ARL-TR-9293 ● SEP 2021

DEVCOM ARMY RESEARCH LABORATORY

Multiple Robot-Arm Synchronization for Convergent Manufacturing: A Review

by Nikhil Murty and Isaac Nault

Approved for public release: distribution unlimited.

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

ARL-TR-9293 ● SEP 2021



Multiple Robot-Arm Synchronization for Convergent Manufacturing: A Review

Nikhil Murty and Isaac Nault
Weapons and Materials Research Directorate,
DEVCOM Army Research Laboratory

Approved for public release: distribution unlimited.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
September 2021	Technical Report	10 January 2020–09 August 2021

4. TITLE AND SUBTITLE
Multiple Robot-Arm Synchronization for Convergent Manufacturing: A Review

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Nikhil Murty and Isaac Nault

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
DEVCOM Army Research Laboratory
ATTN: FCDD-RLW-MD
Aberdeen Proving Ground, MD 21005

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-9293

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
ORCID ID: Isaac Nault, 0000-0002-9597-9199

14. ABSTRACT

This report reviews the use of multiple robot arms in additive manufacturing (AM) for the purpose of identifying research gaps relevant to the Army's *Convergent Manufacturing Science and Technology Strategy*. Use of multiple robot arms for AM in published literature includes fixed printers, swarm printers, robot arms with a movable build plate, hybrid AM, and software tools. The technology has proven to be very useful in reducing build times, improving surface resolution, and reducing the need for support structures. However, the review concludes that there are gaps in the research that must be addressed for the Army to meet its objectives in convergent manufacturing.

15. SUBJECT TERMS
convergent manufacturing, robot arm, additive manufacturing, hybrid manufacturing, advanced manufacturing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Isaac Nault
Unclassified	Unclassified	Unclassified	UU	27	19b. TELEPHONE NUMBER (Include area code) (410) 306-0865

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures iv

1. Introduction 1

2. Multiple Fixed Robot Arms for Scalability 2

3. Robot Printers with a Movable Build Plate 5

4. Swarm Printing 8

5. Multiple Robot Printers for Hybrid AM 13

6. Software Control 14

7. Conclusions 15

8. References 17

List of Symbols, Abbreviations, and Acronyms 20

Distribution List 21

List of Figures

Fig. 1 LPT (left) and MOA (right) algorithms used 3
Fig. 2 Schematic of the multirobot system 4
Fig. 3 Flowchart for creating the segments 4
Fig. 4 Autodesk's Project Escher 5
Fig. 5 LBDMD system 6
Fig. 6 How the reorientation of the build plate works 7
Fig. 7 Bhatt's build-platform and printer in (left) and the simulation in robot studio (right) 7
Fig. 8 System used by Kutzer et al. 8
Fig. 9 How the chunking algorithm works 9
Fig. 10 System architecture for the University of Arkansas' swarm system 10
Fig. 11 The 3-D printer (left) and the mobile platform (right) 11
Fig. 12 System setup for the robotic cement printer (left) and the printers printing together (right) 12
Fig. 13 Minibuilders system: base robot (left), grip robot (middle), vacuum robot (right) 12
Fig. 14 Robot arm moving the build plate between the 3D printer and drill 14

1. Introduction

Critical capability gaps for the US Army and Department of Defense can be addressed by convergent advanced manufacturing capabilities. The importance of advanced manufacturing to the Army's modernization is emphasized in *Army Directive 2019-29, Enabling Readiness and Modernization through Advanced Manufacturing*[1]:

> The implementation of advanced manufacturing will enable the Army to achieve modernization and readiness goals faster and more effectively than ever before. Advanced manufacturing methods increase possibilities for design functionality, optimization, and complexity. Designs that once were considered impossible to realize because of traditional manufacturing limitations can now be produced, allowing engineers to focus design decisions on optimal performance instead of manufacturability.

Further emphasizing the importance of convergent/advanced manufacturing, the 2019 Army Modernization Strategy named the science of additive manufacturing (AM) for next-generation munitions for increased range and lethality the no. 9 priority research area in the entire Army R&D enterprise.[2]

The Army's 2021 *Convergent Manufacturing Science and Technology Strategy*[3] defines convergent manufacturing as

> a system that converges virtual manufacturing, manufacturing processes (additive, subtractive, and transformative), process monitoring and control, and heterogeneous materials in one platform to yield functional devices and components for systems as an output while equipped with modularity, flexibility, connectivity, and re-configurability to enable custom manufacturing of any part for any mission.

The use of multiple robot arms is integral to convergent manufacturing. A robot arm is a versatile robotic motion platform that can be used to precisely control AM or subtractive manufacturing (SM) tools. Even a single robot arm offers a leap forward in capabilities over traditional AM/SM processes that use 3-axis gantry-style motion platforms. A robot arm enables a higher dimensional space of tool-to-build orientations and configurations. Use of multiple robot arms takes it a step further by enabling multiple AM or SM processes to work on a part at the same time. This benefit can enhance the efficiency and scalability of the process, but it can also allow the manufacture of hybrid parts that contain multiple materials, such as functional gradients or electronics.

The use of single robots for AM has been reviewed by Bhatt et al.,[4] but no reviews have been published on multiple robot arms. In this report, the state of the art in multiple robots for AM is reviewed. The report is broken down by use cases. In Section 2, multiple fixed robot arms for the purpose of scalability is reviewed. Robot printers with a robot-actuated build plate are reviewed in Section 3. Swarm printing, a process that uses many nonfixed robots, is reviewed in Section 4. Robot arms for the purpose of hybrid AM are reviewed in Section 5. Commercially available software for controlling multiple robot arms for AM is reviewed in Section 6. Based on the findings of the literature review, gaps in the technology are identified and recommendations to address the gaps pertinent to the Army's convergent manufacturing strategy are made in the conclusions section.

2. Multiple Fixed Robot Arms for Scalability

This section discusses the work being done on multirobot printing using fixed robots. This type of printing divides a large print into multiple sections and uses multiple robots working in conjunction to print and combine each section. Examples of these types of fixed setups include two or four robot arms with extruders attached to the toolhead working together and a Cartesian printer with multiple extruders.

Jin et al.[5] discovered that concurrent scheduling for extruders reduced build times for prints by 33% to 66% when using three extruders. Two baseline algorithms were used to divide the print: the naïve scheduling algorithm (dividing the print into equal-sized parts) and the human-segmented scheduling algorithm (using a person to divide the print). These baseline methods were compared with two different processing algorithms: Longest Processing Time First (LPT: doing the longest jobs first) and Minimum Overlapped Area First (MOA: printing areas with low mutual interference) (Fig. 1). The results showed that LPT and MOA significantly reduced fabrication times at the cost of increased processing time over the baseline. This then led to the conclusion that concurrent scheduling would be very useful for large-scale 3-D printing that normally sacrifices surface finish due to the increase in layer thickness.

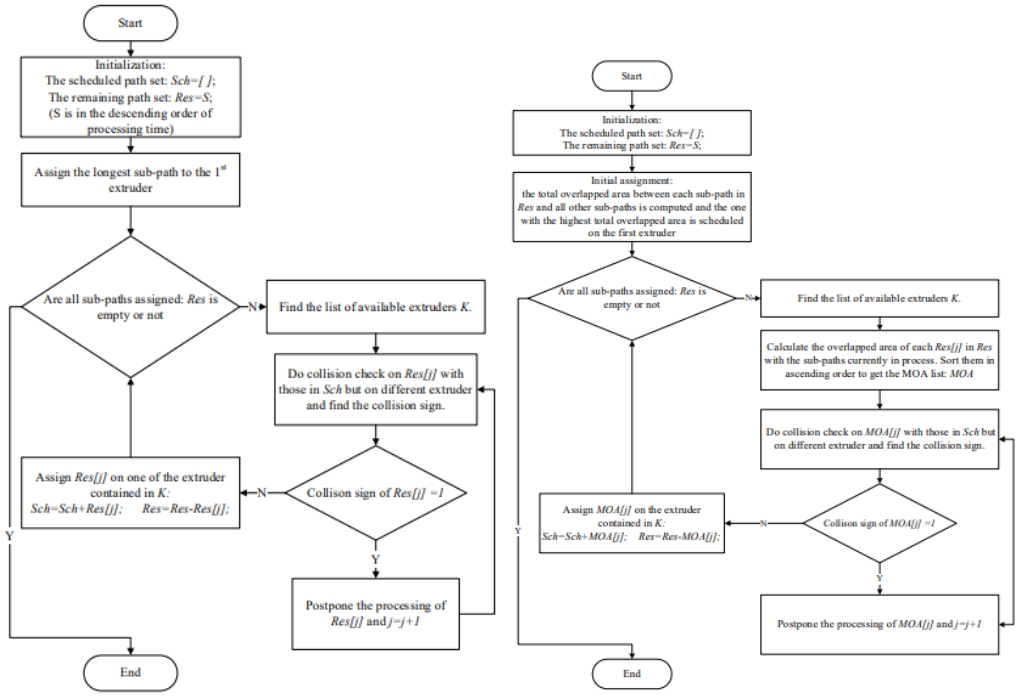


Fig. 1 LPT (left) and MOA (right) algorithms used[5]

To combat this problem with surface finish, Bhatt et al.[6] created a robot system to print multiresolution objects. It consisted of two 6-degrees-of-freedom (6DOF) manipulators, the ABB Robotics IRB 120 and IRB 2600. The IRB 120 has an extruder with a 0.4-mm diameter and the IRB 2600 has a 0.8-mm-diameter nozzle. A serial communication was set up between the robots and a computer using a Python program. Collision was handled by only printing with one robot at a time because the objects were very small. The robots were set up so that the 0.8-mm nozzle would print the first part and the 0.4-mm nozzle would print the last two layers. It was discovered that this hybrid method produced a surface finish close to that of the solely 0.4-mm nozzle print with an average time savings by a factor of 1.8.

Shen et al.[7] used four robots to create a collaborative system for 3-D printing to combat the problem with scalability in large-scale 3-D printing. The printing path division is done in four steps (Fig. 2). As shown in Fig. 3, the algorithm (a) finds the coordinates of the slicing contour points; (b) a minimum bounding rectangle is drawn and the segmentation points are found; (c) a simulated annealing program is done to determine the optimal segmentation points; and (d) the part is segmented and the fill path is rearranged. To prevent collisions, the path is divided into safe areas and interference areas (areas close to the boundaries of another segment), and the computer only allows one robot to work in an interference area at a time. The

study found that when using this collaborative system, they were able to complete prints with nearly four times the efficiency of a single robot printer.

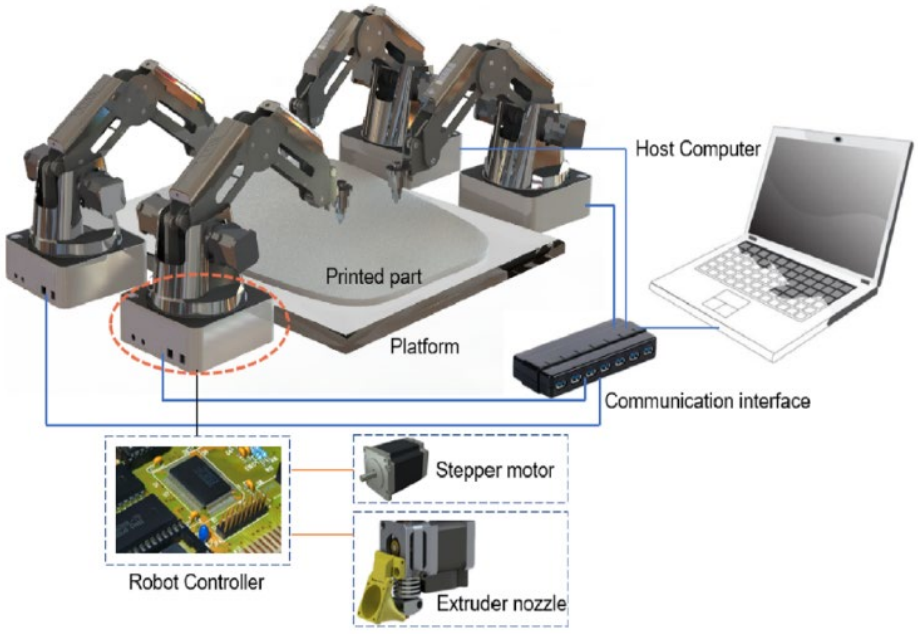


Fig. 2 Schematic of the multirobot system[7]

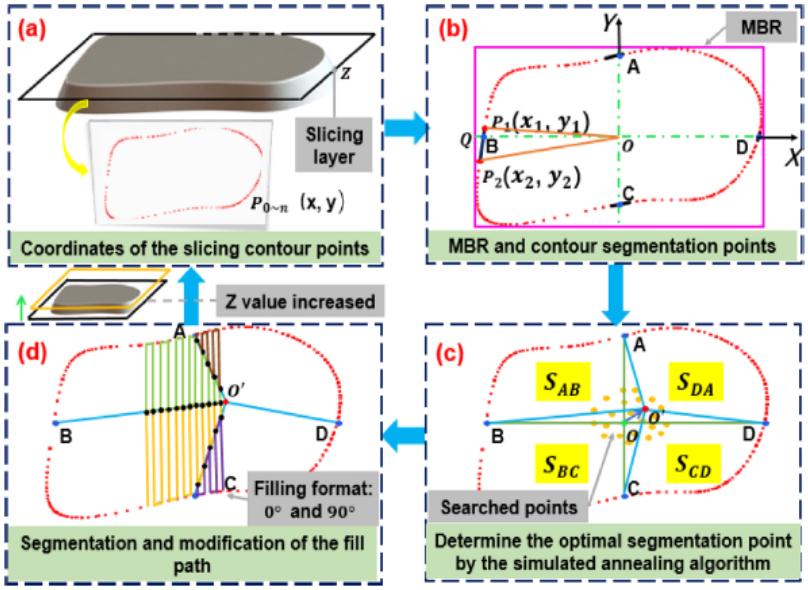


Fig. 3 Flowchart for creating the segments[7]

Multiple other companies and groups are working on multirobot AM. Autodesk's Project Escher (Fig. 4) uses multiple independent extruders in a Cartesian 3-D printer setup to print chunks of the same object.[8] There are also two patents for Cartesian printers using multiple separate heads similar to Project Escher.[9,10]

MX3D, a company based in Amsterdam, has 3-D printed a metal bridge to cross a canal using multiple robot arms at different points to print it.[11]

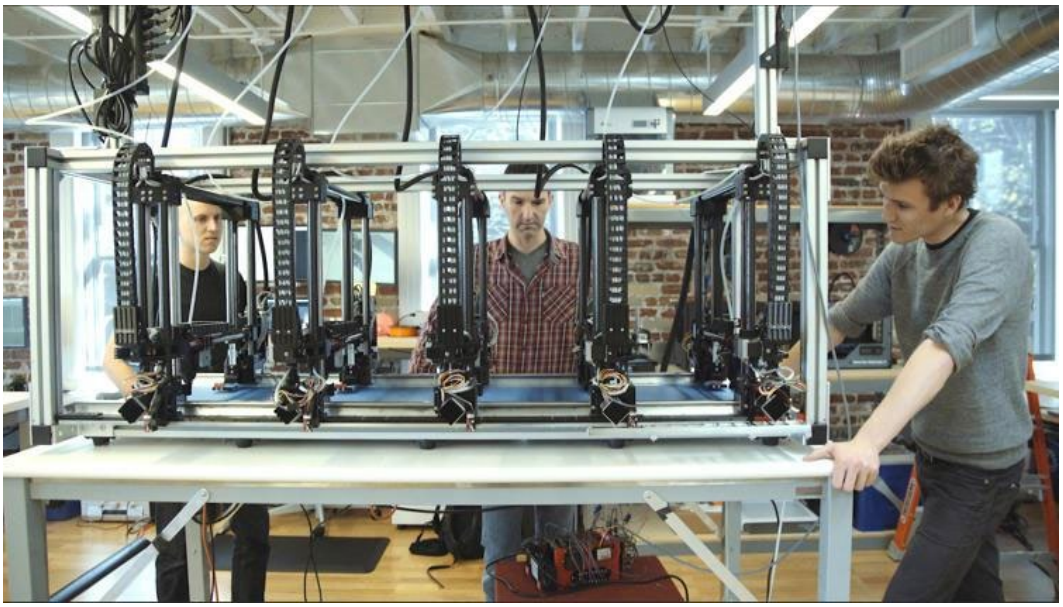


Fig. 4 Autodesk's Project Escher[8]

It has been shown that this form of printing has been used mainly to combat the scalability problem with large 3-D printers. These types of printers can print the same objects at a much faster rate without sacrificing the print quality even though more processing is required to ready the print. These types of printer systems are currently being used in fields such as aerospace and automotive. It could also be expanded to cement printing for construction as that normally has high build times.

3. Robot Printers with a Movable Build Plate

Other groups have been researching the use of a robot arm 3-D printer in conjunction with a rotatable build plate. This type of system uses one robot arm 3-D printer and normally has a 2DOF or 3DOF robot holding the build plate to rotate the object for easier access to the robot.

Ding et al.[12] developed an 8-axis system (6DOF robot arm and 2DOF rotary system) for laser-based direct metal deposition (LBDMD) to reduce the need for support material (Fig. 5). This system splits a revolved part into a core volume and its overhanging features to be added. The slicing algorithm slices the core volume into planar slices, but the overhanging structure is sliced into cylindrical-like slices. The core volume is printed first and then the part is rotated accordingly to add the overhanging structures. The study printed a propeller with four twisted, thin

structures using this system and found an error of less than 1 mm. The study concluded that the system saved a lot on processing power as well as build time.

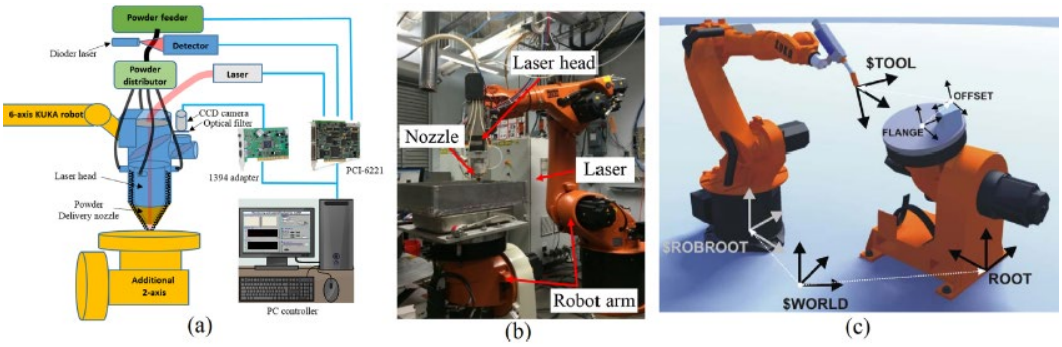


Fig. 5 LBDMD system[12]

Bhatt et al.[13] developed a 3DOF robot arm with an 0.8-mm extruder attached to the toolhead that worked with a 3DOF build plate (Fig. 6). This was made to reduce the need for support material because adding surface material increases the production time, reduces the quality of the surface finish, and adds extra postprocessing time to remove it. To make this system work, an algorithm for layer slicing was developed that computes the average axis of symmetry, then places the direction vectors that determine the number of points in each layer, then determines the layer thickness, and then generates the layer contours. When printing, the build plate is tilted so the extruder makes an angle less than 45° with the horizontal so that gravity acts as a support for the print. The extruder tool path generation works normally when the plate is not rotated, and when the build plate is moved the extruder location's Cartesian values are multiplied with the rotation matrix of the build plate. A collision detection module approximates the build plate and the extruder as a collection of spheres, and if the distance between any of the spheres is less than the sum of the radii of the spheres, the waypoint generation is halted. The study then compared this system with "regular" 3-D printers to print thin shells. To test part accuracy, the study compared scans of the built part to the tessellated CAD model and found that the setup had an average accuracy of 0.222 mm with a max error of 0.558 mm (Fig. 7). Build-time savings were higher than 80% for all the prints and removed the need for postprocessing.

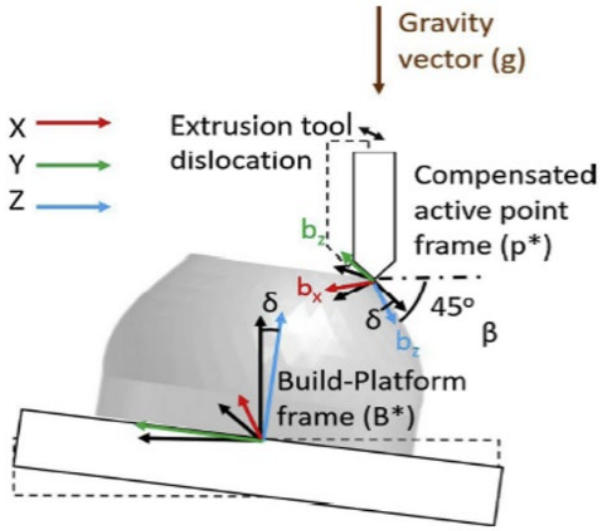


Fig. 6 How the reorientation of the build plate works[13]

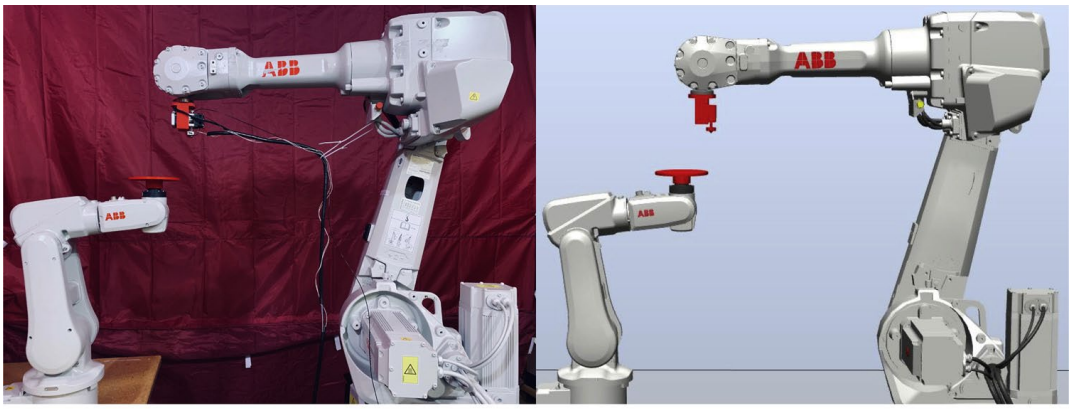


Fig. 7 Bhatt's build-platform and printer in (left) and the simulation in robot studio (right)[13]

Kutzer et al.[14] developed a 12-axis system using two 6-axis robots (UR5 and UR10) with one robot holding a handheld extruder pen while the other holds an existing object to be printed onto (Fig. 8). An example given for this is a computer mouse shell being printed onto the circuit board. The deposition path generation algorithm works to minimize unnecessary seams (locations where the extruder toolpath starts and ends for each closed part curve). Since there are two manipulators there is the possibility of multiple trajectories, so all of them are put into a simulation to check for any problems that may arise in the build. The two robot arms were calibrated to each other using calibration plates with fiducials on them. The study tested the system by making it print a 75-mm-long cylindrical body. The accuracies of the transformations for both robots showed an root-mean-square error of 1.01 mm for the build plate robot and 1.27 mm for the extruder robot. For the cyclic trajectories

used for the study, end-effector tracking errors stabilized at 20 mm and a phase lag of π radians, but both manipulators had the same tracking error characteristics. This study did prove the feasibility of the system but the tracking needs to be refined. It is mentioned that adding integral and derivative control may improve it.

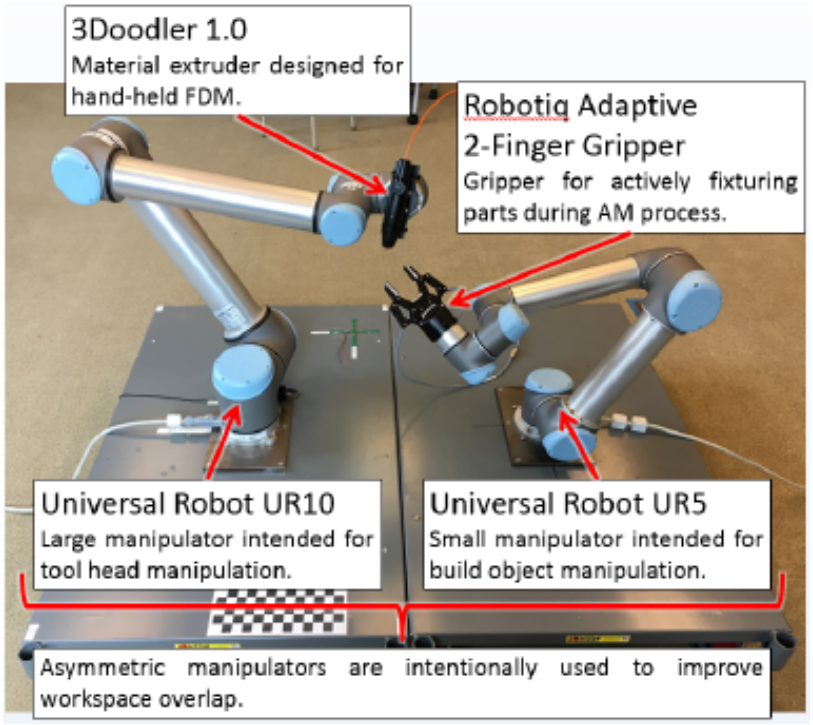


Fig. 8 System used by Kutzer et al.[14]

Stratasys Incorporated offers a commercial 8-axis (6DOF robot arm and 2DOF base) AM system called the Robotic Composite 3D Demonstrator that uses normal fused deposition modeling (FDM) printing. The system is designed to eliminate the need for support material and allows for precise material placement.[15]

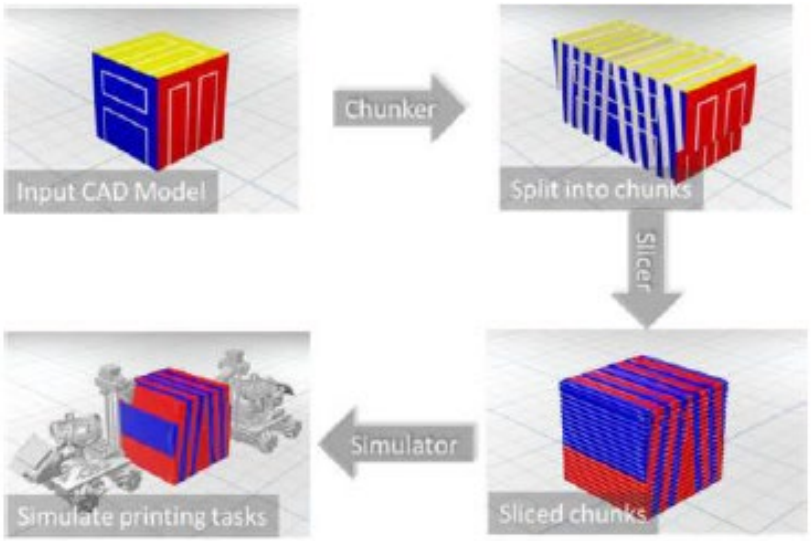
Research has shown that using a rotatable build plate in conjunction with a robot arm printer removes the need for printing support materials and reduces print time and postprocessing time. This system is mainly useful for automotive fields that need large, complicated objects to be printed. However, because it does not create support structures, this system opens up doors for other complex part manufacturers that would normally be inhibited by the long postprocessing times needed for removing support material.

4. Swarm Printing

Robot swarm printing is very similar to multiple robot arm printing except the robots are not fixed to one point and can move. It involves using multiple robot

3-D printers that can autonomously move in any direction while printing instead of having a build plate that moves. Examples of this include extruders affixed to small carts or robot arms that are places on a motorized platform.

A team at the University of Arkansas has published many papers on the development of their own robot swarm system. McPherson and Zhou developed an algorithm that divides a print into multiple chunks for multiple swarm printers to work on.[16] The chunks are sloped into triangle-like shapes to give more bonding surface between chunks, and the printers are meant to finish all of the layers of a chunk before moving onto the next one (Fig. 9). McPherson and Zhou only used two simulated swarm printers, as the algorithm was not optimized for more.[16] Poudel et al. then tested the mechanical strength of prints using this chunking algorithm.[17] It was found that a smaller slope (30°), avoiding shells at contact areas between chunks, and increasing chunk overlapping increased the strength of the print. The tensile strength of the parts printed with the chunking algorithm ranged from 61% to 121% of a normal FDM printed part.[17]



Notes: (1) The chunker splits the printing job into chunks and ensures feasible printing of each chunk and good bonding between chunks; (2) the slicer slices the chunks into layers, generates commands for printing the chunks, schedules the sequence of printing the chunks among multiple robots and inserts communication commands to enable necessary communication among multiple robots; (3) the simulator visualizes the dynamic printing process using the commands generated by the slicer

Fig. 9 How the chunking algorithm works[16]

Poudel et al.[18,19] then created an algorithm that can make a printing schedule for the robots. The algorithm first takes the number of chunks and then creates a dependency matrix that shows which chunk is dependent on which and then generates random printing schedules. Then each of the schedules are checked using the geometric constraints to prevent collisions between robots and collisions between robots and parts and the ones that fail are filtered out. Then the print times are calculated and the one that takes the shortest amount of time is used. The results from this framework showed a significant decrease in printing time.[18,19]

Poudel et al.[20] then further optimized the algorithms and built the swarm printer (Figs. 10 and 11). It is made up of four parts: a SCARA robot printer, a mobile platform for transporting the robot, a floor tile system to help navigate the printer while also providing a power supply for the platform, and a wireless network to communicate between the printers and platforms. When printing, a platform goes to the SCARA arm, unmounts the arm from the floor to the platform, and then moves to a new location where the SCARA robot will mount to the floor. Only one printer can be moved at a time to simplify navigation. Further study is being done on the system to make it more efficient and usable for large prints.[20]

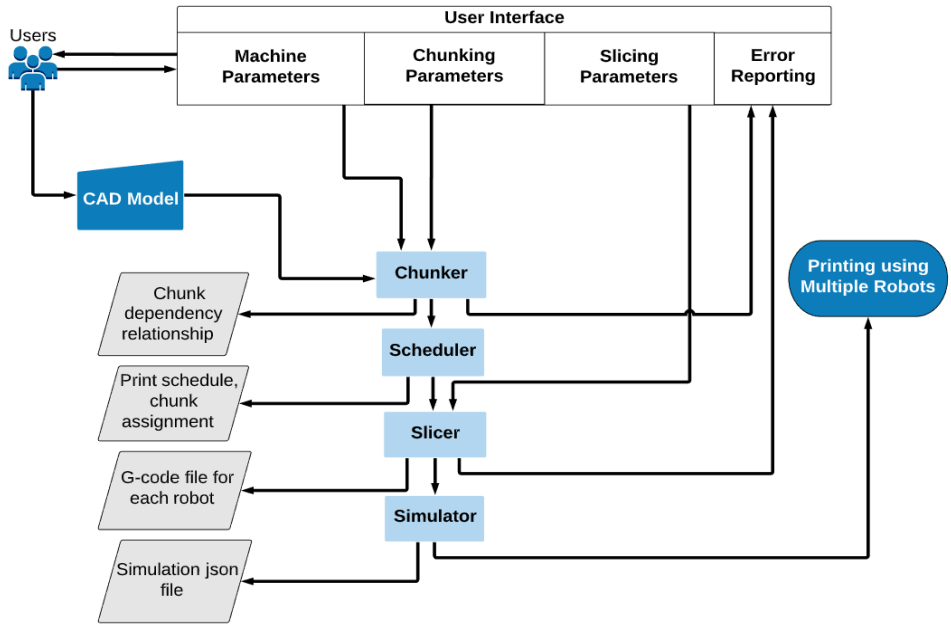


Fig. 10 System architecture for the University of Arkansas' swarm system[20]

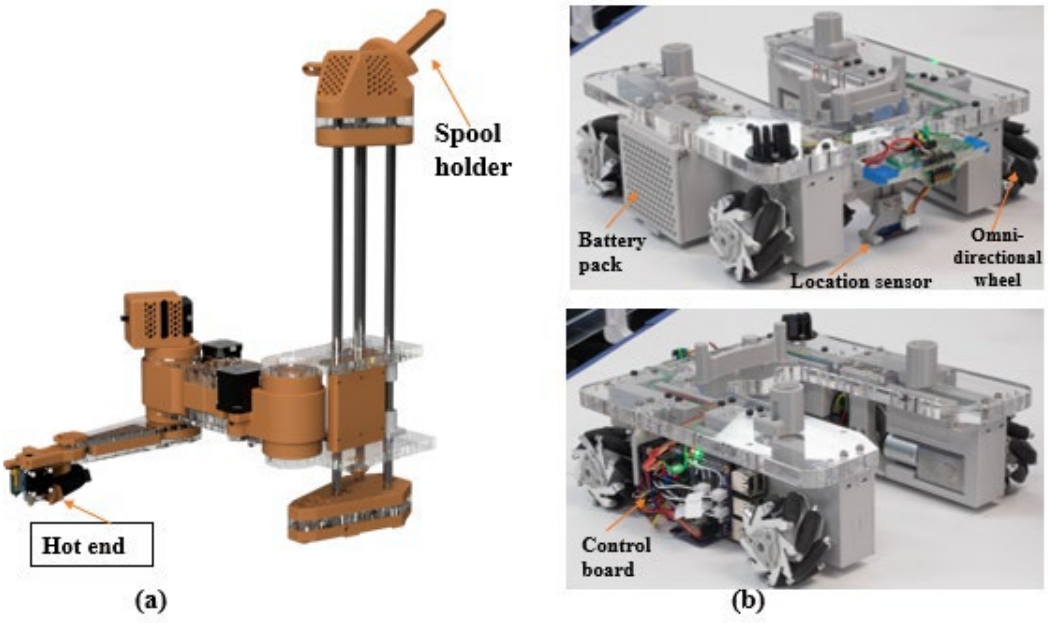


Fig. 11 The 3-D printer (left) and the mobile platform (right)[20]

Zhang et al.[21] developed a mobile cement printer system that uses a 6-axis robotic arm as shown in Fig. 12. Each robot printer consists of the robot arm with the cement nozzle attached to a holonomic mobile platform (meaning it can freely move in any direction) and a pump for the cement. The mobile platform uses wheel encoders, an inertial measurement unit, and a 2-D laser scanner to help localize itself. A camera also localizes the robot using ArUco markers placed on the robots. When printing, the CAD is sliced into thin paths in layers and the coordinated and normal of the path are extracted, which allows for the multirobot placement to be set up as an optimization problem to allow full coverage of the part being printed. This optimization to avoid collision and provide coverage is done by looking at the kinematic reachability of points from the printers. Using the robot's sensors and the camera looking for the markers, the robot is able to position itself where it needs to be. The paths for the robots to move are planned individually and use a coordination diagram to check for collisions. Both the simulated versions and the real versions were able to build a proof-of-concept piece that had complex curves and an internal void. It was mentioned that this type of system may have difficulty on nonflat terrain due to problems with localization and performance of the platform.

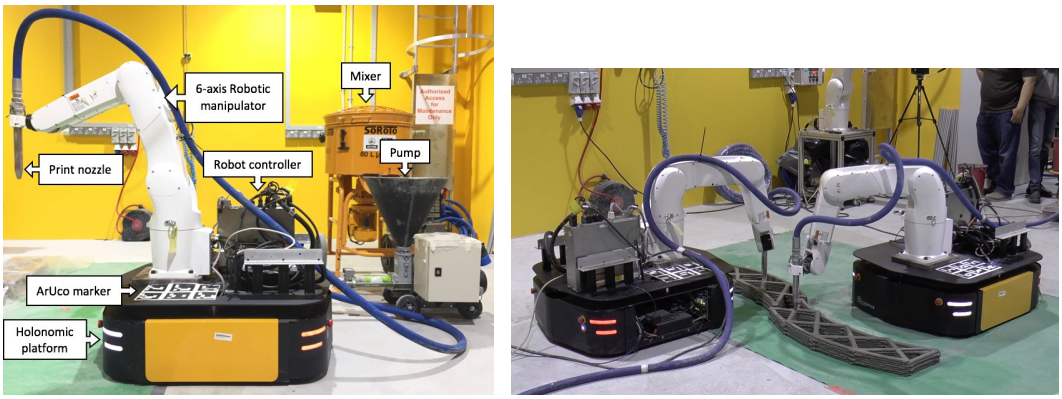


Fig. 12 System setup for the robotic cement printer (left) and the printers printing together (right)[21]

Another group at the Institute for Advanced Architecture of Catalonia developed the Minibuilders, a group of robots that can print structures using fast-drying artificial marble (Fig. 13).[22] The base robot creates a foundation layer of 10 layers by moving along the path and incrementally raising the extruder while printing. The grip robot then attaches to the foundation layer and begins printing on it. Its nozzle can dynamically move and create curves and also fix errors in printing. The vacuum robot then attaches to the walls of the structure using a vacuum generator and deposits material onto it to enhance its structural properties.



Fig. 13 Minibuilders system: base robot (left), grip robot (middle), vacuum robot (right)[22]

Swarm printing's benefits include all of the benefits of using multiple robot-arm 3-D printing. That is, it can divide a large print into multiple smaller sections that can be handled by its own robot while decreasing print time and keeping a good surface finish. It also has the benefits of a much larger print area because the printers are not confined to one spot, meaning even larger objects can be printed.[21] A system like this can be used for construction as well as aerospace, both of which normally have very large objects that need to be manufactured.

5. Multiple Robot Printers for Hybrid AM

This section focuses on setups that use multiple robots for hybrid AM. This type of printing involves normal 3-D printing but also can print different types of materials or also include SM systems. Examples of this type of printing include a setup of one robot-arm 3-D printer and a computer numerical control (CNC) machine or a setup that uses a robot-arm FDM printer and another that prints metal.

In 2007, Liou et al.[23] at the University of Missouri–Rolla developed a hybrid system that used a 5-axis robot arm fitted with a laser deposition system and a 5-axis CNC machine. The system switches between machining and deposition but it is optimized to allow for the least number of switches. The system first computes a skeleton of the object being printed. Then it determines the part orientation, as the base face is used as the fixture while machining. Part decomposition is then done to determine what needs to be deposited or machined. The decomposition results are put in a part adjacency graph used to get multiple build sequences. These sequences undergo a machinability check to test for possible global or local collisions. The ones that fail are filtered out, and the sequence with the fastest build time is chosen. The system was able to save normally between 50%–60% of support structures compared with doing normal laser deposition. No images of the system were given.

Keating and Oxman[24] also developed an AM/SM manufacturing system (Fig. 14). It uses a fixed 3-D printer, a fixed mill, and a 6-axis robot arm that can move the build plate between the two. It was able to print a 2-cm cube and then mill it. The heated build plate was turned off before milling to allow for better adhesion of the cube to the build plate. This system allowed for a single robot to be used without having to change the toolheads every time the manufacturing process was switched.

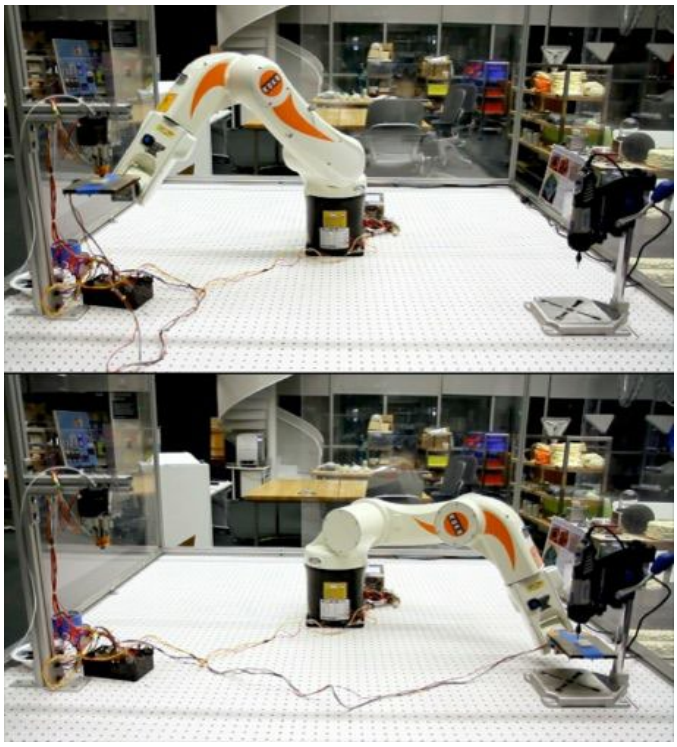


Fig. 14 Robot arm moving the build plate between the 3D printer and drill[24]

The multirobot cement printer developed by Zhang et al. used different materials to prove that it could be used for hybrid capabilities.[21]

Relativity Space has developed a multiarm 3-D printer called Stargate that uses directed-energy deposition to print metal parts for rockets. One arm has a printer head that feeds out the wires and the other arms the object being printed.[25]

Multirobot hybrid printing allows for much-more-complex parts to be printed. Printers can use different materials or can combine AM and SM. Liou et al. mentions that a combined additive/subtractive system may be good for repairing parts because the system can fill cracks and smooth down edges.[23] These types of systems have many uses, but not enough research has been conducted.

6. Software Control

Some companies are developing software to control multiple robots for manufacturing. This is mainly done to work with their own robots but it is possible to use them on other robots.

Siemens has developed its Sinumerik software that can control multiple robots at a time. The software can control multiple processes simultaneously and can simulate the robots with their toolheads. The software works with multiple types of robots

and is not limited to a certain company as long as it can access the robot's electronics and mechanics. It is mainly advertised for CNC machining, but there are some possible capabilities for AM.[26]

KUKA robotics also has developed KUKA.RoboTeam software for KUKA robots that allows the user to control a group of up to four robots. It allows the robots to be geometrically coupled to each other so that they can work in conjunction. The robots can also be synchronized using the software. There is no mention for its use in AM but the software should be able to be used for it.[27]

These software developments would make the use of multirobot AM much easier and accessible by eliminating the need to devise and code the algorithms to run the robots. However, more work will need to be done on them if they are to be used for AM, but this is a good first step.

7. Conclusions

The use of multiple robots in AM has been gaining a lot of traction in large-scale AM. Multiple fixed printers can reduce build times by large amounts as well as provide better surface finish. Swarm printers can do the same but do not have print size limitations due to their ability to move around an area. Using a printer along with a rotatable build plate eliminates the need for printing support structures, thereby saving both time and materials. The printers can even be formatted for hybrid tasks such as AM, SM, or multimaterial applications.

A few challenges face multirobot convergent manufacturing. The largest one is the time and material cost is very high. A single multirobot 3-D printer can be costly due to the cost of the robot and 3-D printer setup as well as the programming required to run the robot. Extra programming and algorithm development is required to make multiples of these robots work together without crashing into one another or their surroundings. Only well-funded groups or companies can reap the benefits of using multiple robots. Another challenge is that there is no one software available to control the robot printers together. All of the papers and teams mentioned in this report created their own software to run their robots. Although companies like Siemens and KUKA are working on this for single-robot 3-D printers, it is not optimized for multirobot or hybrid manufacturing use cases.

Because the use of multirobot printing is very new, there are many gaps in the research that can be studied. Very little research has been published in the case of hybrid systems, especially that of combined AM and SM. The only research found on a concurrent system was from 2007, and the recent work done on it was to have a movable build plate between the printer and CNC. It would also be possible to

combine a robotic 3-D printer with a robot-arm CNC to work concurrently, as Keating and Oxman were able to build them both separately.[24] Developing this could greatly reduce build times by combining both of those stages of manufacturing. Other work in hybrid printing could be the use of different materials or toolheads at the same time to create multimaterial objects. Swarm printing could also be expanded to multiple flying robots, as teams like Hunt et al. were able to develop flying robot printers.[28] Another area of swarm printing that could be researched is developing printers for a nonlab setting (i.e., an Army base). Since they are not restricted to a single area, the swarm printers would be able to print anything that the Army could require, from buildings to vehicle bodies. More work needs to be done in optimizing the processing algorithms to reduce processing times for all of the systems.

The Army cannot rely on existing commercial/academic solutions to achieve its goals in convergent manufacturing. While highly accurate robotic arms are widely available from a number of sources, the software to integrate multiple robots for the purposes of AM is lacking. The Army must invest in research to improve multirobot control software and, in particular, tool-path planning algorithms for multiple robot arms. Some of this research must be kept internal due to the sensitivity of applications that would stand to benefit from convergent manufacturing. Academia and industry may be able to bridge most of the technology gap, but application and process-specific details should be handled by internal R&D.

8. References

1. Jette B. Implementation guidance for *Army Directive 2019-29 (Enabling readiness and modernization through advanced manufacturing).* Office of the Assistant Secretary of the Army (Acquisition, Logistics, & Technology); 2021.

2. Grinston M, McConville J, McCarthy R. *2019 Army modernization strategy*. Department of the Army (US); 2019.

3. Zunino J, Sablon K, La Scala J. 2021 *Army convergent manufacturing science and technology strategy*. Army Futures Command (US); 2021.

4. Bhatt PM, Malhan RK, Shembekar AV, Yoon YJ, Gupta SK. Expanding capabilities of additive manufacturing through use of robotics technologies: a survey. Add Man. 2020;31:100933.

5. Jin Y, Pierson HA, Liao H. Toolpath allocation and scheduling for concurrent fused filament fabrication with multiple extruders. IISE Trans. 2019;51.2:192–208.

6. Bhatt PM, Kabir AM, Malhan RK, Shah B, Shembekar AV, Yoon YJ, Gupta SK. A robotic cell for multi-resolution additive manufacturing. IEEE International Conference on Robotics and Automation (ICRA); 2019.

7. Shen H, Pan L, Qian J. Research on large-scale additive manufacturing based on multi-robot collaboration technology. Add Man. 2019;30:100906.

8. Grunewald SJ. Autodesk's project escher software is super fast 3D printing for large-scale objects. 3DPrint.Com. 2016 Apr 1. https://3dprint.com/127688/autodesk-project-escher/.

9. Uzan M, Yakubov I, inventors. Big GimicArt Ltd, Massivit 3D Printing Technologies Ltd, assignee. Additive manufacturing device. United States Patent 9011136B1; 2015 Apr 21.

10. Fontaine N, inventor. Stacker LLC, assignee. Modular user-configurable multi-part 3D layering system and hot end assembly. United States patent US 20160067920A1; 2016 Mar 10.

11. Hobson B. Producing the world's first 3D-printed bridge with robots "is just the beginning". Dezeen; 2015 Dec 30. www.dezeen.com/2015/12/30/video-interview-robots-worlds-first-3d-printed-bridge-mx3d-joris-laarman-movie/.

12. Ding Y, Dwivedi R, Kovacevic R. Process planning for 8-axis robotized laser-based direct metal deposition system: a case on building revolved part. Rob Comput Integ Man. 2017;44:67–76.

13. Bhatt PM, Malhan RK, Rajendran P, Gupta SK. Building free-form thin shell parts using supportless extrusion-based additive manufacturing. Add Man. 2020;32:101003.

14. Kutzer Michael DM, DeVries LD. Testbed for multilayer conformal additive manufacturing. Technologies. 2017;5(2):25.

15. Caliendo H. Stratasys debuts robotic composite and infinite-build 3D printers. Composites World; 2016 Aug 25. www.compositesworld.com/news/stratasys-debuts-infinite-build-robotic-composite-3d-printers.

16. McPherson J, Zhou W. A chunk-based slicer for cooperative 3D printing. Rap Proto J; 2018 Oct 12.

17. Poudel L, Sha Z, Zhou W. Mechanical strength of chunk-based printed parts for cooperative 3D printing. Procedia Man. 2018;26:962–972.

18. Poudel L, Zhou W, Sha Z. A generative approach for scheduling multi-robot cooperative three-dimensional printing. J Comput Inf Sci Eng. 2020;20.

19. Poudel L, Blair C, McPherson J, Sha Z, Zhou W. A heuristic scaling strategy for multi-robot cooperative 3D printing. J Comput Inf Sci Eng. 2020;20.

20. Poudel L, Marques LG, Williams RA, Hyden Z, Guerra P, Fowler OL, Moquin SJ, Sha Z, Zhou W. Architecting the cooperative 3D printing system. ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers Digital Collection; 2020. https://doi.org/10.1115/DETC2020-22711.

21. Zhang X, Li M, Lim JH, Weng Y, Tay YWD, Pham H, Pham QC. Large-scale 3D printing by a team of mobile robots. Autom Const. 2018;95:98–106.

22. Minibuilders - Institute for Advanced Architecture of Cataloni (IAAC). Small Robots printing large-scale structures; 2018 Oct 11. Iaac.net/project /minibuilders/.

23. Liou F, Slattery K, Kinsella M, Newkirk J, Chou H, Landers R. Applications of a hybrid manufacturing process for fabrication of metallic structures. Rap Proto J. 2007;13:236-244.

24. Keating, S, Oxman N. Compound fabrication: a multi-functional robotic platform for digital design and fabrication. Rob Comput Integ Man. 2013;29.6:439–448.

25. Salmi Bryce. The world's largest 3D metal printer is churning out rockets. IEEE Spectrum: Technology, Engineering, and Science News. 2019 Oct 25. spectrum.ieee.org/aerospace/space-flight/the-worlds-largest-3d-metal-printer-is-churning-out-rockets.

26. Siemens. Increased productivity with SINUMERIK. new.siemens.com/global/en/products/automation/systems/cnc-sinumerik.html.

27. KUKA. KUKA.RoboTeam [accessed 7 July 2021]. www.kuka.com/en-us/products/robotics-systems/software/hub-technologies/kuka_roboteam.

28. Hunt G, Mitzalis F, Alhinai T, Hooper P, Kovac M. 3D printing with flying robots. Proceedings of the 2014 IEEE International Conference on Robotics and Automation (ICRA). https://ieeexplore.ieee.org/document/6907515.

List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
3-D	three-dimensional
AM	additive manufacturing
CAD	computer-aided design
CNC	computer numerical control
DOF	degrees of freedom
FDM	fused deposition modeling
LBDMD	laser-based direct metal deposition
LPT	Longest Processing Time First
MOA	Minimum Overlapped Area First
R&D	research and development
SCARA	Selective Compliance Articulated Robot Arm
SM	subtractive manufacturing

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
1 (PDF)	DEVCOM ARL FCDD RLD DCI TECH LIB
2 (PDF)	DEVCOM ARL FCDD RLW MD I NAULT N MURTY