UI research domain, which suggests importance of those papers. Most of the time, these papers provided fundamental knowledge in the research domain. For example, a set of publications including [1,41–43] have discussed different aspects of utility tunnel development, which set the knowledge foundation for utility tunnel related research, hence, have been frequently co-cited. Note that, most of the top co-cited papers originated from highly influential journals (as identified previously), and here specifically, the Tunnelling and Underground Space Technology and Automation in Construction are in dominant positions.

Table 3. The most co-cited papers in the UI research domain.

Reference	Title	Publication Year	Source Title	Co-Citations
[44]	Development and applications of common utility tunnels in China	2018	Tunnelling and Underground Space Technology	11
[1]	Sustainable development of urban underground space for utilities	1999	Tunnelling and Underground Space Technology	10
[45]	Effects of backfilling on cable ampacity analysed with the finite element method	2008	IEEE Transactions on Power Delivery	9
[46]	Mainstreaming sustainable development into a city's master plan: a case of urban underground space use	2009	Land Use Policy	8
[28]	Automated defect classification in sewer closed circuit television inspections using deep convolutional neural networks	2018	Automation in Construction	8
[42]	Criticality and threat analysis on utility tunnels for planning security policies of utilities in urban underground space	2013	Expert Systems with Applications	7
[43]	Assessing governance issues of urban utility tunnels	2013	Tunnelling and Underground Space Technology	6
[41]	Human factors engineering in utility tunnel design	2001	Tunnelling and Underground Space Technology	6
[47]	Automated detection of sewer pipe defects in closed-circuit television images using deep learning techniques	2018	Automation in Construction	6
[2]	Establishing sustainable strategies in urban underground engineering	2004	Science and Engineering Ethics	6
[48]	4D-CAD-based method for supporting coordination of urban subsurface utility projects	2016	Automation in Construction	6

3.4. Co-Authorship Analysis

Co-authorship analysis is commonly used in bibliometric analysis to reveal collaborations in a certain research domain [17]. For publications in the UI research domain, co-authorship analysis is conducted in two aspects, namely co-authorship analysis regarding scholars and co-authorship analysis regarding countries/regions. Figure 7 presents the time-overlayed co-authorship network generated by VOSviewer, in which the minimum number of documents of an author was set to 3, and the minimum number of citations of an author was set to 20. As a result, 48 labels representing different authors are plotted on the figure (out of 1783 authors in total). The colour of the labels shows the average publication year of papers published by the author.

There is one biggest linked cluster in the lower central position of Figure 7, comprising researchers of Yang Y., Wu C., Li J., Wang M., etc. The other major clusters are located in the upper right, including De Lieto Vollaro R., Vallati A., etc. There are also some smaller clusters scattered in the figure with no links among them, which suggests that the research domain has much potential for collaborations between different research groups. If we focus on the timeline of the published papers, authors in the biggest cluster published the most recent research with an average publication year between 2019–2020, which implies that this cohort of researchers is rising star in the research domain. Other smaller clusters in yellow colour also represent researchers who have been newly involved in this research domain in recent years.

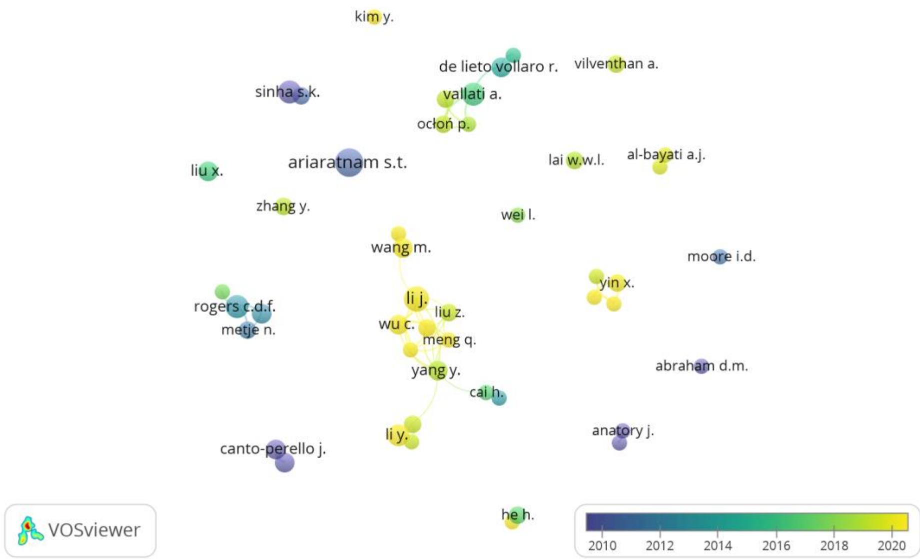

Figure 7. Co-authorship network regarding scholars.

In addition to co-authorship among scholars, a timeline-overlayed co-authorship analysis regarding countries/regions was conducted to reveal the cooperation relationship among them (See Figure 8). The minimum publication number per country/region was set to 7, which leads to 22 countries/regions left out of 70 countries/regions in total. The findings in the figure are consistent with the findings in Section 3.1 that key countries/regions in the research domain include the United States, China, the United Kingdom, Canada, South Korea, etc., since those countries published more papers in the investigated research domain. More importantly, they have more connected links with other countries, which means that most international research collaborations revolve around those countries/regions. It is worth noting that the United States not only published the most papers in the UI research domain but is also located in the central position among the network with the most links with others, implying the leading role of the United States in the research domain. However, the average publication year for the United States is around 2014, which is quite early compared with newly rising countries/regions in the research domain such as China, Austria, the Netherlands, and India, whose publications have an average publication time of around 2018.

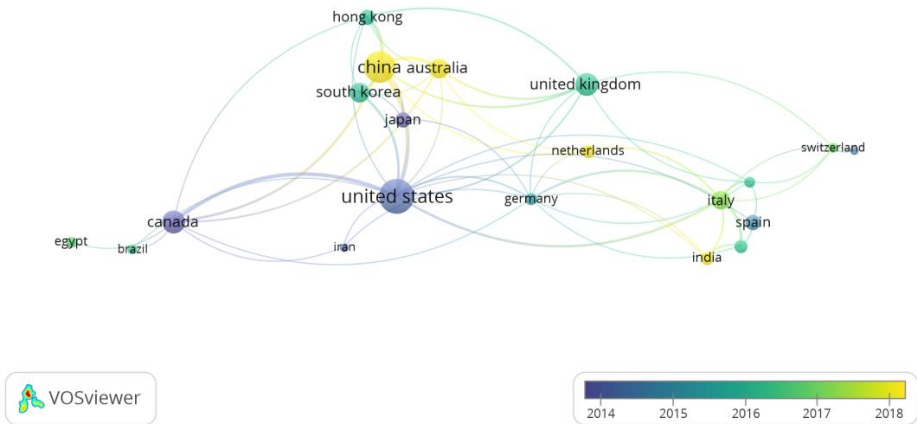

Figure 8. Co-authorship network regarding countries/regions.

3.5. Co-Occurrence Analysis of Author Keywords

Co-occurrence analysis of author keywords has been widely used in previous literature review research, such as [25,37,49] to identify the body of knowledge for the targeted research domain. The co-occurrence network is able to facilitate streamlining the current research focus, patterns, and relationships among different topics [40]. In this research, an author keywords co-occurrence map was generated by VOSviewer as shown in Figure 9. The threshold was set as 4, with results of 37 keywords left in Figure 9 out of 1600 keywords in total. Note that, a thesaurus file was used to merge synonyms. For example, keywords such as building information model, building information modelling, and building information modelling are merged as BIM to make the co-occurrence figure clean and concise. The detailed information on the presented keywords in Figure 9 is tabulated in Table A1.

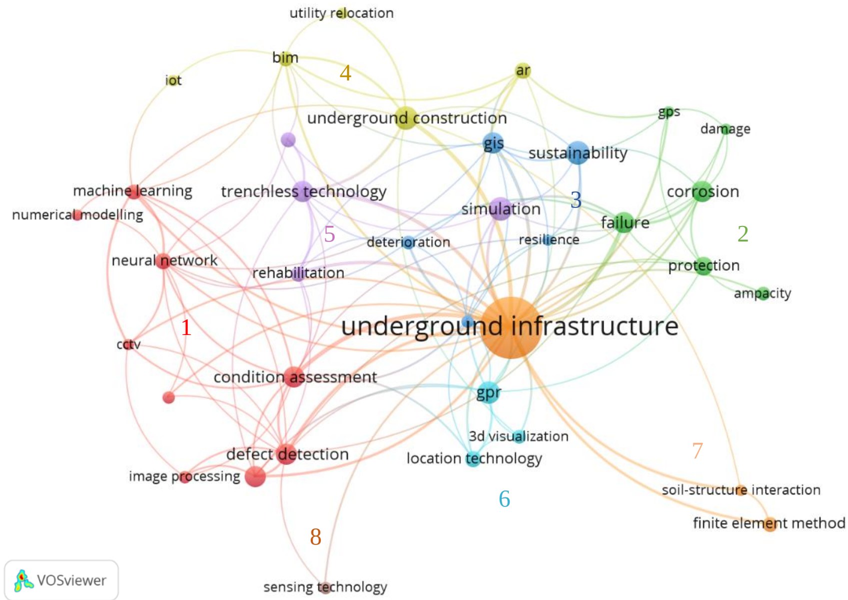

Figure 9. Co-occurrence network of author keywords in UI research domain.

From Figure 9, eight research clusters can be identified based on the colour automatically assigned by the VOSviewer tool. Each cluster is indicated by a number in the figure for better reference. A detailed description of clusters in Figure 9 is shown as follows:

- Cluster 1 is in red, located at the left part of the figure. This cluster has a major focus on using advanced information technologies for condition assessment/inspection for UI. Information technology-related keywords such as machine learning, neural network, and image processing, are the most frequently co-occurring keywords. It also can be seen that closed-circuit television (CCTV) is a widely used technology for defect detection in this research area. Several representative publications related to this research cluster are [47,50–55].
- Cluster 2 is in green colour, located on the right side of Figure 9. This cluster covers the research area of UI failure and protection. Keywords such as corrosion and damage are included in this cluster. Global positioning system (GPS) technology has been adopted in this research area. Representative publications are [56–60].
- Cluster 3 is in blue colour, located on the right side of Figure 9. This cluster concentrates on the topics of asset management-related topics such as sustainability, resilience, and the deterioration problem of UI. In this cluster, Geographic Information System (GIS) is a frequently co-occurring keyword, which indicates that GIS has been well adopted in the asset management-related research for UI. Samples of publications in this area are [61–64]
- Cluster 4 is scattered at the top of Figure 9. The central theme of this cluster revolves around digital technologies for underground construction. Utility relocation management has been frequently investigated in this research cluster (example studies are [65–67]). Digital technologies such as the Internet of Things (IoT) [68], BIM [69,70], Augmented Reality (AR) [71,72] are frequently discussed topics in this cluster.

- Cluster 5 is located at the centre-left of Figure 9. This cluster focuses on the rehabilitation of UI, especially using trenchless technology. As a non-intrusive technique for underground pipe construction and maintenance, trenchless technology gain momentum in recent years. Samples of publications in this area are [73–75].
- Cluster 6 is located in the lower part of Figure 9, which has a central theme of locating and visualisation of UI. Among all the locating technologies, ground-penetrating radar (GPR) received the most attention. In addition to locating UI, better visualisation of the UI is also a frequently investigated topic, especially translating the UI information into 3D maps. Representative publications in the field of locating/visualisation of UI are [72,76–80].
- Cluster 7 is plotted in the lower-right corner of Figure 9, which is relatively the "loneliest" cluster compared with other clusters in the figure. This cluster mainly covers the research in the structure analysis domain indicated by the keywords of soil-structure interaction [81–85] and finite element method [86–88].
- Cluster 8 is the smallest cluster positioning in the lower-left corner of Figure 9, with one keyword of sensing technology surpassing the threshold and presented in the figure. Samples of publications in the field of UI sensing technology are [77,89–91].

4. Discussion

From the bibliometric analysis results, we can see that the research interest in the UI-related research field keeps increasing. It is worth noting that apart from increasing interest in a certain area, the increase in published papers may be rooted in many other factors, such as increasing in research funding, requirements from research institutes, reward systems conducive to scientific publishing, etc. [92,93]. It is also clear to see that the research is highly clustered in certain countries such as the United States, China, Canada, etc. In addition, most of the countries/regions that actively conduct UI-related research are developed economies, and few of them are developing economies. Several examples of research originated from developing countries [56,94–97]. The lack of research focusing on or originating from developing countries may be rooted in various reasons, such as lack of research funding and lack of researchers with modern asset management expertise. That situation indicates potential research opportunities for investigating, designing, constructing, and maintaining UI systems in developing countries. Additionally, there is much space for further collaborations among research groups in different countries/regions to further boost UI research by incorporating different expertise in the research field.

From the keywords co-occurrence analysis, the scope of current UI research is already quite broad. Especially, previous researchers spend lots of effort in applying different kinds of digital technologies (including GPS, GIS, CCTV, IoT, BIM, AR, etc.) in UI construction and maintenance. However, still several aspects have not been covered or could be strengthened in the future. Several future research directions are listed below based on the bibliometric analysis as well as the knowledge and personal opinions of the authors. Note that, it is inevitable that the proposed research directions cannot cover all the possibilities, which requires much more future research on this endeavour.

- Development and application of robotics in UI. As the adoption of robotics is increasing in the construction industry, it opens up opportunities for developing new robots or customising existing robots for conducting tasks for UI construction and inspection, especially, for tasks that cannot be finished aboveground. In the meanwhile, integration of existing digital technology with robotics technology could further improve the construction and maintenance process of UI in different perspectives such as productivity, safety, consistency, etc.
- Smart city development incorporation with smart UI. UI could contribute to the development of smart cities significantly, yet research on synergies between smart cities and smart UI has not been frequently investigated in the UI research domain based on findings through the above bibliometric analysis. A connected and widely spread UI network could be used to collect real-time data that is valuable for smart

city decision-making. Additionally, decisions made by the smart city "brain" could also be implemented by a well-designed UI network.

- Deep AI utilisation. With the development of AI, it is natural that UI-related research will also be benefited from that. There is already plenty of research focusing on applying AI in UI projects but most of them use the supervised learning method, which always requires a huge volume of labelled data as input to train a supervised deep learning model. Other techniques such as semi-supervised learning, unsupervised learning, and reinforcement learning have not been fully explored in the area of AI for UI research.
- Social impact perspective. UI is the basic component of modern cities, and their design, construction, upgrade, failure, demolition, etc. all have certain impacts on the local community or the whole city. For example, an updated plan of the sewer pipe system could be implemented following many available plans, but it is challenging to derive the optimum plan considering technical constraints and more importantly, the social impact constraints. More research efforts regarding the topic could be made in the future to improve the level of city management as well as citizen well-being.
- Human factor perspective. Physical and mental health is important for construction workers, which has drawn much attention from researchers in the area of improving the safety and well-being of construction workers. However, not many existing research studies focused on UI construction and maintenance workers. The special characteristics of UI systems being buried underground make the construction and maintenance operation activities different from that of other general infrastructures. Take CCTV video assessment of sewer pipes as an example, pipe technologists usually need to spend a lot of time reviewing sewer video footage, which is time-consuming and tedious but also a mental challenge since sometimes the sewer videos can be annoying with upsetting objects. Further research aiming at improving the safety and well-being of UI construction and maintenance workers is needed.

5. Conclusions

To address the gap of limited systematic and quantitative review in UI-related research, this study conducted a bibliometric analysis regarding the literature in this field and presented major findings, based on which meaningful directions for future research are provided. This study employed VOSviewer as the main tool to reveal the inside connections of publications, journal sources, scholars, etc., in a quantitative way, and generate different networks to visualise and analyse those connections and relationships. Specific high-impact journals, articles, and scholars were identified, which are good references for researchers in this area. Further, the knowledge domain of UI-related research was revealed, where the most investigated areas that revolve around eight research clusters were presented. This indicates the 20-year research history and focus in this area, which helps to find the way forward for further development. Finally, based on the findings of the existing literature and the knowledge of the authors, five research directions were suggested as potential topics that could be studied with more effort in future UI-related research. The proposed research topics include the development and application of robotics in UI, smart city development incorporation with smart UI, deep AI utilisation, social impact perspective, and human factor perspective. The contribution of the research is twofold: (1) the research unpacked the hidden information of UI-related publications for the past 20 years through bibliometric analysis; (2) potential research directions were proposed as suggestions for future researchers in this field.

The current research also has limitations. First, the literature source is mainly from Scopus due to the capability of VOSviewer, future research could combine the literature from different sources such as Google Scholar, Web of Science, etc. to provide a more comprehensive understanding of the research domain. Another limitation is the future research direction is proposed by authors based on findings as well as our personal knowledge and understanding of the research field, which makes the suggestions inevitably biased and incomplete to some extent. Future research could employ a panel of experts in the field to derive more comprehensive suggestions for future research directions.

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Appendix A

Table A1. Top keywords in UI research.

Label	Links	Total Link Strength	Occurrences	Avg. Pub. Year	Avg. Citations	Avg. Norm. Citations
Underground Infrastructure	30	116	124	2014.65	13.06	1.27
Sustainability	6	10	19	2013.58	29.21	1.51
Simulation	7	13	18	2015.83	14.61	1.12
Underground Construction	9	24	18	2013.50	13.28	1.33
GPR	9	15	17	2015.53	11.94	0.82
Condition Assessment	12	29	15	2015.13	30.60	2.41
Defect Detection	12	21	15	2014.73	16.73	1.52
Failure	9	21	15	2016.53	8.47	1.33
GIS	10	17	15	2014.87	20.73	1.22
Trenchless Technology	10	24	15	2010.67	16.87	1.21
Corrosion	6	12	14	2016.21	10.29	0.93
Inspection	7	15	14	2012.36	18.21	1.11
Protection	7	8	11	2012.09	9.00	0.57
AR	6	13	9	2017.22	22.11	0.97
Location Technology	5	10	9	2013.78	26.22	1.40
Neural Network	12	17	9	2017.33	16.44	1.76
BIM	9	14	8	2020.13	5.50	2.01
Finite Element Method	2	6	8	2015.13	14.00	1.77
Horizontal Directional Drilling	4	6	8	2014.00	13.63	1.31
Rehabilitation	7	15	8	2011.88	23.50	1.25
Machine Learning	9	16	7	2019.29	20.57	4.20
3D Visualization	4	5	6	2018.17	4.33	0.63
Ampacity	2	3	6	2015.33	7.00	0.83
Deterioration	7	11	6	2015.67	10.00	1.08
Asset Management	8	12	5	2015.80	5.00	0.49
Image Processing	4	6	5	2014.00	20.00	1.32
Partial Discharges	3	4	5	2018.20	10.00	1.63
Sensing Technology	2	3	5	2014.00	9.20	0.95
CCTV	6	11	4	2018.50	33.50	5.75
Damage	4	4	4	2019.50	3.75	1.34
GPS	5	8	4	2017.25	2.75	0.57
IOT	2	2	4	2019.25	5.50	1.69
Numerical Modelling	2	2	4	2020.00	2.25	0.78
Resilience	6	7	4	2018.50	8.50	1.15
Soil-structure Interaction	3	7	4	2013.50	21.00	1.55
Utility Relocation	2	3	4	2017.75	5.00	0.41

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