Evolution of Additive Manufacturing in Civil Infrastructure Systems: A Ten-Year Review

Koosha Jamali 1,*, Vinayak Kaushal 2 and Mohammad Najafi 2

1 Department of Civil Engineering, The University of Texas at Arlington, Box 19308, Arlington, TX 76019, USA
2 Center for Undergraduate Infrastructure Research and Education (CUIRE), Department of Civil Engineering, The University of Texas at Arlington, Box 19308, Arlington, TX 76019, USA; vinayak.kaushal@uta.edu (V.K.); najafi@uta.edu (M.N.)
* Correspondence: koosha.jamali@mavs.uta.edu

Abstract: As human beings, we have a moral responsibility to act in a manner that takes the wellbeing of humans and Earth into consideration. When building, we must consider two things: the health of the workforce associated with construction and the state of the planet after building. Many engineers in the past have made groundbreaking achievements to revolutionize the civil infrastructure systems (CIS) industry. However, additive manufacturing (AM) has yet to be significantly recognized throughout the CIS industry. In this review, the use of all fundamental materials utilized by AM in CIS like concrete, metals, and polymers, are discussed. The objective of this study is to expand upon the technology of AM, specifically in CIS and to provide a review on the evolution of AM from 2011 to 2021. The different AM techniques that are utilized to construct said structures are also included. The review study suggests that AM can be useful in the CIS industry, as homes, bridges, and benches were manufactured with this technique. To enhance the reader’s visualization, pictures of the related built structures are also presented. It can be concluded that adopting AM techniques in the CIS industry can save material, speed up the construction process, and create a safer environment for the people that work in the CIS industry. Since the research on this subject is limited, further research on polymer printing along with metal printing is recommended.

Keywords: additive manufacturing; civil infrastructure systems; sustainable construction; construction materials; 3D printing

1. Introduction

One of the recent technological advancements that have become mainstream is the science of additive manufacturing (AM) [1,2]. This technology has decreased our material waste and has sped up our manufacturing process for singular models [3]. When discussing this technology, we always appreciate the American hero Charles Hull for his efforts that led to the advancement of AM. However, we fail to mention Jean-Claude André, the French scientist who had been researching this fascinating technology in the same time frame [4]. We also do not give enough credit to Hideo Kodama, the Japanese rapid prototyping scientist, for all his AM efforts.

Carl Deckard has also contributed to the science of AM and holds the patent in laser sintering of polymer-based materials. Deckard continues to add value to this field by researching the final prints and the general modeling structure [5].

CIS are important components for any nation’s growth and development. As we seek to improve CIS construction methods, we must work efficiently to improve construction sustainability as well. As humans, we also need to maintain our health by creating shelter and the necessary means for living. Another important component for our survival is maintaining the Earth’s wellbeing while we are still not able to live on other planets. In recent years, we have spoken about our place in the universe and our time limit on Earth based on our living standards. We no longer need to fear the Earth’s time limit because we
can minimize our footprint by adjusting our technologies surrounding CIS. Many engineers including Khoshnevis and Lim have researched the possibility of improving AM in CIS to reduce our footprint and construct shelters on other planets with much fewer workers [2]. This review incorporates different AM techniques and briefly addresses their benefits and applications. It is also important to note that this review study helps with understanding different techniques of utilizing AM; this review was also developed because there are not many articles that mention most techniques in a single journal.

2. Additive Manufacturing

2.1. Origin

Almost 40 years ago, AM was invented to create complex parts in record-breaking time. AM is the technology of creating a 3D object by adding layers of material upon each other. This is not a new phenomenon as Kodama first introduced the layer upon layer technology to create an object in 1981 [2].

2.2. Incorporation of AM among Other Fields

Many industries including aerospace engineering, transportation, and the medical field have adopted AM into their works [3]. Aerospace engineering has incorporated AM since it has been proven to drive down costs, reduce weight, and improve safety [6]. In the transportation industry, AM has been utilized to lower costs, reduce manufacturing time, and improve architectural modeling [6]. The medical field has incorporated AM into their methodologies because of many factors such as the high quality of bone prototypes made with it, its ability to be used to craft artificial teeth in dentistry, and its high efficiency in manipulating tissue growth in orthopedic surgery [6].

2.3. Current State of AM in CIS

AM in the CIS industry falls short when compared other industries, as it is a conservative field in terms of modifying its techniques of application. However, there is a copious amount of research surrounding the science of AM in CIS. Concrete, polymer, and metal printing have had great success in terms of reliability, cost cuts, and designer freedom. Currently, there are mobile homes, bridges, and complete homes being built all by using AM [7–9].

2.4. Incentives for Incorporating AM in CIS

There are multitudes of reasons why the CIS industry may be pushed towards automation sooner rather than later. According to Mroszczyk, the CIS industry accounts for 5% of the workforce; however, it is responsible for 15% to 20% of work-related fatalities [10]. By using AM, we can lower on-site accidents by reducing labor [11,12]. Architects will also find the limitations on designer freedom being removed because incorporating building information modeling (BIM) with AM allows the most complex designs to be constructed [12]. This shift in CIS may also be one of the major factors in reducing waste on Earth [11]. It is important to note that the traditional industry of CIS will not rapidly evolve in the United States until the technology of AM and BIM become mainstream.

2.5. Modeling in AM

We need to construct an accurate, efficient, and cost-effective machine to be able to continuously incorporate AM based on the incentives mentioned above. Items made by incorporating AM all have these traits, but they could be more accurate in terms of modeling. Modeling is the process of coordinating dimensions of material on numerous planes. This process has been mathematically improved over time by minimizing the boundary layer of the item within the modeling applications. The main problem of modeling these products made by using AM is that they commonly have deformations [13]. This issue will require a multitude of improvements in extrusion to prevent these deformations from reappearing [14].
The objective of this study is to expand upon the technology of AM specifically in CIS and provide a review on the evolution of AM from 2011 to 2021. Many materials are used to construct structures like concrete, metals, and polymers. Concrete is used for the majority of CIS work including but not limited to foundation work, wastewater treatment facilities, and exterior finishes. Metals are used in foundations, roofs, water pipes, etc. Polymers are used in flooring, windows, pipes, insulation, and much more. Given that there are numerous applications for concrete, metals, and polymers in CIS, it is crucial to review the techniques that are used to achieve acceptable performing products.

3. Additive Manufacturing Techniques

3.1. Stereolithography

Buchanan and Gardner have defined the stereolithography technique to be a form of photopolymerization as “an ultraviolet sensitive liquid polymer is cured using a laser” [8]. Stereolithography has proven to be reliable, accurate, and versatile in terms of solid freeform techniques [15]. Despite being the first AM technique introduced, stereolithography has real-life applications to this day. Some materials used in stereolithography are ceramic resin, durable resin, high temp resin, etc. [16].

3.2. Contour Crafting

Invented by Khoshnevis, contour crafting is an extrusion-based method that utilizes wet concrete and is one of two methods that were developed to manufacture products off-site; however, there was no evidence that on-site production would not be possible [9]. In-situ contour crafting has grown drastically, since working on-site reduces the need for constant transportation and cuts labor by a large margin [17]. Contour crafting was invented for homes, so it is generally only used for concrete [18].

3.3. Concrete Printing

Invented in Loughborough University by engineering researchers, concrete printing was created to reduce the number of difficulties in contour crafting [19,20]. Concrete printing is mostly an extrusion and powder-based technique that can become a leading driver in the AM field, as healthy ecological factors and various material availability have created a promising path [8]. Concrete printing utilizes mortar and cement mixtures as materials.

3.4. D-Shape

Proven to be efficient, successful, and reliable, d-shape technology has been an emerging technology in CIS AM. The process of constructing with d-shape is like all other AM techniques because it creates by adding materials on top of each other. However, one key difference is the drying phase, as it is hardened, dried, and molded by a binder [12]. This makes it like the traditional method of pouring concrete, though it differs due to automation and the materials used. Cement, sand, sandstone, steel fibers, etc. may all be used with this method [21].

3.5. Polymer Printing

Polymer printing has not received the widespread interest that other AM techniques have had. It can be used in plumbing, electrical work, and creating facades [8]. Building numerous amounts of CIS-related objects on-site improves designer freedom, as well as wasting little to no material [8]. Excellent functionality and high mechanical performance in prototype designs have led the conventional molding and casting techniques to the verge of obsolescence [22].

3.6. Rapid Prototyping

Invented by Adrian Bowyer of the University of Bath, UK, for the RepRap project, fused filament fabrication was voted as the most significant 3D-printed object. This method
has turned the AM industry into an industry with unlimited potential. The need for rapid prototyping is not limited to the CIS industry, as the use of a self-replicating unit that allows people in all communities to construct the most complex structures with little to no industry infrastructure [23]. Rapid prototyping can use liquids, solids, and powders of all forms depending on the application [24].

3.7. Metal Additive Manufacturing

Utilized to strengthen previous additive manufactured structures, metal printing now has a larger impact on 3D printing. In recent years, this technique has improved greatly to deliver the best possible product in record breaking time. The need for metal AM is not bound to construction but also affects the automotive industry, industrial engineering, and dental industry [25]. As time will pass, we will observe metal printing in more of our formworks [25]. Many metals including steel, titanium, silver, cobalt, and chrome can be used in metal AM as powders [26].

4. Discussion of AM Results

4.1. Stereolithography

Stereolithography in the medical industry as well as the transportation industry, has witnessed improvements beyond measure. This technology utilizes a beam of laser that activates the resin, which hardens and then creates the desired object. Research has been done in the medical industry to create personalized drugs using stereolithography [27–29]. Since this technique does indeed work in medicine and transportation, we should not ignore its possible impact on the CIS industry.

4.2. Contour Crafting

The evolution of contour crafting has been rapid since it was invented. This method uses a trowel to smoothen the surface of the cement-based paste extruded from the deposition head [12]. This method is very popular among the different methods of AM in the CIS industry. The reason for this is the large diameter of the deposition head that speeds up AM process and the impeccable strength of the hardened material [12].

4.3. Concrete Printing

Reviewing AM over the past couple of years, we could conclude that concrete printing has also grown quickly. A concrete printing device has a printing head, or a concrete depositor laid upon a horizontal axis of the frame. Precise manufacturing, labor cuts, and material use freedom are some of the key conclusions of this method [19]. This method is mostly used in heavy or residential construction, and it can impact the way we operate within the industry [30].

4.4. D-Shape

As time has passed, the d-shape method has left its mark on the CIS industry. D-shape was created as an offsite manufacturing process using powder-based material and unconsolidated material for additional support [12]. As only one company in the world creates these printers, it may not be feasible because there is no competition on this scale. Furthermore, d-shape can construct complex structures rapidly; in fact, this method was used to create the largest object printed in a single session [31].

4.5. Polymer Printing

Polymer printing has also been on the rise, with many things to offer a hand with including but not limited to electrical work, insulation, and plumbing. In the past couple of years, the amount of research on concrete AM was much higher than on polymer AM; however, that might change soon. In a recent study in France, the authors concluded that polymer printing can exceed thermal insulation performance by 30% to 40% [32]. It is also
safer, as this process does not need manual labor to apply polyurethane, which can cause respiratory issues such as asthma upon breathing [33].

4.6. Rapid Prototyping

Rapid prototyping has had its struggles to find its way into the CIS industry. This is because the negative connotation surrounding the term impaired its popularity in this industry [8]. This method was built to be incorporated during the design phase of a construction process [34]. Used to aid the stakeholders of the CIS process in visualizing and coordinating the project after the CAD plan is created, rapid prototyping could decrease CIS errors and the fiscal responsibilities associated with those errors [35–37].

4.7. Metal Additive Manufacturing

The future of metal AM is bright due to the numerous advantages it has compared to conventional welding practices [26]. Directed energy deposition (DED) is superior to the conventional welding methods, as the heat affected zone is smaller, dilution is minimal, and it provides metallurgical bonds. As time passes, we will observe the true capacity for said systems [38].

5. Insights on Utilizing AM

The CIS industry has been vital to the development of society as observed today. It is necessary to incorporate previously mentioned techniques to reduce material waste and increase safety for our workforce. Based on research done by Architect 2030, 40% of annual global greenhouse gasses (GHG) are generated by construction [39]. According to the Occupational Safe and Health Administration, 20% of all accidents in the private industry were from construction [40]. Based on the facts presented in this review study, improving our standards for construction can make the CIS industry safer, reduce GHG, improve designer freedom, make it possible to construct CIS objects faster, and reduce material waste.

6. Recommendations for Further Research

Future research surrounding AM should incorporate cost analyses throughout multiple projects to study the feasibility of this method for the CIS industry. Other scopes of research could be areas for improving final builds using modeling techniques, materials, or equipment. Research can also be done on the comparison of cement printing using different AM methods.

Author Contributions: All authors listed have made a substantial, direct, and intellectual contribution to the work. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Bhardwaj, A.; Jones, S.Z.; Kalantar, N.; Pei, Z.; Vickers, J.; Wangler, T.; Zavattieri, P.; Zou, N. Additive Manufacturing Processes for Infrastructure Construction: A Review. J. Manuf. Sci. Eng. 2019, 141, 091010. [CrossRef]
2. Goldberg, D.; Matsunaka, Y.; Nichols, M.; Rovito, M. History of 3d Printing: It’s Older than You Think [Updated]. 21 December 2018. Available online: https://redshift.autodesk.com/history-of-3d-printing/ (accessed on 3 April 2021).
3. Goldberg, D.; Matsunaka, Y.; Nichols, M.; Rovito, M. History of 3d Printing: It’s Older than You Think [Updated]. 21 December 2018. Available online: https://redshift.autodesk.com/history-of-3d-printing/ (accessed on 3 April 2021).
4. André, J.-C. From Additive Manufacturing to 3d/4d Printing 3: Breakthrough Innovations: Programmable Material, 4d Printing and Bio-Printing; Wiley: Hoboken, NJ, USA, 2018.
5. Williams, J.D.; Deckard, C.R. Advances in modeling the effects of selected parameters on the SLS process. Rapid Prototyp. J. 1998, 4, 90–100. [CrossRef]

6. Wong, K.V.; Hernandez, A. A Review of Additive Manufacturing. Isrn Mech. Eng. 2012, 1–10. [CrossRef]

7. Bogue, R. 3D printing: The dawn of a new era in manufacturing? Assem. Autom. 2013, 33, 307–311. [CrossRef]

8. Buchanan, C.; Gardner, L. Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges. Eng. Struct. 2019, 180, 332–348. [CrossRef]

9. Lim, S.; Buswell, R.; Le, T.; Wackrow, R. Development of a viable concrete printing process. In Proceedings of the 28th International Symposium on Automation and Robotics in Construction (ISARC2011), Seoul, Korea, 29 June–2 July 2011; pp. 665–670.

10. Mroszczyk, J.W. A Strategy for Reducing Construction Fatalities. In Proceedings of the ASSE Professional Development Conference and Exposition, Dallas, TX, USA, 7–10 June 2015.

11. Rouhana, C.; Faek, F.; Jazzer, M.E.; Hamzeh, F. The Reduction of Construction Duration by Implementing Contour Crafting (3D Printing). In Proceedings of the 22nd Annual Conference of the International Group for Lean Construction, Oslo, Norway, 25–27 June 2014. [CrossRef]

12. Lim, S.; Buswell, R.; Le, T.; Austin, S.; Gibb, A.; Thorpe, T. Developments in construction-scale additive manufacturing processes. Autom. Constr. 2012, 21, 262–268. [CrossRef]

13. Manzhurov, A.V.; Lychev, S.A. An Approach to Modeling of Additive Manufacturing Technologies. In Transactions on Engineering Manufacturing Technologies; Springer: Berlin/Heidelberg, Germany, 2015; pp. 99–115. [CrossRef]

14. Fotovvati, B.; Balasubramanian, M.; Asadi, E. Modeling and Optimization Approaches of Laser-Based Powder-Bed Fusion Process for Ti-6Al-4V Alloy. Coatings 2020, 10, 1104. [CrossRef]

15. Melchels, F.P.; Feijen, J.; Grijpma, D.W. A review on stereolithography and its applications in biomedical engineering. Biomaterials 2010, 31, 6121–6130. [CrossRef] [PubMed]

16. Mukhtarukanov, M.; Perveren, A.; Talamona, D. Application of Stereolithography Based 3D Printing Technology in Investment Casting. Micromachines 2020, 11, 946. [CrossRef]

17. Hager, I.; Golonka, A.; Putanowicz, R. 3D Printing of Buildings and Building Components as the Future of Sustainable Construction? Procedia Eng. 2016, 151, 292–299. [CrossRef]

18. Khoshnevis, B. Automated construction by contour crafting—related robotics and information technologies. Autom. Constr. 2004, 13, 5–19. [CrossRef]

19. Kazemian, A.; Yuan, X.; Cochran, E.; Khoshnevis, B. Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture. Constr. Build. Mater. 2017, 145, 639–647. [CrossRef]

20. Yossef, M.; Chen, A. Applicability and Limitations of 3D Printing for Civil Structure. Available online: https://lib.dr.iastate.edu/ccce_conf/35 (accessed on 14 May 2021).

21. Nakazawa, K.; Nakajima, M.; Kobayashi, H. Development of 3-D shape measurement system using fiber grating. Syst. Comput. Jpn. 1987, 18, 11–17. [CrossRef]

22. Wang, X.; Jiang, M.; Zhou, Z.; Gou, J.; Hui, D. 3D printing of polymer matrix composites: A review and prospective. Compos. Part B Eng. 2017, 110, 442–458. [CrossRef]

23. Ko, H.; Witherell, P.; Lu, Y.; Kim, S.; Rosen, D.W. Machine learning and knowledge graph based design rule construction for additive manufacturing. Addit. Manuf. 2021, 37, 101620.

24. Exner, H.; Horn, M.; Streek, A.; Regenfuß, P.; Ullmann, F.; Ebert, R. Advanced Rapid Prototyping Technologies and Nanofabrication; CRC Press: Boca Raton, FL, USA, 2007; pp. 505–690. [CrossRef]

25. Bartlett, J.L.; Li, X. An overview of residual stresses in metal powder bed fusion. Addit. Manuf. 2019, 27, 131–149. [CrossRef]

26. Dutton, B.; Vesga, W. Non-Destructive Evaluation for Additive Manufacturing. In Precision Metal Additive Manufacturing, 1st ed.; CRC Press: Boca Raton, FL, USA, 2020; pp. 195–236. [CrossRef]

27. Karakurt, I.; Aydo˘gdu, A.; Çıkrıkcı, S.; Orozco, J.; Lin, L. Stereolithography (SLA) 3D printing of ascorbic acid loaded hydrogels: A controlled release study. Int. J. Pharm. 2020, 584, 119428. [CrossRef] [PubMed]

28. Stereolithography. Available online: https://www.3dsystems.com/resources/information-guides/stereolithography/sla (accessed on 11 April 2021).

29. ProtoTech Asia. Information about Photopolymerization in Stereolithography. Available online: https://prototechasia.com/en/stereolithography/photopolymerisation (accessed on 14 May 2021).

30. Arianna Maouna Bernardo—Meristone Information Technology Services. Finishing vs. No Finishing on 3D Printed Concrete Wall: Mudbots 3D Concrete Printers. Available online: https://www.mudbots.com/gallery/view-image.php?title=Finishing+vs+No+Finishing+on+3D+Printed+Concrete+Wall&image_id=57 (accessed on 12 April 2021).

31. Jakupovic, A. D-Shape—Report. Available online: http://3dprintetbyggeri.dk/pdf/bes%C3%B8gsrapporter/D-Shape.pdf (accessed on 14 May 2021).

32. Furet, B.; Poullain, P.; Garnier, S. 3D printing for construction based on a complex wall of polymer-foam and concrete. Addit. Manuf. 2019, 28, 58–64. [CrossRef]

33. Dangers of Polyurethane Fumes. Available online: https://enviroklenzairpurifiers.com/dangers-of-polyurethane-fumes/ (accessed on 13 April 2021).

34. Goedert, J.; Bonsell, J.; Samura, F. Integrating Laser Scanning and Rapid Prototyping to Enhance Construction Modeling. J. Arch. Eng. 2005, 11, 71–74. [CrossRef]
35. Gibson, I.; Kvan, T.; Ming, L.W. Rapid prototyping for architectural models. *Rapid Prototyp. J.* 2002, 8, 91–95. [CrossRef]
36. Hough, R. The Magic of Rapid Prototyping. Available online: https://medium.com/minder/the-magic-of-rapid-prototyping-1dcd6b0906 (accessed on 13 April 2021).
37. Architectural Models: Arptech Rapid Prototyping Service: 3d Printing: CNC Machining: FDM: Sla: SLS: Vacuum Casting: Short Run Production. Available online: https://www.arptech.com.au/arch.htm#photogallery (accessed on 13 April 2021).
38. Oh, W.J.; Lee, W.; Kim, M.S.; Jeon, J.B.; Shim, D.-S. Repairing additive-manufactured 316L stainless steel using direct energy deposition. *Opt. Laser Technol.* 2019, 117, 6–17. [CrossRef]
39. Why the Building Sector? Available online: https://architecture2030.org/buildings_problem_why/#:~:text=Buildings%20generate%20nearly%2040%20%25%20of%20annual%20global%20GHG%20emissions (accessed on 16 April 2021).
40. Department of Labor Logo United States Department of Labor. Available online: https://www.osha.gov/data/commonstats (accessed on 16 April 2021).