Representative Title

Breaking the 100 lb/h Barrier via Multi-agent Wire Arc Additive Manufacturing

Contributors

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Problem Definition

In most of the world, the majority of large-scale tooling is currently imported from a relatively small number of countries. Similarly, most large-scale castings are imported. For example, by some estimates, as much as 70% of large-scale castings enter the US market from China. The long lead times for even the raw materials needed for large (>1,000 lb) parts and the environmental concerns about carbon-intensive foundries hamper expansion of traditional production. Together, these issues make many of the current clean energy goals nearly impossible to achieve and increase global supply chain fragility. If more environmentally friendly methods could be developed to replace castings, or augment simpler and smaller castings by adding features in post processings steps, domestic production could resume in many places. This would not only lead to a more robust global supply chain, it would reduce the dependence of the world economy on international shipping, further reducing the environmental impact of production.

Background Perspective

Additive manufacturing on the scale necessary to replace conventional methods for large parts has traditionally been cost prohibitive. For example, the most popular metal additive technology by sales, powder bed fusion, requires extensive safety precautions during the handling of the relatively expensive metal powder feedstock and has relatively low deposition rates.

Wire Arc Additive Manufacturing (WAAM) can achieve much higher deposition rates than powder bed fusion systems. WAAM also generally uses off-the-shelf welding equipment and wire, which makes its adoption much easier than powder bed systems. However, even with WAAM deposition rates, print times can be too long to justify its use over conventional methods for large parts.

To increase the deposition rates of WAAM, a multi-agent architecture can be used. By collaboratively depositing material, total deposition rates can be increased. However, the algorithms necessary to enable such collaboration had not previously been proven for WAAM.

Technical Overview

The MedUSA system comprises three six degree-of-freedom ABB IRB 4600 robots spaced equally around a circular workpiece-positioner that has a diameter of 2.25 m. All the robots are controlled by a single ABB IRC5 unit. A variety of Lincoln Electric welders can be used and are controlled via the ArcLink protocol. The system is enclosed in a caged cell covered with welding curtains and features a retractable ceiling to allow crane access for removing large parts. The cell is equipped with a filtration system to expel weld fumes, and entrances are protected with safety sensors. Three network cameras are mounted on the cell ceiling, and additional cameras are mounted on each robot to monitor the process during operation. A high-level supervisory controller ensures that the robots, the positioner, and the welders all work in unison and captures all relevant data during the print process. The system can reach deposition rates of up to 100.5 lb/h over a cylindrical work volume of roughly 2 m in diameter and almost 2 m in height.

To calibrate the multi-agent system, a Leica AT960 absolute laser tracker was used with Verisurf metrology software to record robot paths and capture the topology of the positioner table. The tracker was also used to calibrate the coordinate frame locations of each robot. The final positional error between each robot end effector was less than 0.07 mm for points in system's global coordinate frame.

One unique aspect of the control architecture for MedUSA is that robots are not assigned to toolpath segments a priori. Instead, this assignment happens at run time based on an optimization algorithm with a cost function that can include terms representing part geometry, thermal profile, and robot and welder state. To generate the initial database of toolpath segments (i.e. the bead list), the part is sliced like traditional additive manufacturing. The resulting G-code is then parsed into a JSON representation, which is used to calculate desired bead properties and information about each bead's location in the system workspace. This information is combined with feedback from the system at runtime, including part temperature, robot and positioner state, welder state, and process variables to rank the remaining beads in the queue. This queue is then used to assign beads to robots as they become available. The run-time assignment of tool-path segments means that MedUSA is also robust to robot, welder, and power supply failures. The robot that fails can simply be removed from the queue of available robots, and the remaining robots can finish the part. A single point of failure no longer leads to lost parts and production time. The bead assignment algorithm is also scalable, so robots can be added or removed based on the production needs of the part currently being manufactured.

In addition to the supervisory controller, each robot maintains two local feedback loops intended to ensure part quality and geometric accuracy. Through arc seam tracking (TAST) uses feedback of welding current to adjust the Z-height of the robot to maintain a constant welding electrode stick out. The correction in Z-height applied by the TAST controller is also used in an adaptive height controller to determine whether the part is over or under-building. The adaptive height controller adjusts the linear deposition velocity, changing the local deposited volume. Heights below the ideal layer height reduce the velocity up to 5% and therefore deposit more material, while heights above the ideal layer height increase the velocity by 15% and therefore deposit less material.

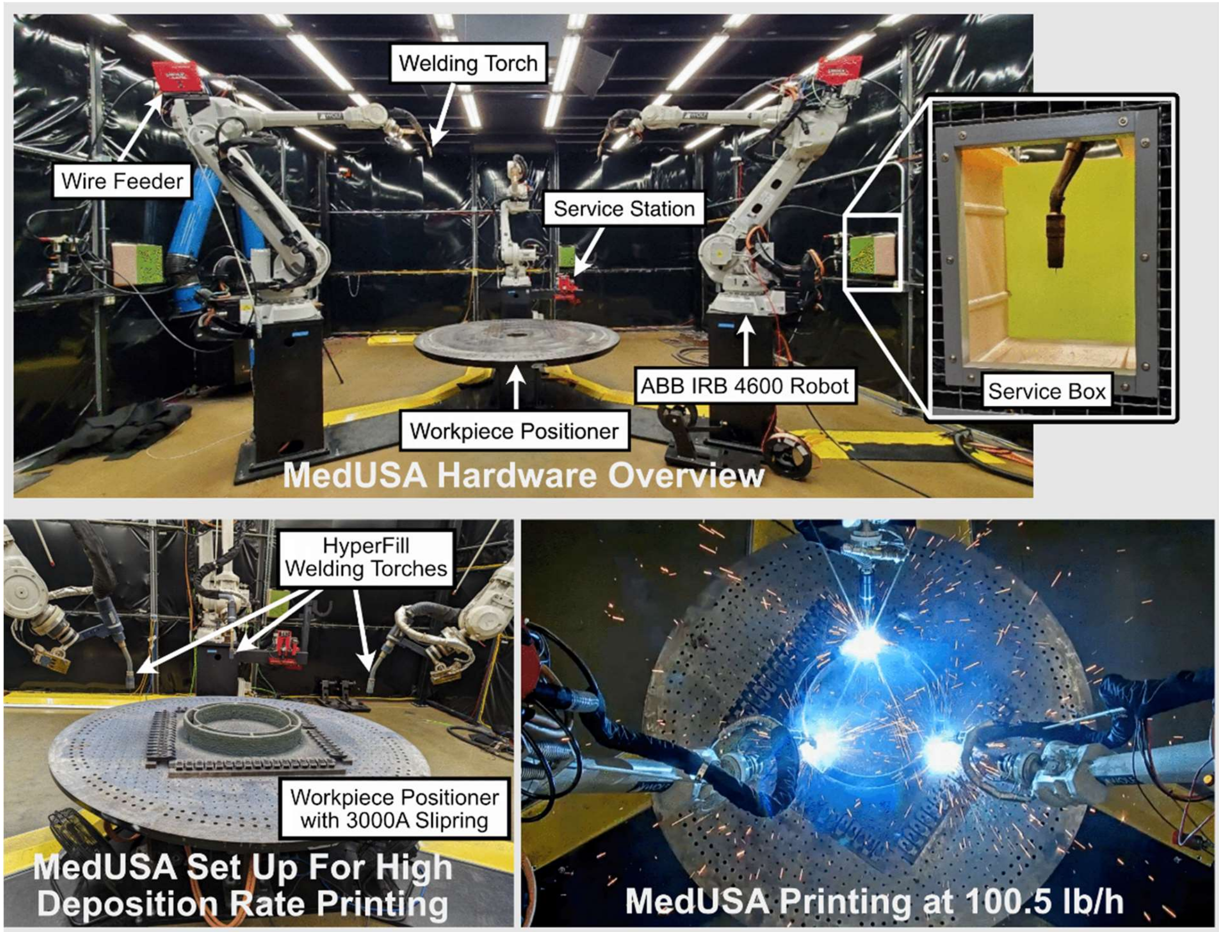
Even with the multi-agent configuration of MedUSA, with standard welders, the maximum deposition rates only approach 50 lb/h. To achieve greater than 100 lb/h deposition rates, high deposition rate welders must also be used. For MedUSA, Lincoln Electric HyperFill torches were used. The current required to reach these deposition rates also necessitated the design and installation of a high-current (3000 A rated) slip ring on the positioner table.

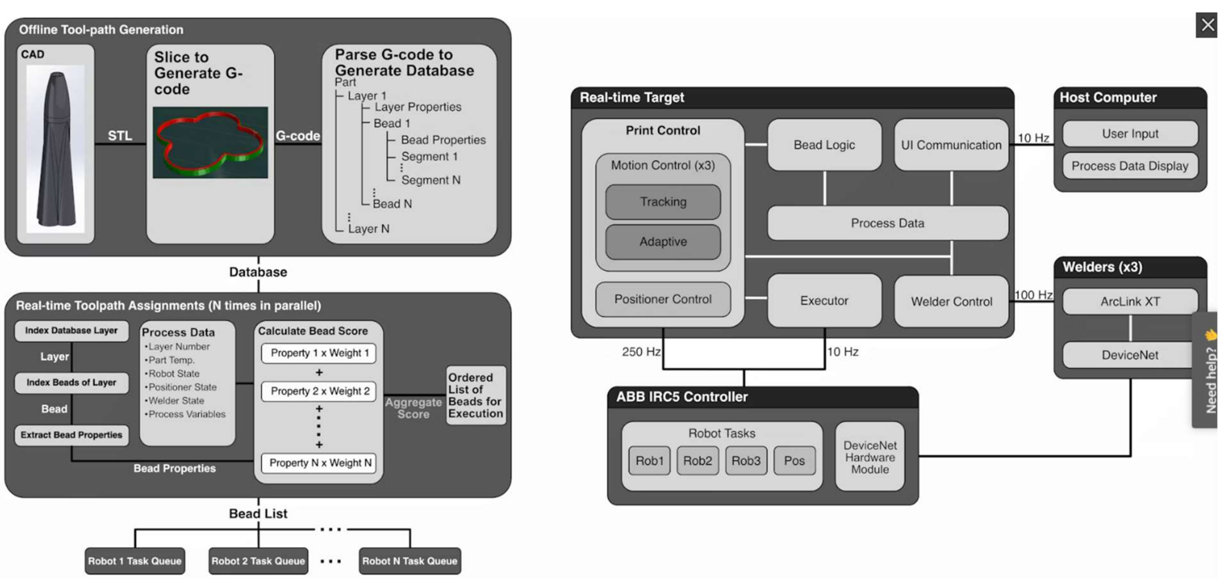
The demonstration part in this case study was built from Inconel 625 using the new high–deposition rate system with a maximum deposition rate of 100.5 lb/h. Its final weight was over 200 lb. The current output of each welder was around 550 A with a voltage of around 30 V for a power output of 16.5 kW per welder and 49.5 kW for the entire system. Two 0.045" Inconel 625 wires were used for each torch.

Reflections

MedUSA presents one way to produce parts in the size ranges that are difficult to source without significant lead time, and the fully electric process means that the production has significantly less environmental impact than traditional manufacturing processes. The geometric flexibility of the WAAM process means that parts can also be improved functionally. For example, multiple parts for tooling applications that have conformal cooling channels have been produced. These same parts were also made more quickly and cheaply than conventional methods.

The flexibility of the system also means that large parts, which generally are produced in small volumes, can be made more economically. For example, the need to create molds, as exists in the casting process, is eliminated. Therefore, producing the parts required for large-scale clean energy applications, such as wind energy, hydropower, or next-generation nuclear power, becomes significantly more attractive for industry. Additional flexibility could also be achieved by using different materials in each robot or by including additional toolheads.

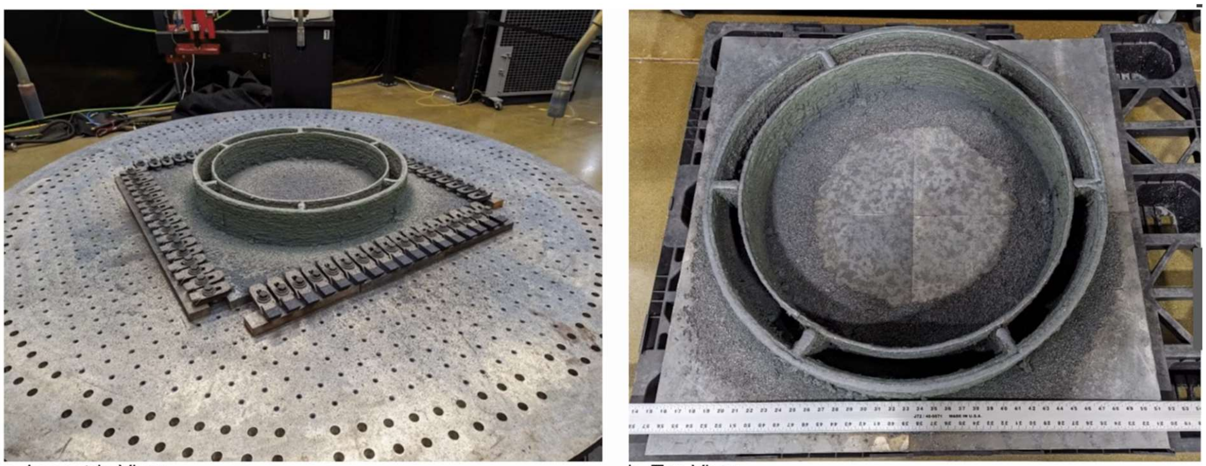




a. Multi-agent Toolpath Generation Workflow

b. System Architecture Overview

Multi-agent Toolpath Generation and System Architecture



a. Isometric View b. Top View

Pictures of the part printed at 100.5 lb/h. The final part weighed over 200 lb and was made from Inconel 625.