A Systematic Review of the Geographic and Chronological Distributions of 3D Concrete Printers from 1997 to 2020

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Abstract –
Although several previous studies have reviewed 3DCPs, they have been based on few cases and do not include the latest 3DCPs. This study analyzed 139 academic papers and 98 types of three-dimensional concrete printers (3DCPs) developed from 1997 to 2020 through a systematic literature review. A chronological distribution analysis showed that the number of papers and printers suddenly increased after 2012. Most papers (89%) and 3DCPs (86%) were produced from 2012 to 2020. A geographic distribution analysis showed that while Switzerland published more papers than the US, the latter developed more than twice as many 3DCPs than Switzerland. The difference is attributed to who led the development: the industry (US) or academia (Switzerland). Among nozzle-traveling 3DCPs, gantry and cable-suspended platforms were the most common types for some time, but the robotic arm type has spread considerably in the last five years. Since 2013, mobile and collaborative 3DCPs have also increased.

Keywords –
Concrete; 3D Printing; Additive Manufacturing; Technical Specification

1 Introduction

Over the last 30 years, additive manufacturing has been explored to improve construction safety, reduce construction time and production costs, and produce geometrically challenging building elements [1]. In 2012, the number of 3D concrete printers (3DCPs) suddenly increased [2, 3]. Early 3DCPs included contour crafting [4] and D-Shape [5].

Recently, 3DCPs have evolved to support large-scale 3D printing [2, 6]. For example, the Institute for Advanced Architecture of Catalonia [7] developed a family of small-scale mobile robots, each of which can perform a specific task during construction. Keating et al. [8] employed a robotic arm system with a long reach and a terrestrial mobile system as a platform to maximize the building size. Zhang et al. [9] utilized multiple mobile robot printers to collaboratively print a large structure. DediBot [10, 11] adopted an aerial drone-based system to overcome the limitations of conventional 3D printing devices.

Although several studies have comparatively reviewed 3DCPs, none have analyzed their geographic or chronological distributions. This study examined the geographic and chronological distributions of studies and 3DCPs through a systematic literature review of 139 academic papers and 98 types of 3DCPs published from 1997 to 2020. The year 1997 was selected as the starting point because the earliest paper found was published in that year.

The rest of this paper is divided into five sections. Section 2 presents a review of previous studies related to the field and identifies their limitations. Section 3 describes the overall design of the literature search. Section 4 reports the results of the analysis. Section 5 discusses the current status and future directions of the technology. Section 6 summarizes the results and concludes the paper.

2 Previous Studies

Previous studies comparatively reviewing 3DCPs are characterized by two main limitations. First, they have been based on only a few cases. Lim et al. [1] comparatively analyzed only four types of 3DCPs: Pegna [12], contour crafting [13], concrete printing [14], and D-Shape [15]. Ma et al. [16] and Zhang et al. [17] analyzed three types: contour crafting, D-Shape, and concrete printing. Bhardwaj et al. [18] reviewed six 3DCPs, and Paul et al. [19] reviewed 10. Second, diverse 3DCPs have recently been developed, such as multiple mobile printers, aerial drone-based systems, and entrained reinforcement cable systems. These new 3DCPs have not been included in previous analyses, although some studies were published in the past couple of years. Moreover, Chung et al. [20] recognized that new 3DCPs could not be properly categorized using the existing classification system for 3D printers and proposed a new classification system; however, the classification was based on only 12 relevant papers.

3 Literature Search Method

A systematic literature review (SLR) is a widely used review method in the medical and management fields [21, 22], as well as in the construction field [23, 24]. SLRs aim to minimize bias through exhaustive literature searches related to a specific research question [22, 25, 26].

This study followed the SLR method proposed by Saade et al. [24], Tranfield et al. [22], and Wohlin [26] and used two methods: a keyword-based search and snowballing—a method for finding additional references through the reference lists of identified papers. Figure 1 describes the flowchart of the keyword-based search and snowballing.

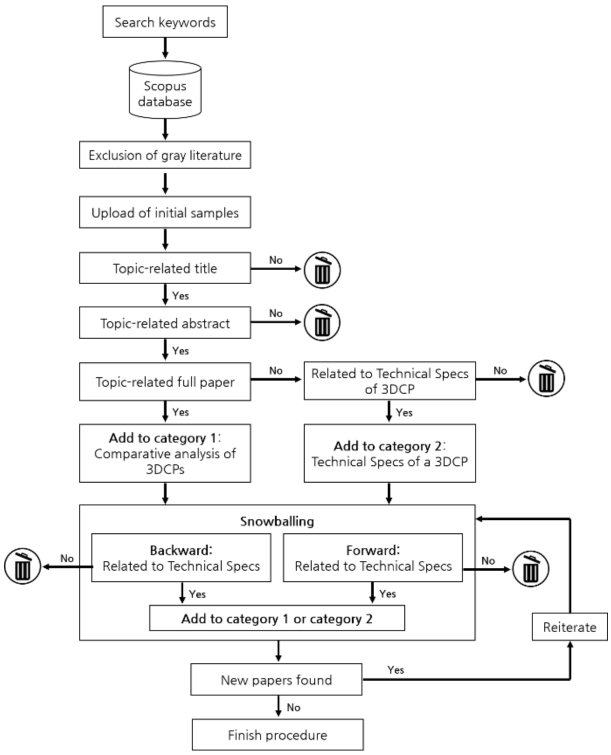

Figure 1. Flowchart of the literature search

The literature search was performed in two steps. The research question on which the search was based was, "What are the geographic and chronological distributions of 3DCPs from their early days to date?" The keyword string [("concrete" AND "3D printing") OR ("additive" AND "manufacturing")] was used to search relevant papers in the Scopus database [27]. To collect as many papers as possible, we intentionally left out specific keywords, such as "classification" or "property," and used generic terms, such as "concrete," "3D printing," "additive," and "manufacturing." Only peer-reviewed journal papers in English were included in the review.

Initially, 433 papers were collected through the keyword search. Irrelevant papers were excluded by reviewing the titles (247 papers), the abstracts (75 papers), and the contents of the full papers (47 papers). The exclusion was performed conservatively. The remaining 64 papers were divided into two categories: a comparative analysis of 3DCPs (29 papers) and a group of studies focusing only on the technical specifications of a 3DCP (35 papers).

Snowballing was then applied. This method is divided into forward and backward snowballing. Forward snowballing identifies studies citing a paper under examination. Backward snowballing identifies studies cited in a paper under examination. Both methods were iterated until no more papers were found. In the first iteration, six papers were added to the first category (comparative analysis), and 51 were added to the second category (technical specifications). A second iteration was then conducted based on these 57 papers, identifying 18 papers, all belonging in the second category. A third iteration returned only one paper, also of the second category. No new papers were found in the fourth iteration, and the process was terminated. In total, the snowballing method identified six papers for the first and 69 papers for the second category. Overall, 139 papers were identified by the two search methods.

4 Results

4.1 Chronological Distribution of Publications

The chronological distribution of the collected papers shown in Figure 2 indicates a growing interest in 3D concrete printing technology. As previously stated, the earliest paper found was published in 1997. Only five papers were published from 1997 to 2004, and 10 papers were published between 2005 and 2012. After 2012, the number of papers suddenly increased, with 89% (124) of the collected papers published from 2013 to 2020. There has been an upsurge in the number of published papers per year (an average of 15.5 papers per year) during the last eight years. This reflects the increasing interest in 3DCPs and 3D printers in general since 2012. One directly related event is U.S. President Barack Obama's speech about 3D printing as the future in February 2013 [28].

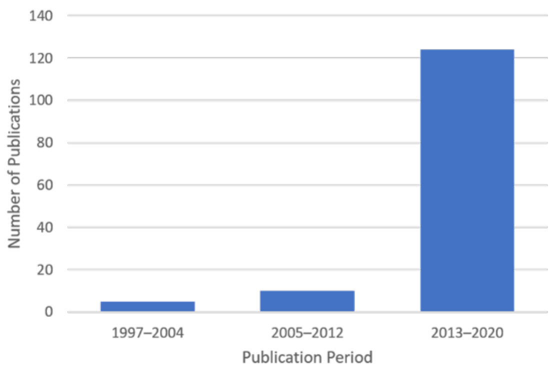

Figure 2. Chronological distribution of publications

4.2 Geographic Distribution of Publications

Figure 3 shows the number of publications per country. The assignment of publications to countries is based on the affiliation of the first author only. As shown in the figure, Switzerland and the US contributed the most publications related to 3DCPs, followed by Germany, France, and the UK.

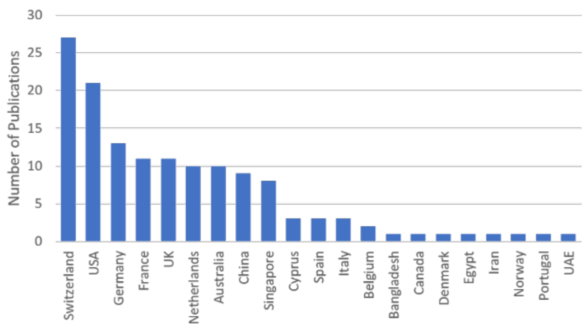

Figure 3. Geographic distribution of publications

4.3 Chronological Distribution of 3DCPs

An analysis of the selected papers identified 98 types of 3DCPs. Figure 4 shows their chronological distribution. Only two were developed from 1997 to 2004, and 12 were proposed between 2005 and 2012. Most (84) 3DCPs were proposed from 2013 to 2020, accounting for 86% of the identified cases. This shows that the number of proposed 3DCPs per year (12.25 per year on average) has substantially increased during the last eight years. This trend is in line with the number of relevant publications and conforms the findings of previous studies [2, 3].

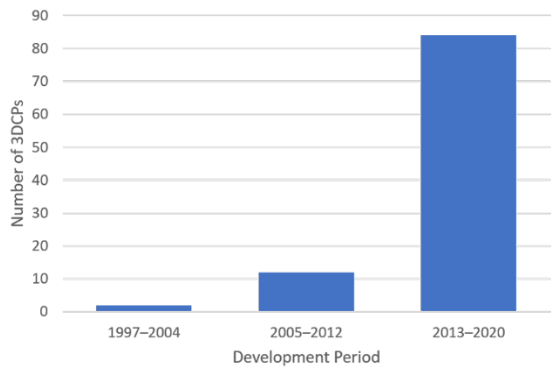

Figure 4. Chronological distribution of 3DCPs

4.4 Geographic Distribution of 3DCPs

Figure 5 shows the number of 3DCPs per country. Many 3DCPs were developed in the US, China, and Germany. An interesting discrepancy can be observed between the number of papers and the number of 3DPCs per country. Although more papers were published in Switzerland than in the US, the number of printers developed in the US was more than double that in Switzerland. This is because many 3DCPs in the US were developed by companies, which tend not to publish their outcomes. In contrast, 3DCPs in Switzerland were developed by research institutions, which are encouraged to publish their work.

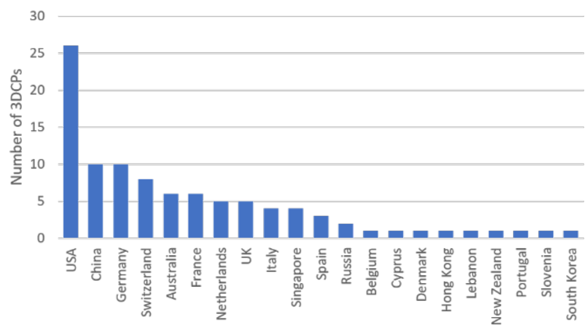

Figure 5. Geographic distribution of 3DCPs

4.5 Distribution of Nozzle-Traveling 3DCPs

To identify chronological trends, 3DCPs were classified based on the classification system proposed by Chung et al. [20]. One of the classification criteria in this system is a type of nozzle-traveling system. Figure 6 shows that the most widely used system has employed a gantry method to move a nozzle since 1997 with some intervals. A cable-suspended platform was the most common system between 2004 and 2010; however, since 2012, the gantry type has become the most common, and several new types of nozzle-traveling systems, such as the scara, delta, crane, and robotic arm types, have emerged. Especially the number of robotic arm type systems has substantially increased during the last five years. This is because this type can extend the printing range without requiring a massive external framework to support the print nozzle [9]. Considering this tendency, it is possible that the number of robotic arm systems will exceed gantry-based systems in the future.

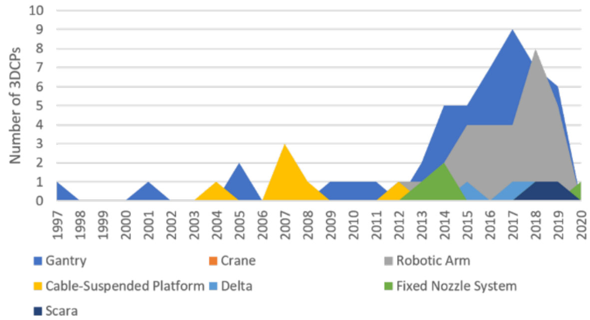

Figure 6. Chronological distribution of nozzle-traveling 3DCPs

4.6 Distribution of Mobile 3DCPs

Another classification criterion is the mobility of the building platform, which means a movable platform equipped with a terrestrial mobile system or an aerial drone-based system. Figure 7 shows that although the fixed system remains the most common system, terrestrial mobile and aerial drone-based systems have printed larger building volumes since 2013. These systems do not require planning or specific infrastructure on the construction site, such as cranes [29, 8]. Given that it enables fully autonomous on-site fabrication, the mobile system can become central to developing 3D concrete printing systems in the future instead of the fixed system. Our analysis also revealed combinations of the nozzle-traveling and mobile platforms: 75% of the terrestrial mobile systems employ robotic arms, and all aerial drones employ fixed nozzles.

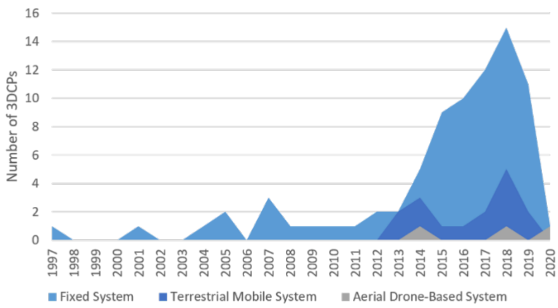

Figure 7. Chronological distribution of mobile 3DCPs

4.7 Distribution of Collaborative 3DCPs

Figure 8 shows the chronological distribution of collaborative robots identified in the 3DCP collection. Eight collaborative 3DCPs have been developed in the last eight years. Although single 3DCPs still represent the most common system, some systems have adopted multiple robots to collaboratively print large-scale structures without increasing the size of the robots. Several researchers have predicted that the collaboration capability of 3DPCs will be a key feature of the technology in the future [2, 8, 9]. Collaborative 3DCPs can be grouped into two types. The first is a collection of different robots designed to perform each task of a series of printing processes. An example is minibuilders composed of three robots [7]. The second type comprises identical robotic 3DCPs simultaneously crowd-printing different parts of a large-scale structure.

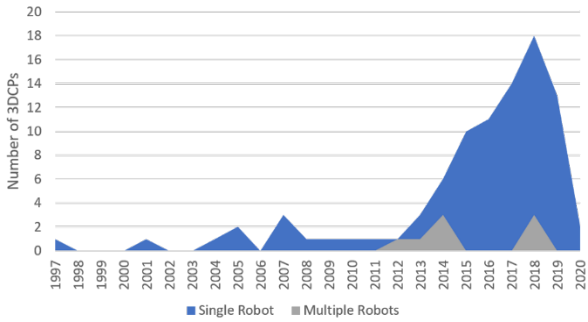

Figure 8. Chronological distribution of collaborative 3DCPs

5 Current Status and Future Directions

This section discusses the current status and future directions of 3DCP technology with regard to nozzle-traveling systems, building platform mobility, and collaborative printing.

Regarding the nozzle-traveling system, the gantry and robotic arm types are currently the most popular. However, most nozzle-traveling systems are designed to print small- or medium-sized structures off site or at fixed locations. To enable 3D-printing of large-scale structures on site in the near future, the development of nozzle-traveling systems on mobile platforms with collaborative printing functionality will be inevitable.

Regarding the mobile platform, although terrestrial mobile and aerial drone-based systems have been developed since 2013, they are still in an early stage. Even if several terrestrial mobile systems were employed on a construction site, they would only be operated on flat concrete slabs. Aerial drone-based systems, on the other hand, are characterized by limited payloads and unstable printing. If they are to be used in real construction projects, these issues must be addressed.

Regarding collaborative printing, although the number of studies on crowd-printing robots has increased, Nanyang Technological University is the only institution that has implemented the collaborative system—and only in a laboratory environment. To raise collaborative printing to a practical level, more studies on robot localization and nozzle trajectory planning are required.

6 Conclusion

This systematic literature review was conducted to address the limitations of previous studies: few reviewed cases and no reviews of new 3DCPs. The collected 139 papers and 98 types of 3DCPs and the analysis results can be used as a basis for developing a technical specification framework of 3DCPs.

The results show a dramatic increase in the numbers of papers and printers developed after 2012, accounting for an average of 15.5 papers and 12.25 3DCPs per year. Although Switzerland boasts the most publications, the US is home to more printers developed. This is because many manufacturers in Switzerland have been research institutions, which tend to publish their outcomes, whereas many manufacturers in the US have been companies, which do not. The robotic arm type of 3DCP has gained considerable popularity in the last five years, in contrast to the cable-suspended platform. Some types of mobile and collaborative 3DCPs have been adopted since 2013. Given that these types offer greater printing efficiency as relatively new technologies, they can become central to the future development of 3DCP systems.

In the future, we plan to identify the properties of 3DCPs based on a comparative analysis of 35 review papers and 98 types of 3DCPs. We also plan to develop and validate a technical specification framework by conducting surveys or focused group interviews. A technical specification framework can be used as a reference for 3DCP developers and users.

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