A Review of Multiple Degrees of Freedom for Additive Manufacturing Machines

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Abstract

Currently, additive manufacturing (AM) technology has received significant attention from both academia and industry. AM is characterized by fabricating geometrically complex components in a layer-by-layer manner, and greatly reduces the geometric complexity restrictions compared with traditional manufacturing. As AM is no longer limited to the normal three degrees of freedom (DOF) (three-axis) systems, there are many new multi-DOF AM machines been developed with various aims. It is, therefore, necessary that a review of the topic with regard to multi-DOF AM is performed for future AM system development. This paper, focuses on reviewing publications related to multi-DOF AM according to the number of DOF on an AM machine. The major part of the paper aims to inspire both researchers and engineers to further develop and improve multi-DOF AM systems to achieve different goals. The final part of the paper discusses the findings together with future research directions.

Keywords: Additive manufacturing; Multi-DOF; Degree of freedom.

1. Introduction

Additive manufacturing (AM) is becoming increasingly popular due to its ability to fabricate complex parts that may not be manufactured by traditional manufacturing technologies (Jiang 2020; Jiang, Xu, et al. 2020). AM is also known as 3D printing, rapid prototyping, freeform fabrication, additive fabrication, additive processes, direct digital manufacturing, rapid manufacturing and layer manufacturing (Jiang, Xu, and Stringer 2018b). The most commonly used AM techniques include Stereolithography (SLA) (Salonitis et al. 2003), Fused Deposition Modeling (FDM) (Jiang, Xu, and Stringer 2019b; Fu et al. 2019; Jiang, Yu, et al. 2020), Selective Laser Sintering (SLS) (Lü, Fuh, and Wong 2001), Selective laser melting (SLM) (Bremen, Meiners, and Diatlov 2012), Sheet Lamination (SL) (Mekonnen, Bright, and Walker 2016), Three Dimensional Printing (3DP) (Sachs, Cima, and Cornie 1990), Inkjet printing (IJP) (Stringer and Derby 2009), Electron beam manufacturing (EBM) (Edwards, O'Conner, and Ramulu 2013), Laser based Metal Deposition (LMD) (Lewis et al. 2000) and Selective laser cladding (SLC) (Liu and Li 2004). The details of these AM techniques can be found in the review papers (Wong and Hernandez 2012; Bikas, Stavropoulos, and Chryssolouris 2016; Bourell 2016; Jiang and Ma 2020).

AM technology has been developed for more than 30 years, since the first AM machine was created. During these years, AM machines have also been improved with one major change being the increased degrees of freedom (DOF) of an AM machine to achieving different goals (e.g. better printed strength, surface quality, more complex parts and functional structures). The DOF of AM machine is defined as the freedoms of the print nozzle, platform or some part of AM machine that has movement freedom. Conventional AM machines are generally limited to three-axis movements (three DOF) with a fixed fabrication orientation in Z. This leads to poorly bonded strength between layers, staircase effects on surface quality, support requirement, limited functions and other problems. Therefore, increasingly researchers have started to investigate innovative AM systems with multi-DOF. Figure 1 shows the number of publications on multi-DOF (more than traditional three DOFs) AM in different years. As can be seen, the number of publications has increased sharply over the last four years. Though in 2019, there have already been 17 papers been published, which is the highest number in all years. According to this trend, publications on multi-DOF AM will probably keep increasing sharply in the next years.

In this paper, publications related to multi-DOF AM are reviewed according to the number of DOF on each AM machine. Publications were searched in Scopus, Google scholar and Web of science, with a total of 58 publications collected. The scope of this paper is limited to multi-DOF AM systems alone, excluding the hybrid multi-DOF systems which combine additive (AM) and subtractive manufacturing (e.g. CNC milling) together (Flynn et.al, 2016). After reviewing these publications, the findings and future directions are discussed in Section 3. The last section ends the paper with some conclusions.

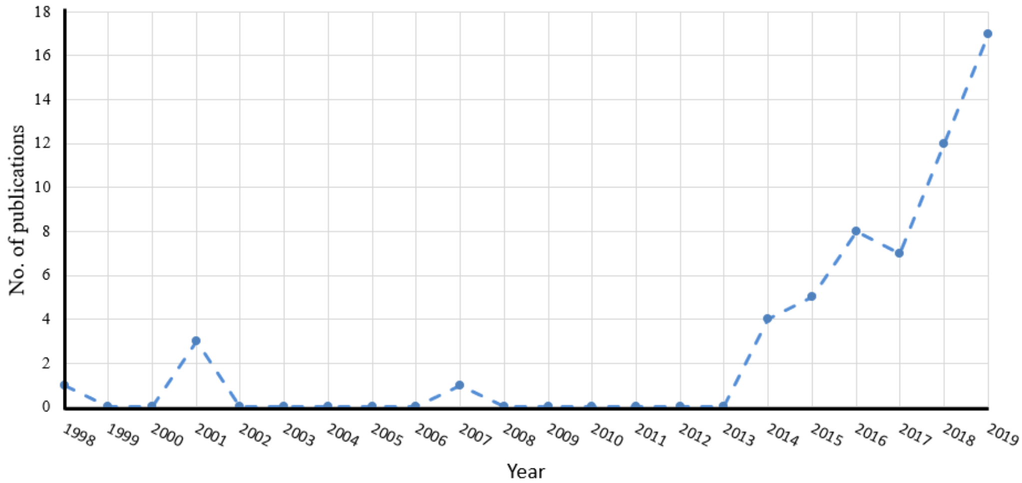


Figure 1 Number of publications on multi-DOF AM in different years.

2. Development of multi-DOF AM

Research studies on multi-DOF AM systems are introduced and classified according to the number of DOF. In each subsection, research works are introduced based on the development of multi-DOF AM systems over time.

2.1. Four-DOF AM

The first four-DOF AM machines were designed by (Ruan et al. 2007) in 2007. They added an extra centroidal axis in the metal AM equipment. A new slicing algorithm was proposed for this four-axis AM equipment, which can generate optimal slices to achieve fabrication without AM supports. In 2014, Hunt et al. (2014) developed a flying AM that combines an AM machine with aerial robotics. This four-DOF AM machine can fabricate structures using polyurethane expanding foam in the air while flying. One year later, Gao et al. (2015) modified a normal FDM printer into a four-DOF printer with a revolving cuboidal platform. They called this new printer as “RevoMaker”. This new printer can achieve less build time and reduces the amount of support material. The working principle is shown in Figure 2.

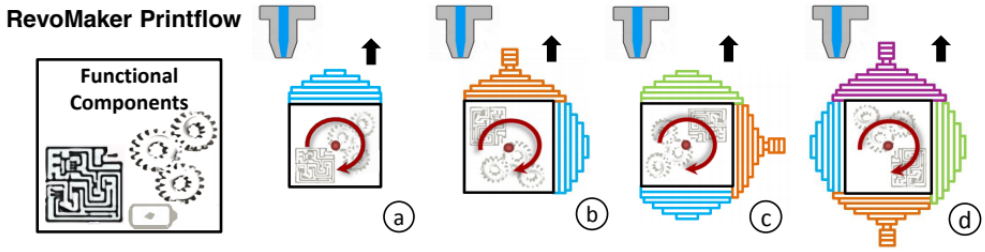


Figure 2 (a)-(d) revolving a cuboidal base for four partitioned geometries around the base (Gao et al. 2015).

In 2016, Wang et al. (2016) designed and analyzed the feasibility of using an industrial robot for extrusion-based AM. They optimized the extrusion process to eliminate the void density and increase the manufacturing efficiency and printed quality of large-scale structures. After one year, Li et al. (2017) proposed a potential in-situ printing platform (four-DOF) that may be directly applied during surgical operations. A double-light-source curing method was used to deposit poly (ethylene glycol) diacrylate (PEGDA) with a 20% (weight/volume) ratio. Figure 3 shows the structure and principle of this designed printer.

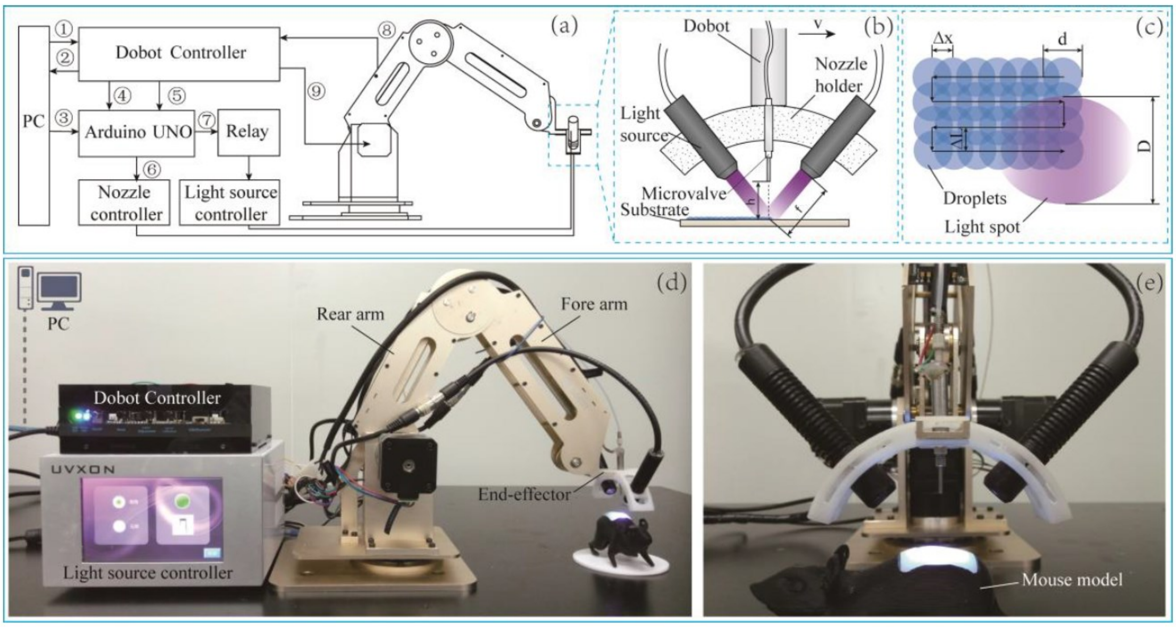


Figure 3 (a) Schematic diagram of hardware structure; (b) schematic diagram of nozzle structure; (c) top view of fabrication process; (d) robotic arm printing platform; (e) double-light-source inkjet light curing nozzle (X. Li et al. 2017).

In the year of 2018, Shen, Ye et al (2018) developed a reconfigurable platform for a Delta FDM 3D printer. They modified the 3D printer' platform with multiple pins that can move up and down. These pins can act as support structures during the fabrication process, thus reducing the support usage during the printing process. Figure 4 shows the structure of this reconfigurable platform.

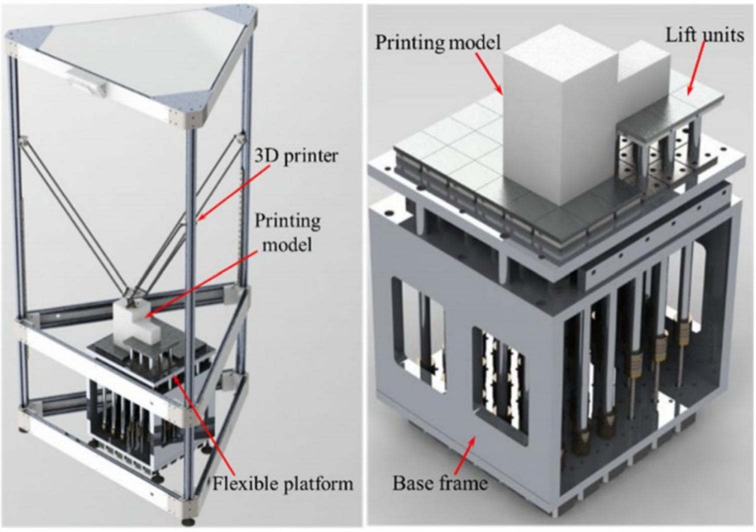


Figure 4 Structure of developed printer in (Hongyao, Xiaoxiang, and Jianzhong 2018).

2.2. Five-DOF AM

The first five-DOF AM machine was developed in 1998, by (Milewski et al. 1998). They designed a five-axis direct metal deposition process, using high-powered laser beam as the energy. A hemispherical shape was fabricated in their machine for showing the feasibility. Three years later, Zhang and Liou (2001) studied an adaptive slicing strategy for a five-DOF laser additive manufacturing process. Their slicing algorithm can generate optimal slice paths to achieve fabrication without using support structures. In the same year, Sundaram and Choi (2001) proposed a direct slicing procedure for CAD models for five-axis AM process. However, no real parts were manufactured in their study, only the procedure was illustrated. In the year of 2014, Pan et al. (2014) designed a five-axis AM machine by integrating multiple tools and axis motions. This printer is similar to CNC machining, accumulating materials onto an existing model (see Figure 5). Light-source curing was used for fabrication in the resin. In the same year, Calleja et al. (2014) optimized the process parameter and strategies for five-axis laser cladding AM. Didier et al (2014) developed a strategy to improve the five-axis laser direct metal deposition process.

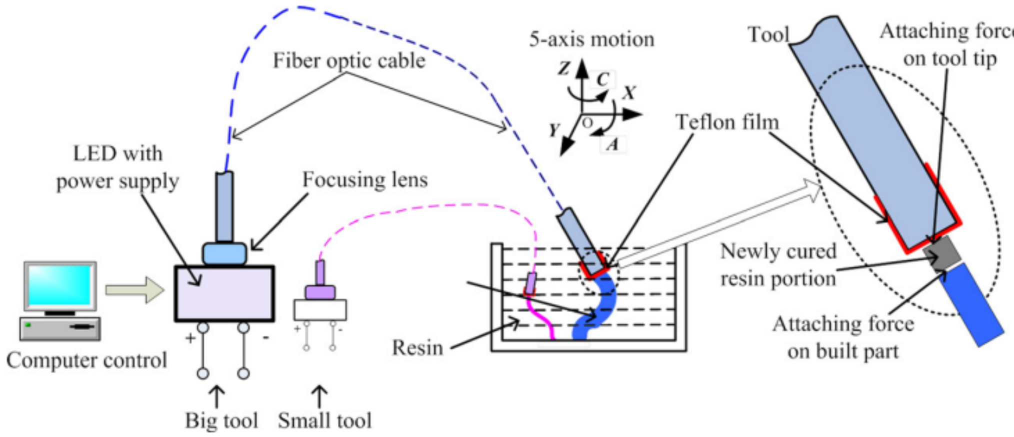
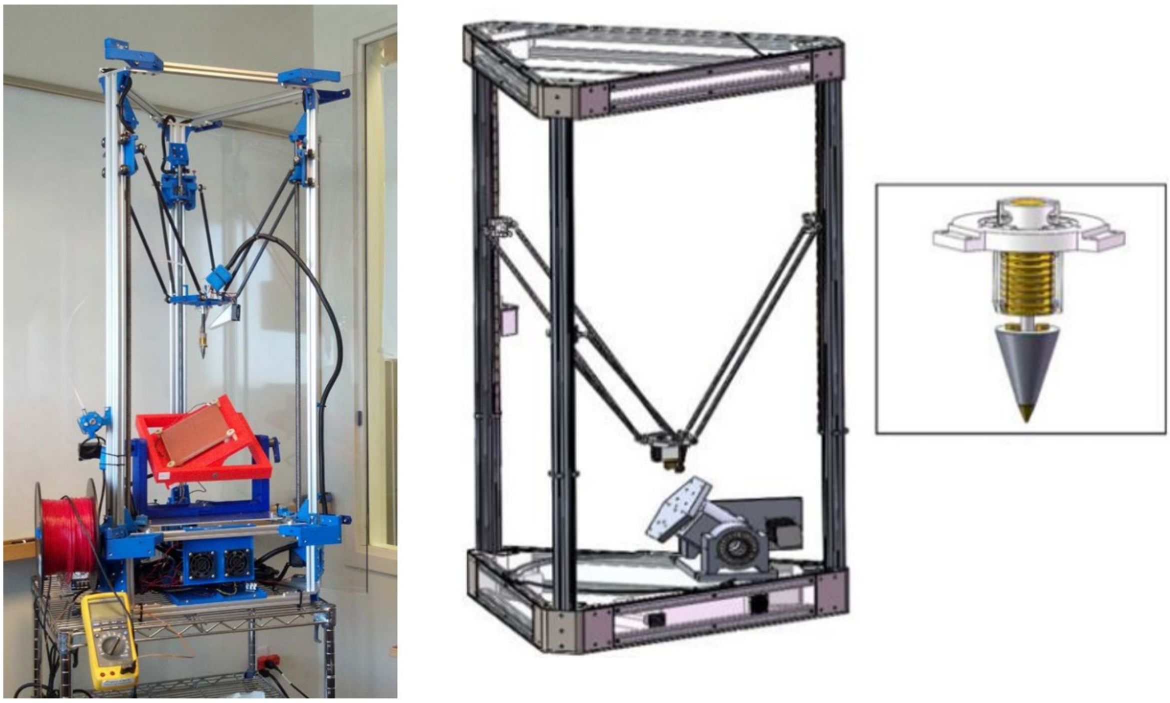


Figure 5 Schematic illustration of the AM machine developed in (Pan et al. 2014).

In 2015, Lee and Jee (2015) proposed a slicing algorithm for five-axis direct metal deposition AM. This algorithm can successfully print overhang/undercut features. Kim et al. (2015) developed a five-axis system to build multi-material parts using FDM technology. In 2016, Wu et al. 2016; Peng et al. (2016) developed a five-DOF printer to fabricate wire mesh models. Such models were printed edge by edge, using freeform motions. Yerazunis et al (2016) proposed a five-axis AM machine for printing parts with improved strength as shown in Figure 6(a). In 2018, Zhao et al. (2018) presented two non-planar slicing strategies for five-axis robotic FDM printer. It was claimed that the new slicing strategies can lead to less number of layers and less part support usage. Shen, Diao et al. (2018) designed a five-axis FDM printer that can improve printed surface quality and reduce support waste. The designed printer has a moving platform and the print nozzle was adjusted and improved accordingly (see Figure 6(b)). With the aim of using zero support, Murtezaoglu et al. (2018) proposed a method to evaluate manufacturing feasibility of part geometries and process planning strategies for a five-axis AM. Zhao et al. (2019) proposed a feature-based path planning method for a five-DOF FDM system.



(a) (b)

Figure 6 Five-axis AM machine in (a) (Yerazunis, Barnwell III, and Nikovski 2016) *and (b)* (Shen et al. 2018)

Currently in 2019, Xu, Chen, and Tang (2019) proposed a novel multidirectional process planning algorithm for five-axis AM for achieving support-free fabrication. Wook et al. (2019) tried to repair metal parts by using a five-axis laser based direct metal deposition machine (see Figure 7). A.Isa and Lazoglu (2019) designed a five-axis 3D printer (see Figure 8(a)) to prevent staircase effects on shell and solid parts. This printer can also achieve fabrication without support. Chen et al. (2019) also investigated a five-axis FDM printer for reducing staircase effect and fabricating thin-shell structures. Grazioso, Di Maio, and Di Gironimo (2019) proposed a new metal five-DOF AM system for non-planar printing, using an internal surface of radome systems as a demonstration. Figure 8(b) shows the structure of this AM system. Plakhotnik et al. (2019) presented an approach to optimize the fabrication process in a five-DOF laser-based metal AM system, considering collisions. Another five-DOF extrusion-based machine was developed by (Nishikawa, Morimoto, and Hayashi 2019), their study also proposed an optimized path generation strategy to fabricate support-free products.

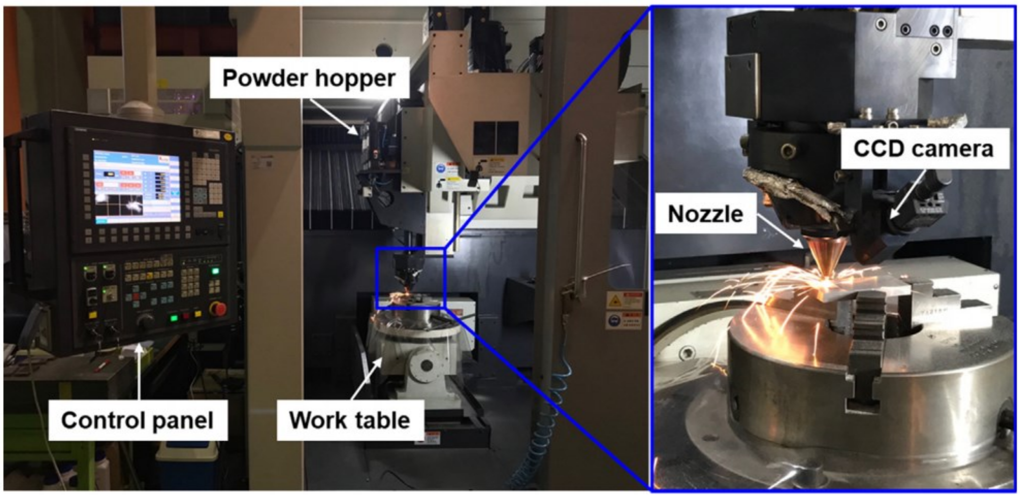
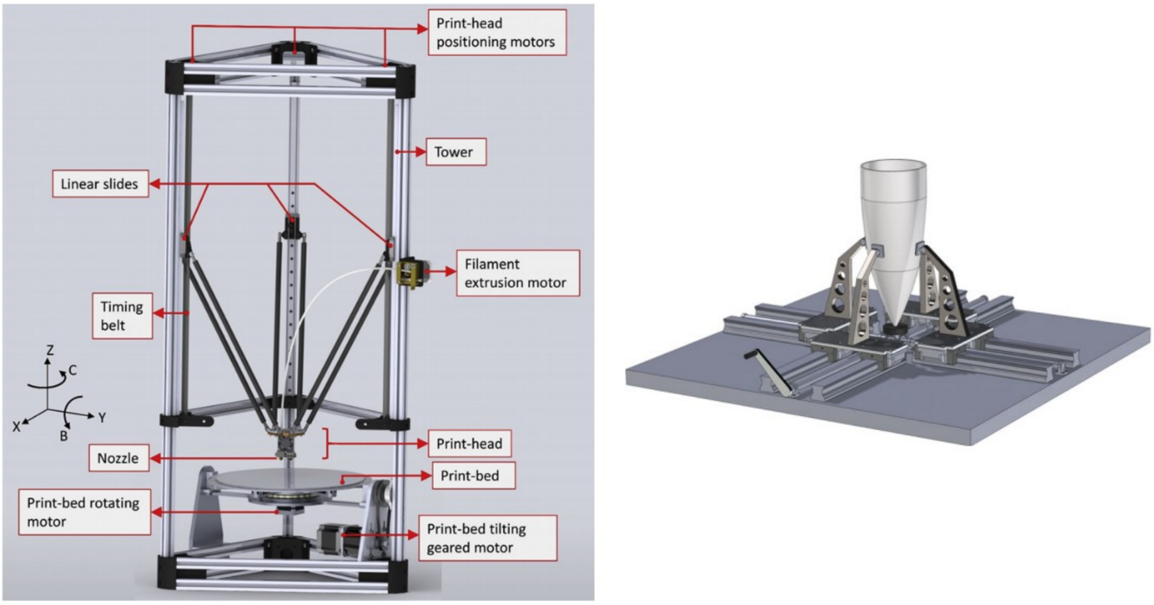


Figure 7 Five-DOF AM systems in (Wook Jin Oh et al. 2019).

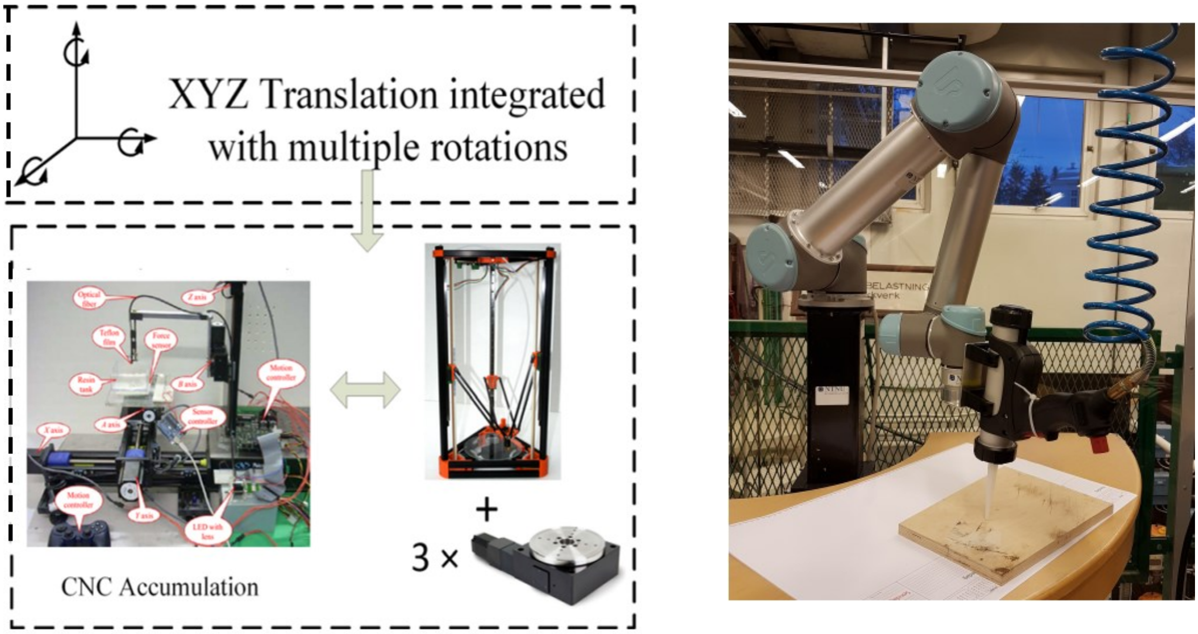


(a) (b)

Figure 8 Designed five-DOF printer in (A.Isa and Lazoglu 2019) *(a) and* (Grazioso, Di Maio, and Di Gironimo 2019) *(b).*

2.3. Six-DOF AM

The first six-DOF AM machine was appeared in 2015, developed by (Song, Pan, and Chen 2015) and (G. Q. Zhang et al. 2015). In (Song, Pan, and Chen 2015), a six-axis FDM printer was designed and tested by the authors. The mechanisms of this printer is shown in Figure 9(a). (G. Q. Zhang et al. 2015) presented a method and process to print components along curved surfaces by a six-DOF industrial robot. In 2016, Sean Doherty et al. (2016) designed a six-axis AM machine that can print parts with reinforcement to enhance the fabricated mechanical properties. Bin Ishak, Fisher, and Larochelle (2016) used an industrial robot arm for AM that can achieve multi-plane printing, enabling printing in multiple planes. In 2017, Danielsen Evjemo et al. (2017) used a robot manipulator for metal AM. In their design, the welding method Cold Metal Transfer (CMT) is adopted to deposit metal (see Figure 9(b)). Shakor et al. (2017) proposed a six-DOF printer that is constructed by Damp Least Squares (DLS) and Resolved Motion Rate Control (RMRC). The buildability, flowability, extrudability and moldability of different concrete mixture designs were tested in this AM machine for construction aims. Wu et al. (2017) developed a six-axis FDM printer "RoboFDM" that can fabricate parts without supports. Tam and Mueller (2017) proposed a new method of material deposition called Stress Line Additive Manufacturing (SLAM) for a six-axis AM machine. This deposition method deposits material along paths derived from principal stress lines that can improve the printed mechanical properties.



(a) (b)

Figure 9 Mechanisms of six-axis printer in (Song, Pan, and Chen 2015) *(a) and* (Danielsen Evjemo et al. 2017) *(b).*

In 2018, Dai et al. (2018) presented a six-DOF printer that can deposit material along curved layers, thus achieving zero support usage (see Figure 10). Kubalak, Wicks, and Williams (2018) proposed a six-DOF AM system to fabricate parts with improved mechanical properties. De Backer, Bergs, and Van Tooren (2018) investigated a six-DOF AM machine to fabricate parts with continuous fiber reinforcement to improve printed strength. Bhatt et al. (2018) developed a robot assisted sheet lamination based AM system. This AM system can fabricate thin multi-functional structures with multiple materials. Izard et al. (2018) investigated a cable-driven parallel robot AM for constructions, with the main focus on acute modelling of the cable and its extension under load. Subrin et al. (2018) improved the mobile robot location in a six-axis AM for performing the fabrication in the best conditions, dedicated for house constructions. In 2019, Kubalak, Wicks, and Williams (2019) studied the influence of layering and deposition direction changes on the tensile properties of six-DOF AM printed structures. Kraljić and Kamnik (2019) proposed a new strategy to slice curved layers to improve printed strength in a six-DOF industrial robot AM. In addition, Shen, Sun, and Fu (2019) introduced a multi-view and all-round vision detection method to detect defects on the outer surface in a six-DOF AM printing process. Figure 11 shows their hardware system structure and the robot FDM printer. Shembekar et al. (2019) proposed trajectory planning algorithms for AM using nonplanar deposition method. Their method can fabricate complex structures with curvatures in a six-DOF AM system shown in Figure 12. Li, Xiong, and Yin (2019) presented a strategy to fabricate thin-wall parts with stable molten pool in a six-DOF metal AM system. With the aim of printing support-free lattice structures, a six-DOF FDM machine was developed by Ishak and Larochelle (2019).

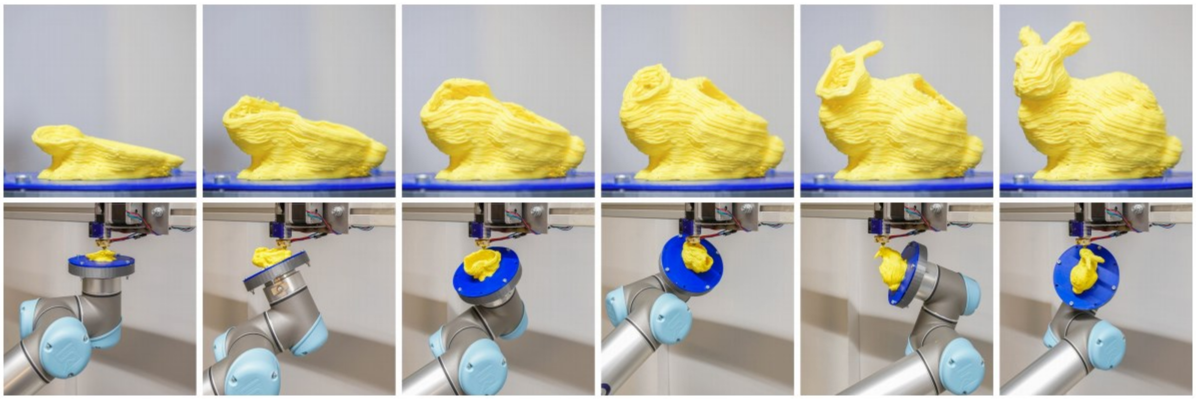


Figure 10 Six-DOF printer printing process examples in (Dai et al. 2018).

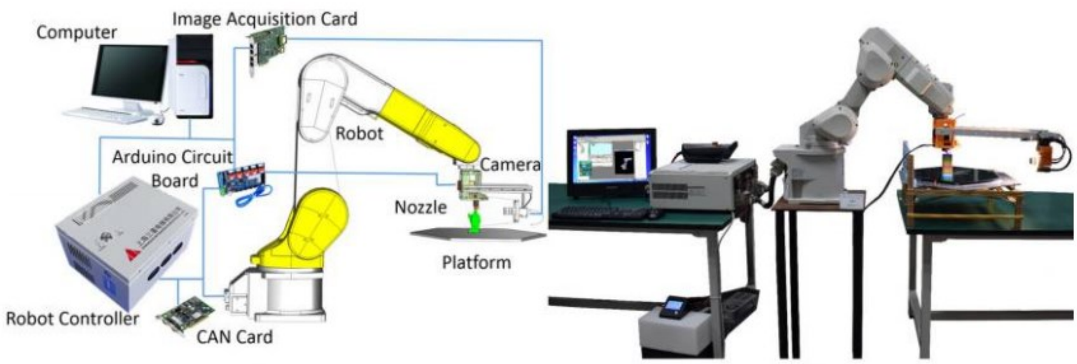


Figure 11 Schematic of six-DOF AM machine in (Shen, Sun, and Fu 2019).

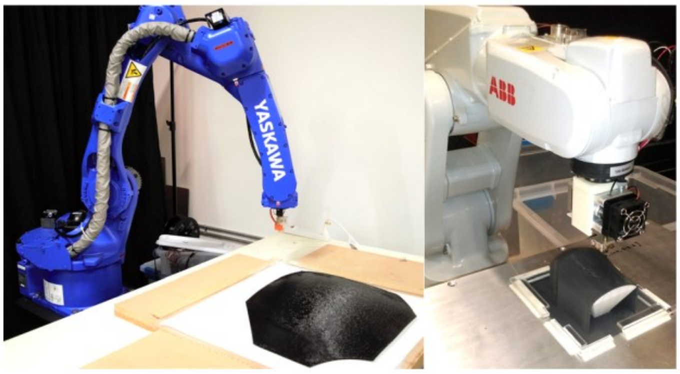


Figure 12 Six-DOF AM system in (Shembekar et al. 2019).

2.4. Seven-DOF AM

Moore and Kurfess (2019) designed the first seven-DOF AM machine in 2001, based on the technique of Stereolithography (SLA). In 2018, Coupek et al. (2018) developed a seven-axis FDM printer with optimized path planning algorithms that can reduce total support usage and build time. Figure 13 shows an example of the printing process with this printer.

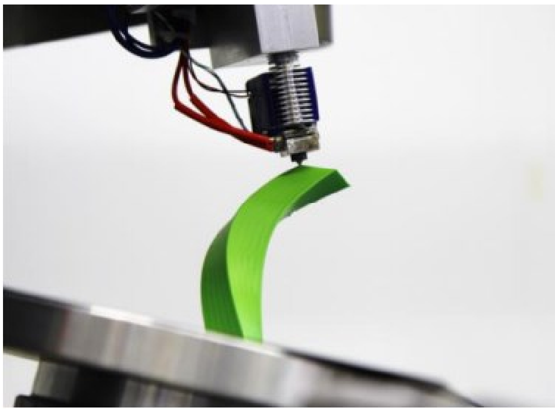


Figure 13 Printing process of seven-DOF printer developed in (Coupek et al. 2018).

2.5. Eight-DOF AM

In 2016, (Ding, Warton, and Kovacevic 2016; Ding and Kovacevic 2016) developed an eight-DOF AM machine, based on laser direct metal deposition technique. They investigated a sensing and control system for improving the process reliability and repeatability of printed metal parts. In 2017, they further proposed a printing process for successfully fabricating complex revolved structures (Ding, Dwivedi, and Kovacevic 2017). Their developed metal eight-DOF AM system is shown in Figure 14. Currently in 2019, the group of Guo (Weng et al. 2019; Jiang, Weng, et al. 2019) tried to print functional parts in an eight-DOF laser based direct metal deposition process. Their designed AM machine is shown in Figure 15(a). Hao et al. (2019) studied the influence of tilt angle between laser nozzle and substrate on bead morphology in an eight-DOF AM system (see Figure 15(b)). Ma et al. (2019) proposed a path planning method for fabricating thin-walled parts in a metal eight-DOF AM system.

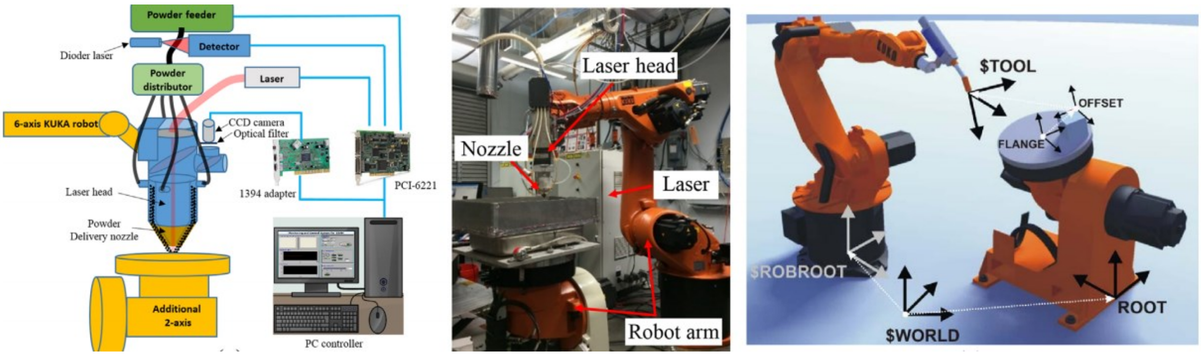
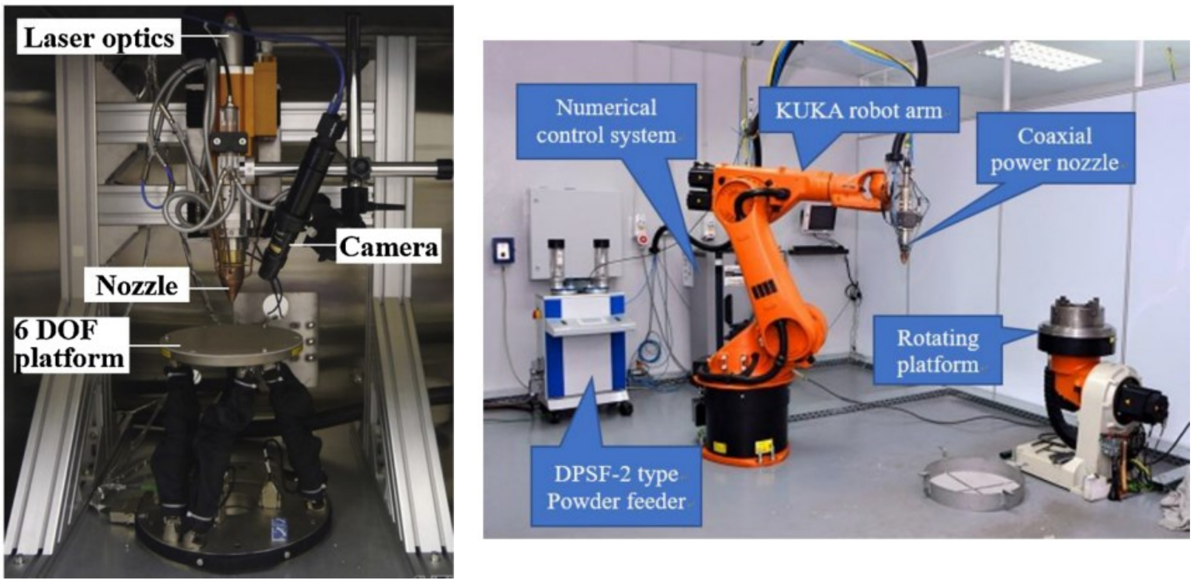


Figure 14 Schematic of eight-DOF AM system developed in (Ding, Dwivedi, and Kovacevic 2017).



(a) (b)

Figure 15 Constructed eight-DOF AM machine in (Weng et al. 2019) *(a) and* (Jingbin Hao et al. 2019) *(b).*

2.6. Twelve-DOF AM

In 2018, Zhang et al. (2018) tried to print a single construction part by combining two robotic AM machines into a single system. As the AM system consists of two six-DOF robotic arms, this AM machine is considered as a twelve-DOF AM system. Figure 16 shows this AM system when it is printing a single part.

Figure 16 Twelve-DOF AM system developed in (Zhang et al. 2018).

3. Findings, Future Directions and Discussion

(1) Most of the research work carried out has been based on five and six-DOF AM systems. Figure 17 presents the number of publications on multi-DOF AM with different number of DOF. As can be seen, the main focus of researchers is on five- and six-DOF AM machines. The reason of this may be due to the ease of control of five and six-axis robots. Most of the five and six-DOF AM systems were based on already existing robots that generally have five or six DOFs. These robots were then integrated into AM fabrication process by altering the robotic control systems. Given this phenomenon, one of future directions is to develop improved multi-DOF AM considering the special characteristics of AM, rather than integrating robots into AM alone. For example, the AM system can be an advanced robot itself with excellent and various functions (i.e. new designed robotic with specific functions for AM rather than integrating conventional robotics into AM).

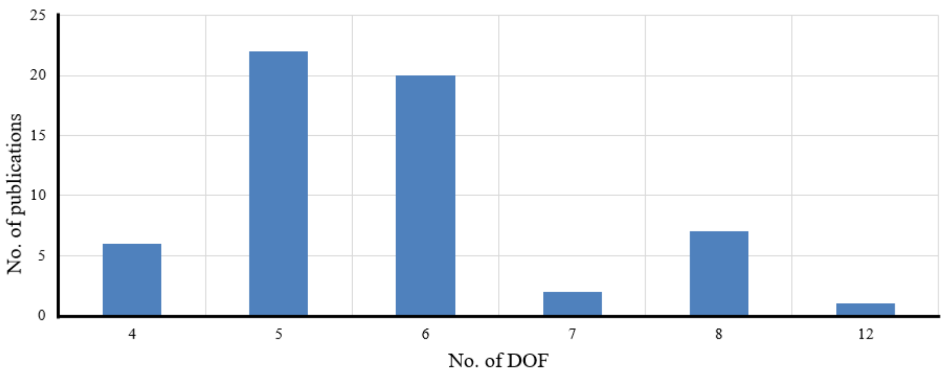


Figure 17 Number of publications on multi-axis AM with different number of DOF.

(2) Multi-DOF AM still require significant further development. Currently, the multi-DOF AM technique is still in its early stage, present studies on multi-DOF AM are mainly for proving the

feasibility of this technique for some specific objectives. Tables 1-6 list the corresponding AM technique, objective and material used in each publication. It could be observed that most studies focus on a specific aim (e.g. support reduction, surface quality improvement or printed strength improvement). Little research has been carried out to develop an advanced multi-DOF AM system that can achieve all (or most of) the objectives (support reduction, surface quality improvement, printed strength improvement, etc.). Such techniques will need significantly more research efforts to be robust enough and to be as popular as FDM. In addition, most of the current multi-DOF AM systems have a high cost because of the involvement of robotics. Low-cost multi-DOF AM systems can be designed and studied in the future.

(3) Higher DOF AM does not have to be better than lower DOF AM. It is not necessary that higher DOF AM systems can achieve better performance than lower one. As can be seen in Tables 1-6, the studies by (Gao et al. 2015), (Shen, Ye, et al. 2018), (Zhao et al. 2018), (Shen et al. 2018), (Dai et al. 2018) and (Coupek et al. 2018) are all aimed at reducing support waste in the fabrication process, even though they have different number of DOFs. It is hard to tell which AM system is better than another, as they do not use the same 3D model for comparison (Jiang, Stringer, Xu, and Zheng 2018). Although in general, the lower the DOF system it is easier to control than the higher DOF AM system, and also has a lower cost as well. In the future, the multi-DOF AM system should be developed in a way that is as simple as possible, as long as the AM system can achieve corresponding goals.

(4) As can be seen from Tables 1-6, current developed multi-DOF AM systems are mainly based on FDM, Laser based direct metal deposition, SLA and sheet lamination. There are few research works on multi-DOF AM reported on other AM techniques such as powder bed fusion and binder jetting. In the future, investigations should be carried out on more AM techniques with multiple DOFs.

(5) As can be seen from Tables 1-6, current applications of these developed multi-DOF AM systems include surgical operation, prototyping and construction. However, conventional three-DOF AM has already been used in industry, aerospace, marine and more fields (Wang et al. 2018; Zheng et al. 2017; Javeed Shaikh Mohammed 2016; Staiano et al. 2018). With the use of multi-DOF AM it is expected that other applications areas (e.g. bioprinting, marine and aerospace engineering) can provide significant advantages and be incorporated in the future.

(6) As can be seen in Tables 1-6, the materials used in current multi-DOF AM systems are mainly polymers, metals and concrete. In addition to these, more materials are expected to be

investigated in the future for multi-DOF AM systems, these include ceramics, ink, metamaterial and 4D printing materials.

(7) The development of multi-DOF AM systems require innovations in both hardware and software components. Algorithms/strategies for freeform trajectory planning are necessary to be investigated and implemented for getting automated CAD/CAM process chains. Fabrication control should be adapted to the requirements of these new trajectories/paths, enabling new material deposition method in these multi-DOF AM systems. Developing new hardware is also required, including the redesign and adaptation of print nozzles, machine structures, etc.

(8) In traditional AM processes, the filament print orientation is generally limited in the Z direction. This leads to the staircase effect on the printed surface and support structures, resulting in deteriorated surface quality and support material waste (Jiang, Xu, and Stringer 2018a; Jiang, Lou, and Hu 2019; Jiang, Hu, et al. 2019; Jiang, Stringer, Xu, and Zhong 2018; Jiang, Xu, and Stringer 2019a). However, multi-DOF AM systems can achieve nonplanar or even freeform printing, which has a major advantage for repairing parts in demand, reducing support waste, improving finished surface quality and improving printed strength (especially in the Z direction compared with conventional three-DOF AM). Tables 1-5 list the corresponding improvement in each multi-DOF AM research work. In addition, multi-DOF AM systems can achieve limitation-free fabrication in terms of the space and size if the systems use a robotic configuration, thus allowing AM systems to build structures that are larger than the AM machine itself.

Table 1 AM technique, objective and used material of each 4DOF AM system.

Ref.	AM technique	Objective	Material
(Ruan et al. 2007)	Laser-based direct metal deposition	Generate optimal slices to fabricate parts with better surface quality and without support	Metal
(Gao et al. 2015)	Extrusion-based	Reduce material usage and support waste	Polymer
(Wang et al. 2016)	Extrusion-based	Investigate high speed printing large-size prototypes	Granular materials
(Li et al. 2017)	Light-source curing method	In-situ printing for surgical operations	Poly(ethylene glycol) diacrylate

(Hunt et al. 2014)	Extrusion-based	3D printing in the air (in mid-flight)	Two part polyurethane foam
(Shen, Ye et al. 2018)	Extrusion-based	Reduce support waste	Polymer

Table 2 AM technique, objective and used material of each 5DOF AM system.

Ref.	AM technique	Objective	Material
(Isa and Lazoglu 2019)	Extrusion-based	Reduce support and improve printed surface quality	Polymer
(Xu, Chen, and Tang 2019)	Extrusion-based	Print parts without support	Polymer
(Lee and Jee 2015)	Directed metal deposition	Develop software for the process management that controls multi-axis tool paths	Metal
(Pan et al. 2014)	Light-source curing	Fabricate conformal features on given curved surfaces	Resin
(Wu et al. 2016; Peng et al. 2016)	Extrusion-based	Reduce collisions and smooth the printing process	Polymer
(Zhao et al. 2018)	Extrusion-based	Reduce support usage and production time	Polymer
(Calleja et al. 2014)	Laser cladding	Optimize process parameters and strategies for fabrication	Metal
(Didier Boisselier, Simon Sankaré, and Thierry Engel 2014)	Laser-based direct metal deposition	Smooth trajectories and stabilize the deposition process	Metal
(Zhang and Liou 2001)	Laser-based direct metal deposition	Achieve fabrication without supports and with better surface quality	Metal
(Shen et al. 2018)	Extrusion-based	Reduce staircase effect and support usage	Polymer
(Zhao et al. 2019)	Extrusion-based	Fabricate parts in STEP format	Polymer
(Murtezaoglu et al. 2018)	Extrusion-based	Propose a method to check fabrication feasibility of geometries and subsequent manufacturing strategies	Polymer

(Sundaram and Choi 2001)	/	Develop a slicing procedure to fabricate parts without support	/
(Milewski et al. 1998)	Laser-based direct metal deposition	Fabricate complex shapes with potentially lower costs and higher quality	Metal
(Yerazunis, Barnwell III, and Nikovski 2016)	Extrusion-based	Improve printed part strength	Polymer
(Kim et al. 2015)	Extrusion-based	Multi-material fabrication	Polymer/wire
(Plakhotnik et al. 2019)	Laser-based direct metal deposition	Fabricate parts without collisions	Metal
(Chen et al. 2019)	Extrusion-based	Reduce staircase effect and fabricate thin-shell structures	Polymer
(Nishikawa, Morimoto, and Hayashi 2019)	Extrusion-based	Fabricate parts without supports	Polymer
(Grazioso, Di Maio, and Di Gironimo 2019)	Aerosol jet printing	Direct additive manufacturing on non-planar surfaces	Metal
(Wook Jin Oh et al. 2019)	Laser-based direct metal deposition	Repair parts	Metal

Table 3 AM technique, objective and used material of each 6DOF AM system.

Ref.	AM technique	Objective	Material
(Dai et al. 2018)	Extrusion-based	Print parts without support	Polymer
(Kubalak, Wicks, and Williams 2019)	Extrusion-based	Improve printed mechanical properties	Polymer
(Sean Doherty et al. 2016)	Extrusion-based	Add reinforcement to printed geometries	Polymer
(Kubalak, Wicks, and Williams 2018)	Extrusion-based	Improve printed mechanical performance	Polymer
(De Backer, Bergs, and Van Tooren 2018)	Extrusion-based	Fabricate parts with continuous reinforcement to improve strength	Polymer
(Shen, Sun, and Fu 2019)	Extrusion-based	Propose a solution to the problem of detecting defects	Polymer

		on the outer surface in the printing process	
(Kraljić and Kamnik 2019)	Extrusion-based	Improve printed part strength and quality	Polymer
(Danielsen Evjemo et al. 2017)	Welding method (Cold Metal Transfer)	Develop a robot manipulator to do metal AM	Metal
(Bhatt et al. 2018)	Sheet lamination based AM	Fabricate thin multifunctional parts with multiple materials	Mylar, fibre, PLA, etc.
(Izard et al. 2018)	Extrusion-based	Investigate the necessary technical implementations on a Cable-driven parallel robots for construction related additive manufacturing	Concrete
(Subrin et al. 2018)	Extrusion-based	Improve the accuracy of the robotic system	Concrete
(Shakor et al. 2017)	Extrusion-based	Optimise different concrete mix designs for additive manufacturing construction	Mixed materials consist of ordinary Portland cement, sand, coarse aggregate and chemical admixtures
(Bin Ishak, Fisher, and Larochelle 2016)	Extrusion-based	Develop multi-plane toolpath motions for robot arm additive manufacturing	Polymer
(Song, Pan, and Chen 2015)	Extrusion-based	Develop a low-cost 6-DOF 3D printer	Polymer
(Zhang et al. 2015)	Extrusion-based	Free-form Fabrication	Polymer
(Wu et al. 2017)	Extrusion-based	Print 3D models without support structures	Polymer
(Tam and Mueller 2017)	Extrusion-based	Improve printed mechanical behaviour	Polymer
(Li, Xiong, and Yin 2019)	Wire and arc AM	Fabricate thin-wall parts with stable molten pool	Metal
(Ishak and Larochelle 2019)	Extrusion-based (FDM)	Fabricate support-free lattice structures	Polymer
(Shembekar et al. 2019)	Extrusion-based	Print complex geometries with curvatures	Polymer

Table 4 AM technique, objective and used material of each 7DOF AM system.

Ref.	AM technique	Objective	Material
(Moore and Kurfess 2019)	Stereolithography (SLA)	Achieve greater functionality and flexibility	Liquid photopolymer
(Coupek et al. 2018)	Extrusion-based	Reduce support and fabrication time	Polymer

Table 5 AM technique, objective and used material of each 8DOF AM system.

Ref.	AM technique	Objective	Material
(Ding, Dwivedi, and Kovacevic 2017)	Laser-based direct metal deposition	Print complex revolved parts and reduce production time	Metal
(Ding, Warton, and Kovacevic 2016)	Laser-based direct metal deposition	Process reliability and the repeatability of finished components	Metal
(Ding and Kovacevic 2016)	Laser-based metal AM	Investigate the feasibility of fabricating metallic structural materials with the developed eight-axis AM system	Metal
(Jingbin Hao et al. 2019)	Laser cladding	Optimize the process of eight-axis laser cladding	Metal
(Ma et al. 2019)	Wire and arc AM	Fabricate thin-walled structures	Metal
(Weng et al. 2019; Jiang, Weng, et al. 2019)	Laser-based direct metal deposition	Fabricate functional parts and improve overall efficiency	Metal

4. Conclusions

In this paper, multi-DOF AM machines have been reviewed according to the number of DOF. Corresponding AM techniques, objectives, material used and the application of each research work have been identified. In summary, the review shows that significant research achievements have been made in multi-DOF AM in the past few years, but research in this field is still far from mature. More advanced multi-DOF AM systems still need to be investigated in terms of the range of materials used, increased application areas and reduced costs. The major goal for the future is to achieve low-cost multi-DOF AM systems that can be designed and programmed to maximize the capability of the system to produce finished support-free and/or functional AM parts.

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