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Fuzzy Logic Control in Metal Additive Manufacturing: A Literature Review and Case Study

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Abstract: Since the development of the Fuzzy Logic theory by Zadah (1965), motivated by the human-level understanding of systems for the development of computational and mathematical frameworks, it has become an active research field for a broad spectrum of research in academia and the industry, from systems modelling to systems monitoring and control. In this research, the authors intend to highlight the use of Fuzzy Logic theory in metal additive manufacturing processes. The modelling of such processes has a lot of uncertainties due to the large underlying physics during the operation, which makes the Fuzzy Logic Controller a promising tool to deal with such a process. This work will provide a survey of the previous efforts and a case study to illustrate the approach's effectiveness in such a complex manufacturing technique.

Keywords: metallic additive manufacturing,laser powder bed fusion, control, fuzzy logic

1. INTRODUCTION

In the 1960s, when the Fuzzy Logic (FL) theory was initiated by Lotfi A. Zadeh (Zadeh (1965)), it was challenging to appreciate its merits due to the absence of a practical application. It took almost a decade to see the first FL controller for an actual industrial application, which Mamdani and Assilian proposed in 1975 for steam engines (Tan (1998)). After that, the application of the FL grows rapidly to cover different aspects. The approach helps in reducing the gaps between the theoretical (ideal) side and the practical (uncertain) side by considering the uncertainty and the inaccuracy of the models (Lhachemi et al. (2019)).

The FL theory is a non-linear representation of the engineering problem, including the human factor and statistical information in evaluating the process (Jing et al. (2021)). It allows treatment of system variables in gradient logic rather than binary logic (e.g. 0 or 1) (Wang (1997)), which is closer to the practical world where the relationship between the variables includes complex categorisation of the membership status. The strength of FL can be seen in three main points:

1. FL formulate and consider the human expertise and knowledge to define the objective problem and the decision variables (Elkaseer et al. (2018); Farshidianfar et al. (2013)).
2. FL can be suitable for systems that have no accurate description (Lhachemi et al. (2019); Tan (1998)).
3. FL can be an economical alternative compared to other intelligent systems (Farshidianfar et al. (2013)).

FL applications include many sectors in the fourth industrial revolution. Among these are 3D printing or what is known scientifically as additive manufacturing (AM). AM is an advanced technique of producing parts using layer by layer fabrication (Al-Saadi et al. (2021)). It has the power to produce parts with customised properties and shapes without going through traditional manufacturing steps. This gives the AM processes the ability to offer revolutionary design in various fields in the industry such as aerospace, energy, automotive and tooling (Tapia and Elwany (2014)).

AM has seven main categories (Seifi et al. (2017)) that can process various types of material (plastic, metal, ceramic, etc.) in different formats (liquid, wire, and powder) using different techniques. A promising technique of AM process is the selective laser melting (SLM) process. SLM is a laser powder bed fusion AM method, where a metallic powder is melted selectively in high resolution using a high power-density laser source to fabricate parts and build it layer by layer (Gupta (2017); Mercado Rivera and Rojas Arciniegas (2020)). As a result, it can produce parts with complex geometries, lightweight structures, and internal channels, improving product performance and industrial specifications (Vasileska et al. (2020)).

However, the level of development of metallic processes still hampers their widespread adoption. The quality and repeatability of the metal parts produced by the process continue to face many challenges. The process contains complex underlying physical phenomena, a large number of parameters, and transformations occurring during the process in a short time (Druzgalski et al. (2020)). There have been extensive research efforts over the world in

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the last two decades in modelling and control of AM processes (Gupta (2017)). The investigations emphasise the importance of a control-oriented model and the control strategies to enhance product quality. Nevertheless, more research is required to attain efficient online closed-loop controllers that can compensate for the perturbations during the process. Since most control-oriented models are based on simplification and reduction, the classical controller can face many limitations and drawbacks.

Motivated by the ability of FL theory to handle complex and uncertain models, this research work will provide a brief literature review about the use of the fuzzy logic theory (modelling and control) in the field of metal additive manufacturing in general. In addition, a case study of designing a fuzzy controller for an L-PBF process, which will be used to illustrate the advantages of FL-based control over classical PID control (the compassion is limited due to publication size).

The paper after this section will be organised as follows: Section 2 will consider why we need to consider FL in AM, section 3 discusses a fuzzy logic application in AM, section 4 presents a case study, section 5 contains a discussion including a review of future opportunities and section 6 finishes the paper with a conclusion and future work.

2. WHY DO WE NEED TO CONSIDER FUZZY LOGIC IN METALLIC AM

With all the advantages that metallic AM processes have, there are several concerns about the repeatability and reproducibility to adapt the technology worldwide (DebRoy et al. (2019); Dowling et al. (2020). The research investigations presented in the literature show that the system dynamics vary continuously during the process. The variation depends on how the heat has accumulated during the fabrication of the object, which depends on the object geometry. Consequently, the operation parameters for most existing metallic AM processes are determined by trial and error in advance, or via the heuristic use of offline numerical and analytical models. Such process paramteres, are then 'fixed' during the fabrication (Tang and Landers (2009); Wang et al. (2020)). Such a method works well with regular shapes but not with complex geometry. Research investigations showed that maintaining the parameters unchanged increases the heat affect zone (Tang and Landers (2009)). Consequently, heat accumulation and other complexities cause irregular melting pool morphology, excessive dilution, leading to various defects such as thermal distortion, lack of fusion, and cracking. Thus, the properties of the produced parts cannot be reliably guaranteed, which is a major barrier for critical applications.

Another approach predetermined the optimal processing set of parameters for specific mechanical properties to enhance product quality using thermal models (Fox et al. (2016)). However, the approach is not economical nor robust enough to deal with perturbations.

Using an online control system can compensate for disturbances and minimise heat accumulation during the process, thus improving the quality of the produced parts(Gupta (2017); Fleming et al. (2020)). Proportional (P) and Proportional-Integral (PI) controllers were used in the first attempts to investigate the controllability of the melt pool size by manipulating the laser power Craeghs et al. (2010). The studies presented the effectiveness and importance of the online control algorithm. However, the controller's performance was limited because the designed controller was based on a simplified second-order model.

Different control algorithms were implemented and investigated, varying from classical to more advanced controller techniques. From the previous author work (Al-Saadi et al. (2021)) the lack of an adequate process model that can be used to design a practical online control algorithm was noted. Furthermore, it will be very challenging to find such a model without linearisation in order to apply classical control theory. Unfortunately, the linearisation of the process can exclude a part from its featurethat could challenge control performance (Ibrra and Webb (2016)). Thus applying classical approaches is not the optimal solution in such a case.

Modern control systems such as ones that include artificial intelligence can provide a solution to enhance complex performance without needing an accurate model (or even any model). However, since such techniques are data-driven, their quality depends on the amount of available or accessible data; a real data shortage is a significant obstacle for any implementation. Based on the aforementioned section, FL theory presents a middle ground between the simplicity of the classical controllers and the complexity of the advanced control methods. Thus, it is worth deeply investigating the use of fuzzy controllers to enhance the quality of metallic AM processes and to evaluate the method's strengths and limitations in this context.

3. FUZZY LOGIC CNTROLLER (FLC) APPLICATION IN AM

Based on the best of the authors' knowledge, using a fuzzy logic controller in the L-PBF process has not been yet investigated. However, there are few attempts to apply it with other metallic AM processes, that can be further developed and investigated towards building a FLC for L-PBF.

The idea was investigated first in Hua and Choi (2005), where an FLC is designed and implemented for the direct metal deposition process. The purpose of the controller was to manipulate the input power to achieve the desired bead height. Theoretically, under the assumption of linearity, the controller shows promising results compared to the conventional control algorithm. However, the controller's performance in the actual experiment was limited due to the sensor capability.

In Farshidianfar et al. (2013), a neuro-fuzzy (NF) algorithm was used to identify and control a cladding process. The model was first identified using the NF system based on experimental data and then using the same technique, a controller was designed to vary the processing speed to control the height of the deposition. Generally, the obtained result showed promising results for the system performance.

Another investigation was recently done in Li et al. (2020). The FLC was used to control the deposition height in the wire and arc process by varying the speed. The proposed control system used the data of the previous layer to update the speed for the coming layer. The investigation shows better accuracy in the geometry of the printed sample.

The previous studies focused on the metallic AM process; however, other research efforts were conducted on polymers printers. In Moor et al. (2018), the FL was used to enhance the quality of the product by detecting defects and correcting the process parameters. The proposed system scans the printed part and compares it with the CAD model. In Keskekci Abdullah Burak ,Senol Ramazan (2020), the FLC was used to control the working environment temperature to overcome the warping problem. Compared with the PID controller, the system has 22% less warping. The use of an adaptive fuzzy-PID controller to control the temperature of the process (bed, nozzle, ambient temperature) was investigated in Liang et al. (2019). The research shows an enhancement in system performance in terms of overshoot percentage and tracking performance.

4. CASE STUDY

In this section, the FL controller effectiveness is shown using a case study example. It is worth mentioning that there is no previous investigation of using FLC on a L-PBF process. The section will start with a brief description of the L-PBF process, followed by the formulation of the control problem, controller design and simulation results.

4.1 System overview

Selective laser melting is a metallic PBF process that uses a focused laser beam to melt the mounted powder selectively (Nematollahi et al. (2019)). The process can produce metal parts directly with quality equivalence, or better in some applications, to the ones produced using traditional manufacturing. The narrow laser source allows selective melting of the powder in the order of tens of microns in thickness and building of parts with a significantly satisfactory resolution (Wang et al. (2020)). The thermal energy produced by the laser system is sufficient to melt the powder at the point of incidence and re-melt the surrounding solidified powder. Thus, the process can produce well-bonded and high-density parts (Gibson Rosen, David W., Stucker, Brent. (2010)).

The SLM requires a set of steps to produce the desired parts (Gunasekaran et al. (2020)). The beginning is to convert the 3D CAD model into cross-section layers and save it in a suitable file format. Then, the file is loaded to the machine using specific software. Before starting the printing process, a set of parameters will be selected and configured to ensure building quality. The selection of the parameters will be discussed in the coming section. Then, the powder is deposited in the building area, and a focus laser beam with pre-selected power is used to melt the powder based on the data from the file. After fabricating the first layer, the roller spreads a new layer of powder on the platform. The process is repeated until the final product is completed. Finally, the part can be removed and cleaned manually or with the help of another machine. The remaining or unused powder can be reused after specific preparation.

4.2 Problem formulation

Using the L-PBF process, the part quality depends on the melt pool dimensions and the thermal behaviour during the fabrication. The heat accumulation during the process causes irregularities in melting pool morphology, excessive dilution, thermal distortion, and cracking. Thus, the properties of the produced parts cannot be guaranteed. Therefore, maintaining the melt pool size is essential to ensure quality. In order to achieve that, a fuzzy control system will be designed to regulate the melt pool dimension by manipulating the laser power to reduce the impact of the temperature accumulation during the fabrication.

The controller will be designed based on the knowledge gained from the literature and the process model simulation presented in Wang et al. (2020). Then the controller's performance will be tested on a linearized version of the model and compared with the performance of the PID controller.

4.3 Fuzzy control system design

The basic structure of the fuzzy controller:
A fuzzy logic controller (FLC) is like any other conventional controller. It has inputs from the system and outputs that control the plant. However, the main difference appears in the decision making of the control signal. The control signal is based on human or/and statistical knowledge. Figure (1) presents the basic structure of the FLC. The input could be the system output, states, or error signal. On the other side, the output of the fuzzy system will be the control signal. The fuzzifier block converts the crisp input from the system to fuzzy sets using membership functions. The inference block presents the heart of the fuzzy system, where the predefined set of rules, membership function, and the input sets are used to assign the output sets. Finally, the output sets are converted to crisp values through defuzzification.

Generally, the FLC can be classified into two main classes, non-adaptive and adaptive fuzzy control (J.Ross (2010); Wang (1997)). In the first class, the controller parameters and structure are maintained fixed during the process. The main advantages of such an alternative are the simplicity of configuration and implementation. Nevertheless, it could have limitations with a complex system. Contrariwise, the adaptive fuzzy controller provides better handling for a complex system in the cost of complexity of the control structure. In such a category, the parameters or/and structure can change based on the input and output information. This particular work will focus on the primary non-adaptive fuzzy controller.

Fuzzy logic control design:
In order to enhance the product quality produced by the SLM process, most of the research efforts emphasise controlling the geometry or temperature of the melt pool during fabrication. Thus a closed-loop control system is required. Figure(2) illustrates the basic schematic diagram of the closed-loop system of the SLM process. The desired

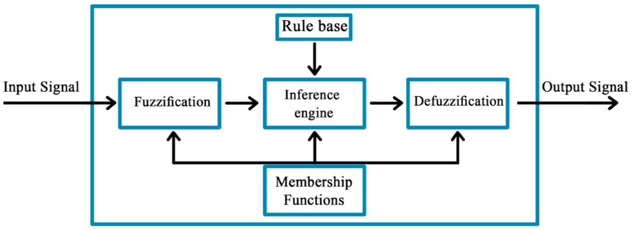

Fig. 1. The fabrication procedure using the SLM process

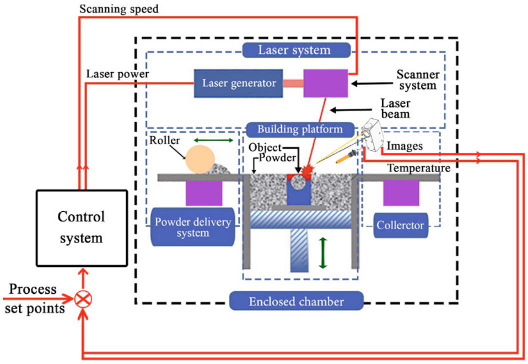

Fig. 2. The basic schematic diagram of the closed-loop system of the SLM process

output could be either melt-pool geometry or temperature, where the control variable is the laser scanning speed or power. This work investigates the control of the melt-pool area by varying the laser power. The inputs to the FLC are selected to be the error signal and the rate of change of the error. The input signals are divided into five linguistic levels: high negative (HN), negative (N), zero (Z), positive (P), and high positive (HP), where the controller output "the laser power" is split into five levels: very negative (VN), negative (N), zero (Z), positive (P), and very positive(VP). The input and output signals' membership functions are selected to be gaussian functions and illustrated in figure(3). Tables (1) and (2) summarise the range of the signals and the fuzzy rules used in the simulation. It is worth mentioning that the selection of the linguistic variables, membership functions and fuzzy rules is a research area that requires more investigation, which will be a part of future work.

Table 1. The range of the input and output signal, that's used in designing the FLC

Variable name	Range
Error (m)	$(-10 \text{ to } 10)\text{x}10^{-9}$
Change of error (m)	$(-3 \text{ to } 3)\text{x}10^{-6}$
Laser power (W)	0-500

Table 2. Fuzzy rules

Variable		Change in error				
		HP	P	Z	N	HN
Error	HP	VP	VP	VP	VP	VP
	P	VP	P	P	P	VP
	Z	VP	Z	Z	Z	VN
	N	VN	N	N	N	VN
	HN	VN	VN	VN	VN	VN

4.4 Simulation and Analysis

The designed FLC in the previous section was simulated and compared with the PID controller. The PID controller parameters were selected using the auto-tune toolbox in MatLab using the same assumptions and model information used to design the FLC. The reference value was selected to be $11\text{x}10^{-9}\ mm^2$. This value represents the steady-state value of the melt-pool cross-sectional area, which is computed using the model presented in Wang et al. (2020). Both controllers' performance was evaluated in responding to a step-change and disturbance rejection. The disturbance rejection is selected to mimic the worst case of heat accumulation during the process. The simulation results are presented in figure (4). Generally using a closed-loop controller improved the system response, thus enhancing the building quality. Comparing the system performance using the PID controller and the fuzzy logic controller, the following points can be noted:

- The PID controller suffered from overshoot and undershoot at the beginning of the simulation and when the disturbance signal was introduced. Reflecting this into reality, a geometrical error and defects will be presented, and it will be obvious in the edges of the printed item. On the other hand, the FLC showed significant effectiveness in achieving the desired geometry and reducing the effect of the heat accumulation to a negligible level.
- The system with FLC was two times faster than the system with the PID controller. Such a result is expected due to the way of defining the two controller structure. Practically, having a fast control system has a significant impact on capturing the dynamics of the process and responding to perturbations in a sufficient time.
- The PID controller produced a zero steady-state error, whereas the FLC records an error around 1 % of the desired value.

Table (3) summarises the system's key performance indices using both controllers.

5. DISCUSSION AND FUTURE OPPORTUNITIES

Many research questions can be raised based on the presented literature and the case study. These questions present future research opportunities, which can be listed as follows

- What will be the controller's performance with the nonlinear model? In the presented case study, the controller was simulated based on a linearized model of the SLM process. However, the real system, as mentioned before, is highly nonlinear. The questions

Table 3. Key performance indices of the system using both controllers

	Controller type	
Performance index	PID	Fuzzy
Overshoot	9%	0%
Settling time	0.003	0.0055
Error	0	1%
Disturbance rejection	Caused an overshoot	Barely affected the system

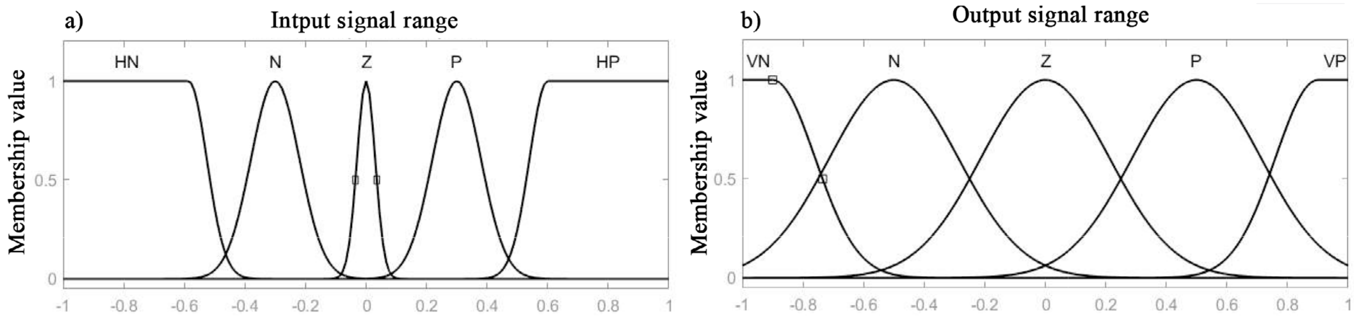

Fig. 3. Input membership function (a) nad Output membership function (b)

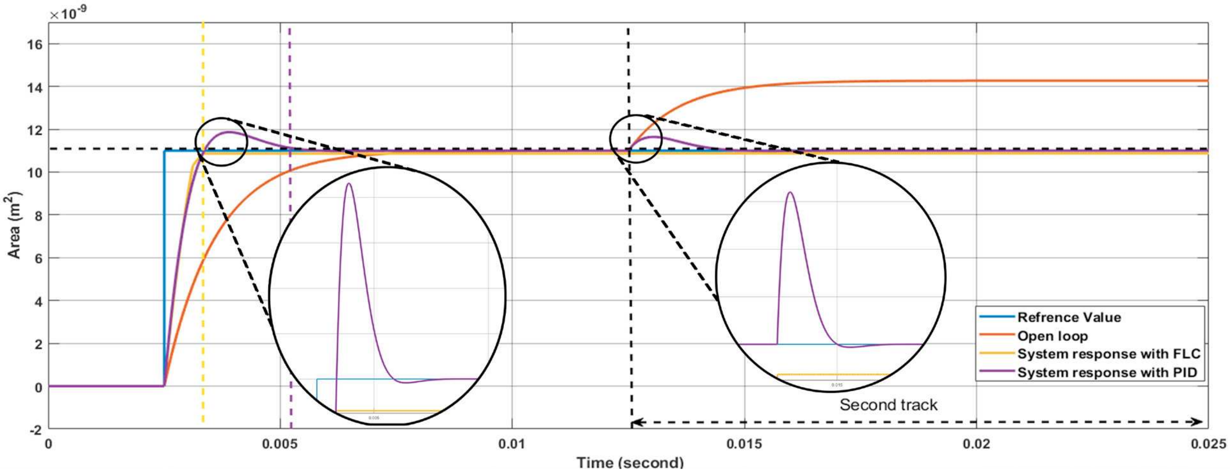

Fig. 4. System response under different conditions: open-loop, using FLC, and using a PID controller.

here are: to what extent can the fuzzy controller cope with the system's nonlinearity? Will the basic fuzzy inference system perform well, or there will be a need to use a more complex fuzzy structure?

- What will be the cost of guaranteeing stability, optimality, and robustness? The presented simulation of the fuzzy controller was achieved after trial and error tuning. However, although it gives good results, it misses considering the issues and the analysis of stability, optimality, and robustness. As mentioned in Al-Saadi et al. (2021), these issues were not investigated even for the classical controllers.
- What will be the advantages and the limitations of the Adaptive Fuzzy controller? In section 4, the adaptive fuzzy controller is mentioned as another class of FLC. Such a type could be a powerful tool when the system is extended to MIMO level or when the controller is required to modify the process parameters in and between the layers. On the other hand, it could affect the performance of the system response.
- How effective will the fuzzy controller be in practice? Although the theoretical investigations showed a promising result, there could be practical limitations. Based on the existing literature, the feedback signal is a noisy signal with a delay because of sensory issues. Thus it is crucial to investigate the performance of the FLC under these conditions and analyze the limitations in a practical implementation.

The above questions require more investigation and analysis and present future research opportunities.

6. CONCLUSION

This research work was aimed to highlight the use of fuzzy logic theory in the field of metallic additive manufacturing. In addition to the literature, a case study of designing a fuzzy controller for a selective laser melting process was presented. The investigation illustrates the effectiveness of such a control algorithm. The conducted literature review and the simulation of the case study showed promising results for the use of FLC and emphasised its capability of improving the performance of metallic additive manufacturing. However, more investigation and analysis are required to determine the applicability of the controller as well as some applications on real hardware.

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