

8-2023

Developing Control System for Manufacturing Processes

Md Shahriar Forhad
The University of Texas Rio Grande Valley

Follow this and additional works at: <https://scholarworks.utrgv.edu/etd>



Part of the [Manufacturing Commons](#)

Recommended Citation

Forhad, Md Shahriar, "Developing Control System for Manufacturing Processes" (2023). *Theses and Dissertations - UTRGV*. 1336.

<https://scholarworks.utrgv.edu/etd/1336>

This Thesis is brought to you for free and open access by ScholarWorks @ UTRGV. It has been accepted for inclusion in Theses and Dissertations - UTRGV by an authorized administrator of ScholarWorks @ UTRGV. For more information, please contact justin.white@utrgv.edu, william.flores01@utrgv.edu.

DEVELOPING CONTROL SYSTEM FOR MANUFACTURING PROCESSES

A Thesis

by

Md Shahriar Forhad

Submitted in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE IN ENGINEERING

Major Subject: Manufacturing Engineering

The University of Texas Rio Grande Valley

August 2023

DEVELOPING CONTROL SYSTEM FOR MANUFACTURING PROCESSES

A Thesis
by
Md Shahriar Forhad

COMMITTEE MEMBERS

Dr. Farid Ahmed
Chair of Committee

Dr. Jianzhi Li
Committee Member

Dr. Benjamin Peters
Committee Member

August 2023

Copyright 2023 Md Shahriar Forhad

All Rights Reserved

ABSTRACT

Forhad, Md Shahriar, Developing Control System For Manufacturing Processes. Master of Science in Engineering (MSE), August, 2023, 45 pp., 7 tables, 24 figures, references, 35 titles.

Process control has been a critical component in today's manufacturing industry. Industrialists nowadays want reliable control to assure precision manufacturing. Modern control systems must be more dynamic, so that any needed modifications may be made quickly to accomplish the desired product change. For innovative research and development, system customization is critical to ensure freedom for experimental works. In addition, full control of manufacturing systems is necessary to realize and implement Industry 4.0. Often, it is difficult to achieve such control due to limited access to proprietary equipment. To this end, this thesis focuses on developing a custom control platform for laser powder bed fusion (LPBF) and proprietary equipment.

In this work, a total control platform for a custom LPBF testbed has been developed and demonstrated. Features in this control platform include tool path generation for galvo-based laser scanning, in-situ laser process parameter control, emergency process shutdown, and feedback control for the in-house sensing system. As explained earlier, limited access to proprietary equipment hinders full control of the system, hence, often it is difficult to automate those machines and the production without human intervention. Besides, the occurrence of

sudden faults needs to be corrected faster, which is sometimes challenging for human operators. To this end, a proprietary software automation system is developed to automate a task sequence for laser material processing using TCP/IP communication. Also, a gesture control feature is integrated with the control system to enable gesture-driven instructions.

The developed control platform is expected to facilitate running custom experiment using the LPBF testbed such as implementation of random scanning pattern, in-situ layer/scan wise laser process parameter change, and close-loop feedback for process monitoring and control. In addition, the control of proprietary equipment will help develop robust control platform where Application Programming Interface (API) access to the equipment is limited.

DEDICATION

I dedicate this thesis to my outstanding professors Dr. Jianzhi Li and Dr. Farid Ahmed, whose profound mentoring and advice have been the foundation of my academic development. I also owe a debt of gratitude to my dear sisters Fahima Akter and Fahmida Akter, whose unflinching support, motivation, and confidence in my abilities have sustained me throughout this journey.

ACKNOWLEDGMENTS

My respected professors Dr. Farid Ahmed and Dr. Jianzhi Li have provided me with significant advice, mentorship, and substantial knowledge during the course of my research. My aspirations have been boosted by their passion to the subject of manufacturing engineering and my dedication to encouraging an inquisitive mindset. My continued influence on my academic goals is demonstrated by this effort.

My sisters' unending support and confidence in my abilities have served as a constant source of inspiration for me. My steadfast commitment to overcoming obstacles and pursuing achievement has been motivated by their unshakable faith in my potential. The substantial influence of their assistance is honored in this thesis.

This work is a representation of the collaborative inspiration, prodding, and constant support of my professors and friends. I hope it will serve as a way for me to express my gratitude for all, who have done to help me advance both academically and personally.

With heartfelt gratitude,

Md Shahriar Forhad

TABLE OF CONTENTS

	Page
ABSTRACT	iii
DEDICATION	v
ACKNOWLEDGMENTS.....	vi
TABLE OF CONTENTS.....	vii
LIST OF TABLES.....	ix
LIST OF FIGURES.....	x
CHAPTER I INTRODUCTION.....	1
Motivation	3
Research Goal	5
Laser Powder Bed Fusion Process	6
Report Organization	8
CHAPTER II DEVELOPING CONTROL FOR GALVO, LASER AND LINEAR ACTUATORS FOR A LASER POWDER BED FUSION PROCESS	9
Context and Background.....	9
Methodology	11
Challenges	16
Execution Procedure	17
Result and Discussion	24
Conclusion.....	26
CHAPTER III IMPLEMENTATION OF AUTOMATION AND MACHINE LEARNING APPLICATION FOR A LASER-BASED PROPRIETARY EQUIPMENT	27
Context and Background.....	27
Methodology	29
Experimental Setup	32
Result and Discussion	35
Conclusion.....	39

REFERENCES.....	41
BIOGRAPHICAL SKETCH.....	45

LIST OF TABLES

	Page
Table 1: Two-Axis Galvanometer System Scan Head Properties showing the calculated value for the resolution for the movement from the center is 7.99 μm and for the repeatability is 9.98 μm	15
Table 2: Straight Line movement in position of a section with constant power.....	20
Table 3: Example of an Instruction Packet.	22
Table 4: Instruction set for task creation in Excel file.	30
Table 5: Excel command example for turning on the laser.	32
Table 6: Excel command example for executing tasks to move the linear stages.	33
Table 7: Buttons and respective functions.	34

LIST OF FIGURES

	Page
Figure 1: Basic control flow diagram for Laser Powder Bed Fusion process.	6
Figure 2: Process and plan for LPBF: A) CAD Design, b) Segmentation into Layers, c) Programming for different layer in Z-axis , d) Flowchart of the process, e) Strategy for the laser path generation (Liu et al., 2020).....	7
Figure 3: Schematic diagram of the LPBF process (Jiao et al., 2018).....	7
Figure 4: Outline of the report.	8
Figure 5: Laser width and direction control in LPBF.	12
Figure 6: Loading effect and series voltage drop in electrical circuit.....	14
Figure 7: CAD design for generating G-code.	16
Figure 8: Laser path creation using SAM designed by National Institute of Standards and Technology.....	17
Figure 9: Laser Path creation for different layers by SAM (layer is kept as 10mm for understanding purpose)	17
Figure 10: Steps for data preparation.....	18
Figure 11: G-code execution in the system.....	19
Figure 12: Constant power straight line with multiple instructions for position (X,Y) and Laser Power.....	21
Figure 13: Typical Microstepping accuracy for the Z-axis and reservoir by (X-LRT-C Series: High Load, Motorized Linear actuators with Built-in Controllers and Dust Covers, 2022).....	23
Figure 14: The rotation of the galvo mirrors created a straight-line movement of the point laser.	24
Figure 15: Digital unsigned 8bit control output shown in LEDs.....	25
Figure 16: Graphic user interface of the control software.	25
Figure 17: A typical cloud-connected smart Industry.....	28
Figure 18: Flow chart for (a) executing task by pressing button (set on/ off/ standby the laser), (b) executing tasks (linear stage/galvo movement, laser parameter control) by G-Code.....	31

Figure 19: Experimental setup to control laser source and linear actuators by the instruction sent from the central (server) computer to the proprietary equipment (client) computer.	34
Figure 20: Server Program Interface in the central computer.....	35
Figure 21: Client Program Interface in machine computer.	35
Figure 22: System and laser process control: (a) 3-axis state and galvo system control, (b) control of laser marking, and (c) control of laser engraving custom images.	37
Figure 23: Sending gesture control instruction from the server: (a) sending Laser ON instruction and (b) sending Laser Standby instruction.	37
Figure 24: Receiving control instruction at the client: (a) Turning laser on after instruction received from the server and (b) Turning laser standby after instruction received from the server.	38

CHAPTER I

INTRODUCTION

In manufacturing industries different control systems (technologies and methods) are used to manage and regulate various operations. Effective control is important for quality assurance and safety optimized performance. There are basically two types of control system. One is open loop where the output doesn't have any impact on the input. And the other one is closed loop feedback system where the output plays a role in the change of input to obtain expected results from the system. Usually there are various types of mechanical and electrical controllers. Hydraulic Control Systems, Pneumatic Control Systems, Mechanical Linkage Systems (gears), Valve Control Systems are popular mechanical control systems. Furthermore, electrical control systems like Distributed Control Systems (DCS), Programmable Logic Controllers (PLCs), Robotic system are getting more attentions among the industrialists. Distributed Control Systems (DCS) is basically computer-based control system which is the main focus for this thesis.

Laser powder bed fusion (LPBF) is becoming more popular in manufacturing industries like aerospace, automotive and medical sector. In this system we can develop complex parts without the need for further assembly or joint inside. High quality printing with fine resolution are the primary advantages of LPBF process which qualifies it to print complex structures (Casini, 2022). But the control of such a system is so much complicated and faster response is too much crucial. In LPBF system metal powder is melted or sintered to build designated parts.

The melting or the sintering process is usually accomplished by high powered laser movement (scanning). The laser moves so much faster by reflection of optical devices where the optical devices are moved according to the control instructions received. The sending, receiving and execution of laser movement is so fast and complicated that faster and accurate control devices are mandatory for better quality output. Thus, a 3D printed model is created by layer-by-layer laser melting or sintering of a CAD model from bottom to top. This work emphasizes on developing control algorithms for a LPBF system to ensure good quality 3D printed model.

The proprietary equipment is difficult to integrate with external devices from different manufacturers without the Application Programming Interface (API). But when that equipment is controlled by a computer, it is possible to automate the operation in a collaborative work with other devices by controlling the input of the computer (i.e. keyboard, mouse input) using programming. This work emphasized on developing automation for proprietary equipment by programming in python without API from the manufacturer, so that it can later be integrated with different devices.

Motivation

In manufacturing industries, the quality of the products depends upon the quality of control of the process. In research labs, customized experiments with wide varieties are performed to figure out the optimized condition for a system to achieve the required quality result. The University of Texas Rio Grande Valley (UTRGV) has some great facilities for additive manufacturing, where researchers change the quantity of different materials, process parameters, design of the model, and investigate the results. To change the process parameters in situ, the commercially available machines are limited to some extent. Also, there are limited opportunities to use different types of sensors. We felt the need for a customized 3D printing machine that would be able to adapt the printing process to meet specific requirements. It would help us develop alloys with tailored mechanical, thermal, and chemical properties. Since we would be able to change process parameters at every single layer manually or automatically dependent upon the responses of the sensors, it would be able to reduce waste and within a short period of time, we would be able to implement different process parameters to investigate optimized conditions for our target product.

The control of a LPBF system the commercially available machines employ various sensors, actuators and control devices. In-situ monitoring is becoming more popular, (Soundarapandiyam et al., 2023) monitored each layer by X-ray radiography, (J. Li et al., 2023) proposed imbalanced data generation and fusion model, (Taherkhani et al., 2023) listed sensors for in-situ monitoring. In commercial machines we have limited number of machines at a time to monitor the process. (Wang et al., 2023) developed customized LPBF system, monitored the

thermal emission using LDR and changed the laser power using closed loop feedback system where notable development in the quality was validated by microscopic imaging and 3D scanning. No previous work displayed effective in-situ laser power control in LPBF (Wang et al., 2023). Besides, usually the whole process follows the same laser scanning pattern in a single run. To ease research and find out optimized parameters the mixing of laser patterns for layers (checkboard, parallel, spiral pattern etc.) has become a necessity. A well customized machine is required for in-situ monitoring and updating process parameters. That will help us to get closer to our desired properties for the materials.

Therefore, we started building a Selective Laser Melting system. To be acquainted with computer-based control and automation another side project was performed, where a laser-based system was controlled by taking instructions over TCP/IP. Which gave me the basic knowledge of how to develop a cloud-based control system. In modern industries, cloud-based control is becoming more popular, and it gives us the flexibility to monitor and control lots of machines from a central control center, data analysis and help us improve the process parameters faster.

To learn more about computer-based control another project was introduced where automation of a proprietary equipment (without API) was accomplished. In that system networking was utilized to communicate between computers and easy automation algorithm was introduced. Thus, it was established that proprietary equipment can also be a part of the cloud computing where monitoring and control can be implemented.

Research Goal

The primary research goal of this study is to develop custom control systems for additive manufacturing equipment. The proposed study has two subgoals as given below:

1. Design and implement control for an LPBF test bed for customized experimental studies such as in-situ laser process parameter tuning to ensure quality (microstructures, density, hardness, mechanical strength, etc.) of the printing. Specific research goals include:

- I. Adjusting laser parameters (power, pulse width, scanning speed)
- II. Synchronizing linear stages such as wiper, Z-axis, beam shutter & shaper for smooth operation of the LPBF system.
- III. Integrating sensors to monitor and update LPBF process parameters.

2. Develop and demonstrate automation for a proprietary system without access to the API of the system and communicate with a central server by TCP/IP protocol for executing commands (Laser on-off, Linear stage move).

Laser Powder Bed Fusion Process

The laser powder bed fusion process consists of some specific steps to be completed. Basic control flow diagram for Laser Powder Bed Fusion process is depicted in (Figure 1). At first, the CAD model for the part is sliced into equal-sized layers (Figure 2). This is the thickness resolution for the process. In the from the CAD design G-Code is prepared providing laser power (Guo et al., 2019; Karimi et al., 2018; Nagesha et al., 2021), laser scanning position, hatch distance (Kumar, 2014), scanning speed and strategy (Craeghs et al., 2010; Grossin et al., 2021; Jiang et al., 2021; Spierings et al., 2018; Valente et al., 2019), exposure time, point distance (Wysocki et al., 2018) considering their impact on the system. Then the G-Code is implemented by controlling different processes (linear actuators, valves, galvo scan head and laser source). Auxiliary equipment is also used to remove oxygen from the build chamber and fill it with argon or nitrogen, as well as heating to ensure the proper temperature. Various sensors are used simultaneously to monitor the environment (temperature, oxygen content etc.).

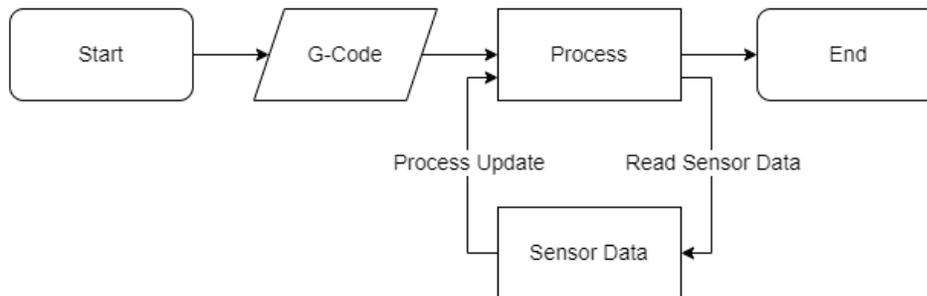


Figure 1: Basic control flow diagram for Laser Powder Bed Fusion process.

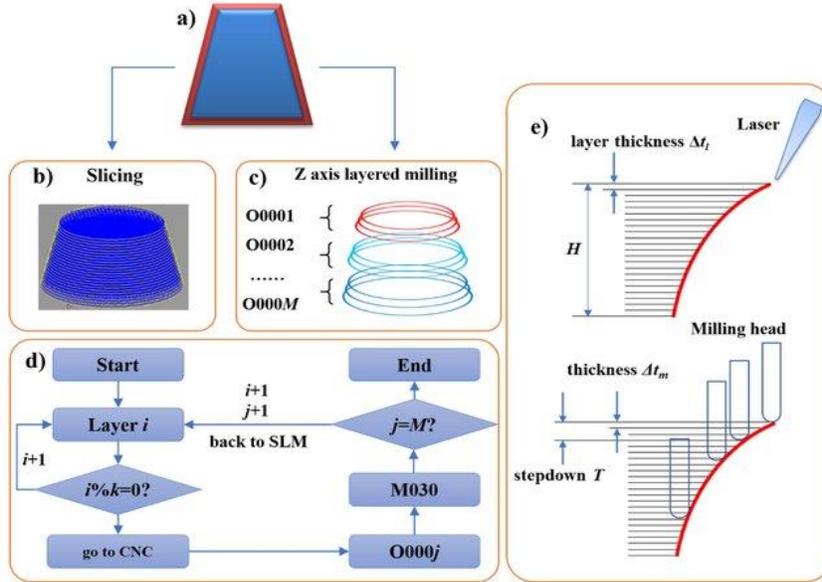


Figure 2: Process and plan for LPBF: A) CAD Design, b) Segmentation into Layers, c) Programming for different layer in Z-axis, d) Flowchart of the process, e) Strategy for the laser path generation (Liu et al., 2020)

During the execution of LPBF process, the powder reservoir moves up to supply metal powder, a wiper (recoater) is used to spread the metal powder on the build plate, then laser scanning is executed to melt/sinter material for that layer, build plate moves down, wiper moves to its initial position and repeats the process for each layer (Figure 3).

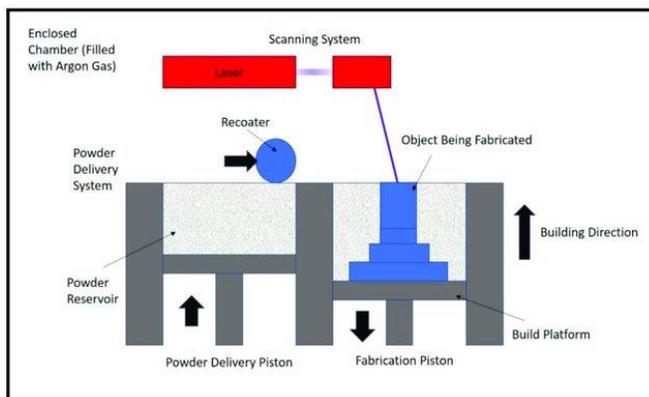


Figure 3: Schematic diagram of the LPBF process (Jiao et al., 2018)

Report Organization

Figure 1 depicts how the report is organized. The background of the study, its inspiration, and the fundamentals of the laser powder bed fusion process are explained in Chapter I. Case Study 1, Developing Control for Galvo, Laser and Linear Actuators for A Laser Powder Bed Fusion Process, is thoroughly explained in Chapter-II. This chapter presents the background, methodologies, challenges, execution procedure and result for the case study. Contents of Chapter II, Case Study 2: Implementation of Automation and Machine Learning Application For a Laser-Based Proprietary Equipment. This chapter includes a description of the background, methodology, experimental setup, and case study results.

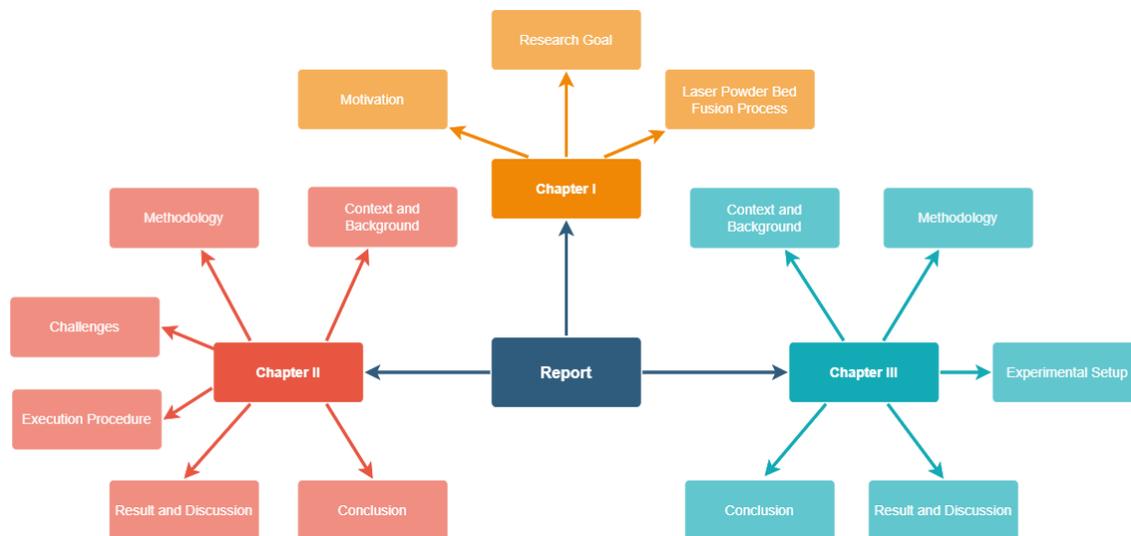


Figure 4: Schematic outline of the thesis report.

CHAPTER II

CASE STUDY 1: DEVELOPING CONTROL FOR GALVO, LASER AND LINEAR ACTUATORS FOR A LASER POWDER BED FUSION PROCESS

Context and Background

Additive Manufacturing (AM) also known as 3D printing has been recognized as a potentially breakthrough technology in manufacturing, with significant applications in the aerospace, automotive and health care sectors (Markl & Körner, 2016). The primary purpose of this method is to create parts with a given material from 3D model data. AM comprises a set of specialized techniques, e.g. extrusion, sintering, melting, photopolymerization, jetting, lamination, and deposition to allow layer wise material accumulation. 3D printing has been found suitable for a variety of materials e.g. metals, polymers, ceramics (Y. Li et al., 2018). However, recent trend shows an inclination towards research in metal-based AM techniques. Specially a lot of these focus on Laser Powder Bed Fusion (LPBF) since it holds major market share (Gu et al., 2019). However, proprietary machines have several restrictions and are unable to meet all the criteria in a scientific setting. It is really difficult, sometimes impossible, to alter the sequences or update parameters during the process or integrate additional sensors and utilize feedback to update the process parameters for a specific scientific experiment in a proprietary machine. This necessitates the development of one's own LPBF system, in which various scientific tests may be carried out to help in the creation of alloys with high entropy, tensile strength, and corrosion resistance via in-situ monitoring and updating of the process parameters.

Because, different alloys are extremely significant in the fabrication of machine components, particularly in the aerospace and automotive sectors.

Few studies have been found making an effort to develop their own LPBF system (Yeung et al., 2021). The LPBF system requirements are outlined in (Lane et al., 2016), which also gives an overview of the facility's current design and construction status. Recently, it has been discovered that the National Institute of Standards and Technology (NIST) is interested in creating and using its own LPBF system to accelerate the research on AM. For example, the laser path planning on an LPBF additive manufacturing (AM) testbed, a jerk-limited control was approached by (Yeung et al., 2018). Later, the meltpool images from the initial scan with a constant laser power were utilized in studies by (Yeung et al., 2020) to train data-driven predictive meltpool model and alter the laser intensity for future scans, which ultimately resulted in a decrease in variance in the meltpool. As a result, a new door for machine learning applications for AM was opened. With the addition of prescribing optimal process parameters for a certain set of attributes, which one day could enable to make goods with more precise tolerances at cheaper costs. While there are different parameters play role in the quality of outcome in a LPBF, in an experiment, on a specially designed LPBF system, (Yeung & Lane, 2020) changed the laser's power to account for residual heat. Later, the AM Metrology Testbed software was developed by the National Institute of Standards and Technology to advance research into LPBF methods (Yeung et al., 2021).

In the essence of having a customizable LPBF system in our lab, we opted to build our own, where we may alter process settings based on different sensor responses and seek a better method to manufacture a superior alloy. This paper makes the following contributions:

- Developed G-code from positional & laser value for LPBF system to be used in a specific galvo and laser controller,
- Introduced parallel safety feature for LPBF system to turn off laser instantaneously at emergency,
- Ensured respective linear actuator control for a LPBF system.

Methodology

The development of a LPBF system requires different control elements like oxygen amount in the build chamber, temperature control of the build chamber and build bed , etc. Usually, noble gas is used to replace oxygen at certain pressure in the build chamber. Since there are lots of control elements in an AM system, this this paper will cover certain aspects explained below:

Linear actuator for Z-axis

High standards for accuracy must be met. The usual layer thickness that we want to employ for our system is 50 micrometers, and the Z-axis overall accuracy minimum requirement is 5 micrometers. Additionally, Python is compatible with this device. Figure 13 depicts the device's microstepping characteristic curve for this arrangement and that information justifies the usage of that device in the context of accuracy. The Maximum Cantilever Load is important because it must support the weight of the build plate, the printed object, and the powders that are poured or wiped onto it. Maximum Cantilever Load for the linear actuator in this instance is 120 N-m.

Two-Axis Galvanometer System Scan Head (Galvo)

To construct the desired pattern, it directs the laser in a precise direction. It is one of the most important components of the system. The xy2-100 protocol instructions must be carried out, and it must travel at least at 1000 mm/s. Additionally, the device also needs to withstand 1000Watt laser power. Table 1 lists the characteristics of the utilized device. A separate controller is used to control the Galvo. Figure 5 shows the optical movement of laser from laser source to the optical unit to change the laser width, and then to the galvo scan head control with two mirrors to move the laser to a specific direction on the build plate.

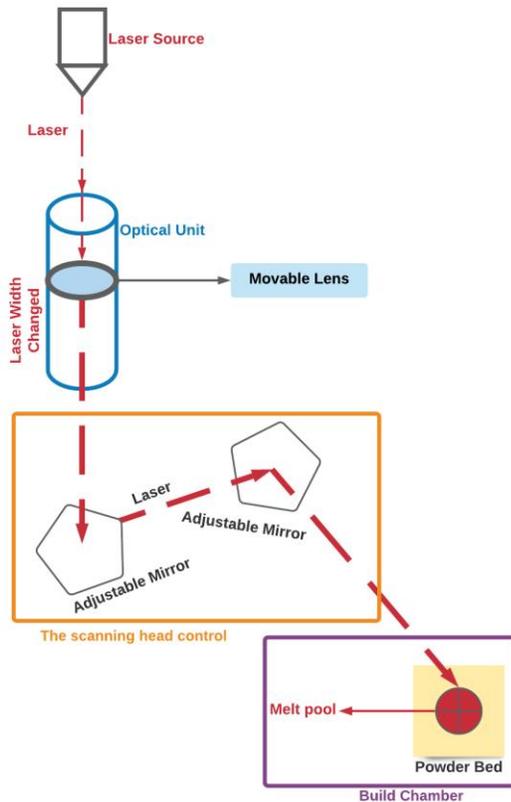


Figure 5: Laser width and direction control in LPBF.

Galvo and Laser Controller

The controller uses the xy2-100 protocol to communicate control signals to the galvo. The device may execute G-code that has been uploaded on its memory card or it can receive G-code commands in real-time and execute them. However, there are certain restrictions. The device we utilized can only accept and execute 1460 bytes at a time at max. Consequently, the G-code command had to be broken up into segments, each of which could only be a maximum of 1460 bytes. Different strategies have been used to guarantee correct control instructions.

Communication

A link between the computer and the controller device is represented by an object created using object-oriented programming. The device facilitates both USB and Ethernet communication. TCP/IP protocol is used for communication because ethernet (100 Mbps) communication is significantly faster than USB (115200 bps) for the controller. The gadget features a 26 pin and a D-SUB25 galvo scanner output connection that connects to the galvo and sends control signals to it. To transmit signal to the galvo, utilize the D-SUB25. It also contains a connection for controlling lasers. The laser control port may output data in 8-bit digital and 0–10 volt analog formats. Various considerations must be made while deciding between digital and analog control functions. Because the control input signal for our laser is 0-10 Volt, it is possible to use either an analog or digital output with a DAC (Digital to Analog converter) from the controller. The choice of digital control signal is made because analog voltage output has a loading effect (Figure 6). Due to the loading effect, the internal impedance has a voltage drop according to the flow of current and thus we don't receive the supplied voltage at the load point in closed circuit connection. Additionally, there is a series voltage drop in the connection between the driver

circuit and the laser. Since 0-10 volts represents 0-1000 watt, 1% (0.1 volt) drop in supplied analog control voltage due to the loading effect and series drop would ensue 10 Watt output error in laser. The controller and the laser communication wire can be long enough with the digital output without affecting or interrupting the laser output. G-code instructions are split into 1457 byte packages to prevent the device from becoming overburdened with instructions while also ensuring that the greatest number of instructions are supplied at once.

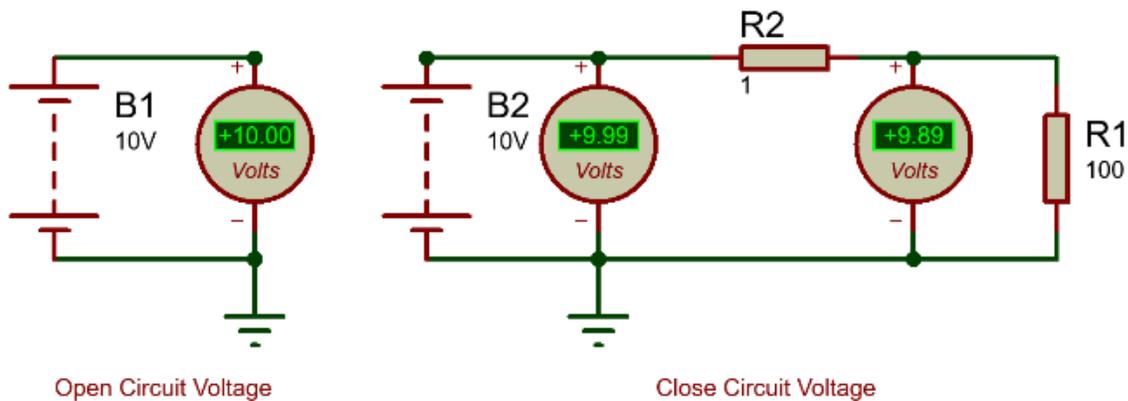


Figure 6: Loading effect and series voltage drop in electrical circuit. In the open circuit voltage (left), there is no voltage drop due to current flow. But in closed circuit (right) there is an internal voltage drop in the source and a transmission drop in the line where the line resistance is considered as $R2=1\Omega$ for simulation.

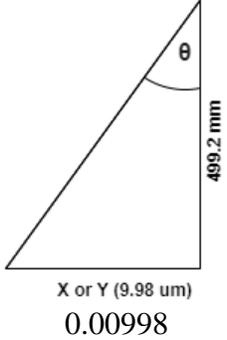
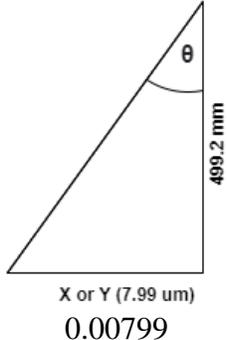
Wiper Control

An important aspect of AM is wiper design. Size, shape, and material of the wiper blades all have a big impact on how well they work. Otherwise, the powder might not distribute evenly or the printed output might have scratches. A motorized linear actuator with a controller makes controlling the wiper simple. Besides, Wiper, linear actuators, and integration with motors and motor drivers are further options. Since managing a linear actuator is analogous to operating a wiper, in this experiment a linear actuator is controlled to signify that component. Currently the wiper can move at speed of 7-18 mm/s in our system.

Powder Reservoir Z-axis Control

This stage's precision requirements can go up to 7 micrometers. The Maximum Cantilever Load for the linear actuator in use here is 120 N-m.

Table 1: Two-Axis Galvanometer System Scan Head Properties showing the calculated value for the resolution for the movement from the center is 7.99 μm and for the repeatability is 9.98 μm .

Wavelength Range (nm)	1064
Maximum Scan Angle-Degree (Optical)	22.5
Repeatability (urad)	20
Repeatability (mm from center-at 499.2 mm distance)	
Resolution (urad)	16
Resolution (mm from center- at 499.2 mm distance)	

Challenges

A thorough understanding of electrical and electronics, programming, automation, CAD design, mechanical system design, heat transfer, optics, and material science is required to build an LPBF system. Furthermore, selecting design criteria is critical; available components should be used as much as possible; bespoke parts are time-consuming and expensive. Integration of many components from various companies is a significant difficulty. Furthermore, while diverse organizations have their own software, a common API or programming platform with libraries (python, c++, or c#) is rarely seen. As a result, modules/objects are required to be coded from scratch (here laser, galvo and linear actuators control) and checked thoroughly to ensure proper control.

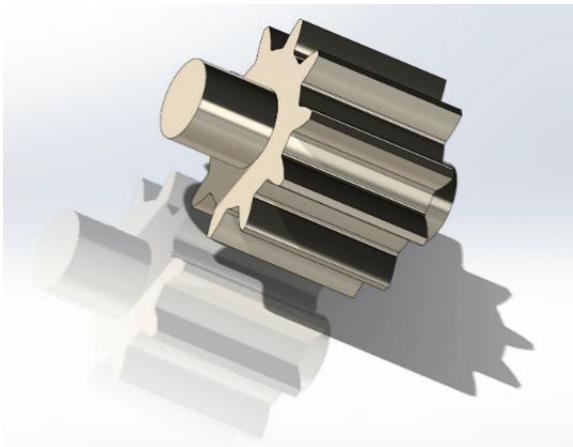


Figure 7: CAD design for generating G-code.

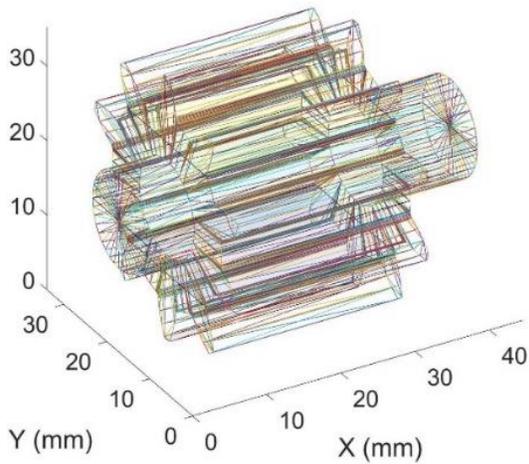


Figure 8: Laser path creation using SAM designed by National Institute of Standards and Technology.

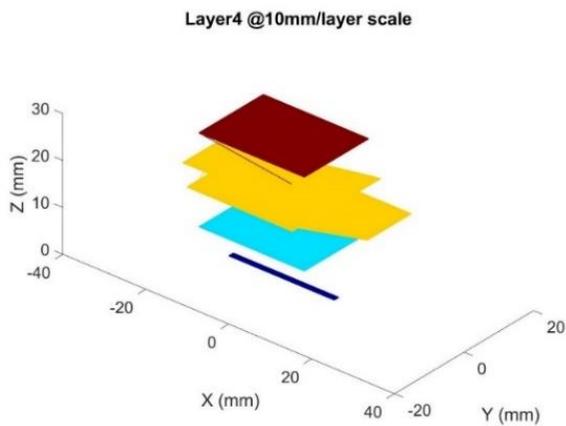


Figure 9: Laser Path creation for different layers by SAM (layer is kept as 10mm for understanding purpose)

Execution Procedure

There are several processes that must be finished prior to execution of G-code. For instance, the build chamber must be airtight and oxygen-free to guarantee that there is no oxidation at the high temperature (during the melting of the metal powder). In this work, the data

preparation from CAD files, as well as the creation and execution of G-Code for scanning with galvo are covered.

Data Preparation: Figure 10 provides an explanation of data preparation. The CAD file is fed to the SAM program from the NIST (Yeung et al., 2019). The program may be customized in a wide range of ways, including feed speed, laser power, Hatch space, Theta interlayer, and mode island distribution. After thorough analysis and computation, the X, Y, and L (position and laser power) data of each layer are recorded in a separate CSV file by SAM. Figure 8 and Figure 9 provide visual representations of the laser path and layers for the CAD model shown in Figure 7. Since the obtained values are in accordance with the NIST devices, some adjustment is necessary for our system. Numerous positional values in the same straight line are included in the produced position data, yet the laser power remains constant (Figure 12). The start and end points of the straight line can be used to limit the amount of InPk delivered to the galvo scanner controller in this situation since there is no need to execute each individual position in a single line while keeping the laser power constant. Since, each InPk has jump and mark speed instructions at the beginning, the scanner follows those speeds accordingly irrespective of high-speed data transfer.

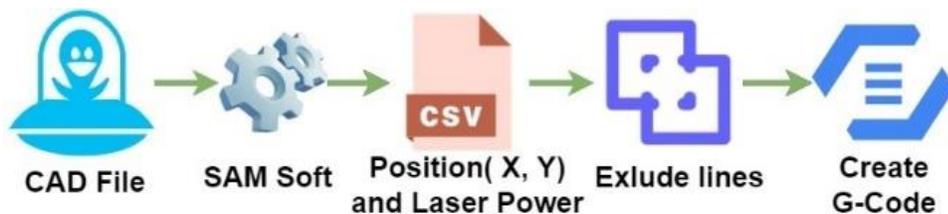


Figure 10: Steps for data preparation.

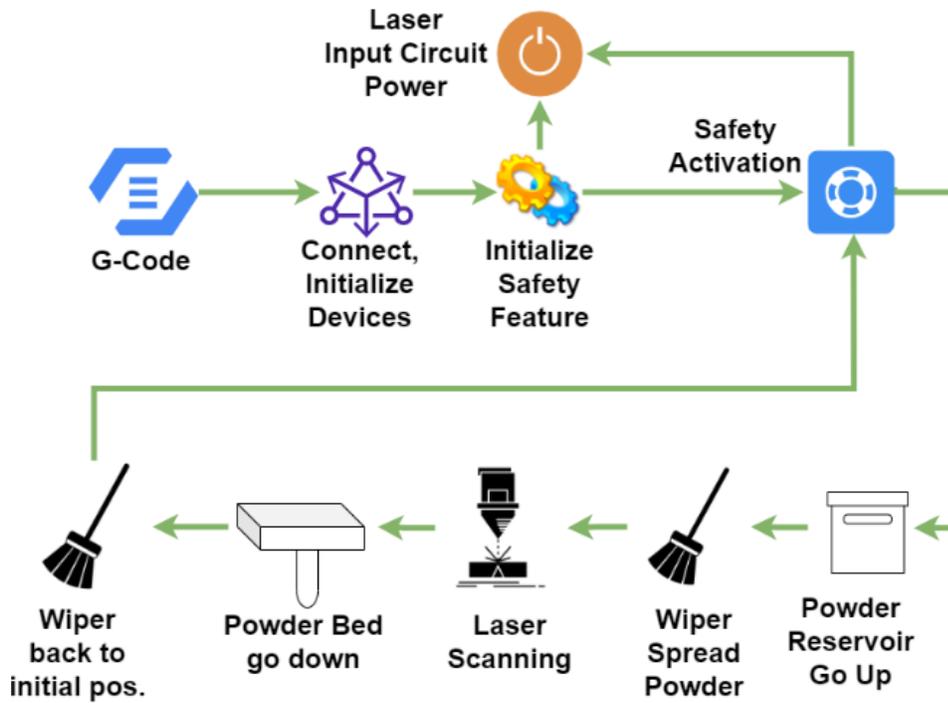


Figure 11: G-code execution in the system.

G-Code Generation: Python programming is used to build G-code by reading csv files containing positional (X, Y) and respective laser power (L) values. Since NIST designed their program for their hardware, it is logical to assume that some changes to the code are necessary to adapt it to work with our equipment. Initially, developing the G-code presented some difficulties. Even though there was no change in laser power, the program still generated a lot of instructions for a straight line (Table 2 and Figure 12). Therefore, it was necessary to develop a function that would identify the pattern and exclude unnecessary instructions for the same line while maintaining a consistent laser power. Once more, the produced position value from the SAM software was in the nanometer range whereas galvo precision is in the micrometer (Table 1). Thus, rounding is used to only have position values in the micrometer range, allowing for more instructions to fit into a InPk. Given that the scanner's jump and mark speed instructions must be provided at the start of each InPk and that the device uses ethernet for data transport, the high-

speed data transfer rate had no adverse effects on the speed of scanner's movement. On the other hand, (Arya et al., 2000) found that effectively selecting the simmer current might boost the effectiveness and longevity of the laser lamp. Therefore, at the end of each InPk there is a provision to set the laser power to zero or at a lower value that will not cause any burning of the metal but will not completely turn off the laser. As a result, the order of instructions in each packet was typically as follows: first, choose the jump and mark speed (M704 A60000 B54000), next, add unit as and absolute value instructions (G21,G90), and then, various laser power-movement paired instructions (M702 & G1). A sample g-code InPk can be found in Table 3.

Table 2: Straight Line movement in position of a section with constant power.

Line	X	Y	L
416000	-0.255641	-6.298378	395
416001	-0.250085	-6.304132	395
416002	-0.244528	-6.309886	395
416003	-0.238971	-6.31564	395
416004	-0.233415	-6.321394	395
416005	-0.227858	-6.327149	395
416006	-0.222301	-6.332903	395
416007	-0.216744	-6.338657	395
416008	-0.211188	-6.344411	395
416009	-0.205631	-6.350165	395
416010	-0.200074	-6.35592	395
416011	-0.194517	-6.361674	395
416012	-0.188961	-6.367428	395
416013	-0.183404	-6.373182	395
416014	-0.177847	-6.378936	395
416015	-0.17229	-6.38469	395
416016	-0.166734	-6.390445	395
416017	-0.161177	-6.396199	395
416018	-0.15562	-6.401953	395
416019	-0.150064	-6.407707	395
416020	-0.144507	-6.413461	395

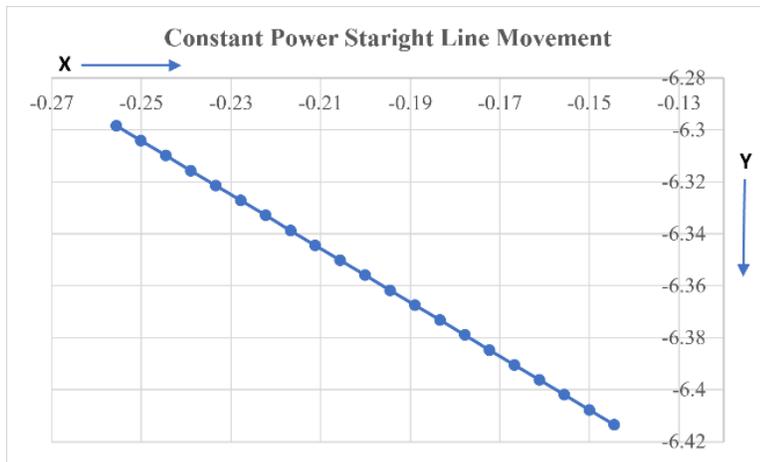


Figure 12: Constant power straight line with multiple instructions for position (X,Y) and Laser Power. From the Table 2 and the figure, it is clear that this whole motion is in a single line with constant power which can be executed just by one line of G-code instead of having multiple instructions.

G-Code Execution: Figure 11 shows the G-code execution phases and the [Algorithm 1](#) can be read for understanding the steps. The COM and Ethernet ports are used to link the corresponding equipment (linear actuators, galvo scanner controller, and Arduino—for carrying out safety functions). Afterward, the devices are initialized (moving to the home position or specific points, energizing relays, etc.). Following that, a new computer thread is created to track the safety features. The computer then waits in parallel with other instructions being executed for a quit command (clicking the "Emergency Clr" button) for testing purposes; this command can be upgraded to be integrated with responses from other sensors. Since this functionality operates parallel in a separate thread, it may respond and be executed immediately even if the computer is issuing commands to other devices or collecting sensor data. At the start of each layer's scanning, the safety activation function will always assess the safety scenario. When there are no safety concerns, the powder reservoir will rise at a predetermined rate that may be adjusted to improve the delivery of powder. The wiper will then distribute the powder from the reservoir in order to execute a layer of laser scanning. The powder bed will descend after the scanning is finished so

that the solid portion created in the powder bed won't be damaged when the wiper returns to its original position. If any safety issue arises in the middle of these operations (linear actuator movement, laser scanning), the safety feature running in the parallel thread ensures that the power is cut to the analog input of the laser, ensuring laser output as zero watts, and it also triggers an emergency off flag, which causes the system to stop executing the next layer. By immediately turning off the laser, the technology provides more safety than traditional ones.

Table 3: Example of an Instruction Packet.

M704 A60000 B54000				
G21	M702 0	M702 0	M702 0	M702 0
G90	G0 X20.570 Y2.866	G0 X19.430 Y3.327	G0 X6.273 Y8.890	G0 X5.717 Y8.890
M702 49725	M702 49725	M702 49725	M702 49725	M702 49725
G1 X21.203 Y2.930	G1 X20.405 Y2.893	G1 X6.979 Y8.878	G1 X6.134 Y8.890	G1 X5.578 Y8.890
M702 0	M702 0	M702 0	M702 0	M702 0
G0 X19.430 Y4.766	G0 X19.430 Y3.903	G0 X7.069 Y8.784	G0 X7.458 Y7.518	G0 X7.914 Y6.471
M702 49725	M702 49725	M702 49725	M702 49725	M702 49725
G1 X19.430 Y4.622	G1 X19.430 Y3.759	G1 X7.082 Y8.628	G1 X7.871 Y7.091	G1 X7.914 Y6.327
M702 0	M702 0	M702 0	M702 0	M702 0
G0 X21.093 Y2.900	G0 X20.217 Y2.943	G0 X6.829 Y8.890	G0 X7.914 Y7.047	G0 X5.439 Y8.890
M702 49725	M702 49725	M702 49725	M702 49725	M702 49725
G1 X20.976 Y2.877	G1 X19.975 Y3.050	G1 X6.690 Y8.890	G1 X7.914 Y6.903	G1 X5.300 Y8.890
M702 0	M702 0	M702 0	M702 0	M702 0
G0 X19.430 Y4.479	G0 X19.430 Y3.615	G0 X7.093 Y8.472	G0 X5.995 Y8.890	G0 X7.914 Y6.183
M702 49725	M702 49725	M702 49725	M702 49725	M702 49725
G1 X19.430 Y4.335	G1 X19.430 Y3.471	G1 X7.119 Y8.301	G1 X5.856 Y8.890	G1 X7.914 Y6.039
M702 0	M702 0	M702 0	M702 0	M702 0
G0 X20.851 Y2.863	G0 X19.634 Y3.260	G0 X6.551 Y8.890	G0 X7.914 Y6.759	G0 X5.161 Y8.890
M702 49725	M702 49725	M702 49725	M702 49725	M702 0
G1 X19.430 Y4.047	G1 X19.436 Y3.320	G1 X7.256 Y7.871	G1 X7.914 Y6.615	M2

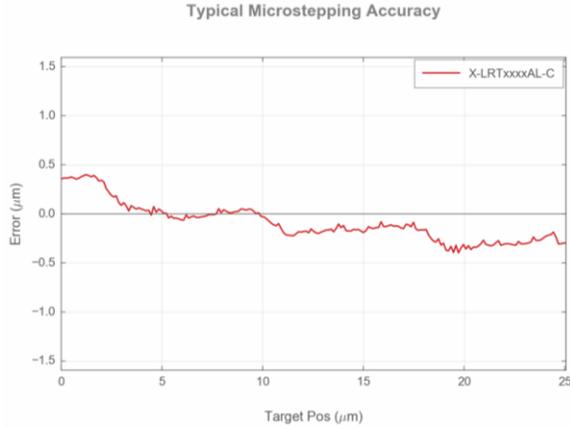


Figure 13: Typical Microstepping accuracy for the Z-axis and reservoir by (X-LRT-C Series: High Load, Motorized Linear actuators with Built-in Controllers and Dust Covers, 2022). At 25 μm target position the error is less than 0.4 μm .

Algorithm 1 G-Code Execution

if G-code prepared and saved earlier **then**

 Load G-code File

$MGCode \leftarrow G_{CodeLines}$

else

 Read CSV File and Create G-Code

$MGCode \leftarrow G_{CodeLines}$

end if

Now we have the G-code information in a variable

MGCode is 2 layered: $MGCode[Layer = 0,1,2,\dots][[G\text{-Code Package} = 0,1,2,\dots]]$

Connect and initiate linear actuators, galvo and safety features

for $MGCode[Layer]=0,1,2\dots$ **do**

if No safety or emergency issue found **then**

 Powder reservoir go up

 Wiper move forward to spread powder

for G-Code Package=0,1,2... **do**

 Send G-Code package instruction to the galvo controller

end for

 Powder bed move down according to layer thickness

 Wiper take back to initial position

else

 Trigger emergency mode

 ▷ initiate laser power supply off

 Exit execution activities

end if

Result and Discussion

This system successfully created G-code from the output CSV file from SAM software. Then the galvo execution shows moving the laser following a pattern and the digital output was demonstrated with LED's. The linear actuators were moving accordingly. The output of the galvo can be found in Figure 14. A point source laser is seen as a line due to the high-speed movement of the galvo. The digital unsigned 8 bit output (Figure 15) in the LED signifies digital 0-10 Volt analog voltage input for the laser.

The control software (Figure 16) has options to manually move the linear stages and galvo. It can load g-code and send commands to the devices to execute the process. It also has a emergency off button to turn off the system immediately.

This approach is ineffective in situations where the laser power remains constant but there are numerous changes in the position values that result in an instruction packet that is longer than 1460 bytes. Application of that will require some upgrading to guarantee appropriate instruction implementation. Since the speed of the scanner must be changed at beginning of the G-code, any necessary modifications to the jump or mark speed must be made during G-code generation. Therefore the jump or mark speed can not be updated without update of the G-code.



Figure 14: The rotation of the galvo mirrors created a straight-line movement of the point laser.

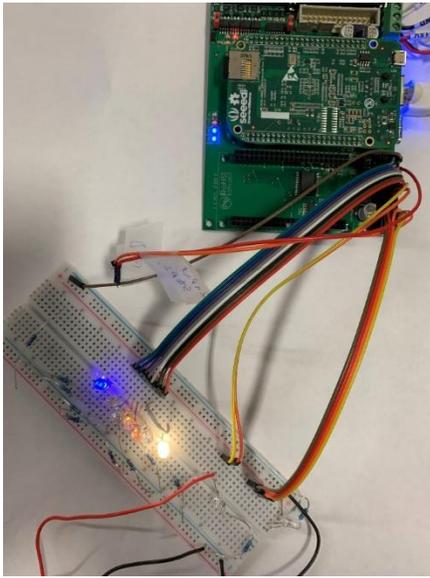


Figure 15: Digital unsigned 8bit control output shown in LEDs. Turning on of the LEDs represents logic high and vice-versa.



Figure 16: Graphic user interface of the control software.

Conclusion

This paper focuses on some important control methodologies of a LBPF system. The galvo and laser power control are thought to be extremely crucial for the system, and this research has effectively completed those tasks. This might be useful if one wants to construct his/her own AM system with extra functionalities. Different sensor responses may be a wonderful data source for analysis, and system parameter management can be performed accordingly. Upgradation to the code may easily provide in-situ monitoring and decision-making for the remelt of a current layer if it is not melting properly. Besides, this model can be updated to perform in-situ change of mark-speed of the galvo.

CHAPTER III

CASE STUDY 2: IMPLEMENTATION OF AUTOMATION AND MACHINE LEARNING APPLICATION FOR A LASER-BASED PROPRIETARY EQUIPMENT

Context and Background

Automation is a critical component of modern laboratories and Industry 4.0, which calls for various technologies including cloud computing, big data, cyber security, advanced robotics, Internet of Things (IoT), and additive manufacturing (Saturno et al., 2017) (Vite & Morbiducci, 2021) to ensure quality products and services. On an industry floor, a group of machines is required to communicate with each other using standard communication protocols for seamless operation. Figure 17 represents a typical cloud-connected smart industry, where a central computer communicates with the machine computer, which sends control instructions to the control devices and monitors the process by different sensors and updates the information to the cloud server. It can also take instructions from the cloud and request for execution to the machine computer. But many PE does not have that kind of feasibility and always need manual input to perform tasks. This hinders the advancement and adaptation of automation in cyber manufacturing systems.

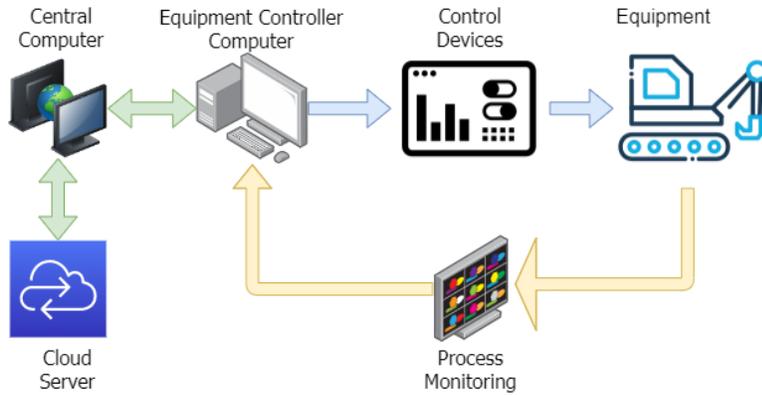


Figure 17: A typical cloud-connected smart Industry.

Using PE has several constraints like limitations to system upgradation (upgradation of OS, replacing PC with higher configuration), limited monitoring facilities (adding extra sensors and having feedback response), and limited direct automation opportunities without an Application Programming Interface (API). Despite this, industries and researchers rely on proprietary software due to its ease of use, ready-made software, QC-passed machines, and performance reliability. It was necessary to find a way to reduce the limitation of the usage of proprietary software to take advantage of its benefits.

Current literature has limited studies on automation and communication among multiple proprietary equipments. Limited research and development activities on automation for PE-based manufacturing can be attributed to the lack of access to the device, and manufacturers' unwillingness to share the API. Therefore, researchers have demonstrated alternative approaches to automate machines that use proprietary software to find a way out of these issues. Using pictures, Yeh et al. (Yeh et al., 2009) demonstrated a visual way to search and perform automated keyboard-mouse functionalities by analyzing information from the graphical user interfaces that led to several application-based studies in the following years. Controlling a laboratory instrument by simulating keyboard and mouse actions was presented using the

software interface (Carvalho, 2013). In that work, even though the proposed script offers automation features, the script requires modification as the task changes, and it did not address any networking between systems. Tentarelli et al. [7] proposed similar script-based automation with the advantage of allowing input to repeat sequential tasks. In advanced manufacturing, highly programable task sequences and integration of multiple systems are a growing demand.

In this study, we discuss how to automate proprietary equipment and introduce gesture control to show how Machine Learning (ML) can be applied to manufacturing sectors. To this end, this research offers the following:

- The control and operation of PE are demonstrated by sending instructions from a network via TCP/IP (Transmission Control Protocol/Internet Protocol).
- The intense calculation of ML and subsequent decision-making to control the PE are performed using a network computer, thus letting the PE computer only to focus on executing the task.
- Control of laser process parameters and the 3D linear stage is demonstrated using the server computer to automate a variety of functions (e.g. laser ON/OFF/Standby, laser power, feed rate, linear stage movement, G-code execution) at the PE computer.
- To simplify the generation of automation sequences, an Excel file-based command has been developed that has the potential to eliminate the need for a coding expert on site.

Methodology

The proposed communication platform works based on TCP/IP protocol between server and clients. The system first set up the server (the central controller) with an IP address and the

client (PE) is connected to the server. After the connection is established, the client waits for instructions from the server. The server reads and sends instructions to control the laser system from a previously saved Excel file (e.g. Table 5 and Table 6) or execute predefined functions attached to the buttons or drop-down menus shown in Figure 20. At the PE client end, it performs the automation tasks as it receives commands from the server. For instance, at the client end, the server dictates the execution of tasks such as: double-clicking the program icon, waiting for 2 seconds, searching for the run button, pressing the run button, looking for the command box, clicking and typing a G-code, etc. The client interprets the pixels of its display to identify and locate the target picture (icon or button) followed by clicking the target icon/button.

Table 4: Instruction set for task creation in Excel file.

S N	Function Name	Action Details	SN	Function Name	Action Details
1	px	pixel x	11	scroll	scroll mouse according to val
2	py	pixel y	12	enter	press the 'enter' button
3	val	value (number, character, key, string)	13	ci	click on the icon
4	jump	<ul style="list-style-type: none"> • if succeed, jump to val • if fail, jump to fail 	14	gci	click on the icon after the grayscale conversion
5	minwin	minimize windows	15	dci	double click on the icon
6	mc	move cursor	16	dgci	double click on the icon after the grayscale conversion
7	ccc	click cursor at the current position (px, py)	17	press	press keyboard key (val)
8	ccp	click the cursor at the pixel position	18	type	type string (val)
9	dccc	double click the cursor at the current position (px,py)	19	hotkey	press hotkey1 and hotkey2 together (i.e., win+D, ctrl+a, alt+tab, etc.)
10	dccp	double click the cursor at the pixel position			

The server and client programming requires designing three program modules to facilitate all the tasks performed in this project. The ‘**Server_client**’ module is designed to establish communication between the server and client using TCP/IP protocol for fast data

transfer and specific identification of the PE. It also makes communication independent of the operating system's platforms like Windows, iOS, and Linux. Different functions are built into the module to transfer instructions, analyze, and execute tasks. The ‘**Automation**’ module is designed using a library called pyautogui (Sweigart, 2019), which simulates the input from the mouse and keyboard. This library can be executed only in Windows, MacOS X, and Linux. To execute certain instructions like a laser on/off with gesture ‘**Hand_Gesture_Control**’ module is designed. This module utilizes the mediapipe (Lugaresi et al., 2019), a machine-learning framework to detect different landmarks on the palm and face. This module tracks the coordinates of 21 landmarks on hand and the distance between two landmarks is used to perform an action.

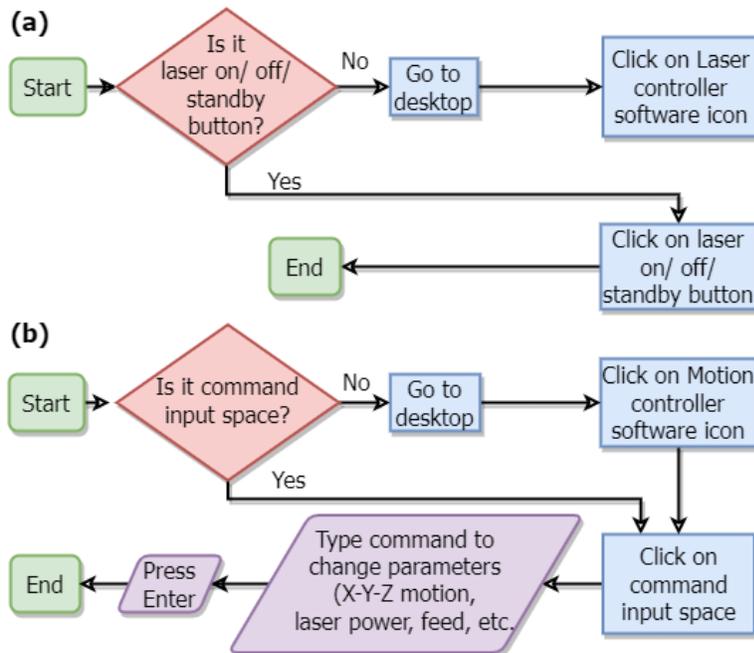


Figure 18: Flow chart for (a) executing task by pressing button (set on/ off/ standby the laser), (b) executing tasks (linear stage/galvo movement, laser parameter control) by G-Code.

Experimental Setup

Figure 19 shows the experimental setup where a network switch box was used to connect the server and client computer. The client computer was connected to the PE that controlled the laser process parameter (average power, pulse repetition rate, and laser ON/OFF/ Standby) and movement of the linear actuators in 3 directions (X, Y & Z). The controller receives instructions from the PE computer and sets the laser process parameters and controls the movement of linear actuators. Figure 18 (a) exemplifies a scenario where the mouse click-based command was used to control the laser input (Laser ON/OFF/Standby and Shutter ON/OFF), while the Figure 18 (b) shows a situation where both the mouse and keyboard inputs were simulated to control system's process parameters utilizing G-code. To execute these functions, a sequence of tasks was first defined in Excel files (Table 5 and Table 6) and subsequently loaded by the PE computer.

Table 5: Excel command example for turning on the laser.

serial	resources	func	func1	delay _sec	...	val	fail	Explanation
0	laser_on_b.png	ci	jump	2		4	1	<ul style="list-style-type: none"> Identify pixels for laser_on_b.png If found, click the button, and go to step 4 (which is null here » task completed) If fail, go to step 1, and wait for 2s
1		minwin		0.5				<ul style="list-style-type: none"> Display the desktop and wait for 0.5s
2	laser_ctrl_taskbar.png	ci		2				<ul style="list-style-type: none"> Find pixels for laser_ctrl_taskbar.png, click and wait 2s
3	laser_on_b.png	ci		2				<ul style="list-style-type: none"> Find pixels for laser_on_b.png, click, and wait for 2s.

Table 6: Excel command example for executing tasks to move the linear stages.

serial	resources	func	func1	delay_sec	...	val	fail	Explanation
0	command.png	ci	jump	2		4	1	<ul style="list-style-type: none"> •Identify pixels for command.png •If succeed, click and go to step 4 •If fails, go to step 1 •Wait for 2s
1		minwin		0.5				<ul style="list-style-type: none"> •Display or Hide Desktop •Wait for 0.5s
2	motion_ctrl_taskbar.png	ci		2				<ul style="list-style-type: none"> •Identify pixels for motion_ctrl_taskbar.png, click. •Wait for 2s
3	command.png	ci		2				<ul style="list-style-type: none"> •Identify pixels for command.png •Wait for 2s
4		type		2		F15		<ul style="list-style-type: none"> •Type 'F 15', i.e., set the feed rate to 15 mm/s' •Wait for 2s
5		enter		1				<ul style="list-style-type: none"> •Press 'enter' •Wait for 2s
6		type		2		G0 X50		<ul style="list-style-type: none"> •Type 'G0 X50', i.e., rapid linear movement x to position 50 • Wait for 2s
7		enter		4				<ul style="list-style-type: none"> •Press 'enter' •Wait for 4s

Figure 20 shows the server user interface where the Server IP Address and Port box were first filled with the IP address and the Port number. Then the Init Server and Start Server buttons were utilized to initialize and start the server. The client interface is shown in Figure 21, where the server IP address and port number were assigned and initialized by the client by clicking the Init Client button. The Conn Server button was then pressed to send a request to the server to connect. Subsequently, the Conn Client button in the server was pressed to accept the request from the client, therefore the server-client connection was established. In addition, on the right side of the server interface, laser and shutter control-related commands were placed and executed. Later different tasks were completed by specific buttons according to Table 7.

Table 7: Buttons and respective functions.

Button	Interface	Function
Msg to Server	client	send a message to the server
Listen Server	client	read messages from the server
Listen Client	server	read messages from the client
Msg to Client	server	send a message to the client
Send Auto Cmd	server	execute proprietary software supported command
File Auto Exec	server	execute the file that was previously saved in the resources folder, that excel file was generated according to the instruction provided in Table 1
Hand Gesture	server	read hand landmarks and turned the laser on/off according to that instruction (Figure 23)
Custm Func	server	drop-down menu ['ENABLE X Y Z','HOME X Y']
Keyboard Mouse Func (x,y or val)	server	executed different keyboard and mouse related functions from the drop-down menu ["Mouse_Move (x y)","Click (x y)","Click_Current", "Double_Click (x y)", "Double_Click_Current", "Type", "Press_Hotkey", 'Minimize_all', "Enter", "Esc", "Win_Key", "Scroll (Val)"]
Code File	server	executed the PE-supported instruction sets saved in a file
Press Run	server	press run button

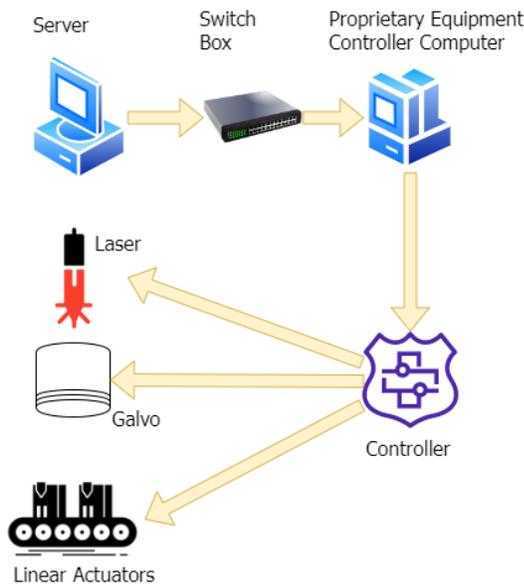


Figure 19: Experimental setup to control laser source and linear actuators by the instruction sent from the central (server) computer to the proprietary equipment (client) computer.

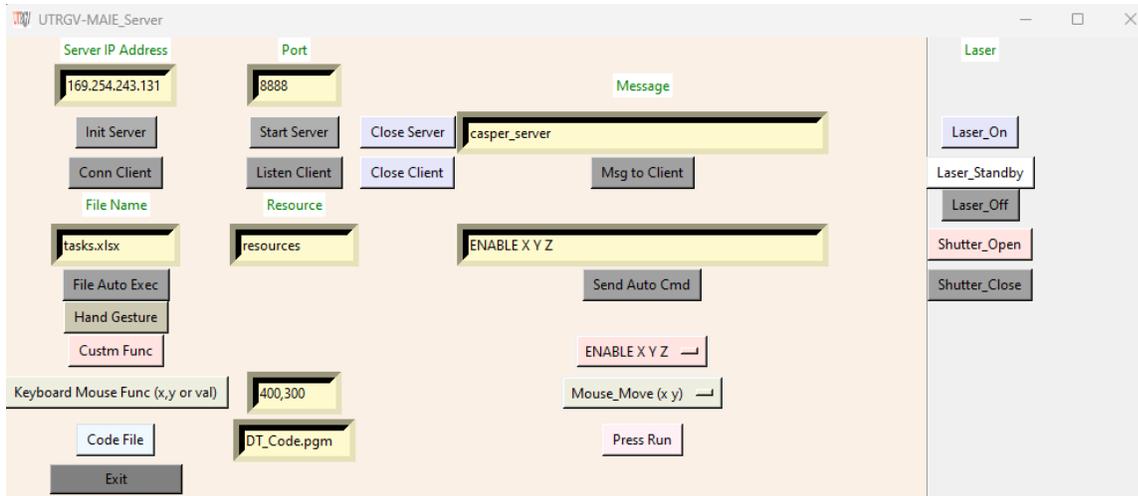


Figure 20: Server Program Interface in the central computer.

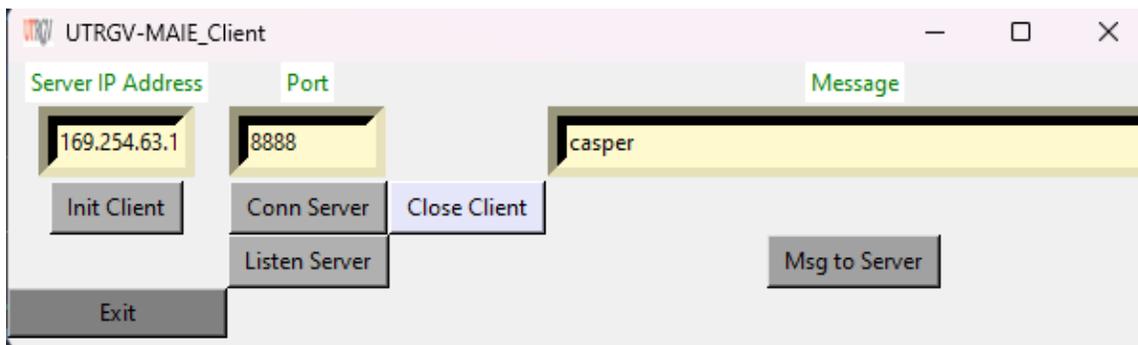


Figure 21: Client Program Interface in machine computer.

Result and Discussion

In this study, control of two PE software (Aerotech Motion soft and Laser LLC) was successfully implemented through a server-client interface. The Aerotech Motion soft controls the linear 3D motion (X, Y, and Z axes), galvo scanning, and laser process parameters, while the Laser LLC determines the mode of laser operations (ex. ON, OFF, and Standby). The Python-based PE software was designed to load and execute a set of commands previously stored in an Excel file. Drop-down menus were constructed in the proposed Python application to execute

commonly used control tasks. In addition, a previously coded instruction set was sent from the server to the client to perform a predefined laser processing task. To evaluate the performance of the proposed application, several laser processing tasks were performed as shown in Figure 22. Using the 3D linear stage motion and laser process parameter control, the circles and the lines were inscribed as shown in Figure 22 (b). Also, as shown in Figure 22 (c), the UTRGV mascot and logos were engraved using galvo and laser control. The client-server interface was also tested to demonstrate human-machine interaction for a laser-based system. Machine vision technology was incorporated into the software to implement gesture-driven control of the laser system. As shown in Figure 23 (server end) and Figure 24 (client end), the turning ON and Standby of the laser was successfully accomplished by hand gesture. The server computer detects 21 landmarks [6] on hand. Then as gestured to turn on the laser, the distance in pixels between landmarks 9 and 12 was considered. When the Pythagorean pixel distance between these two landmarks was greater than 50, then the server sent an instruction to click on the ON button at the Laser LLC software. For a gesture with a Pythagorean pixel distance of less than 30, similarly, the server sent an instruction to execute Standby at the Laser LLC software. In both cases, upon receiving the instruction from the server, the client executed Laser ON/Standby operation. As shown in Figure 23 (a), the server detects hand landmarks, makes a decision, and sends Laser ON instruction by hand gesture, while Figure 23 (b) server detects hand landmarks, makes a decision, and sends Laser Standby instruction by hand gesture. The hand pictures show the detected landmarks and the picture below the hand shows the python terminal output.

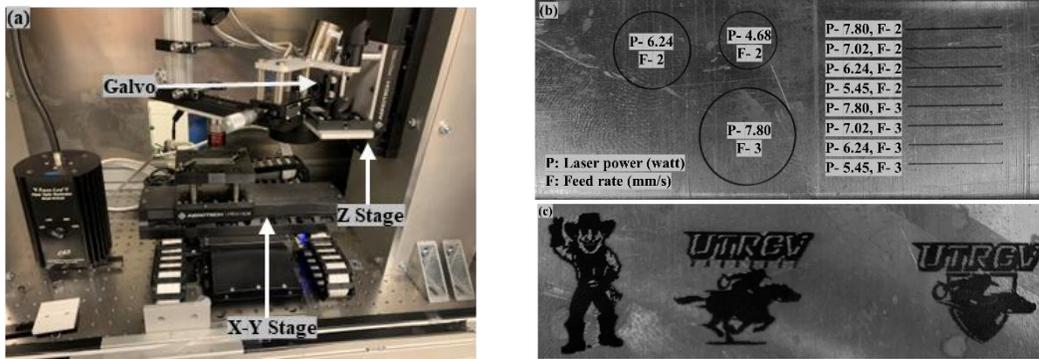


Figure 22: System and laser process control: (a) 3-axis state and galvo system control, (b) control of laser marking, and (c) control of laser engraving custom images.

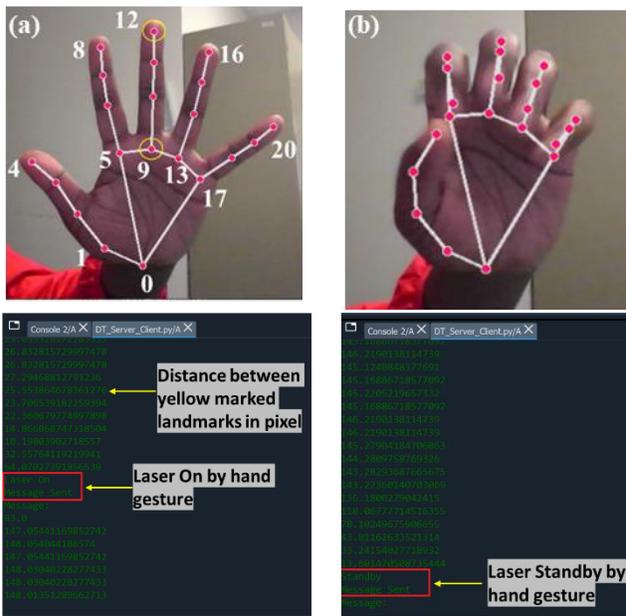


Figure 23: Sending gesture control instruction from the server: (a) sending Laser ON instruction and (b) sending Laser Standby instruction.

In the developed application, the server-client platform was used to execute manufacturing instructions on the machine PC without having administrative privileges on the machine PC. Therefore, at the machine's end, any unauthorized changes in system files are unlikely to happen. Restricted access keeps the system comparatively safer since hacker

task on the client/machine PCs. Also, the application can be utilized to realize synchronous automation by parallel controlling machines (proprietary or not).

This study has opened some ideas for future development. In our project, it might happen that a computer doesn't operate as expected, that tasks take a lot longer than they usually do, or that the PC temporarily stops functioning. Monitoring CPU-RAM utilization and GUI response makes it simple to address these issues. Picture-to-text conversion and then storing the necessary data on a dedicated PC or cloud would add great productivity in manufacturing industries. By analyzing the current parameters of a process, the system can better understand the present situation, the status of the previous command, etc. Installation of several sensors and routine monitoring of them can be used to monitor the product in real time. Aside from that, if the model is effectively trained using a data-driven model the process can be optimized. Since TCP/IP protocol is utilized in communication, it can easily be developed for cloud computing and IoT. But cybersecurity must be ensured before the implementation.

Conclusion

The development of automation of pps with instructions received via TCP/IP provides a way of automation for Industry 4.0, where all the machines including proprietary ones can be monitored and automated from a central server. As the project employed ML for hand gestures, by leveraging custom machine learning, this idea can also be further adapted for customizing process parameters, developing decision-making systems, etc. Eventually, the system can be connected to the cloud to allow remote management from anywhere. Thus, cyber manufacturing

can be ensured for proper data management and smart control implementation with Artificial Intelligence (AI).

This study has some limitations and opened some ideas for future development. The graphic user interface (GUI) offers essential data that may be read via picture-to-text conversion and then stored on a dedicated PC or cloud. By reading the current parameters of a process, the system can better understand the present situation, the status of the previous command, etc. It might happen that a computer doesn't operate as expected, that tasks take a lot longer than they usually do, or that the PC temporarily stops functioning. Monitoring CPU-RAM utilization and GUI response make it simple to address these issues. Installation of several sensors and routine monitoring of them can be used to monitor the product in real-time. Aside from that, if the model is effectively trained using a data-driven model the process can be optimized. Since TCP/IP protocol is utilized in communication, it can easily be developed for cloud computing and IoT. But, cybersecurity must be ensured before implementing that.

REFERENCES

- Arya, R., Thomas, M., Bhujle, A. G., & Bhawalkar, D. (2000). Effects of simmer current on flashlamp impedance and their combined influence on the output of a quasi-CW Nd:YAG laser. *Quantum Electronics, IEEE Journal Of*, *36*, 872–878. <https://doi.org/10.1109/3.848361>
- Biswas, B., Mukhopadhyay, A., Bhattacharjee, S., Kumar, A., & Delen, D. (2022). A text-mining based cyber-risk assessment and mitigation framework for critical analysis of online hacker forums. *Decision Support Systems*, *152*, 113651. <https://doi.org/https://doi.org/10.1016/j.dss.2021.113651>
- Carvalho, M. C. (2013). Integration of analytical instruments with computer scripting. *Journal of Laboratory Automation*, *18*(4), 328–333.
- Casini, M. (2022). Chapter 8 - Advanced building construction methods. In M. Casini (Ed.), *Construction 4.0* (pp. 405–470). Woodhead Publishing. <https://doi.org/https://doi.org/10.1016/B978-0-12-821797-9.00006-4>
- Craeghs, T., Bechmann, F., Berumen, S., & Kruth, J. P. (2010). Feedback control of Layerwise Laser Melting using optical sensors. *Physics Procedia*, *5*(PART 2), 505–514. <https://doi.org/10.1016/j.phpro.2010.08.078>
- Grossin, D., Montón, A., Navarrete-Segado, P., Özmen, E., Urruth, G., Maury, F., Maury, D., Frances, C., Tourbin, M., Lenormand, P., & Bertrand, G. (2021). A review of additive manufacturing of ceramics by powder bed selective laser processing (sintering / melting): Calcium phosphate, silicon carbide, zirconia, alumina, and their composites. *Open Ceramics*, *5*, 100073. <https://doi.org/https://doi.org/10.1016/j.oceram.2021.100073>
- Gu, D., Xia, M., & Dai, D. (2019). On the role of powder flow behavior in fluid thermodynamics and laser processability of Ni-based composites by selective laser melting. *International Journal of Machine Tools and Manufacture*, *137*(July 2018), 67–78. <https://doi.org/10.1016/j.ijmachtools.2018.10.006>
- Guo, M., Gu, D., Xi, L., Du, L., Zhang, H., & Zhang, J. (2019). Formation of scanning tracks during Selective Laser Melting (SLM) of pure tungsten powder: Morphology, geometric features and forming mechanisms. *International Journal of Refractory Metals and Hard Materials*, *79*, 37–46. <https://doi.org/https://doi.org/10.1016/j.ijrmhm.2018.11.003>
- Jiang, P. F., Zhang, C. H., Zhang, S., Zhang, J. B., Chen, J., & Chen, H. T. (2021). Additive manufacturing of novel ferritic stainless steel by selective laser melting: Role of laser

- scanning speed on the formability, microstructure and properties. *Optics & Laser Technology*, 140, 107055. <https://doi.org/https://doi.org/10.1016/j.optlastec.2021.107055>
- Jiao, L., Chua, Z., Moon, S., Song, J., Bi, G., & Zheng, H. (2018). Femtosecond Laser Produced Hydrophobic Hierarchical Structures on Additive Manufacturing Parts. *Nanomaterials*, 8, 601. <https://doi.org/10.3390/nano8080601>
- Karimi, P., Raza, T., Andersson, J., & Svensson, L.-E. (2018). Influence of laser exposure time and point distance on 75- μ m-thick layer of selective laser melted Alloy 718. *The International Journal of Advanced Manufacturing Technology*, 94(5), 2199–2207. <https://doi.org/10.1007/s00170-017-1019-1>
- Kumar, S. (2014). 10.05 - Selective Laser Sintering/Melting. In S. Hashmi, G. F. Batalha, C. J. Van Tyne, & B. Yilbas (Eds.), *Comprehensive Materials Processing* (pp. 93–134). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-08-096532-1.01003-7>
- Lane, B., Mekhontsev, S., Grantham, S., Vlasea, M., Whiting, J., Yeung, H., Fox, J., Zarobila, C., Neira, J., McGlaulin, M., Hanssen, L., Moylan, S., Donmez, M., & Rice, J. (2016, May). *Design, Developments, and Results from the NIST Additive Manufacturing Metrology Testbed (AMMT)*. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=921551
- Li, J., Cao, L., Liu, H., Zhou, Q., Zhang, X., & Li, M. (2023). Imbalanced data generation and fusion for in-situ monitoring of laser powder bed fusion. *Mechanical Systems and Signal Processing*, 199, 110508. <https://doi.org/https://doi.org/10.1016/j.ymssp.2023.110508>
- Li, Y., Zhou, K., Tan, P., Tor, S. B., Chua, C. K., & Leong, K. F. (2018). Modeling temperature and residual stress fields in selective laser melting. *International Journal of Mechanical Sciences*, 136, 24–35. <https://doi.org/10.1016/J.IJMECSCI.2017.12.001>
- Liu, C., Yan, D., Tan, J., Mai, Z., Cai, Z., Dai, Y., Jiang, M., Wang, P., Liu, Z., Li-Chia, C., Lao, C., & Chen, Z. (2020). Development and Experimental Validation of a Hybrid Selective Laser Melting and CNC Milling System. *Additive Manufacturing*, 36, 101550. <https://doi.org/10.1016/j.addma.2020.101550>
- Lugaresi, C., Tang, J., Nash, H., McClanahan, C., Uboweja, E., Hays, M., Zhang, F., Chang, C.-L., Yong, M., Lee, J., & others. (2019). Mediapipe: A framework for perceiving and processing reality. *Third Workshop on Computer Vision for AR/VR at IEEE Computer Vision and Pattern Recognition (CVPR)*, 2019.
- Markl, M., & Körner, C. (2016). Multiscale Modeling of Powder Bed–Based Additive Manufacturing. [Http://Dx.Doi.Org/10.1146/Annurev-Matsci-070115-032158](http://Dx.Doi.Org/10.1146/Annurev-Matsci-070115-032158), 46, 93–123. <https://doi.org/10.1146/ANNUREV-MATSCI-070115-032158>
- Nagesha, B. K., Anand Kumar, S., Vinodh, K., Pathania, A., & Barad, S. (2021). A thermo – Mechanical modelling approach on the residual stress prediction of SLM processed HPNGV aeroengine part. *Materials Today: Proceedings*. <https://doi.org/https://doi.org/10.1016/j.matpr.2020.12.940>

- Saturno, M., Pertel, V., & Deschamps, F. (2017, March). *Proposal of an automation solutions architecture for Industry 4.0*.
- Soundarapandiyan, G., Leung, C. L. A., Johnston, C., Chen, B., Khan, R. H. U., McNutt, P., Bhatt, A., Atwood, R. C., Lee, P. D., & Fitzpatrick, M. E. (2023). In situ monitoring the effects of Ti6Al4V powder oxidation during laser powder bed fusion additive manufacturing. *International Journal of Machine Tools and Manufacture*, *190*, 104049. <https://doi.org/https://doi.org/10.1016/j.ijmachtools.2023.104049>
- Spierings, A. B., Dawson, K., Uggowitz, P. J., & Wegener, K. (2018). Influence of SLM scan-speed on microstructure, precipitation of Al₃Sc particles and mechanical properties in Sc- and Zr-modified Al-Mg alloys. *Materials & Design*, *140*, 134–143. <https://doi.org/https://doi.org/10.1016/j.matdes.2017.11.053>
- Swiegart, A. (2019). *Automate the boring stuff with Python: practical programming for total beginners*. No Starch Press.
- Taherkhani, K., Ero, O., Liravi, F., Toorandaz, S., & Toyserkani, E. (2023). On the application of in-situ monitoring systems and machine learning algorithms for developing quality assurance platforms in laser powder bed fusion: A review. *Journal of Manufacturing Processes*, *99*, 848–897. <https://doi.org/https://doi.org/10.1016/j.jmapro.2023.05.048>
- Valente, E. H., Gundlach, C., Christiansen, T. L., & Somers, M. A. J. (2019). *Effect of Scanning Strategy During Selective Laser Melting on Surface Topography, Porosity, and Microstructure of Additively Manufactured Ti-6Al-4V*. <https://doi.org/10.3390/app9245554>
- Vite, C., & Morbiducci, R. (2021). Optimizing the Sustainable Aspects of the Design Process through Building Information Modeling. *Sustainability*, *13*, 3041. <https://doi.org/10.3390/su13063041>
- Wang, R., Standfield, B., Dou, C., Law, A. C., & Kong, Z. J. (2023). Real-time process monitoring and closed-loop control on laser power via a customized laser powder bed fusion platform. *Additive Manufacturing*, *66*, 103449. <https://doi.org/https://doi.org/10.1016/j.addma.2023.103449>
- Wysocki, B., Idaszek, J., Zdunek, J., Zniatowski, K. R., Pisarek, M., Yamamoto, A., Wojciech, W., & Eszkowski, W. (2018). The Influence of Selective Laser Melting (SLM) Process Parameters on In-Vitro Cell Response. *International Journal of Molecular Sciences Article*. <https://doi.org/10.3390/ijms19061619>
- X-LRT-C Series: High load, motorized linear stages with built-in controllers and dust covers*. (2022, September 28).
- Yeh, T., Chang, T.-H., & Miller, R. C. (2009). Sikuli: using GUI screenshots for search and automation. *Proceedings of the 22nd Annual ACM Symposium on User Interface Software and Technology*, 183–192. <https://doi.org/https://doi.org/10.1145/1622176.1622213>

- Yeung, H., Hutchinson, K., & Lin, D. (2021, May). *DESIGN AND IMPLEMENTATION OF LASER POWDER BED FUSION ADDITIVE MANUFACTURING TESTBED CONTROL SOFTWARE*. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933133
- Yeung, H., & Lane, B. (2020). A residual heat compensation based scan strategy for powder bed fusion additive manufacturing. *Manufacturing Letters*, 25, 56–59. <https://doi.org/https://doi.org/10.1016/j.mfglet.2020.07.005>
- Yeung, H., Lane, B., & Fox, J. (2019). Part geometry and conduction-based laser power control for powder bed fusion additive manufacturing. *Additive Manufacturing*, 30, 100844. <https://doi.org/https://doi.org/10.1016/j.addma.2019.100844>
- Yeung, H., Lane, B. M., Donmez, M. A., Fox, J. C., & Neira, J. (2018). Implementation of Advanced Laser Control Strategies for Powder Bed Fusion Systems. *Procedia Manufacturing*, 26, 871–879. <https://doi.org/https://doi.org/10.1016/j.promfg.2018.07.112>
- Yeung, H., Yang, Z., & Yan, L. (2020). A meltpool prediction based scan strategy for powder bed fusion additive manufacturing. *Additive Manufacturing*, 35, 101383. <https://doi.org/https://doi.org/10.1016/j.addma.2020.101383>

BIOGRAPHICAL SKETCH

Md. Shahriar Forhad is a committed person who is currently studying for a Master of Science in Manufacturing Engineering at The University of Texas Rio Grande Valley in Edinburg, Texas. In the field of advanced manufacturing and control systems, he has a deep interest in electronics, automation, and robots.

At Chittagong University of Engineering and Technology (CUET), Bangladesh, where he earned a Bachelor of Science in Electrical and Electronic Engineering, Forhad's career as an engineer officially began. Forhad showed a remarkable knack for translating theoretical ideas into workable solutions while attending CUET. He showed a significant interest in electronic circuits and programming.

Forhad's academic endeavors and extracurricular activities have continually demonstrated his commitment to using cutting-edge technology for the improvement of manufacturing processes, which is driven by a deep interest in automation and robotics. He has investigated the complex interactions between control systems, precision engineering, and real-time monitoring due to his curiosity and inventive nature.

In his quest for academic achievement, Forhad's research activities have resulted in a captivating thesis abstract that emphasizes the crucial role that process control plays in contemporary industry. His dissertation centers on creating a Laser Powder Bed Fusion device

with complex control algorithms. In order to provide additive manufacturing with unmatched accuracy and efficiency, this ambitious project aims to automate real-time defect detection and response methods. Forhad wants to transform the way manufacturing is approached in both commercial settings and research labs by solving the limits of proprietary machines and developing a proprietary software automation solution.

In the future, automation, robotics, and cutting-edge manufacturing methods will all be seamlessly integrated, according to Forhad's vision. His commitment to pushing the envelope of innovation and his steadfast focus to improving manufacturing techniques show that he has the capacity to make an enduring impact on the industry.

A testimonial to Md Shahriar Forhad's zeal for engineering, automation, and manufacturing is his academic career, in conclusion. Forhad is preparing himself to make substantial contributions to the improvement of control systems and industrial procedures.