Chapter 10

Possibilities and challenges of using robot manipulators in additive manufacturing (AM)

Linn Danielsen Evjemo, Trond Arne Hassel, Eirik B. Njaastad, Salar Adel, Ingrid Fjordheim Onstein, Mathias Hauan Arbo, Vegard Brøtan, Andrej Cibicik, and Jan Tommy Gravdahl

Robotisation of AM processes

In this section, we present a discussion on the advantages and shortcomings of using articulated robotic manipulators (i.e., robotic manipulator arms) for two additive manufacturing (AM) processes, which are directed energy deposition (DED) and material extrusion (MEX). Two different DED processes with metal and polymer feedstocks are considered, Wire-arc and laser DED for metallic materials, while for polymers, we look at the most applied AM process, namely the MEX process.

Introduction to AM processes

DED are AM processes in which focused thermal energy is used to fuse materials by melting as they are being deposited [1] (Figure 10.1). These production technologies consist of a feedstock material in the form of metal wire or powder. The heat source can be one or more lasers, electric wire arcs, an electron beam, or plasma. The first two are the most common ones, and there are also variants that combine different heat sources or different feedstocks.

Laser melting is quite versatile and depends on many parameters. The wavelength, power, pulsing, focus, and beam shaping are part of the picture. Combining this with the use of several lasers, feed of material, heating of substrate and material, robot movements, etc., the parameter window becomes enormous. However, most available systems come with one material form and one laser. Often, this is a powder-fed system with a powerful fibre laser with just over 1,000 nm wavelength. These systems offer speed, size, and flexibility. It has the possibility to produce fine details and has a relatively low impact on the substrate, but it is in no way as fast as wire arc or electron beam methods. DED systems with laser melting are possible to automate by attaching a building head to a robot flange; however, special safety considerations should be accounted for.

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The manufacturing method Wire-Arc Additive Manufacturing (WAAM) uses a wire-arc welding process as its thermal energy source (Figure 10.1). A welding gun and the heat input from an electric arc are used to weld metals together. The most used arc-welding method in WAAM is gas metal arc welding (GMAW), also known as MIG/MAG (metal inert/active gas) welding [2]. When using GMAW, the welding wire deposited by the welding gun works both as a filler wire for the building process and as an electrode. The welding gun can be attached to a robot manipulator, and material can be deposited along a pre-programmed path, making the method possible to automate. Gas tungsten arc welding (GTAW) is another method that can be used for WAAM, but GTAW uses a non-consumable tungsten-alloy electrode inside the weld gun. The filler material is added to the welding process separately from and in front of the welding gun along the motion path. This means that a rotational degree of freedom (DOF) around the welding gun axis becomes an important process control parameter when automating the process, which is an additional complication compared to GMAW. The wire feeder is also an additional physical obstacle, which should be considered when doing path planning for a robotised and autonomous system. Plasma arc welding (PAW) is another type of arc welding that also uses a non-consumable electrode and a separate filler wire, which leads to the same complications as the GTAW process. This is the main reason why GMAW is more commonly used for WAAM than the two other arc welding methods.

Several of the advantages of using WAAM compared to other manufacturing methods for metal structures are listed by Williams et al. [3]: Investing in the equipment is both relatively low-cost and low-risk, as both welding equipment and industrial robot manipulators are available in a lower price range compared to more specialised equipment and can be re-sold or used in other parts of production if necessary. Depending on the demands on the material quality of the product, the building method is not restricted by the size of a building chamber, as building materials such as aluminium or steel do not require an inert atmosphere for the building. Then the size of the structure is only limited by the collision-free workspace of the robot manipulator, which can be further expanded using rails or a gantry system. An enclosed chamber is necessary when using, for example, titanium to create an inert atmosphere for gas shielding. WAAM has gained much interest in the industrial manufacturing sector because of the possibility of a high deposition rate. Deposition rates for WAAM typically vary between 1 kg/h and 4 kg/h, meaning that it is possible to produce larger parts at a reasonable rate, though this depends on the material and process parameters [4, 5].

MEX is a well-known AM process for polymer products that can both be used for production and rapid prototyping (Figure 10.1). The general steps of a polymer MEX process are as follows: the material is fed at a constant rate through a building head, where it is softened by a heating element and pushed through the nozzle. The nozzle is normally positioned over and in close vicinity of the underlying layer, such that the softened material is pushed towards

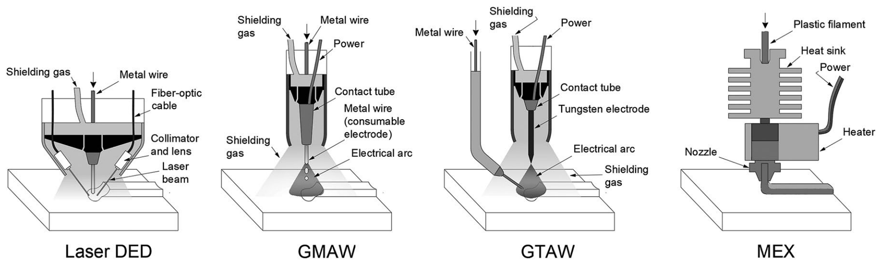


Figure 10.1 Schematic drawings for several AM processes.

and bonds with the previous layer. For many materials, it is beneficial to preheat the building plate to facilitate the bonding of the first layer.

The commercial product range is large, starting with small and relatively inexpensive extruders such as Prusa i3 MK3S and up to large robot-mounted extruders such as Massive Dimension MDPE10, which has a deposition rate of up to 4.5 kg/h. The two above-mentioned products represent two different types of polymer MEX in terms of the material feed system. Prusa i3 utilises a polymer filament feeding system, while MDPE10 has a polymer pellet feeder.

Cartesian manipulators are the dominating robotic platform for industrial implementations of DED with laser melting and polymer MEX processes. Such manipulators have only three translational DOFs and cannot change the tool orientation. This means that deposition is done layer by layer along one axis, with a limited possibility of non-planar layers and reorientation of the build axis [6]. As layer orientation and layer curvature affect the mechanical properties of the part [7, 8], the choice of the kinematics of the manipulator may be important for the mechanical properties of the resulting part. Utilisation of 6-DOF robotic manipulator arms for AM processes has largely been done by the research community. MEX using a 6-DOF robot manipulator was also performed in work within SFI manufacturing: in 2017, a cup structure was built in viscous glue deposited by a caulking gun attached to a robot manipulator in order to demonstrate a building process that was not based on layers but rather a path with a continuous increase in the vertical position of the tool [9]. Several new commercial AM systems have, however, been made available on the market, such as the Meltio Engine DED system with laser melting or the Massive Dimension MDPE10 polymer MEX system. Both can be installed on 6-DOF robot manipulator arms. It is worth noting that WAAM processes normally utilise general-purpose robotic welding equipment installed on a 6-DOF robot manipulator arm.

Process time and cost

Generally, wire-based DED processes using wire have a low cost of usage. For higher-range metal production equipment, the cost may be between 200,000 and 450,000 Euros. This kind of single-wire equipment can generally add

0.5–5 kg/h. The material cost is the same as for welding and varies a lot according to the material. Carbon steel can be bought under 1 Euro/kg, while some nickel alloys may have a kilogram price above 300 Euro. The main costs are the equipment, operator, and post-processing of parts, while the costs for maintenance, software, and gas are negligible. A 450,000-Euro system applied for 1,500 hours per year, with a down payment over five years, will cost 60 Euro/h. A 316 L stainless steel 1 mm wire costs 3.5 Euro/kg, and an operator costs around 50 Euro/h. Given that, even at the 5 kg/h processes, equipment and operator costs are the main expenses.

Advantages and shortcomings of using robotic manipulator arms

Industrial robot arms are an integral part of modern manufacturing environments and have been since the introduction of the Unimate in 1961 [10]. The general advantages of industrial robot arms over special-purpose machinery were outlined by the creator of Unimate, Joseph F. Engelberger, in his book "Robotics in Practice" from 1983 [11] and still hold true today: industrial robot arms are off-the-shelf products, meaning that they are readily available in various sizes and cost ranges, they can be used for many different tasks, and their broad userbase results in more information available for debugging, more funding available for development, and more skilled operators available for hire.

Most industrial robot arms are composed of six serially linked revolute joints, generally partitioned into three joints to position the wrist centre and three joints to orient the end-effector around the wrist centre [12]. These are sometimes referred to as articulated robots and have a large reachable workspace with respect to their footprint when compared to other kinematic structures such as generalised Stewart platforms and Cartesian manipulators. A subset of the workspace is also reachable with any arbitrary orientation of the end-effector. This means that the robot arms can deposit material in non-planar layers, such as on existing structures, can be moved into installations to perform *in-situ* repair, and can share workspaces with other manipulators for hybrid manufacturing. The Norwegian company Fieldmade is developing such moveable container-based solutions. One of their systems is now active close to the Johan Castberg oilfield, run by Equinor. Furthermore, the German company LaserCladding GmbH is actively servicing ships and cranes through laser beam robotic DED at the Hamburg docks.

For AM processes where the material solidifies quickly after depositing, such as MEX with plastic filament, overhangs can be created without support material by reorienting the tool with respect to the build surface. This has the potential to reduce material usage and construction time. For welding processes, the ability to orient the tool ensures that the filler wire can be positioned ahead of the tool path.

The added freedom of the serially linked revolute joints also introduces added complexity. Cartesian manipulators will have a convex build volume (with respect to linear position), meaning that any straight path in the build volume is a straight path in the joint space of the manipulator. For industrial robot arms, the straight path may pass near a kinematic singularity and result in unreasonably large joint velocities, or the task space of the robot may not be convex because of the specific kinematic topology or due to joint limits [13]. This means that a toolpath may have to be verified for the specific kinematics of the manipulator setup before execution. Industrial robot arms also tend to prioritise positioning accuracy, which is achieved by having high joint and link stiffness, resulting in a high arm mass relative to the tool [14]. This means that sharp corners and rapid changes in acceleration may be more difficult to achieve than in other kinematic structures where there is less mass situated close to the tool.

Robot motion study

One of the main parameters of any additive process is the traverse speed (i.e., travel speed) of the nozzle. Therefore, the difference between the actual speed and the set-point speed was studied experimentally using a Meltio engine build head [15] mounted on a KUKA IONTEC KR 70 R2100 robot [16].

To verify the actual traverse speed and location accuracy of the experimental setup, the movement of the robot was recorded with a Leica Absolute Tracker AT960-MR laser tracking system, where 10 points in space were measured per second during robot movement. The location and velocity accuracy were determined from these measurements. The experimental setup is shown in Figure 10.2. Note that the laser reflector is mounted to the wire nozzle under the build head to ensure that the measurements reflect actual nozzle movement.

The robot was found to round all sharp corners and reduce the traverse speed through the corners, as shown by Figure 10.3a, where the x and y coordinates from one layer of a script for building a cube have been plotted with speed shown as a grayscale highlight for each point. The set traverse speed was 10 mm/s, and a reduction down to 6–8 mm/s is observed for most of the sharp corners.

In addition to a reduction of traverse speed, the corner rounding also resulted in considerable gaps between the perimeter line and the infill lines, since the infill lines would bend apart towards the perimeter, leaving a gap between the three lines. This has also been observed by metallographic examinations, where porosities have been found in this exact location, as shown in Figure 10.4.

The traverse speed was found to vary by approximately 30–40% across the entire range of relevant traverse speeds for AM, 5–15 mm/s, as shown by the last subplot in Figure 10.5. An interesting note is that the robot was able to move through curves with a speed of 11–12 mm/s when the set speed was

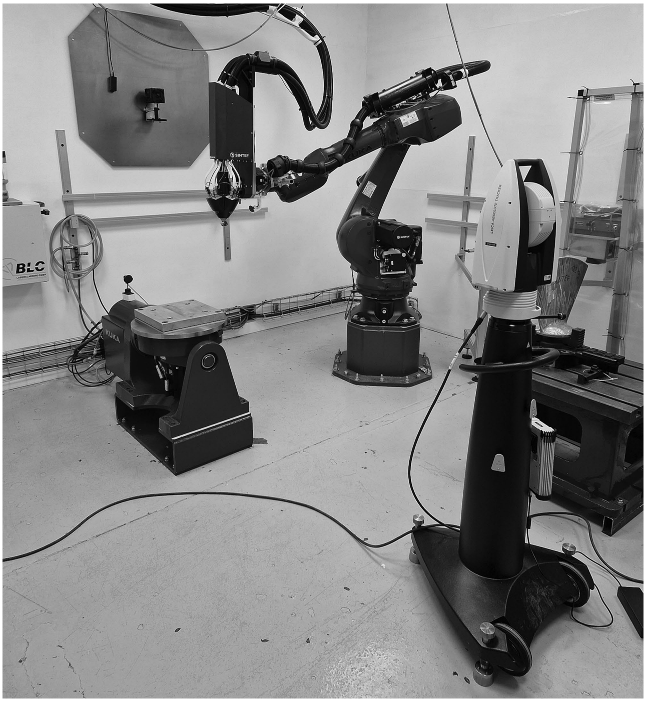
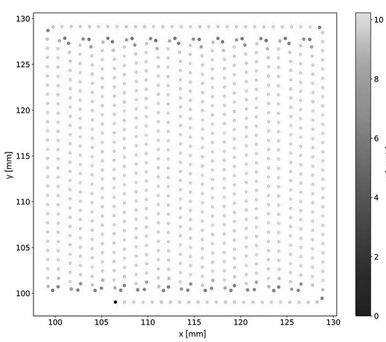
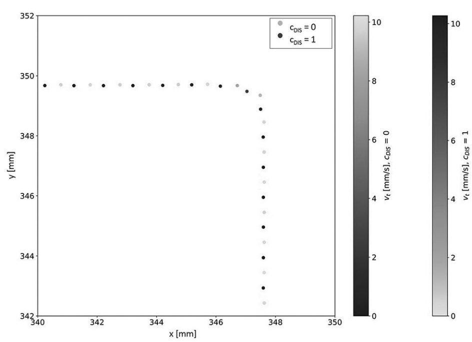


Figure 10.2 Experimental setup for robot motion study.



(a) Plot showing a complete base layer of a standard 30x30 mm cube



(b) Plot showing two paths around corner of cube perimeter for two different c_{DIS}-settings. Note how c_{DIS}=0 slows down the traverse speed slightly more, while still producing a rounded corner.

Figure 10.3 Plots showing robot movement in the xy-plane with traverse speed described through grayscale plots.

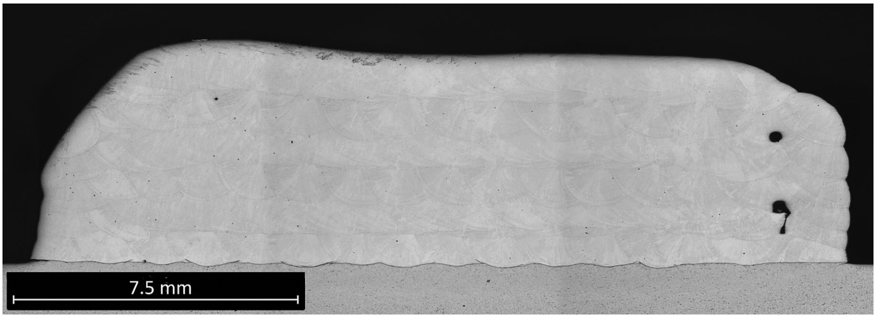


Figure 10.4 Microstructural imaging showing porosities in the finished build originating from a gap between perimeter and infill movement.

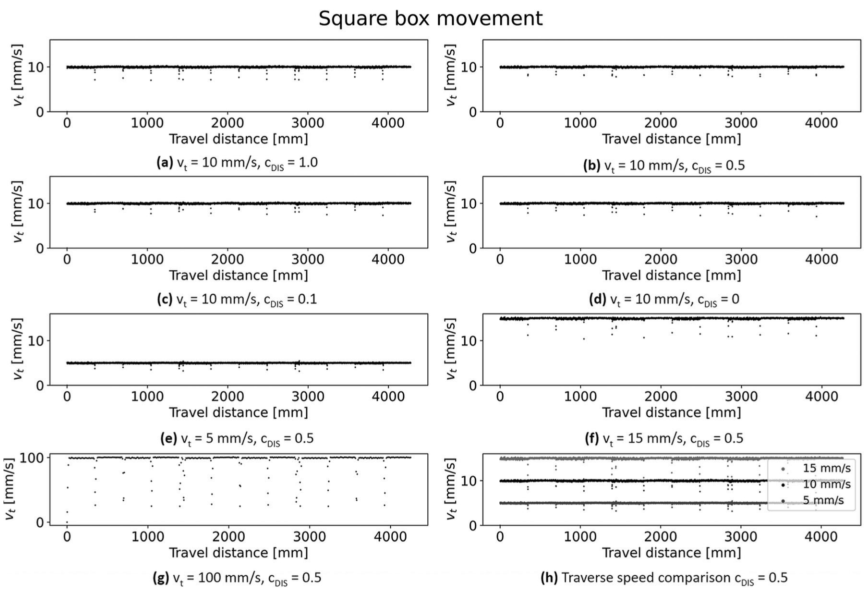


Figure 10.5 Profiles showing variations in traverse speed with different blend zone lengths and different traverse speeds.

15 mm/s but was still not able to keep a constant speed of 5 mm/s, since the same percentage-wise reduction of speed is observed also for 5 mm/s. This indicates that there are software limitations in the robot control system that produce these speed drops, not the physical ability of the robot.

The blend zone, or C_{DIS}, is a parameter that is defined in every robot programme written in KRL (Kuka Robot Language). It defines how far ahead the robot is allowed to adjust its trajectory for speed optimisation, meaning that a bigger C_{DIS} should result in more stable speed at the cost of reduced position accuracy around corners. It can be observed from subplots (a) to (d) in Figure 10.5 that the traverse speed reduction is almost identical for all the tested C_{DIS}-values. Setting the blend zone to 0.0 mm was expected to result in a full stop at the corners of a square movement due to the practical limitations of robot acceleration. This, however, did not happen, supporting the hypothesis that the robot controller overrides some of the programmed limitations of the robot. This is further supported by close studies of corner rounding with different blend zone sizes. Figure 10.3b shows that varying the blend zone from 0 to 1 mm has a very limited impact on the corner radius.

The findings give rise to a couple of considerations for AM applications:

- Consider real-time synchronisation of robot motion parameters and AM process parameters, e.g., wire or filament feed, electrical current (GMAW/GTAW processes), or laser power (laser-based AM processes). Such synchronisation can compensate for deviations in robot movement, but a more important aspect, beyond the motion study, is to improve the quality of the deposit and geometric accuracy by allowing additional material feed at unsupported external surfaces and other areas where constant parameters typically result in rounded edges and other deviations. Likewise, material feed and energy input can be adjusted to avoid accumulation in overlapped areas.
- Avoid the use of perimeters in path planning if possible. Since the rounding of corners may result in porosities between infill and perimeter, it may be better to not build with perimeter so that this problem is avoided.
- It has been shown that the robot will always round corners to a certain degree, meaning that fully sharp corners cannot be achieved. This is not a major limitation since a slight rounding can often be favourable to avoiding stress risers and other detrimental effects from sharp corners in the component design. Regardless, it must be considered in the design of parts that will be built with robot-mounted AM equipment.

Possibilities for industrial applications

Over the last decades, the interest in using AM to produce both prototypes and end-products in a near-net-shape has grown rapidly, and with it, the need for building larger components at a higher speed using these methods. We have seen a substantial increase in the use of robots for AM in the last five years. The Dutch company MX3D completed a 12.2-m walking bridge in Amsterdam in 2019. The bridge was made solely by their robotic WAAM system and got a lot of attention worldwide. Her Majesty, the Queen of Holland, opened this 6-tonne architectural wonder that is supposed to hold 20 tonnes. In the US, however, a company called Relativity Space has started testing the use of robotic WAAM to make 33.5-m space rockets.

Table 10.1 Important standards and guidelines related to specifications of AM parts [17]

Standard or guideline ID	*Description*
ISO/ASTM 52900 and ISO 17296-2	Standard terminology in AM process specification
DNV- CP-0267	Additive Manufacturing (AM) – approval of manufacturers
DNV- CP-291	AM feedstock
DNV- CP-B203	The qualification of parts made by AM for the oil and gas and related industries. Purchase, quality management, and manufacturing of parts.
DNV- CG-0197	AM – qualification and certification process for materials and components
API 20S	Additively manufactured metallic components for use in the petroleum and natural gas industries
ISO/ASTM FDIS 52943-2	AM of metallic parts with directed energy deposition in the aerospace industry.
ISO/ASTM 52901	Requirements for purchasing parts made from AM and guidelines on what information are to be exchanged between the customer and AM supplier
ISO/ASTM52907	Methods for characterising metallic powder
ISO/ASTM52910	Requirements, guidelines, and recommendations for using AM in product design

In the Norwegian industry, Westad Industri has been an early adopter in creating high-performance butterfly valves for the offshore industry by making surface claddings applied by a robotic DED system using laser and powder.

SINTEF Manufacturing also has a large robot cell with a multi-laser DED system, applying both wire and powder. SINTEF sees these types of metallic systems as an improvement over single laser systems as they are more stable, have fewer environment, health, and safety problems, and can produce parts relatively faster without spatter.

As discussed, the use of robotic systems for AM is seen as well-suited for large-scale parts and gives high flexibility for control. However, there are challenges mentioned in this book chapter that need to go into consideration for optimal process stability and part finish.

Table 10.1 lists the relative standards used for purchasing, setting requirements, and certain recommendations for AM parts ordering. However, in many sectors, components need to be classified and certified by the appropriate class society dedicated to the intended application area. Det Norske Veritas (DNV), for instance, is one such class society dedicated to the marine and offshore industries. Based on the guidelines, manufacturers become certified/approved for AM production according to the DNV guidelines and can achieve approval for manufacturing components with given materials after documenting their achieved properties.

Robot path planning for AM processes

In this section, we discuss robot path planning for AM processes. A robot path is a set of points or curves in the joint or operational space that the robot follows during the execution of motion [18]. The robot path is executed by the robot controller using firmware-specific velocity and acceleration profiles. Here, we consider path planning as an offline procedure, where the robot path is generated for the entire AM task before task execution starts.

Aspects of robot path planning for different AM processes

A pipeline for an AM process is shown in Figure 10.6. This is a general representation covering a conventional AM process [19]. In this section, we will concentrate the discussion on the steps closely related to path planning. Once the part to be produced is modelled in a computer-aided design (CAD) programme, it is converted to a sliceable representation, such as a stereolithography file, where the part surface is discretised by triangle elements. This way, a part can be intersected by a plane, creating one or more closed polylines. The process of obtaining the polylines by intersection of the sliceable part with multiple parallel planes is referred to as slicing. The next step is path planning, where planning parameters and the set of polylines are used to form tool paths. Path planning varies depending on the AM process, material, software capabilities, and desired results. For example, for the polymer MEX process, it is common to have to path planning sub-steps: path planning for outer and inner walls based on parameters for the number of perimeter shells, and path planning for filling the material between the walls based on the chosen infill density and desired infill pattern. The tool path planning also plans tool control such as start/stop of material feed or extrusion rate. The next step is the generation of robot instructions. In this step, the points of the planned path are converted to a list of high-level commands readable by the robot controller, such as G-code or a native robot input language. Once the list of robot instructions is generated, the robot controller can execute the motion and control the AM tool. Post-processing, for example, to remove support material, may be required depending on the AM process and the part design.

Path planning is highly dependent on the process involved. For example, the welding methods used within WAAM all have in common that the arc

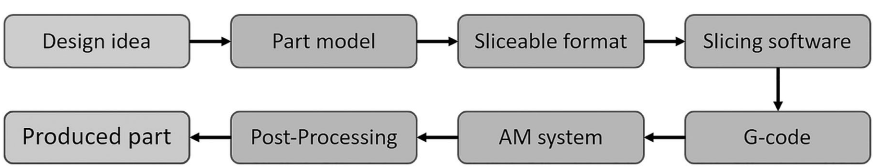


Figure 10.6 Typical pipeline for an AM process.

initiation and flame-out, i.e., the starting and stopping of the welding process, lead to uneven material deposition [20]. As material is therefore deposited continuously, the planned path should not cross its own path within a planned layer, as this could lead to a heap-up of material. Sharp turns can also be challenging depending on the movements of a robot manipulator, as the material flow is separate from the robot movements, and a lower movement speed will lead to more material being deposited over a given distance. The starting and stopping points of the build are generally challenging for many AM methods.

As part of the PhD work in SFI Manufacturing, several thin-walled structures with intersections and overhangs were built using WAAM [21]. These structures were all built using offline control of the robot's path, with some manual adjustments of the welding parameters during the welding process. Early experiments were done investigating how corners and transitions between layers could be solved for a continuous and automated WAAM process. Specifically, cold metal transfer (CMT) welding was used, which is a very stable and spatter-free type of GMAW with heat input in the lower range of GMAW techniques. The early experiments showed that, in line with the robot motion study presented earlier, sharp corners were challenging. As the material deposition rate remained the same while the traverse speed was reduced in corners, material would accumulate in those areas. The effect was reduced by using rounded corners in the part design.

Similarly, the transitions between layers for a continuous building process were solved by having a smooth increase in the vertical position of the tool over several centimetres when transitioning to a new layer. Increasing the vertical position of the welding gun at a single point was also tested, but while keeping a constant rate of material deposition, even an increase of only a couple of millimetres created a delay large enough to cause a significant heap-up of material at a single point along the path. This would accumulate for each passing layer, eventually causing large deformations in the structure. Experiments were also done to investigate how the path could be planned to avoid intersections within a layer, as this would lead to double deposition of material at the point of intersection. If stopping and re-starting the welding process are to be avoided, to steer clear of the issues related to arc-initiation and flame-out, this is something that should be considered. By instead designing the path to include opposing angles positioned so close together that the metal would melt together, it was possible to recreate "intersections" in the pattern of each layer without having the tool cross its own path. One such structure can be seen in Figure 10.7, and full details on these builds can be found in [22].

A framework for set-based control of the joints of a 6-DOF robot manipulator was also tested for thin-walled WAAM structures [23, 24]. This method is meant to simplify the movements of the robot manipulator by defining the position and/or orientation control of the end-effector to stay within a given set rather than at a specific value, and the idea was that this could be used to create a smoother building process for WAAM. The structure was a cylindrical structure with a continuous, helix-shaped path, and the set-based constraints were set to allow for a small deviation away from a vertical orientation of the tool, i.e., orthogonally onto the substrate [25]. Because the change in orientation of the tool was not symmetrically distributed around the circular structure, even a very small difference in the orientation (approx. 6°) led to a significant variation in how the material was deposited and accumulated as the building process progressed. The conclusion was that for WAAM, the orientation of the tool impacts the build too much for the set-based control framework to be a suitable method of control, and it was clear that the orientation of the tool is a significant part in the robot path planning.

The structure shown to the right in Figure 10.7 was also built using CMT, with continuous material deposition along an upward spiralling helix path with a continuously increasing radius, thereby creating an overhang. This could have been solved using a *mobile* building surface around a *fixed* point of material deposition, as demonstrated by [26] and [27], and this seemed to be the dominating approach at the time. However, if the building surface could remain fixed with a mobile and flexible point of material deposition, it could be possible to use the technique in a more practical scenario, as discussed further in [21]. In an industrial context, this could, for example, allow for repair work on ships or other large structures that cannot easily be moved or tilted around a fixed nozzle. So, by having the orientation of the welding gun follow the angle of the increasingly tilting wall, it was possible to create such an overhang without the need for support structures. The final angle was approx. 43 degrees, and future work should investigate how prominent such an overhang can become before the structure starts showing significant deformations. More details on this can be found in [28]. Future work should also focus on real-time monitoring of the building process as well as feedback control of the robot's

Figure 10.7 Structures with overhang and intersections built using WAAM.

path. Combining these could improve the quality of the build by adjusting the path of the robot to compensate for deformations during the build.

In the case of using GTAW, an additional degree of freedom about the welding gun axis must be taken into consideration. This is due to the wire must be fed in front of the weld arc along the path. In a robotic setup without a rotary table, this can restrict the execution of certain continuous paths, as the wrist joint of the robot has rotational limitations. An illustrative example of that could be a continuous coil-like path for building a thin-walled cylinder. To execute such path, a rotary table for a workpiece is mandatory.

Path generation on non-planar surfaces using CAD models

Many commonly used AM methods are based on gantry systems with a fixed building direction, and the planned layers for the manufacturing process are therefore also planar and perpendicular to the preceding layer. This pipeline then follows the typical pipeline for AM as presented in Figure 10.6. Allowing for curved layers could greatly improve the flexibility of the AM process and make it possible to construct geometries that would otherwise need additional support structures. In the following sections, two path planning methods to enable printing along non-planar layers are presented.

To enable path planning along non-planar layers, a method based on the CAD model in the STEP format was proposed by one of the master students in SFI Manufacturing. While the STL format contains an approximation of the surfaces of an object, the STEP model contains an accurate description of the surfaces. This method only considers the faces of the CAD model, where a face is a surface bounded by a set of edges. The method consists of two main steps: sampling the desired surface into a point cloud and generating the path based on the points.

The surface is parametrised by a system based on curvilinear coordinates. These coordinates are used to sample the surface by iterating through them with a given step length. The sampling is gathered in a one-point cloud. The results of the sampling on two different surfaces can be seen in Figure 10.8. The next step is to generate the path based on the point cloud. Three different

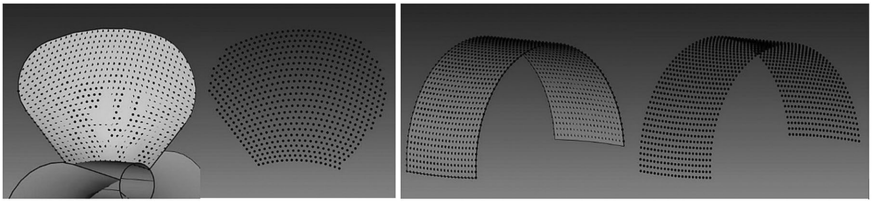


Figure 10.8 Resulting point cloud from sampling a propeller blade and bridge [29] (CC BY-NC-ND 4.0).

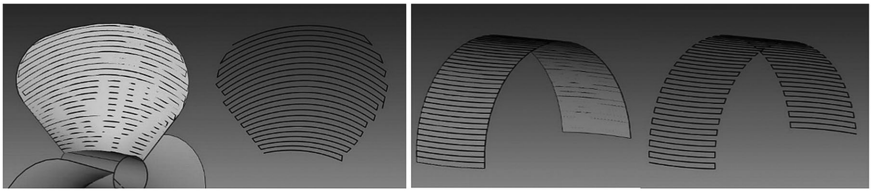


Figure 10.9 Path generated using the weighted greedy algorithm [29] (CC BY-NC-ND 4.0).

algorithms for generating the path were tested, including a solver for the Travelling Salesman Problem, greedy choice, and weighted greedy choice.

The path generation method was tested on two different CAD models: a curved rectangular surface resembling a bridge and a propeller blade. The bridge was chosen to demonstrate how a path for printing in overhang can be achieved, and the propeller blade to demonstrate printing along nonlinear paths. The result of the path generation using the weighted greedy algorithm can be seen in Figure 10.9.

The sampling algorithm captured the geometry of the surface well. Both surfaces were captured with a constant step length. For more complex geometries, a shorter or varying step length step length could be appropriate. Out of the three different algorithms that were tested for path generation, the weighted greedy choice gave the best results. Results from the other two algorithms can be seen in [29] and [30]. The paths generated with the weighted greedy algorithm show how non-planar paths can be realised using a 6-DOF robot manipulator.

Path planning for curved layers

Many commonly used AM methods are based on gantry systems with a fixed building direction, and the planned layers for the manufacturing process are therefore also planar and perpendicular to the preceding layer. Allowing for curved layers could greatly improve the flexibility of the AM process and make it possible to construct geometries that would otherwise need additional support structures. A framework for performing robotic AM using a 6 DOF robot manipulator was proposed by Dai et al. [27], aiming to decompose arbitrary objects into manufacturing layers and then automate toolpath generation for multi-DOF AM. The methods suggested by Dai et al. have no constraints on the shape of the generated manufacturing layers, allowing for curved layers, as well as planar ones.

Two of the algorithms suggested by Dai et al. [27] were implemented and tested using simulations by one of the master students in SFI Manufacturing in 2019 [31]. Based on a digital model, a discretisation process divides the continuous volume into a final number of voxels before accumulating these voxels into printing layers. A tool path is planned for each layer, which can then be translated into machine instructions before executing the build process itself. The scope of the master's project mainly covered 2D objects. After using 2D objects to refine and understand the algorithms, tests were done on one 3D object, as the methods suggested by Dai et al. were designed for 3D objects as well [27].

The algorithms were tested on six different input objects, all with different overhangs. The method tested in the thesis was greedy growing convex front advancing (GCFA), with and without incremental shadow prevention (GCFA-ISP). The GCFA algorithm processes each voxel locally, accumulating them into a sequence of manufacturing layers in a bottom-to-top manner. As the methods suggested by Dai et al. had no constraints on the shape of the layer, curved layers were also generated [27]. Additional constraints ensured a self-supported and collision-free manufacturing process. A weakness of the greedy strategy is that it will always go for the locally optimal choice, which might create challenges later in the manufacturing process. The improved GCFA-ISP scheme introduces an additional constraint to avoid shadowing, i.e., reduce the number of voxels that cannot be included in current or future building layers due to their position compared to already planned layers, as shown in Figure 10.10.

The algorithms were reviewed and altered to generate satisfying and realisable results from the simulations. Building without support structures was enabled by reducing the number of neighbouring voxels eligible for being accumulated into the next layer. The altered GCFA-ISP algorithm was stricter, ensuring that, before adding a voxel to the next generated layer, this voxel must cause the shadowing of *less* voxels compared to the greedy scheme. The methods for curved layers were also compared to an existing object decomposition method [31]. The results from the master's thesis showed that the platform size impacts the generation of the layers and that a larger surface can lead to more voxels being shadowed. For all the tested structures, the results improved for curved layers compared to planar layers when considering the number of voxels that were missed when generating the path for each layer. This shows how a manufacturing process can benefit from the flexibility provided by a 6-DOF robot manipulator with the ability to deposit material at a non-vertical angle. For more details, see [27, 31].

Robotic AM using commercial CAM software

Hardcoding the robot's movements for complex parts can be quite complex and time demanding. Just as in a CNC-machining operation, CAM software is used to programme plan and programme the code that executes the build job. Hence, the software has an input of CAD design and an output of G-code, as described in Figure 10.5. There are several available CAM software packages that are applicable to robot-controlled AM. Most of these

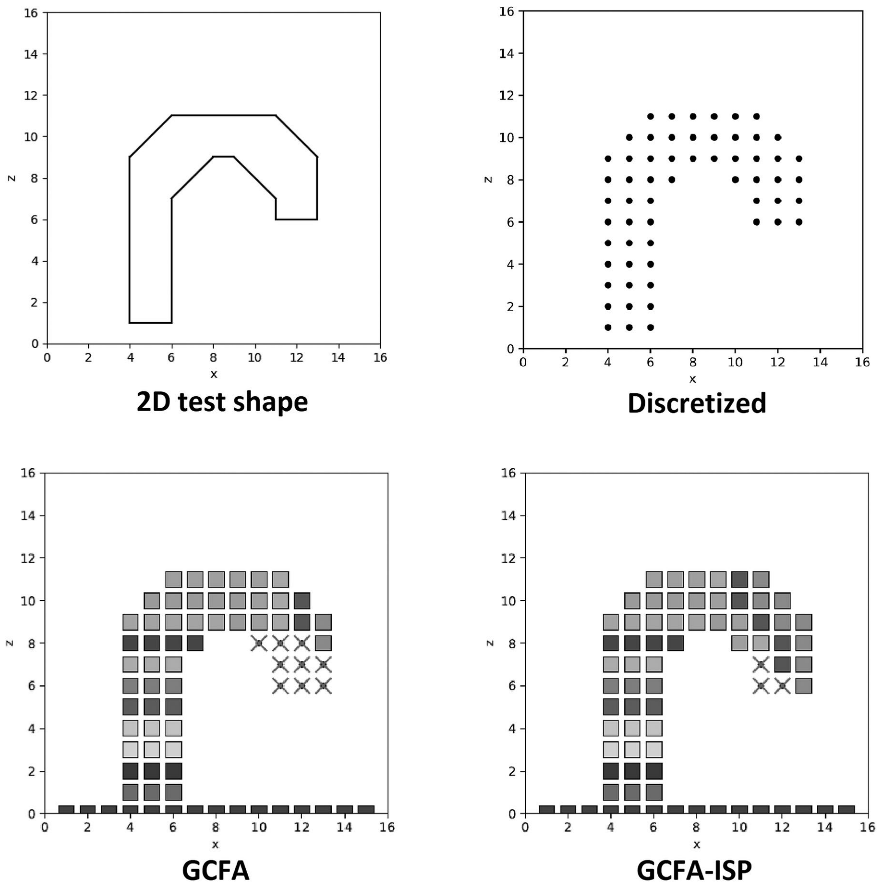


Figure 10.10 2D test figure with overhang. Using the improved GCFA-ISP algorithm reduces shadowing [31].

are derived from machining, e.g., SKM DCAM, ModuleWorks, Robotmaster (Mastercam), Siemens NX, Catia, SprutCAM, and Grasshopper.

Vision sensor technology for robotic AM processes

The integration of sensor technology in the field of AM is essential for the assessment of 3D geometry and the optimisation of the production process. The sensors allow for continuous monitoring and control of various stages of the AM process, helping to ensure the process's repeatability and consistency with the final product. For instance, measuring the height and shape of the deposit during the build process can provide valuable information to make adjustments and improve the geometric accuracy of the final product. In addition to 3D geometry evaluation, real-time monitoring of process parameters, such as the temperature of the melt pool, can help maintain the desired process conditions to achieve acceptable material quality [32]. The use of robot manipulators in AM presents the opportunity for an increased building volume and an expanded degree of geometric complexity compared to traditional cartesian machines. Despite these advantages, it also raises the likelihood of deviations occurring in the manufacturing process, as robot manipulators typically have good repeatability but lower geometric accuracy. Previous research has shown the potential of using different camera technologies and customised vision-based setups in AM processes [33]. Integrating sensors into industrial MEX systems is a vital area of research, which involves the development of advanced sensor concepts for high-temperature and large-volume environments and efficient sensor modules that can function within the constraints of moving machine parts and frame structures [34]. With these advancements in sensor technology, manufacturers will be able to more effectively monitor and control the AM process, ensuring a consistent and high-quality final product. In the following, a brief introduction to optical measuring techniques for in-process assessment of geometric deviations is given.

Profile laser scanning

Profile laser scanning is a non-contact, non-destructive measurement technique that is widely used in various industrial applications. By projecting a laser beam onto an object and capturing the resulting light scattered from its surface using a camera, the three-dimensional geometry of the object can be extracted by image processing techniques (Figure 10.11). The working

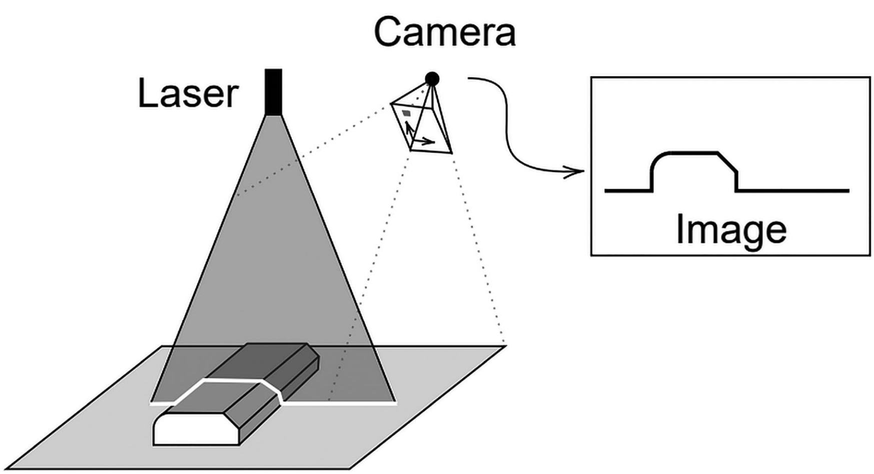


Figure 10.11 Working principle of line laser scanners.

principle of profile laser scanning is based on triangulation, a fundamental geometric principle that involves determining the position of an object based on the intersection of two lines. In profile laser scanning, the laser source and the camera are positioned so that the laser beam and the camera line of sight intersect at the surface of the object being scanned.

The distance between the camera and the object can then be calculated based on the position of the laser beam in the camera's field of view. Profile laser scanning is a fast, efficient, and accurate method of measuring objects and surfaces. Line-profile laser scanners can be used for dimensional measurements of parts and assemblies, quality control, reverse engineering, and 3D scanning. One of the critical applications of line laser scanners in AM is the detection of defects and imperfections on the surface of the printed part. A reconstruction of item surfaces can be done using a line laser scanner quickly, inexpensively with excellent accuracy. Moreover, this only requires a single camera and a single laser light beam to be projected at a fixed angle from one another. A single point cloud is created from all the collected profiles as the item is repeatedly profiled as it passes past the laser line scanner. The accuracy and precision of profile laser scanners depend on various factors, such as the laser source intensity, the camera resolution, and the environmental conditions. However, with advances in laser and camera technology, profile laser scanning is becoming increasingly accurate and reliable, making it a valuable tool for industrial AM applications. The line laser scanner helps identify the cause of defects. By analysing the structure of any manufactured part, the scanner can detect any issues in real-time manufacturing processes and the potential to correct them, resulting in fewer failed manufactured parts and increased efficiency. These kinds of technologies have the potential to integrate with different AM systems and provide a better diagnostic of the structure of manufactured objects as well as the capability to identify deviations in active production processes.

3D cameras

3D imaging is a non-contact, non-destructive measurement technique increasingly popular for capturing and analysing the shape and texture of objects in three dimensions, providing more comprehensive information than traditional 2D vision. Various types of 3D cameras are available, including structured light cameras, time-of-flight cameras, and stereo cameras. In stereovision, two cameras are positioned at different angles to capture the same scene. These cameras work together to triangulate the depth of objects within the scene and generate a point cloud, a 3D representation of the scene. Structured light cameras combine a projector with a camera to project and image a known pattern, such as grids or horizontal bars, onto a scene. The depth of objects in the scene can then be determined. The principle is illustrated in Figure 10.12. Time-of-flight 3D cameras measure depth by evaluating the time it takes for a light pulse to travel to an object and return.

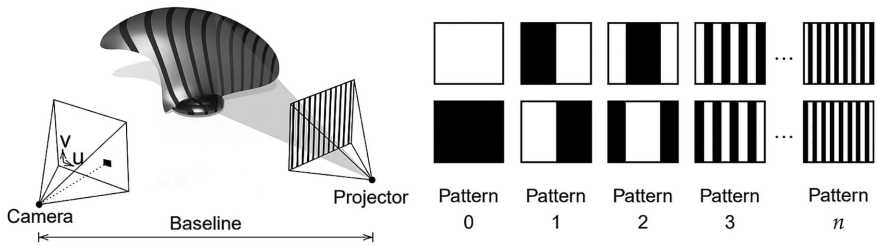


Figure 10.12 Left: Structured light imaging principle. Right: binary structured light patterns which are successively projected onto the object.

3D cameras are becoming increasingly important in the manufacturing and inspection processes, as they can provide detailed information on the geometry and shape of products, improving production accuracy and consistency. 3D cameras are also helpful in other robotic and automation systems, as they provide real-time information on the position and orientation of objects in the environment. The term *point cloud* refers to a group of data points in three dimensions that are often generated by a laser scanner or other sensor. Point cloud data can be utilised to construct a digital model that can be employed in the AM process by capturing the geometry of an object. Making a digitised representation of an existing component and utilising the representation to manufacture a copy using AM is one manner to use point cloud data in AM. Making duplicates of unique or challenging-to-manufacture products or generating replacement parts for machinery or other equipment can benefit from this. Another way to use the point clouds generated from the sensor is to utilise the data to increase the accuracy of the AM process by comparing the finished product's quality to the original design. One way to determine if any deviations or mistakes were made during the manufacturing process is to compare the final product's point cloud data to the original design's point cloud data. Such comparisons can assist in finding and fixing problems early on, enhancing the finished project's overall quality.

Thermal cameras

Thermal cameras play a valuable role in AM by providing insights into heat-related aspects and can be used for monitoring and controlling the AM process. These cameras capture images in the infrared radiation spectrum and estimate the temperature of the objects within their field of view.

Thermal cameras are beneficial for monitoring the temperature of the melt pool, as it is an important parameter affecting the final product's quality. By monitoring the melt pool, one can determine the melt pool size, shape, temperature, and solidification rate, among other things. The use of thermal cameras enables the detection of anomalies and deviations in the manufacturing process, helping to identify potential sources of defects and improve the consistency of the final product. For example, suppose the temperature of the melt pool is higher or lower than the desired range. In that case, thermal cameras can detect the deviation, and the process parameters, such as the heat input and travel speed, can be adjusted to maintain optimal conditions, reducing the risk of manufacturing defects such as porosity and cracking. In metal AM processes such as WAAM and DED, thermal camera temperature estimates can be used to maintain a desired interpass temperature between the layers or beads, avoiding defects such as excessive hardness. In addition to monitoring the temperature of the melt pool, thermal cameras can also be used to monitor the thermal behaviour of the build platform, the cooling system, and the heating elements, which are critical components of the AM process.

Feedback control for AM processes

Although closed loop control is currently being used in AM, both for cartesian machines and robotic manipulators, it is almost exclusively used for ensuring that the print head or deposition tool follow the pre-designed reference trajectory. The concept of utilising feedback control for supervising or directly controlling the shape or quality of the build during production is a largely unexplored idea, both in literature and industry. This type of feedback control can be envisioned as an outer control loop in an AM system, where the usual robot control system constitutes the inner loop. The concept is illustrated in Figure 10.13. The literature review [35] explores this topic and divides it into three areas: geometric error detection and correction, deposition process control, and thermal monitoring for layer scheduling and cooling control. It is concluded that, in addition to control design, advances in measurement and sensing for feedback and in 3D reconstruction are needed for realising this concept. The main difference from the classical AM process in Figure 10.6 is that in Figure 10.13, sensor measurements are used as control feedback to improve the quality and geometric precision of the produced parts.

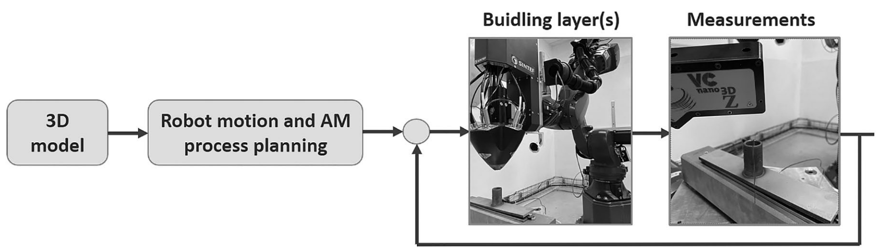


Figure 10.13 The concept of feedback control in AM processes.

Conclusions

We have presented a review of the work on utilisation of robotic manipulator arms for AM processes done in the SFI Manufacturing project. The review was limited to DED and polymer MEX AM processes, where two variations of DED were discussed: laser melting and wire-arc AM (WAAM).

Generally, Cartesian manipulators are the dominant robotic platform in industrial AM implementations. Serially linked robotic arms can provide greater flexibility to the process, e.g., due to the possibility of varying tool orientation, but introduce additional complexity due to the transformation from joint to task space. Robotisation of AM processes might also require synchronisation of AM processes and robot motion parameters to increase quality and reduce geometrical deviations.

From the perspective of industrial implementations, the cost of equipment might be significant; however, the classification and certification of AM produced parts is a more critical problem. We have provided a table with several relevant standards and guidelines.

Classical path planning for AM processes is industrially done using CAM software. It might work well for standard cases; however, path planning with overhang and path planning on curved surfaces is still an open research field and is of little use in industry.

Sensor data can be beneficial for AM processes. We have provided application examples of profile laser scanners and 3D cameras for geometry quality control both at the bead and entire part level. In addition, thermal cameras can be used for parameter monitoring of melt pools in DED processes, which allows for early defect detection.

Finally, we have provided some insights into possibilities for feedback control for AM processes. Such process control can provide significant benefits for the improving quality and geometric tolerances of products and should be more researched in the future.

Declaration

The authors declare no competing interests and confirm that the manuscript has been read and approved for publication by all named authors.

References

1 ISO/ASTM, *52900:2021(E)*, ISO/ASTM, 2021.
2 E. Halmøy, *Sveiseteknikk*, 4 ed., NTNU, 1991.
3 S. W. Williams, F. Martina, A. C. Addison, J. Ding, G. Pardal and P. Colegrove, "Wire+ Arc additive manufacturing," *Materials Science and Technology*, vol. 32, no. 7, pp. 641–647, 2016.
4 A. Thakur, H. Gebrelibanos and T. Gabrey, "Arc welding process selection through a quality and costs," *International Journal of Current Engineering and Technology*, vol. 9, no. 3, pp. 383–394, 2019.

5 D. Ding, Z. Pan, D. Cuiuri and H. Li, "Wire-feed additive manufacturing of metal components: technologies, developments and future interests," *The International Journal of Advanced Manufacturing Technology*, vol. 81, pp. 465–481, 2015.
6 D. Ahlers, F. Wasserfall, N. Hendrich and J. Zhang, "3D printing of nonplanar layers for smooth surface generation," in *IEEE 15th International Conference on Automation Science and Engineering (CASE)*, Vancouver, 2019.
7 S. Kersten, M. Praniewicz, T. Kurfess and C. Saldana, "Build orientation effects on mechanical properties of 316SS components produced by directed energy deposition," *Procedia Manufacturing*, vol. 48, pp. 730–736, 2020.
8 T. Yao, J. Ye, Z. Deng, K. Zhang, Y. Ma and H. Ouyang, "Tensile failure strength and separation angle of FDM 3D printing PLA material: Experimental and theoretical analyses," *Composites Part B: Engineering*, vol. 188, no. 1359–8368, 2020.
9 L. D. Evjemo, S. Moe, J. T. Gravdahl, O. Roulet-Dubonnet, L. T. Gellein and V. Brøtan, "Additive manufacturing by robot manipulator: An overview of the state-of-the-art and proof-of-concept results," in *22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Limmasol, Cyprus, 2017, pp. 1–8.
10 J. F. Engelberg, "Historical perspective and role in automation," in S. Y. Nof (Ed.), *Handbook of Industrial Robotics, Second Edition*, John Wiley & Sons, Inc, 1999, pp. 3–10.
11 J. F. Engelberger, *Robotics in Practice*, Springer, 1983.
12 V. Scheinman, J. M. McCarthy and J.-B. Song, "Mechanism and actuation," in B. Siciliano and O. Khatib (Ed.), *Springer Handbook of Robotics, Second Edition*, Springer, 2016, pp. 67–89.
13 K. M. Lynch and F. C. Park, *Modern Robotics*, Cambridge University Press, 2017.
14 A. Albu-Schäffer, S. Haddadin, C. Ott, A. Stemmer, T. Wimböck and G. Hirzinger, "The DLR lightweight robot - Design and control concepts for robots in human environments," *Industrial Robot*, vol. 34, no. 5, pp. 376–385, 2007.
15 "Meltio Engine robot integration," *Meltio*, [Online]. Available: https://meltio3d.com/metal-3d-printers/meltio-engine-robot-integration/. [Accessed 01 09 2023].
16 "Kuka KR IONTEC robots," *Kuka*, [Online]. Available: https://www.kuka.com/en-de/products/robot-systems/industrial-robots/kr-iontec. [Accessed 01 09 2023].
17 K. Boivie, S. M. Aabo and T. Leirmo, "Smart spare parts management," SINTEF Open Report, Trondheim, 2022.
18 B. Siciliano, L. Sciavicco, L. Villani and G. Oriolo, *Robotics: Modelling, Planning and Control*, Springer, 2009.
19 A. W. Johnsgaard, "3D printing with robot manipulator," Master's Thesis, Norwegian University of Science and Technology, Trondheim, 2022.
20 F. Martina, J. Mehnen, S. W. Williams, P. Colegrove and F. Wang, "Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V," *Journal of Materials Processing Technology*, vol. 212, no. 6, pp. 1377–1386, 2012.
21 L. D. Evjemo, "Additive manufacturing of thin-walled structures by robot manipulator: An experimental approach focusing on arc welding," PhD Thesis, Norwegian University of Science and Technology, Trondheim, 2022.

22 L. D. Evjemo, G. Langelandsvik and J. T. Gravdahl, "Wire arc additive manufacturing by robot manipulator: Towards creating complex geometries," *IFAC-PapersOnLine*, vol. 52, no. 11, pp. 103–109, 2019.
23 S. Moe, G. Antonelli, A. R. Teel, K. Y. Pettersen and J. Schrimpf, "Set-based tasks within the singularity-robust multiple task-priority inverse kinematics framework: General formulation, stability analysis, and experimental results," *Frontiers in Robotics and AI*, vol. 3, no. April, pp. 1–18, 2016.
24 S. Moe, J. T. Gravdahl and K. Y. Pettersen, "Set-based control for autonomous spray painting," *IEEE Transactions on Automation Science and Engineering*, vol. 15, no. 4, pp. 1785–1796, 2018.
25 L. D. Evjemo, S. Moe and J. T. Gravdahl, "Robotised wire arc additive manufacturing using set-based control: Experimental results," *IFAC-PapersOnLine,* vol. 53, no. 2, pp. 10044–10051, 2020.
26 J. S. Panchagnula and S. Simhambhatla, "Manufacture of complex thin-walled metallic objects using weld-deposition based additive manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 49, no. February, pp. 194–203, 2018.
27 C. Dai, C. C. L. Wang, C. Wu, S. Lefebvre, G. Fang and Y.-J. Liu, "Support-free volume printing by multi-axis motion," *ACM Transactions on Graphics,* vol. 37, no. 4, pp. 1–14, 2018.
28 L. D. Evjemo, G. Langelandsvik, S. Moe, M. H. Danielsen and J. T. Gravdahl, "Wire-arc additive manufacturing of structures with overhang: Experimental results depositing material onto fixed substrate," *CIRP Journal of Manufacturing Science and Technology,* vol. 38, pp. 186–203, 2022.
29 I. F. Onstein, *An Additive Manufacturing Path Generation Method Based on CAD Models for Robot Manipulators*, Norwegian University of Science and Technology, 2018.
30 I. F. Onstein, L. D. Evjemo and J. T. Gravdahl , "Additive manufacturing path generation for robot manipulators based on CAD models," *IFAC-PapersOnLine*, 2020.
31 H. Boge, "Robotic additive manufacturing: Testing and evaluation of curved layer generation," Master's thesis, Norwegain University of Science and Technology, Trondheim, 2019.
32 D. Hu and R. Kovacevic, "Sensing, modeling and control for laser-based additive manufacturing," *International Journal of Machine Tools and Manufacture*, vol. 43, no. 1, pp. 51–60, 2002.
33 T. G. Spears and S. A. Gold, "In-process sensing in selective laser melting (SLM) additive manufacturing," *Integrating Materials and Manufacturing Innovation*, vol. 5, no. 2, pp. 16–40, 2016.
34 A. Oleff, B. Küster, M. Stonis and L. Overmeyer, "Process monitoring for material extrusion additive manufacturing: a state-of-the-art review," *Progress in Additive Manufacturing*, vol. 6, pp. 705–730, 2021.
35 A. H. Moltumyr, M. H. Arbo and J. T. Gravdahl, "Towards Vision-based Closed-loop Additive Manufacturing: A Review," in *3rd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS)*, Gjovik, Norway, 2020.