Autonomous Additive Manufacturing System (AAMS)

Technical descriptions

Rev. 20220903

Overview

The Autonomous Additive Manufacturing System (AAMS) is a novel Metal Additive Manufacturing system that predicts and corrects any possible defects that may occur to the parts being printed, thus delivers parts with improved quality. AAMS consists of three major subsystems, biz. Metal Additive Manufacturing (MAM), Machine Learning Inference (MLI), and Closed-loop Control (CLC).

The MAM subsystem is an in-house developed Directed Energy Deposition (DED) additive manufacturing system. It consists of a 1 kW fiber laser, a dual-hopper powder feeder, and a Computer Numerical Control (CNC) 3-axis movement system. All components are integrated and controlled via the CLC software. The MAM subsystem is capable of printing complex metal parts of one or more materials with high dimensional accuracy and functional gradient. The MLI subsystem consists of a high-speed infrared (IR) camera and a pre-trained machine learning inference model, integrated with the control software of AAMS. The pre-trained machine learning inference system maps the underlying relations between temperature distribution of melt pools, print quality, and processing parameters such as laser power, powder feeding rate, hatch space etc. During printing, the high-speed IR camera captures temperature distribution of the melt pool and feeds the data to the pre-trained ML inference model. The ML model will then analyse the data in real-time and output predictions on final parts quality resulting from current processing parameters, as well as a vector of target processing parameters to improve the print quality, if needed. The CLC subsystem is an integrated control software that can control the processing parameters of AAMS in a closed-loop fashion. It starts by following the G-code commands of the parts to be printed. During printing, the CLC continuously monitors the outputs from the MLI subsystem and adjusts on the processing parameters in real-time, ensuring a good print quality of the final part. Combining the three subsystems, AASM achieves real-time monitoring and processing parameters adjusting to correct potential defects and ensure good and repeatable print quality.

The AAMS is desirable for industries such as aerospace, automotive, biomedical etc., where metal parts with complexes geometries and superior properties are sought after. Compared with current DED machines available on the market, AAMS is competitive for its low cost (under CAD $200k compared to more than $500k) and high reliability and minimal training/initial setup costs empowered by machine learning technologies.

The highlights of the novel and patentable aspects of AAMS can be summarized as:

1. It is the first autonomous direct energy deposition metal additive manufacturing system that delivers prints with improved quality with minimal human intervention;
2. It is empowered by a novel Machine Learning (ML) inference model trained on large metal AM datasets;
3. It implements a Closed-loop control system that corrects the processing parameters in real-time;
4. It is a hybrid MAM system that can produce parts with fine quality by in-situ post-processing

5. It can be used for printing parts of various materials and geometries with minimal initial set-ups.

A schema of AAMS is shown in Figure 1, and the AAMS prototype machine is show in Figure 2.

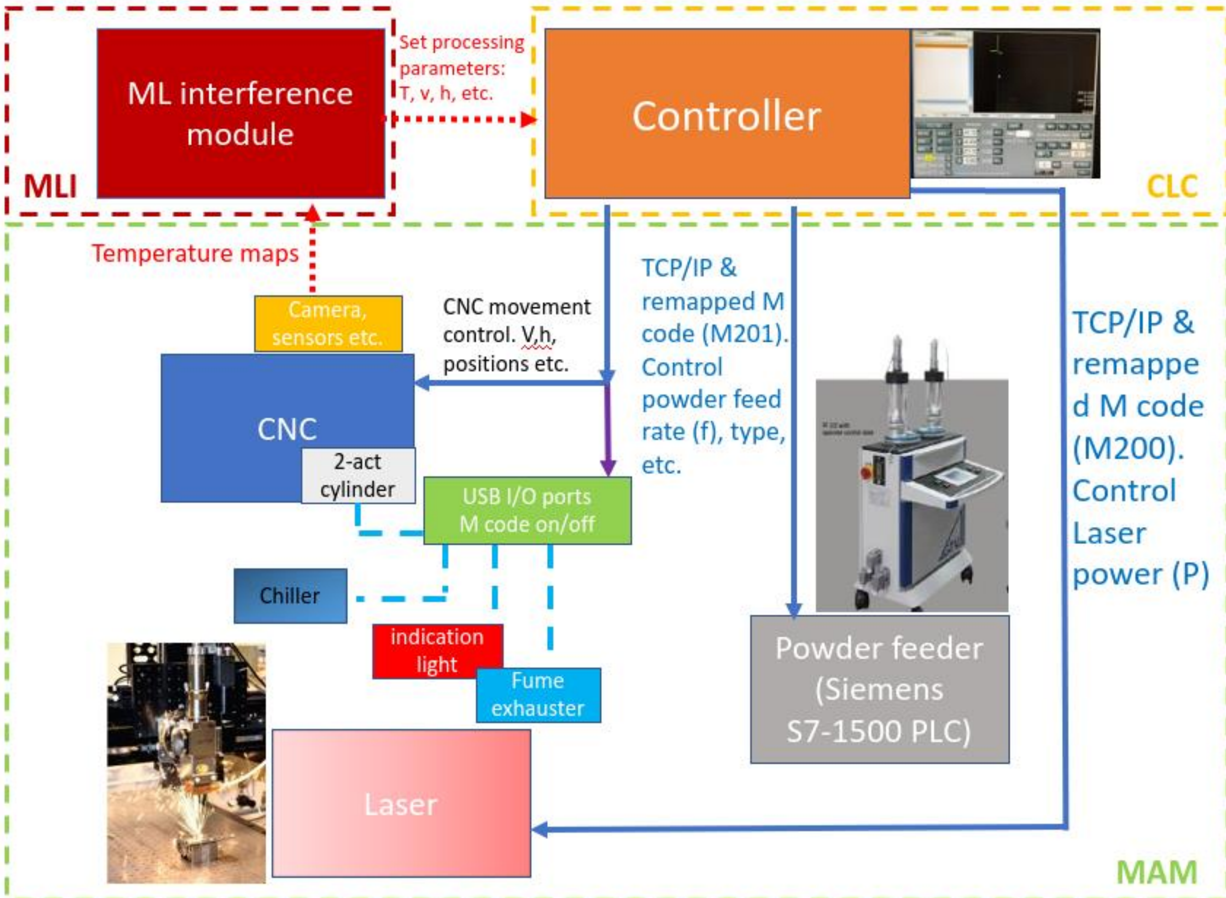

Figure 1 Schema of the AAMS design, outlining the MAM, MLI, and CLC subsystems in dash line boxes in green, red, and orange, respectively.

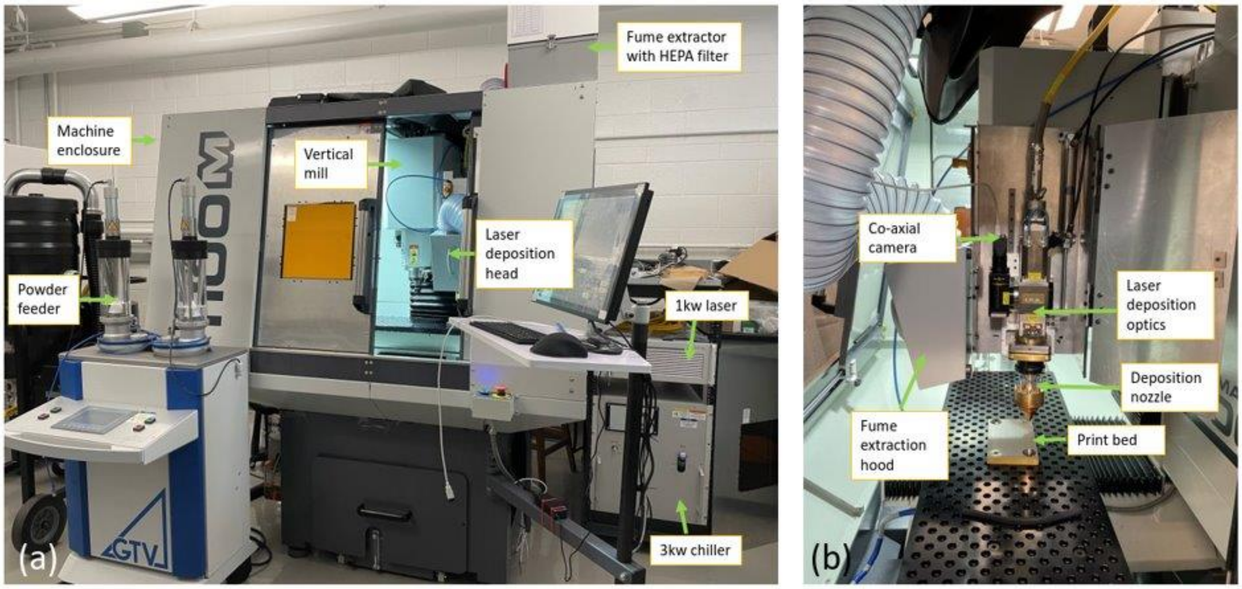

Figure 2 AAMS prototype (a) Overview of the AAMS prototype showing all major components. (b) Interior of AAMS showing laser deposition head setup.

Metal Additive Manufacturing (MAM) Subsystem

The MAM subsystem is an additive manufacturing system empowered by the Directed Energy Deposition (DED) technology. DED is a category of additive manufacturing or 3D printing techniques that enables the creation of parts by melting materials while they are deposited on a substrate. When in operation, a 3-axis Cartesian motion system moves in coordination with a laser and powder feed, so that the metal powder being deposited from a nozzle is melted in place to form the part. The MAM is a hybrid system where a CNC vertical milling system is integrated with the DED machine for in-situ part post-processing. The major components of the MAM are listed in Table 1.

Table 1 Summarization of major components for the DED machine

Heat source - Laser	IPG 1kw fiber laser YLR-1000-MM-WCY14
Chilling unit	Termotek P30280, 2800W capacity
Deposition head	Fraunhofer Coax 14 + IPG FLW D30
Powder feeder	GTV PF 2/2
Exhaust system	Airfiltronix 200A HS3000A1VK
CNC vertical mill	Tormach 1100M+

As shown in Figure 1, the MAM subsystem uses a variety of communication protocols to connect the controller and its control software (I.e., the CLC subsystem) to the multiple components in the machine. The machine is setup to run as a local area network (LAN) with all ethernet connected devices connected to the LAN. The CNC's custom controller board (ECMv1.5) communicates with the control software over TCP/IP. This connection enables control of the CNC machine's hardware as well as some of the custom hardware added for this project. A USB control board is integrated with the controller board to allow digital input and output relay control. This board is controlled using special M-codes sent from the PC to read the inputs terminals and trigger the output relay terminals.

The laser source used in this project is also configured to operate using TCP/IP Ethernet on the same LAN. The laser source controller can accept predefined TCP/IP commands to trigger laser functions or provide alarm, status, and operational feedback. These commands are integrated into the CLC subsystem using custom M-code and programming by the inventors.

The powder feeder currently is not setup for remote control and currently must be manually controlled using the HMI. In the future this unit will support remote control using Ethernet and the S7 protocol which is proprietary to Siemens PLCs. A high-speed IR camera will also be setup in the future to capture melt pool temperature maps as the input of the MLI subsystem.

The laser deposition head actuator cylinder, fume extractor, and water Chiller will be controlled using the USB control board. These will be directly controlled using the M-code in the CLC subsystem.

Machine Learning Inference (MLI) Subsystem

At the core of this subsystem are pre-trained Convolutional Neural Network (CNN) model for feature extraction from images, and Reinforcement Learning (RL) model for real-time processing parameters feedback. As shown in Figure 3, real-time captured temperature maps will first be fed into a CNN model to extract processing zone features such as temperatures, porosities and spatters, which will become the input of the RL mode. The RL model, which has learnt the mapping between processing zone features and processing parameters such as laser power, powder feeding rate, hatch space etc., infers the processing zone features and outputs the target processing parameters that would lead to a successful print. After comparing the target processing parameters with the current ones, an error signal will subsequentially be generated and used to adjust in real-time processing parameters. Here, a successful print refers to a part with the best print quality, i.e., minimal porosity, spattering, residual stress, cracks etc. The MLI subsystem is integrated into the control software via Python language, enabling AAMS to flawlessly produce qualitied parts with minimal human intervention during the process.

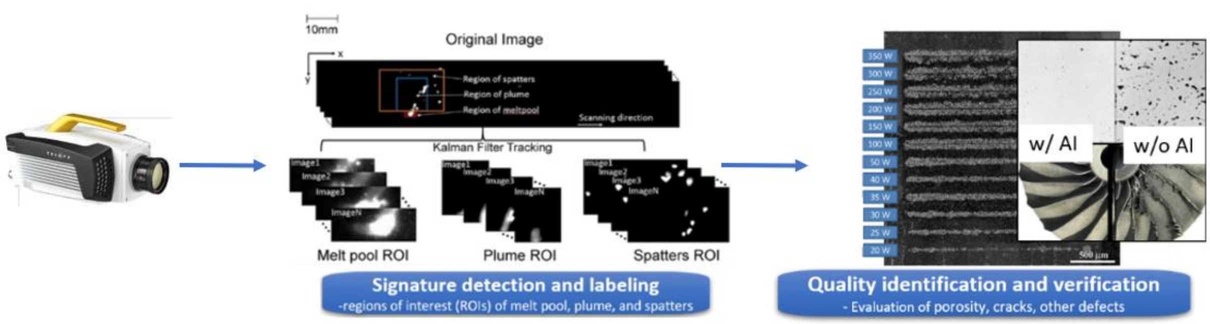

Figure 3 Schema of the MLI subsystem. A high-speed IR camera

Closed-loop Control (CLC) Subsystem

The CLC subsystem is a closed-loop control software framework based on the open-source software LinuxCNC and PathPilot. The CLC integrates in the Graphic User Interface (GUI) control for the laser and powder feeder. Other GUI elements are also available for the USB-controlled DED head actuator and chiller unit. Figure 4 shows the software main screen with the GUI elements shown divided by boxes with different colours.

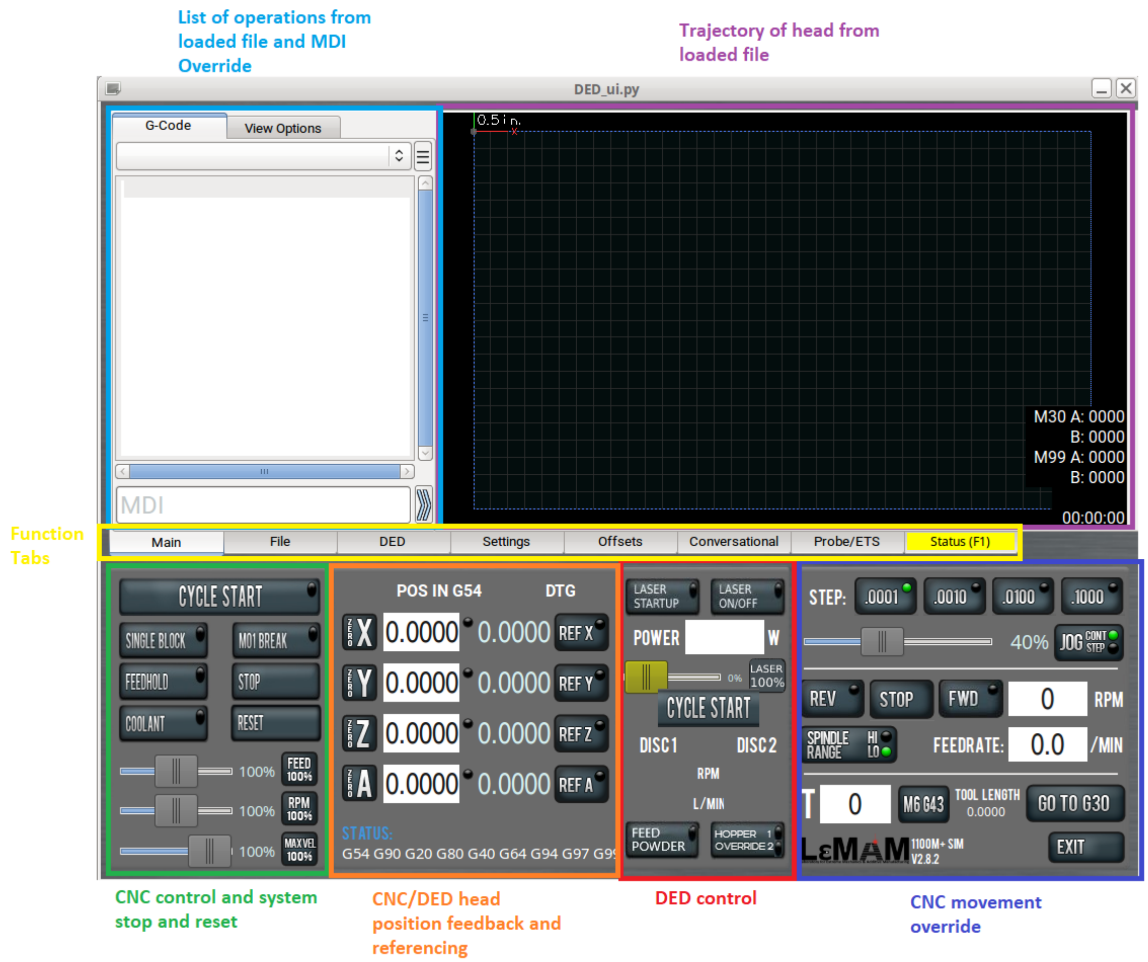

Figure 4 Main screen of the CLC GUI

Control of the AAMS relies on G-code and M-code to program the movement of the print head in the X, Y and Z dimensions and operate the machine's components such as chiller, laser and powder feeder. A number of custom G and M codes were created to specifically control the machine. G-codes are typically used for movement and parameter changes while M-codes are used for setup and configuration. During the manufacturing process, CLC will receive the error signal generated from MLI, and adjust the G/M code in real-time to achieve closed-loop control.

Preliminary Testing

The AAMS prototype was first tested with a 2 mW laser, without metal powder being fed to verify its motion control system. Figure 5 (a) (b) demonstrate AAMS in printing, and figure 5 (c) shows the in-situ monitoring of the laser spot with the co-axial camera.

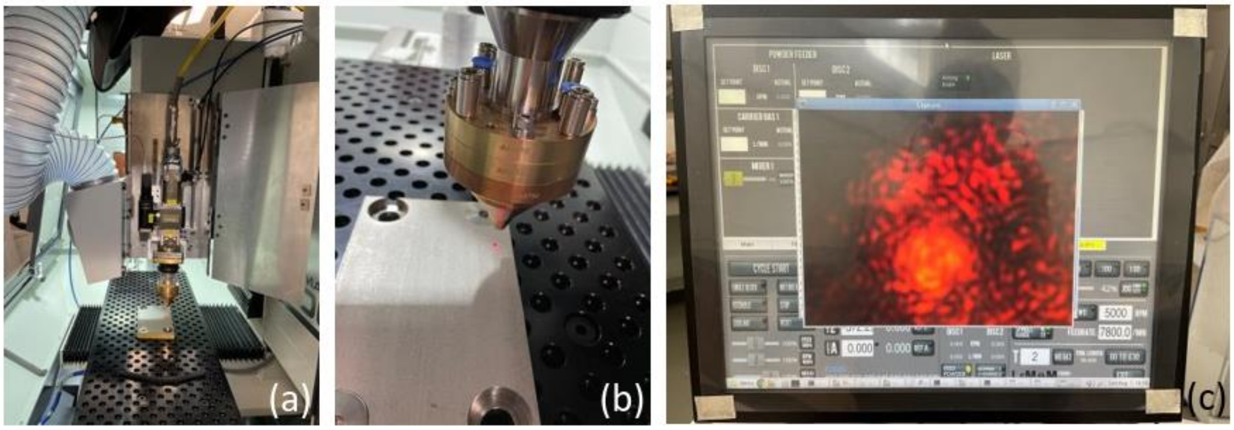

Figure 5 (a) AAMS deposition head in printing with 2mW laser activated. (b) Zoomed view of the deposition nozzle, build plate, and laser spot. (3) The in-situ capture of the laser spot using a co-axial camera.

The system was then tested with 17-4 Stainless steel powder to print pre-define square tracks of 2mm height to test the functionalities of the MAM subsystem. Figure 6 (a) shows the MAM subsystem in action. Figure 6 (b) and (c) give the details of the printed square tracks. As can be seen from the results, the print quality and accuracy are satisfactory. It is worth noting that this is still preliminary testing, and no calibration has been performed prior to testing. The printing results are expected to improve significantly after printer calibration and will further improve with the implementation of our machine learning and closed-loop control systems.

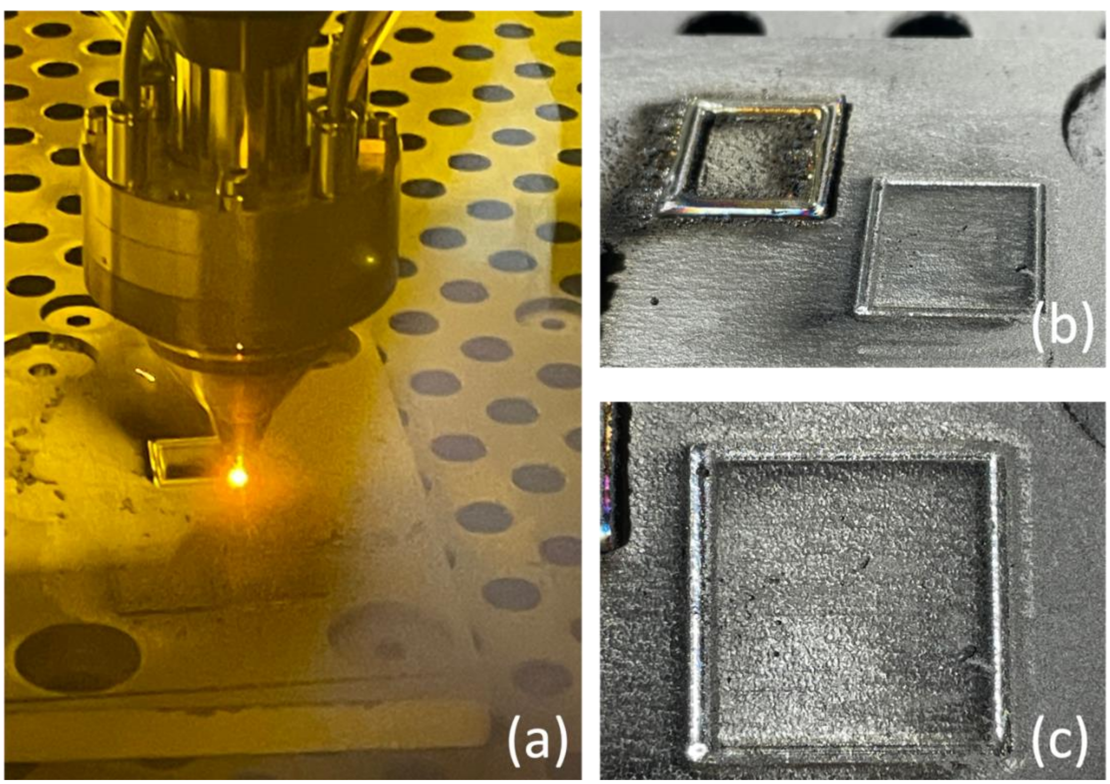

Figure 6 (a) MAM subsystem printing square tracks (b) Printed square tracks (c) Zoomed view of printed square tracks

A link to a video clip demonstrating our DED testing can be found below:

https://drive.google.com/file/d/176-ueDN4CsQ-70n8UaRryMG_UIj4RRhk/view?usp=sharing