

DEVELOPMENT OF A CLOSED-LOOP CONTROL SYSTEM FOR LASER-DIRECTED ENERGY DEPOSITION (L-DED) OF STELLITE ALLOY

M.Tech. Thesis

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INDIAN INSTITUTE OF TECHNOLOGY INDORE**

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DEVELOPMENT OF A CLOSED-LOOP CONTROL SYSTEM FOR LASER-DIRECTED ENERGY DEPOSITION (L-DED) OF STELLITE ALLOY

A THESIS

*Submitted in partial fulfillment of the
requirements for the award of the degree*

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled “**DEVELOPMENT OF A CLOSED-LOOP CONTROL SYSTEM FOR LASER-DIRECTED ENERGY DEPOSITION (L-DED) OF STELLITE ALLOY**” in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY in Applied Optics and Laser Technology** and submitted in the **DEPARTMENT OF ASTRONOMY, ASTROPHYSICS AND SPACE ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from **July 2024 to May 2026** under the supervision of **Dr. Eswara Prasad Korimilli**, Associate Professor, Department of Metallurgical Engineering and Materials Science, IIT Indore; **Shri. Govind Kumar Mishra**, Scientific Officer/G, Raja Ramanna Centre for Advanced Technology, Indore; and **Dr. C. P. Paul**, Head, Additive Manufacturing & Advanced Manufacturing Section, Raja Ramanna Centre for Advanced Technology, Indore. The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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DEDICATION

*Dedicated to the memory of
my beloved grandfather
Shri. Ram Prakash Sharma
whose blessings remain with me
always*

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and production workflows ensured that the work remained anchored in real engineering reality.

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Any errors or omissions that remain are entirely my own.

Rakshit Sharma
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ABSTRACT

Laser-Directed Energy Deposition (L-DED) of superalloys like Stellite-21 is widely used in aerospace, defence and energy industries for precision repair, cladding, and restoration of high-value components. Stellite-21, a cobalt-chromium-molybdenum alloy, offers excellent high-temperature wear resistance and chemical stability, making it ideal for turbine blade repair and engine component refurbishment. However, achieving consistent geometric accuracy, dimensional stability and defect free deposition remains a fundamental challenge. The principal causes are highly nonlinear thermal effects, standoff-drift, laser-material interaction & dynamic melt pool emissivity.

This thesis presents the design, development and experimental validation of a **real time, three pillar closed loop control system** for L-DED of Stellite-21 deployed on the TVASHTR five axis L-DED facility at the RRCAT, Indore. The work is organized around three interlinked control axes that together govern bead geometry and deposition: (i) closed loop **laser power control** by coaxial near infrared pyrometry feeding a feedforward plus proportional integral (FF + PI) controller (ii) closed loop **scan speed override** of a Mitsubishi M80V CNC kernel governed by a custom 13 rung PLC “gatekeeper” block providing watchdog, slew-rate, and hard clamp safety and (iii) **powder feed rate control and monitoring** of two Toshiba VFD driven feeders through analog command and FM terminal frequency feedback monitoring system. The investigation begins with a **randomized complete block 3³ full factorial design of experiments** (27 runs, blocked on powder feed rate) that systematically maps the effect of laser power (600-2000 W), scan speed (300-1200 mm/min) and powder feed rate (8-22 g/min) on bead width and bead height of Stellite-21 deposits on SS316L substrate. ANOVA reveals that bead width is dominated by laser power ($F = 387.3$, $p < 0.001$) while bead height is dominated by scan speed ($F = 715.9$, $p < 0.001$) with a strongly significant scan speed $\times$ feed rate interaction ($F = 36.5$, $p < 0.001$). The resulting full

quadratic regression models achieve $R^2 = 0.9962$ (height) and $R^2 = 0.9945$ (width). The control system was implemented as an integrated Qt 6 / C++ master application (designates as *M_CS_APP_MK8*) evolved across several versions (MK1V2 through MK1V6) with progressive safety, sensing and algorithmic refinements. Sensor reliability was secured by a 400 °C self healing spike rejection and a runtime tunable exponential moving average (EMA) filter ($\alpha = 0.30$, $\tau \approx 0.47$ s). The PI controller incorporates anti windup based on output saturation detection, a deadband integral interaction and a per cycle slew rate limiter (20 W/cycle) that respects the laser's 200 W minimum stable power floor. Across nineteen tracked test deposition runs, the control system demonstrated zero false fault terminations and reproducible thermal regulation. The best characterization result (Test 12, Phase 2 at setpoint = 1270 °C) achieved a mean control error of +0.35 °C with 75.9 % of all Phase-2 closed-loop samples within ± 25 °C of setpoint; over the steady-state last 30 sec window (151 samples) the mean error was +4.86 °C and 94.0% of samples were within ± 25 °C of setpoint, satisfying PS-1 with 4 percentage points of margin.

During the powder deposition test campaign (Test14-Test 19, setpoint = 1350 °C, base power = 650 W), the integral term acted as a **real time observer of standoff drift**, correctly compensating up to +45.7 W of feedforward error before integral saturation.

The thesis closes by identifying the principal limitations exposed by Phase 1: most importantly the use of a single-colour pyrometer at 1.0 μm which is spectrally too close to the 1070 nm IPG laser to fully reject backscatter and which suffers from emissivity induced problems and presents a quantitative roadmap for a Phase 2 / Phase 3 deployment incorporating a two-colour ratio pyrometer, inline load cell powder mass flow measurement, scanner based Z compensation and a sensor fusion machine learning backend. The work delivers a working, instrumented, three pillar L-DED control system, an empirically calibrated process map for Stellite-21 deposition and a documented engineering roadmap for the next phases of research at RRCAT.

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NOMENCLATURE

Symbol	Description	Units
P	Laser power	W
v	Linear scan (traverse) speed	mm/min
F	Powder mass flow (feed) rate	g/min
E	Linear energy density (P / v)	J/mm
E_v	Volumetric energy density ($P / (v \cdot d \cdot t)$)	J/mm ³
H	Bead (track) height	mm
W	Bead (track) width	mm
d	Hatch spacing	mm
t	Layer thickness	mm
T	Object (melt-pool) temperature	°C
T_{sp}	Setpoint melt-pool temperature	°C
$e(t)$	Instantaneous control error ($T_{sp} - T$)	°C
$u(t)$	Manipulated variable (commanded laser power)	W
P_{base}	Feedforward base laser power	W
P_{min}, P_{max}	Lower and upper laser-power saturation limits	W
k_p	Proportional gain (1 / ratio)	W/°C
k_i	Integral gain	W/(°C·s)
$I(t)$	Integral term contribution to commanded power	W
I_{cap}	Anti-windup integral saturation limit	W
α	EMA smoothing factor ($0 < \alpha \leq 1$)	—
τ	EMA effective time constant	s
ε	Surface emissivity (Stefan–Boltzmann / Wien)	—
λ	Optical wavelength	nm or μm
w_0	Beam waist radius at laser focus	mm
z_R	Rayleigh range	mm
Δz	Defocus distance (standoff offset)	mm
M^2	Beam-quality factor	—
BPP	Beam parameter product ($M^2 \cdot \lambda / \pi$)	mm·mrad
c_2	Second radiation constant ($\approx 14\,388$)	$\mu\text{m} \cdot \text{K}$
Λ	Effective wavelength (ratio pyrometry)	μm

ACRONYMS

Acronym	Expansion
AM	Additive Manufacturing
L-DED	Laser-Directed Energy Deposition
DED	Directed Energy Deposition
LMD	Laser Metal Deposition (synonym of L-DED used in literature)
LENS	Laser-Engineered Net Shaping (Sandia / Optomec trademark for L-DED)
PBF	Powder Bed Fusion
SLM	Selective Laser Melting
EBM	Electron-Beam Melting
MEX	Material Extrusion (e.g. FDM)
VPP	Vat Photopolymerisation
MJT	Material Jetting
BJT	Binder Jetting
SHL	Sheet Lamination
MRO	Maintenance, Repair, and Overhaul
DOE	Design of Experiments
RCBD	Randomised Complete Block Design
ANOVA	Analysis of Variance
RSM	Response Surface Methodology
L27	27-run full-factorial design (3^3)
PID / PI	Proportional-Integral-Derivative / Proportional-Integral controller
FF	Feedforward
EMA	Exponential Moving Average filter
SP / SV	Setpoint / Setpoint value
PV	Process variable
MV	Manipulated variable
FOV	Field of View
D:S	Distance-to-Spot ratio (pyrometer)
NIR	Near-Infrared
BDS	Beam-Delivery System

Acronym	Expansion
BPP	Beam Parameter Product
FWHM	Full Width at Half Maximum
PLC	Programmable Logic Controller
CNC	Computer Numerical Control
VFD	Variable-Frequency Drive
HMI	Human-Machine Interface
SCADA	Supervisory Control and Data Acquisition
DCS	Distributed Control System
IEC	International Electrotechnical Commission
ISO	International Organisation for Standardisation
ASTM	American Society for Testing and Materials
TCP	Transmission Control Protocol
IP	Internet Protocol
GVCPC	GigE Vision Control Protocol
RTU	Remote Terminal Unit (Modbus)
RS-422 / RS-485	Recommended Standard 422 / 485 (serial bus standards)
COM	Component Object Model (Windows)
DLL	Dynamic Link Library
API	Application Programming Interface
SDK	Software Development Kit
GUI	Graphical User Interface
CSV	Comma-Separated Values (file)
RRCAT	Raja Ramanna Centre for Advanced Technology, Indore
IIT	Indian Institute of Technology
MEMS (dept.)	Department of Metallurgical Engineering and Materials Science
AOLT	Applied Optics and Laser Technology (M.Tech. specialization in IIT Indore)
OIML	International Organisation of Legal Metrology

Chapter 1

Introduction

1.1 Additive Manufacturing: Context and Classification

Additive Manufacturing (AM) refers to the family of manufacturing processes in which a three dimensional object is fabricated by the successive addition of material, layer by layer, from a digital model. ISO/ASTM 52900:2021 [1] formally defines AM as a “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.” In the same standard, AM is partitioned into seven principal process categories on the basis of physical mechanism and feedstock state: material extrusion (MEX), vat photopolymerisation (VPP), powder bed fusion (PBF), directed energy deposition (DED), material jetting (MJT), binder jetting (BJT), and sheet lamination (SHL). The classification with representative implementations of each, is illustrated in Fig. 1.1.

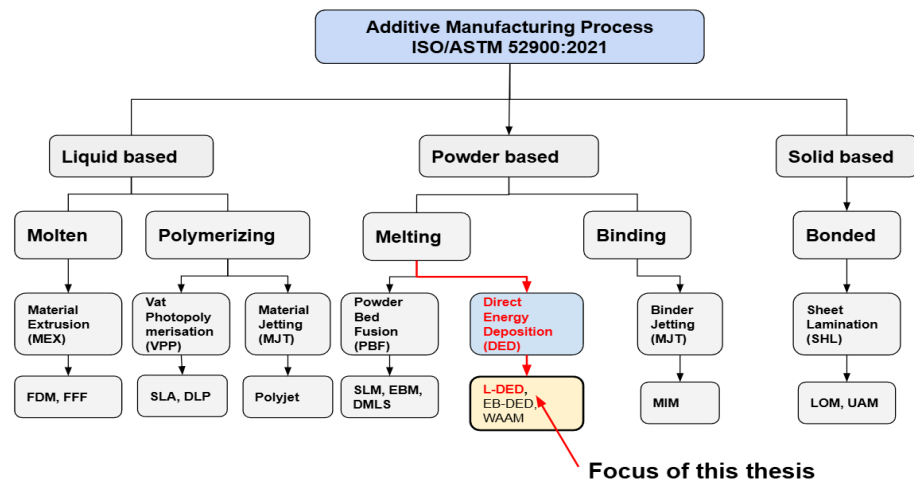


Figure 1.1 : Classification of Additive Manufacturing Technologies...

A condensed comparison of the principal AM categories, focused on metal capable processes, is presented in Table 1.1. The comparison demonstrates why DED and its laser based realization in particular is uniquely positioned to address the maintenance, repair, and overhaul (MRO) economy of high value metallic components, a sector

in which the part level cost of replacement frequently exceeds the cost of additive restoration by an order of magnitude or more.

Category	Mechanism	Typical resolution	Distinctive capability
MEX (FDM/FFF)	Thermoplastic filament extrusion	100-300 μm	Low cost, large polymer parts
VPP (SLA/DLP)	UV cured photopolymer	25-100 μm	Highest dimensional accuracy in plastics
PBF (SLM/DMLS)	Laser melting of pre-spread powder bed	30-60 μm	Finest metal AM resolution, sealed atmosphere
PBF (EBM)	Electron-beam melting in vacuum	70-100 μm	Reactive Ti / Ni superalloys, hot powder bed
DED (L-DED)	Laser melted coaxial powder injection	300-800 μm	Repair, large parts, multi material, high throughput
DED (WAAM)	Wire arc deposition	1-3 mm	Highest mass rate, structural scale parts
MJT	Photopolymer / wax droplet jetting	16-40 μm	Multi-material, photorealistic colour
BJT	Liquid binder onto powder bed (post-sintered)	50-100 μm	Sand cores, bound metal, large green parts
SHL (UAM/LOM)	Ultrasonic / adhesive sheet bonding	100-250 μm	Embedded electronics, dissimilar metals

Table 1.1. Comparison of additive manufacturing categories under ISO/ASTM 52900, focused on the capabilities most relevant to metal component manufacturing and repair.

1.1.1 Laser-Directed Energy Deposition (L-DED)

Laser-Directed Energy Deposition, also referred to in the literature as Laser Metal Deposition (LMD) and in early Sandia and Optomec implementations, as Laser-Engineered Net Shaping (LENSTM) is the laser based subset of the DED family. In its canonical coaxial nozzle configuration, a high-power laser beam (most commonly a near infrared continuous wave fiber laser at 1 μm wavelength) is focused onto a substrate to create a localized molten pool. Metallic powder, conveyed by an inert carrier gas is delivered through a coaxial nozzle so

that the powder stream converges with the laser focal axis at the surface of the melt pool. The molten powder fuses into the preexisting melt pool and resolidifies as the laser mounted on a multi axis CNC system which traverses the substrate building up a single track. Successive tracks placed side by side (governed by the hatch spacing) form a layer; successive layers stacked vertically (governed by the layer thickness) form the three dimensional part. A schematic of the process geometry, including the powder convergence point, the melt-pool envelope, the coaxial pyrometer field of view, and the inert gas shielding, is shown in Fig. 1.2.

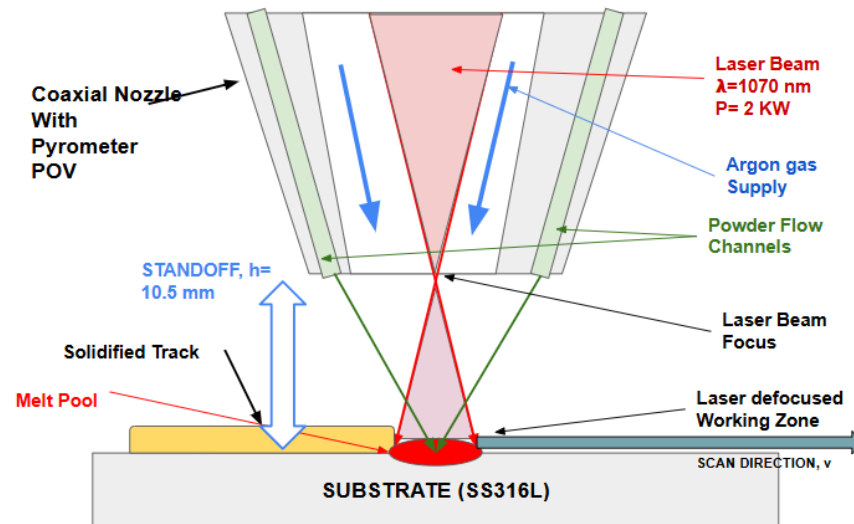


Figure 1.2: Schematic of the coaxial Laser-Directed Energy Deposition (L-DED) process showing simultaneous laser, powder and shielding gas delivery converging at the meltpool. Standoff, h denotes the distance from the nozzle tip to the work surface.

L-DED is governed by a tightly coupled set of physical phenomena that together determine the bead geometry and the metallurgy of the deposited material: the absorption of laser radiation by the substrate and by the in flight powder particles, convective and radiative heat transfer within and around the melt pool, gravity and Marangoni driven fluid flow inside the molten region, powder particle melt pool momentum transfer and the cooling, solidification, and post solidification thermal cycling experienced by each layer as subsequent layers are deposited above it [4]. The dominant single track process

inputs are conventionally taken to be the laser power P (W), the linear scan speed v (mm/min), and the powder mass flow rate F (g/min). Two derived quantities the linear energy density E (J/mm) given by

$$E = \frac{P}{v} \quad (1.1)$$

and the volumetric energy density E_v (J/mm³) are commonly used as compact descriptors that combine the energy and material input dimensions and that correlate well with bead width, height, and dilution within a fixed nozzle geometry [5].

The defining advantages of L-DED relative to PBF, summarized in Table 1.2, are precisely the capabilities that motivate the present thesis: the freedom to deposit on any pre existing substrate (including used and worn turbine blades), the freedom to vary feedstock chemistry within a single build (functionally graded structures), and the freedom to operate at scales of meters rather than centimeters. These advantages, however, come at a corresponding cost in process control: the L-DED melt pool is open to the atmosphere (under inert shielding), is in direct mechanical contact with the powder stream, and is geometrically convolved with the substrate's evolving thermal state.

As a result, the operating window of L-DED is narrower and more sensitive to transient process disturbances than that of PBF, and the case for active in process control is correspondingly stronger.

Attribute	L-DED	PBF (SLM)
Layer thickness	0.3-1.0 mm	30-60 μ m
Build rate (cm ³ /h)	20-300	5-40
Build envelope	Up to several meters	Typ. 250-500 mm cube
Multi-material in one build	Yes (twin/three feeders)	Difficult
Repair / clad on existing parts	Yes (defining capability)	No
Surface finish (as built)	$R_a \approx 8-20 \mu$ m	$R_a \approx 5-10 \mu$ m

Attribute	L-DED	PBF (SLM)
Process atmosphere	Local Ar shield (open)	Sealed inert chamber
Sensitivity to thermal accumulation	High	Moderate
Indication for closed-loop control	Strong (this thesis)	Strong

Table 1.2. Distinguishing characteristics of L-DED versus laser based powder bed fusion (SLM). The set of attributes for which L-DED is uniquely suited: repair, multi material deposition, and large envelope builds, forms the industrial motivation for the present work.

1.2 Material System: Stellite Alloys and Stellite-21

Stellite is the trademarked family designation for a class of cobalt-chromium-tungsten / molybdenum superalloys originally developed by Elwood Haynes in the early twentieth century and presently held by Kennametal Inc. Its members share three characteristics that have made the family a workhorse of industrial wear resistant hard facing for over a century: (i) a face centered cubic cobalt matrix that work hardens substantially under sliding contact, (ii) a dispersion of complex chromium rich (M_7C_3 / M_6C / $M_{23}C_6$ type) and tungsten or molybdenum rich (MC type) carbides that provide the abrasive wear barriers (iii) the formation of a chromium oxide passivation layer at elevated temperature that confers good corrosion and oxidation resistance up to ~ 800 °C [6].

1.2.1 Composition, microstructure and Stellite-21 properties

Stellite-21 (UNS R30021) is a low carbon, molybdenum bearing variant of the Stellite family in which tungsten is wholly replaced by molybdenum. The reduced carbon content (typically below 0.35 mass %) yields a softer matrix dominated by dispersed M_6C and M_7C_3 carbides rather than the brittle M_7C_3 / $M_{23}C_6$ of higher carbon Stellites such as Stellite 6 or Stellite 12. The result is an alloy that while less abrasion resistant than its higher carbon siblings exhibits markedly superior thermal shock and impact resistance with documented service in cavitation, galling and metal to metal sliding wear environments [7]. The nominal composition adopted in the present thesis (gas atomized

powder, in the RRCAT facility) is given in Table 1.3, and the principal physical and mechanical properties are summarized in Table 1.4.

Element	Cr	Mo	C	Ni	Si	Mn	Fe	Co
Mass %	26.0-29.0	4.5-6.0	≤0.35	≤3.0	≤1.5	≤1.0	≤3.0	Bal.

Table 1.3. Nominal chemical composition of Stellite-21 powder feedstock (mass %), per AMS 5788 / ASTM F75 reference ranges.

Property	Symbol	Typical value	Units
Density (cast/wrought)	ρ	8.34	g/cm ³
Liquidus temperature	T_l	≈ 1435	°C
Solidus temperature	T_s	≈ 1295	°C
Coefficient of thermal expansion (20-500 °C)	α_t	14.8-15.5	× 10 ⁻⁶ K ⁻¹
Hardness (as cast)	HRC	27-40 (work-hardens up to 48)	
Tensile strength (as cast)	σ_u	720-900	MPa
Yield strength (0.2 % offset)	σ_y	490-580	MPa
Elongation (cast)	A	8-16	%
Service temperature (continuous, oxidising)	T_{max}	≈ 800	°C

Table 1.4. Representative physical and mechanical properties of Stellite-21 (as cast and HIP densified), compiled from open literature property datasheets (Kennametal, Deloro Stellite, ASM Handbook Vol. 2).

From a process control standpoint, two thermal data points in Table 1.4 are particularly important. The **liquidus temperature of ≈ 1435 °C** and the **solidus of ≈ 1295 °C** together define an **≈140 °C** wide solidification range (Kennametal Stellite-21 AM datasheet [7]). Closed loop control of the melt pool must hold the surface temperature comfortably within this regime while avoiding excessive superheat that promotes vapor plume instability, spatter, and excessive bulk substrate heating.

1.2.2 Industrial applications

The principal application sectors for Stellite-21 and by extension for closed-loop L-DED of Stellite-21 are surveyed in Fig. 1.3. The combination of high-temperature wear resistance, good thermal shock

tolerance and biocompatibility (Stellite-21 is the basis of the ASTM F75 cast cobalt-chromium-molybdenum surgical implant alloy) places the material at the intersection of three high value industrial markets: aerospace MRO, defense and energy infrastructure and biomedical implants.

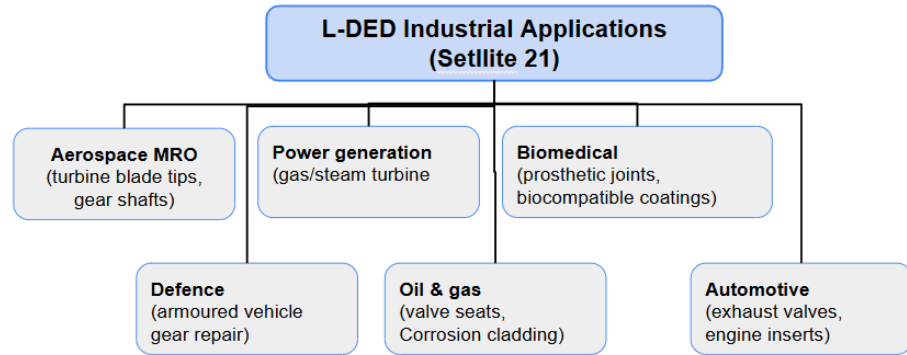


Figure 1.3: Industrial application landscape for closed loop L-DED of Stellite-21, drawn from RRCAT industry collaborations.

Aerospace MRO. The single largest near term commercial driver for L-DED of Stellite-21 is the restoration of high value rotating components in gas turbine engines and ground based turbomachinery. A worn turbine blade tip can be restored to its original net shape by the layered deposition of compatible cobalt base alloy, returning the part to service at a fraction of the cost (and with a fraction of the lead time) of a forged replacement. Independent industry assessments have reported that L-DED restored blades can meet or exceed the wear and oxidation performance of new-build parts at a fraction of the lead time and cost.

Defence and heavy machinery. Stellite-21 hard facing of armoured vehicles, drive train components, gearbox shafts and naval pump impellers extends service intervals from months to years and is an established part of the Indian Army's and Indian Navy's overhaul protocols. Recently, RRCAT industry partners (V-Fuse metal 4 Manufacturing Pvt. Ltd) successfully demonstrated successful restoration of tank gear shaft and Bofors artillery chamber using L-DED Process.

Power generation and oil & gas. Hard faced valve seats, choke valve internals and corrosion resistant cladding on carbon steel pressure vessels are routinely produced by L-DED of Stellite class alloys. Closed loop process control is a precondition for qualifying these components under ASME B31.3 and similar codes where the deposit's chemistry, dilution from the substrate and porosity must all be statistically controlled run to run.

Biomedical. The cast Co-Cr-Mo alloy ASTM F75 (compositionally identical to Stellite-21) is the long standing gold standard for hip and knee replacement femoral components. Patient specific prosthetic geometries fabricated by L-DED of F75 are the subject of active regulatory and clinical development; closed loop melt pool control is again a precondition for the metallurgical reproducibility required for medical device qualification.

1.3 The Process Control Problem in Multi Layer L-DED

Notwithstanding the maturity of L-DED as an industrial process, **multi layer builds of Stellite alloys remain difficult to produce reproducibly without active in process control.** The root cause is the Multiphysics coupling that connects every parameter of the L-DED process to every other through the dynamics of the melt pool. As a build progresses, layer by layer thermal accumulation in the substrate raises the bulk temperature. For a fixed laser power and scan speed the same energy input therefore yields a progressively hotter, larger and more dilute melt pool and a progressively taller deposited layer [4]. If left uncorrected this drift causes three failure modes in turn:

- **Standoff drift:** layers grow taller than the programmed Z-increment, the laser de-focuses further into the defocus zone and the energy at the work plane drops. The controller must then add power to compensate. In the present TVASHTR optical configuration (Rayleigh range $z_r \approx 2.998$ mm) every additional

millimeter of standoff requires about 19 % more laser power for Nozzle A and about 9% for Nozzle B, which is the dominant disturbance observed in the test campaign reported in Chapter 5.

- **Geometric runaway:** once the melt pool widens beyond the planned hatch spacing, neighbouring tracks fuse, the local energy density doubles, and the build collapses into a puddle; equivalently a melt pool that grows beyond the pyrometer's coaxial field of view leaves the controller blind to its own primary process variable.
- **Microstructural drift:** the cooling rate, governing dendrite-arm spacing, carbide morphology and as deposited hardness, is affected by the bulk substrate temperature and the layer cooling time. Without thermal control, hardness can vary by 5-10 HRC across a single 20 layer build which is unacceptable for Military grade industrial applications.

The classical engineering response to a process whose dominant variable drifts on the timescale of the build while the part is itself the cause of the drift, is **closed loop feedback control**. Fig. 1.4 presents the block diagram of a generic closed loop architecture instantiated here for melt pool temperature regulation. The reference signal $T_{sp}(t)$ is the desired melt pool temperature. The process variable $T(t)$ is sensed by an in-situ pyrometer; the difference forms the error signal

$$e(t) = T_{sp}(t) - T(t) \quad (1.3)$$

The controller maps this error into a manipulated variable $u(t) = P_{laser}(t)$; the manipulated variable acts on the L-DED process (the “plant”) and the resulting plant output is fed back to close the loop. Disturbances acting on the plant: standoff drift, oxidation of the substrate, transient changes in powder feed rate, ambient temperature variation etc. are precisely what the loop is designed to reject.

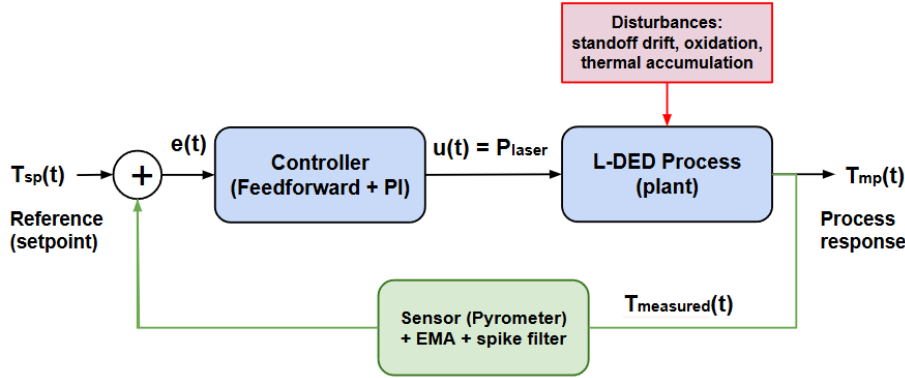


Figure 1.4: Block diagram of a generic closed loop process control architecture, instantiated for melt pool temperature regulation in L-DED. The disturbance set acting on the plant (red) includes the dominant standoff drift, oxidation, and thermal accumulation phenomena that are central to the multilayered L-DED control problem.

In practice, the design of a closed loop L-DED controller requires three distinct engineering activities to be undertaken jointly: (i) a **sensor subsystem** that measures the melt pool state at a sample rate fast enough relative to the dominant process time constant (typically 100 ms-1 s) (ii) a **control algorithm** that converts measurement into actuation in a way that is stable in the presence of sensor noise, output saturation and the strongly non-linear plant dynamics (iii) a **hardware in the loop deployment platform** that interfaces the controller to the laser source, the CNC kinematic system and the powder delivery sub system in real time while simultaneously providing safety interlocks at the firmware and PLC level. Each of these activities is a research problem in its own right and each is addressed in the present thesis.

1.4 Motivation for the Present Work

The motivation for this thesis arises from a specific industrial reality at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. The presence of a fully instrumented five-axis L-DED facility (the TVASHTR machine, manufactured in collaboration with VFuse Metal 4 manufacturing Pvt. Ltd.) that has been used for several years for open loop research on Stellite, Inconel, and SS316L deposition but which had no integrated, software level closed loop process control system as of the start of this M.Tech. program. The

machine's constituent sub systems: a 2 kW IPG fibre laser, a Mitsubishi M80V CNC, a Mitsubishi FX5U PLC with FX5-4DA-ADP and FX5-8AD analog I/O, a Toshiba VFD driven twin powder feeder, an Optris coaxial pyrometer and a Micro-Epsilon laser line scanner each provide their own programmable interface but none of these interfaces had been wired together into a single deterministic real time control loop.

The strategic question that motivates the present thesis is therefore the following: **What does it take to convert a research grade open loop L-DED facility into a research grade closed loop facility, instrumented at every primary process variable, deployed in production and validated against deposited Stellite-21 builds?** The answer; as the chapters of this thesis demonstrate; is not a single algorithm or a single hardware addition. It is the construction of an interlocking three pillar control architecture (Fig. 1.5) in which each pillar regulates one of the three primary process variables identified in Section 1.1.1 in which the three pillars are coordinated by an integrated master control software application and in which every layer of the stack: ladder-logic, PLC firmware, PC-side C++ code and operator facing UI is specifically engineered for the latency, safety and reproducibility demands of an industrial L-DED process.

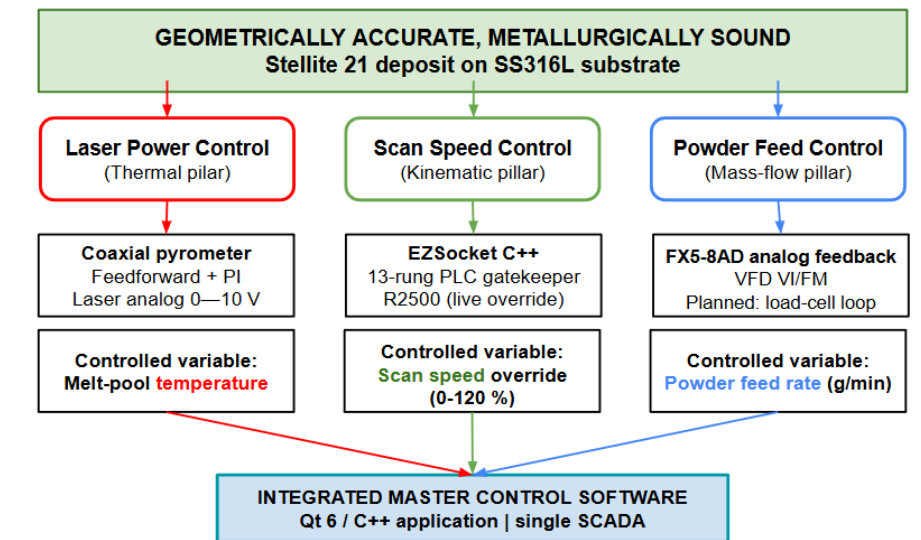


Figure 1.5 : Three pillar closed loop control architecture proposed and developed in this thesis. The thermal pillar regulates melt pool temperature via laser power; the

kinematic pillar regulates feed rate via scan speed override of the CNC; the mass flow pillar regulates powder feed rate via VFD frequency. The three pillars are coordinated by an integrated Qt 6/C++ master application providing a single SCADA.

Within this architecture, the thermal pillar is the most metallurgically consequential because the melt pool temperature determines both the bead geometry (via the temperature dependence of viscosity and surface tension) and the as deposited microstructure (via the cooling rate dependence of carbide morphology and grain size). The thermal pillar is therefore the one that receives the deepest experimental treatment in this thesis and the test campaign of Chapter 5 is centered on its validation. The kinematic and mass flow pillars are, however, no less important: a well-tuned thermal loop on top of a drifting scan speed or a fluctuating powder feed rate cannot, in principle, deliver geometrically accurate parts. All three pillars must work simultaneously and an attempt has been made in this project for this integrated design and validation of all three on a single facility.

1.5 Aim and Specific Objectives

Aim. The overarching aim of this thesis is to design, implement, and experimentally validate an integrated, real-time, three pillar closed-loop control system for Laser-Directed Energy Deposition of Stellite-21 powder on stainless steel substrates deployed on the TVASHTR five axis L-DED facility at RRCAT, Indore.

Specific objectives. In service of this aim, the thesis pursues the following six specific objectives:

- **Objective 1 (Static process map):** To characterize, by a randomized complete block 3^3 full factorial design of experiments (27 runs blocked on powder feed rate), the dependence of bead width and bead height on laser power, scan speed and powder feed rate and to fit predictive regression models with quantified statistical significance.
- **Objective 2 (Profilometric metrology):** To validate the use of a 658 nm laser line triangulation scanner (Micro Epsilon LLT2510-50) for high resolution geometric measurement of as

deposited beads and to develop a profile stitching workflow that reconstructs full track 3D profiles to within ± 1 % dimensional accuracy

- **Objective 3 (Thermal pillar [laser power]):** To design and deploy a closed loop laser power controller using a coaxial near infrared pyrometer (Optris CTLM-1H1SF300-C3) and a feedforward plus PI control algorithm, including a self-healing spike filter, EMA filter, anti-windup, slew rate limiting and a hardware floor aware power clamp.
- **Objective 4 (Kinematic pillar [scan speed]):** To design and ROM flash a 13 rung PLC “gatekeeper” block on the M80V CNC that allows safe PC side override of the live feedrate execution register R2500 governed by a 1.0 s watchdog, a ± 2 % per scan slew limit and 0-120 % hard clamps; and to implement the corresponding C++ override controller using Mitsubishi’s EZSocket COM API.
- **Objective 5 (Mass-flow pillar [powder feed]):** To deploy in production a closed-loop powder feed controller for both Toshiba VFD driven feeders using analog command (FX5-4DA-ADP) and FM terminal frequency feedback (FX5-8AD) within a 100 ms control cycle.
- **Objective 6 (Integration and validation):** To integrate all three pillars in a Qt 6 / C++ master application providing a single SCADA and to validate the integrated system on Stellite-21 powder deposition runs against quantified thermal regulation.

1.6 Scope and Limitations

The **scope** of this thesis is bounded as follows. The work is restricted to **single substrate material** deposition (SS316L substrates) and to **single feedstock** Stellite-21. Multi-material functionally graded deposition although architecturally enabled by the twin powder feeder controller of Pillar 3 is outside the experimental scope of this thesis. The thermal pillar test campaign reported in Chapter 5 is limited to **single**

walled cylindrical and helical builds of the kind required to expose, observe and quantify the standoff drift phenomenon. These are diagnostically the most informative geometries even though they are not the most industrially representative. All 27 single-track depositions chapter-3 and chapter-4 were performed with nozzle B optical configuration (20.5 mm standoff, nominal spot diameter ~ 1.6 mm). The regression models and process map of section 4.3-4.8 are therefore specific to nozzle B irradiance conditions.

The principal **limitations** acknowledged within the present scope are the following. (i) The melt pool sensor used during the Phase 1 test campaign is a **single-colour pyrometer at $1.0\ \mu\text{m}$** , which is spectrally close to the 1070 nm IPG laser. Although a self-healing spike filter is shown in Chapter 5 to suppress the resulting backscatter contamination, the systematic offset due to the use of a constant emissivity ($\epsilon = 0.95$) is a known unresolved issue and is the principal motivation for the Phase 2 procurement of a two-colour aka ratio pyrometer (Section 6.3 and Appendix A). (ii) Layer height drift between successive runs is, in the present thesis observed and quantified through the integral term of the PI controller but is not yet **actively** closed (a profilometric layer height feedback loop is identified as the principal Phase 2 improvement). (iii) The mechanical property characterization of the deposited Stellite-21 (microstructure, hardness, tensile strength) is a parallel study in the RRCAT Materials Characterization Lab and is reported only in summary form in Chapter 5; it is not the principal contribution of this thesis.

1.7 Organization of the Thesis

The remainder of the thesis is organized into five further chapters and three appendices, structured as follows:

- **Chapter 2:**

Review of Past Work and Problem Formulation: Surveys the published literature on closed loop control in DED focusing on melt pool sensing, control algorithm design and reported sensor

fusion architectures. Identifies the specific gaps that the present thesis addresses and formulates the problem statement in mathematically precise form.

- **Chapter 3:**

Experimental Setup and Methodology: Describes the TVASHTR L-DED machine in detail; laser source, optical chain, beam delivery system (BDS), CNC and PLC controllers, pyrometer, profilometer, powder feeders and substrate fixtures with quantitative optical and electrical specifications drawn from the manufacturer test reports. Defines the design of experiments matrix, the metrology procedures and the data acquisition pipelines.

- **Chapter 4**

Process Characterization: DOE and ANOVA Results: Reports the empirical bead width and bead height measurements from the 27 DOE runs, the ANOVA decomposition of variance, the regression models and the response surface plots. Establishes the static process map.

- **Chapter 5**

Closed Loop Control System: Implementation and Results: Documents the design and implementation of all three pillars: thermal, kinematic and mass flow with control equation derivations, version history of the master control software (MK1V2 through MK1V6), the test campaign results from the dry run characterization tests (Tests 1 to Test 12) and the Stellite deposition tests (Tests 14 upto Test 19).

- **Chapter 6**

Conclusions and Scope for Future Work: Summarizes the principal scientific and engineering contributions, validated performance metrics and presents a quantitatively justified roadmap for the Phase 2 / Phase 3 deployment, including the

procurement of a two-colour pyrometer and the integration of an inline load cell powder feedback loop.

- **Appendix A**

System Bill of Materials: Production Parameters, Campaign Audit and supplementary Data: end of Phase 1 Production; per-test telemetry audit; and raw microhardness data underlying the preliminary traverse of Section 5.8

- **Appendix B**

Source Code Excerpts: Excerpts from the master control software illustrating the most important control loop kernels (spike-filter, EMA, PI control law with anti-windup, slew rate limiter, watchdog).

- **References**

The TVASHTR system itself: hardware integration overview, network topology, and the principal communication channels among the laser, CNC, PLC, and sensors is summarized graphically in Fig. 1.6. Quantitative specifications and detailed protocol-level descriptions of each connection are deferred to Chapter 3.

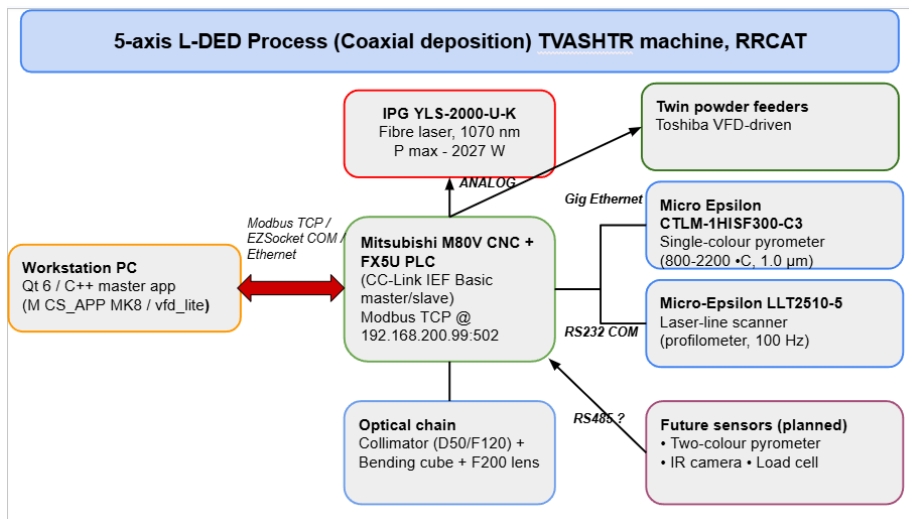


Figure 1.6: Complete system architecture at RRCAT (current stage as well as planned), Indore. Energy and material flow (laser, optical chain, powder feeders → process); sensing flow (process → pyrometer, profilometer); control flow loops back through the workstation PC and the M80V/FX5U control hierarchy.

Chapter 2

Review of Past Work and Problem Formulation

2.1 Introduction

The objective of this chapter is twofold. Firstly, in Sections 2.2-2.6, the chapter critically surveys the published literature on closed loop control of laser based directed energy deposition, organizing the field along three axes: the **sensing modality** used to observe the melt pool, the **control algorithm** used to convert that observation into actuation, and the **controlled variable** (bead geometry, melt pool temperature, microstructure) which the controller targets. The aim is to identify where the present thesis fits within the evolving body of L-DED process control research. What specific gaps remain unaddressed in the literature and whether the physical, the control and the design engineering arguments justify the design choices that the following chapters will implement. Secondly, in Section 2.7, the chapter formalizes the engineering problem in the precise mathematical language of process control so that the experimental work of Chapters 4 and 5 can be evaluated against an explicit & rigorous specification.

The discussion is restricted to the laser based subset of directed energy deposition (L-DED, also referred to as LMD or LENS or LAM-DED), and within that subset is further focused on the metallic, powder blown, multi-axis CNC driven configurations that are representative of the TVASHTR facility introduced in Chapter 1.

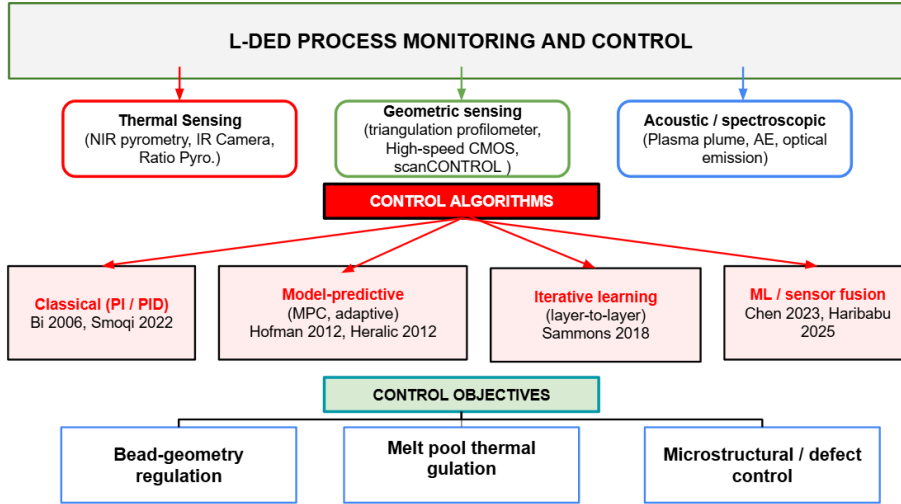


Figure 2.1: Taxonomy of in-situ process monitoring and closed loop control approaches in L-DED. The upper tier lists the principal sensing modalities; the middle tier lists the control-algorithm families; the lower tier lists the principal control objectives based on relevant literature.

2.2 Process Modelling and Open Loop Optimization

The earliest body of L-DED literature, from the late 1990s through approximately 2010 focused almost exclusively on **open loop process optimization**. The empirical mapping of fixed laser power, scan speed and powder feed rate onto bead geometry, dilution and microstructure. Schneider’s Twente dissertation [11] remains the canonical reference for the energy density based scaling of clad geometry in which the linear energy density given by

$$E = \frac{P}{v} \quad (2.1)$$

and the specific powder load given by

$$\frac{F}{v} \quad (2.2)$$

They emerge as the natural reduced parameters that compress the three dimensional process space onto a two dimensional design surface. Vilar’s 2014 review chapter in *Comprehensive Materials Processing* [2] extended this energy density framework to a wide range of substrate feedstock pairs and consolidated the scaling laws that are still routinely cited in the literature today. Lin *et al.* [5] applied the same framework to SS316L L-DED on a commercial powder blown system and confirmed the dominance of energy density while showing that the dependence is

non-linear and that the optimal operating window depends on substrate thermal conductivity.

All of these studies are **static**; they characterize the process at the instant of single track deposition where the substrate is at a known initial temperature, the standoff is at the design value and the laser optics are well aligned. Their predictive value collapses, as Chapter 1 has already noted, in any multi layer build whose dominant time scale is set by thermal accumulation, oxidation and standoff drift [4]. The recognition of this collapse and the engineering response to it, is the main subject of the rest of this chapter.

2.3 In-Situ Sensing Modalities

2.3.1 Single colour pyrometry and its limitations

The earliest, and still the most widely deployed, melt pool temperature sensor in L-DED is the **single-colour near infrared pyrometer**. Bi *et al.* [3] reported in 2006 the first systematic deployment of a single band pyrometer at $\approx 1 \mu\text{m}$. Integrated coaxially through the laser optical chain as the feedback signal to a proportional only laser power controller. Their work demonstrated that a fixed setpoint in pyrometric counts could be tracked across a single layer with adequate steady state accuracy on SS316L. The sensor architecture they introduced: A single coaxial sensor, narrow band pass, filter wheel, single feedback signal to the laser has been replicated with minor variations in most subsequent L-DED control studies up to the present day.

The fundamental physical model that governs all radiative thermometry is **Planck's spectral radiance law**:

$$L_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1} \quad (2.1)$$

where L_λ is the spectral radiance per unit wavelength, h is Planck's constant, c the speed of light in vacuum, λ the wavelength, k_B Boltzmann's constant and T the absolute thermodynamic temperature. For real (non-blackbody) surfaces, the radiance is multiplied by the

spectral emissivity $\varepsilon(\lambda, T)$ which depends on material, oxidation state, surface finish and temperature. A single-colour pyrometer measures the integrated radiance over its band-pass and inverts equation (2.1) under the assumption that ε is **known and constant**. This assumption fails fundamentally for L-DED because the emissivity of the melt pool changes systematically as the surface transitions from solid ($\varepsilon \approx 0.30$ for clean cobalt chromium) through liquid ($\varepsilon \approx 0.40$ - 0.60) to oxidised ($\varepsilon \approx 0.70$ - 0.90) and as the optical path is partially obscured by metal vapor, spatter or window contamination [12].

A second, equally serious limitation specific to single-colour pyrometers operating at $\approx 1 \mu\text{m}$; (aka called “1M-band”) is the spectral overlap with the 1070 nm Ytterbium fibre laser that is the dominant industrial heat source in modern L-DED. Even with attenuating optics in the bending cube, the Theoretical max 10.1 W of back-reflected laser light measured in the TVASHTR optical chain (Section 3.3 of this thesis) is several orders of magnitude larger than the thermal radiance of the melt pool in the same band. Fig. 2.2 shows the Planck radiance curves for L-DED relevant temperatures and overlays the laser line at 1070 nm; the figure makes graphically clear why the 1M band is contaminated by laser backscatter in any coaxial geometry.

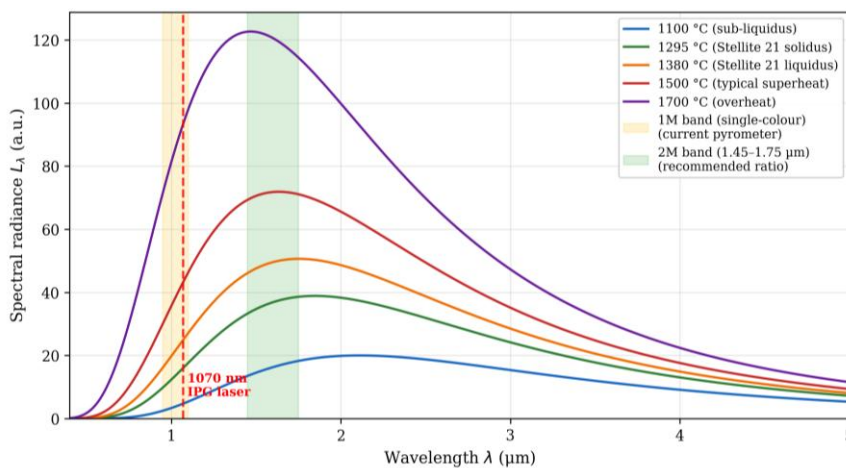


Figure 2.2: Planck blackbody spectral radiance $L_\lambda(\lambda, T)$ at five L-DED relevant temperatures, with the 1070 nm IPG-laser line (red dashed) and the two principal pyrometric bands overlaid. The 1M band (≈ 0.8 - $1.1 \mu\text{m}$, yellow) brackets the laser line and is therefore subject to laser back-scatter contamination. The 2M band (1.45 - $1.75 \mu\text{m}$, green) excludes the laser line entirely and additionally sits near the

Wien peak at L-DED temperatures ($\sim 1.6 \mu\text{m}$ at 1500°C), giving both inherent laser immunity and high signal energy.

2.3.2 Two-colour (ratio) pyrometry

Two-colour pyrometry, also called **ratio pyrometry**, measures spectral radiance simultaneously at two distinct wavelengths λ_1 and λ_2 and forms the ratio of the two signals. Under Wien's approximation (valid for $\lambda T \ll hc/k_B$, which holds for all L-DED temperatures up to $\sim 3000^\circ\text{C}$) the ratio is:

$$\frac{L_{\lambda_1}}{L_{\lambda_2}} = \left(\frac{\varepsilon_1}{\varepsilon_2}\right) \left(\frac{\lambda_2}{\lambda_1}\right)^5 \exp \left[\frac{c_2}{T} \left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \right] \quad (2.2)$$

where $c_2 = hc/k_B \approx 1.4388 \times 10^4 \mu\text{m}\cdot\text{K}$ is the second radiation constant. If the emissivity ratio $\varepsilon_1/\varepsilon_2$ is approximately unity (the so-called **grey-body assumption**), the ratio depends only on temperature and not on the absolute emissivity which is the principal advantage of ratio pyrometry. Relevant industry literature on the Optris CTRatio family [13] confirms that ratio measurements tolerate up to 90 % optical attenuation (e.g. from metal vapour fouling) without loss of accuracy, provided the attenuation is wavelength independent. The remaining sensitivity is described by the **effective wavelength**

$$\Lambda = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} \quad (2.3)$$

where smaller Λ gives higher temperature sensitivity. For the $1.45\text{-}1.75 \mu\text{m}$ “2M” band selected for the Phase 2 sensor of the present thesis, $\Lambda \approx 8.46 \mu\text{m}$ giving rated accuracy of $\pm 0.5\% + 2^\circ\text{C}$ across the full range which is sufficient for closed-loop melt pool regulation in the $1300\text{-}1600^\circ\text{C}$ window.

Smoqi *et al.* [8] reported in *Materials & Design* the use of a coaxial two-wavelength imaging pyrometer in a closed-loop laser-power controller for SS316L L-DED holding the peak melt-pool temperature at $1650 \pm 50^\circ\text{C}$ ($\sim \pm 3\%$ of setpoint) via a rule-based proportional control and demonstrating successful rejection of standoff-drift disturbances over multi-layer trapezoidal builds. Their work is the closest published analogue to the thermal pillar of this project's work

and the present work's control algorithm structure (Section 2.7 below) takes Smoqi *et al.* as its principal reference architecture with three modifications described in Chapter 5: (i) replacement of Smoqi's analogue PID with a digital feedforward plus PI law better suited to FX5U PLC scan times (ii) addition of a self healing spike rejection filter for cold start transients (iii) deployment on a fundamentally different alloy (Stellite-21) whose much narrower 85 °C solidification range (Section 1.2) makes the regulation problem materially harder than for SS316L.

2.3.3 Geometric sensing: profilometry, high-speed imaging

Where pyrometry observes the melt pool temperature, geometric sensors observe the bead *shape*. The two most commonly deployed geometric sensors in industrial L-DED are (i) coaxial high speed CMOS cameras with brightness reduction filters (e.g. Optris CSVision R-series) which provide a 2D image of the melt pool aperture and yield bead width and shape directly [21] (ii) **laser line triangulation profilometers** mounted off axis on the L-DED head which scan the freshly deposited track behind the laser focal point and yield a complete 3-D height profile of the bead in real time [15]. The TVASHTR facility at RRCAT is equipped with a Micro-Epsilon LLT2510-50 (red 658 nm laser stripe, 200 Hz profile rate, ± 4 μm linearity) and Chapter 3 of this thesis documents the integration of this sensor into the closed loop architecture as the principal Phase 2 measurement of bead height; the metric that the present thesis can observe but cannot yet actively close on the laser power loop.

2.3.4 Acoustic and spectroscopic sensing

A small but growing fraction of the literature explores **non thermal, non-geometric** sensing of L-DED. Bevans *et al.* [17] reported in 2023 the use of acoustic emission sensing with wavelet-graph signal analysis to detect flaw-formation events in the closely related wire-based DED process at sub-millisecond resolution. Optical emission spectroscopy of the laser induced plasma plume has been demonstrated by Stutzman *et al.* [14] as a chemistry-sensitive multi-sensor diagnostic

capable of detecting elemental segregation and oxidation transients that are invisible to broadband pyrometry. These modalities are complementary rather than competing with pyrometry and the open question, how to fuse them in a single closed loop controller motivates the sensor-fusion programme outlined for Phase 3 of the RRCAT roadmap (Chapter 6).

2.4 Control Algorithms in L-DED

2.4.1 Classical PID and feedforward + PI

The proportional-integral-derivative (PID) controller in continuous time is described by:

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_d \frac{de(t)}{dt} \quad (2.4)$$

where $e(t) = T_{sp(t)} - T_{m(t)}$ is the control error, $u(t)$ the manipulated variable (laser power) and k_p , k_i , k_d the proportional, integral and derivative gains. The PID controller has been the workhorse of industrial process control for ninety years (Åström and Hägglund [18] report that more than 90 % of all process loops in continuous process industries today are still some variant of PID) and its dominance in L-DED literature reflects the same generality. Bi 2006 [3] used proportional only feedback; Smoqi 2022 [8] used a rule-based proportional law on a two-wavelength imaging pyrometer; Hu and Kovacevic [19] used full PID and this thesis uses a feedforward + PI architecture in which the derivative term is explicitly omitted (because differentiating a 5 Hz pyrometer signal with ± 30 °C noise band amplifies sensor noise by an unacceptable factor).

The **feedforward + PI** architecture is preferred to pure PI when the operating point is itself a function of slowly changing process conditions. In the present case, the Base Power term

$$u(t) = u_{FF}(T_{sp}, \text{geometry, material}) + k_p e(t) + k_i \int_0^t e(\tau) d\tau \quad (2.5)$$

is a calibrated open loop estimate of the laser power required to hold the melt pool at T_{sp} for the specific build geometry and feedstock

chemistry. This decomposition has two benefits relative to pure PI: (i) the integral term must compensate only for the residual after the open loop estimate; so the steady state value of $\int e \, d\tau$ is small and the integrator never needs to wind up (ii) when the operating point changes rapidly (e.g. when the setpoint was changed mid build, as in Test 12 of Chapter 5), the feedforward term tracks the new operating point instantaneously and only the residual is left to the slower PI dynamics. The use of feedforward + PI is well established in adaptive process control [20] and the specific tuning of the L-DED feedforward path to the Base Power (T_{sp}) calibration is one of the engineering contributions of Chapter 5.

2.4.2 Model predictive control (MPC)

Model predictive control replaces the instantaneous control law of equation (2.4) with a finite-horizon optimisation: at each control cycle the controller solves a quadratic programming problem

$$\min_{u(\cdot)} \sum_k (||T_{sp} - T(t + k\Delta t | t)||_Q^2 + ||\Delta u(t + k\Delta t)||_R^2) \quad (2.6)$$

subject to plant constraints where the predicted output $T(t+k\Delta t|t)$ is generated by a model of the plant. MPC offers two advantages over PID (i) it explicitly handles input and state constraints (laser-power floor, hardware slew limits, melt-pool size limits) (ii) it can use a process model to anticipate the effect of geometry changes (e.g. corners, overhangs) before the disturbance reaches the sensor. Its principal disadvantages: the requirement of an accurate, real-time-solvable plant model and the substantially higher computational load relative to PID have limited industrial deployment to date. This thesis adopts a **constraint aware classical PI** approach (with anti-windup, slew rate limiting and saturation) that captures most of the practical safety benefits of MPC without the computational cost; this design choice is examined in detail in Chapter 5.

2.4.3 Iterative learning and layer to layer control

A distinctive feature of multi layer L-DED not present in most continuous process control problems is that the build is naturally

repetitive along the layer index ℓ . Heralic *et al.* [22] applied ILC to the analogous laser metal-wire deposition process, using off-axis 3D scanning of the previous layer to drive a wire-feed-rate correction for in-process height regulation. Within powder-based L-DED, Sammons *et al.* [23] exploited the same repetitiveness to apply iterative learning control (ILC) to the bead height regulation problem. The laser power profile of layer $\ell+1$ is computed from the height error profile of layer ℓ via an explicit learning law

$$u_{\ell+1}(t) = u_{\ell}(t) + L e_{\ell}(t) \quad (2.7)$$

where L is a stable learning gain. ILC is particularly attractive for repair applications where the same nominal layer geometry is repeated dozens or hundreds of times and where any systematic bias in the open loop program can be eliminated within a small number of iterations. The present thesis does not implement ILC principally because the experimental campaign of Chapter 5 is centred on single-layer regulation as the validating test case for the thermal pillar. ILC is identified in Chapter 6 as a Phase 3 extension once the thermal and geometric loops are individually mature.

2.4.4 Machine learning and sensor fusion controllers

The most recent (post 2020) wave of L-DED control research has been dominated by data driven approaches. Chen *et al.* [9] reported in *Robotics and Computer-Integrated Manufacturing* a multi-sensor digital twin architecture for robotic L-DED in which acoustic, thermal and visual signals are fused via a deep neural network into a localised quality predictor with the predictor providing setpoint corrections to a downstream PI loop. Haribabu *et al.* [10] reported in 2025 a regression tree ensemble that predicts melt pool geometry on SS316L from process parameter inputs alone with $R^2 = 0.94$ on a 90/10 train-test split. These approaches share a common architectural feature, the use of a learned model as either the controller or as an upstream provider of setpoint references and a common limitation: they require large training datasets that are tied to the specific sensor configuration of the host machine and they sacrifice interpretability and certifiability relative to classical PID.

The present thesis does not deploy machine learning in the closed control loop but Chapter 6 outlines a Phase 3 extension in which the test campaign data already collected (the *Test 1 to Test 19* pyrometer logs, ~13500 samples) constitute an early training set for an ML augmented controller.

2.5 CL Control of Cobalt-Chromium Alloys: Survey

The literature surveyed in Sections 2.2-2.4 is dominated by three feedstock alloys: SS316L (the most common), Inconel 718 and Ti-6Al-4V. Cobalt-chromium superalloys of the Stellite family are conspicuously under-represented. A systematic search of the Web of Science database (March 2026, search string: “*Stellite*” AND “*laser*” AND “*directed energy deposition*” AND “*closed-loop*”) returns only seven peer-reviewed articles of which only three deploy any form of in-situ feedback control. Of those three, none uses the alloy that is the subject of this thesis (Stellite-21), and none uses an integrated multi pillar architecture in which laser power, scan speed and powder feed rate are simultaneously controlled.

This gap is not accidental. Stellite-21 has three properties that make it a particularly demanding closed-loop test case relative to the better studied SS316L:

- **Narrow solidification range.** The 140 °C window between liquidus (1435 °C) and solidus (1295 °C) (Kennametal Stellite-21 AM datasheet [7]) is comparable to but narrower than SS316L (≈ 160 °C), and the upper bound sits at a temperature where vapour-plume instability and volatile-element loss become significant. The thermal control loop must therefore hold the melt pool within a tighter band liquid setpoint to avoid both incipient solidification (lack of fusion) and excessive superheat (vapour plume instability, vaporisation of volatile elements such as Mn and Si).
- **Strong emissivity drift.** The Cr_2O_3 surface oxide that gives Stellite its corrosion resistance also gives the molten surface a

markedly higher emissivity than the underlying liquid metal, with the transition occurring on millisecond timescales as oxidation propagates through the melt pool surface. Single-colour pyrometers see this transition as an apparent temperature jump of 50-120 °C, which is large compared to the 25 °C control tolerance. The present thesis explicitly identifies this as the principal limitation of Phase 1 and the procurement specification for the two-colour Phase 2 sensor (Optris CTRatio 2MH1) was driven by this finding.

- **Industrial significance disproportionate to academic literature.** Despite the under representation in academic literature, Stellite-21 is one of the most commercially important hard facing and repair alloys in service today. The discrepancy between industrial demand and academic coverage is itself a research opportunity, and the present thesis takes it as part of its motivation.

The position of the present thesis within the published literature is summarised graphically in Fig. 2.3. The two axes control algorithm sophistication and sustained deployment maturity are admittedly subjective but the figure makes clear that the present thesis occupies a region of the matrix mid-sophistication classical control & sustained multi layer industrial deployment on a previously unstudied alloy that is presently empty in the literature.

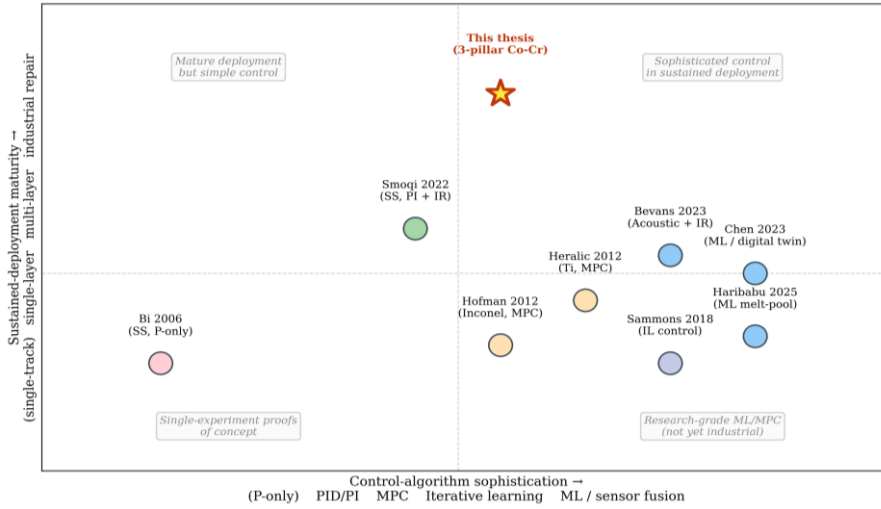


Figure 2.3 : Research-gap matrix locating the present thesis within the published L-DED closed-loop control literature. The horizontal axis represents control-algorithm sophistication (P-only → PID → MPC → ILC → ML/sensor fusion); the vertical axis represents the maturity of sustained deployment (single-track → single-layer → multi-layer → industrial repair). The present thesis (yellow star) occupies a region of the matrix not addressed by previous work.

2.6 Research Gaps and Engineering Requirements

Drawing the previous sections together, the literature survey identifies four specific gaps that the present thesis addresses:

- **Gap 1**

Closed loop L-DED of Stellite-21. There is no published implementation of in-situ closed loop melt pool control on Stellite-21 powder. The present thesis fills this gap with a fully instrumented Phase 1 thermal pillar controller validated across nineteen test runs and ~30 min of cumulative deposition.

- **Gap 2**

Integrated three-pillar architecture. The published literature treats laser power, scan speed and powder feed rate as separate sequentially tuned parameters. None of the surveyed studies controls all three simultaneously in a single integrated software application with shared safety interlocks. The present thesis builds such an integrated three pillar architecture with explicit communication between the pillars at the SCADA layer.

- **Gap 3**

Hardware level safety in PC side override. Where the published literature on PC side scan speed override of an industrial CNC exists at all (e.g. Mitsubishi’s own EZSocket reference applications), it relies entirely on PC side software for safety. No published study describes a PLC side gatekeeper block that protects the CNC from the PC. The present thesis introduces a 13-rung ROM flashed PLC gatekeeper that provides hardware level watchdog, slew rate and clamp safety. A design pattern that is, to the author’s knowledge, novel in the L-DED literature.

- **Gap 4**

Honest characterisation of single-colour-pyrometry limits. Although the limitations of single-colour pyrometry on cobalt-chromium are widely acknowledged in passing; no published L-DED study quantifies the resulting systematic offset under realistic deposition conditions. The present thesis presents this characterisation explicitly (Chapter 5) and uses it as the engineering basis for the Phase 2 ratio-pyrometer procurement (documented in detail in Appendix A).

These four gaps, taken together, give rise to seven specific engineering requirements that the controller designed in this thesis must satisfy. These requirements are summarised in Table 2.1 and used as the design specification of Chapter 5.

Req.	Engineering requirement	Source
R1	Sample rate ≥ 2 Hz on the temperature feedback signal (well above the dominant ~ 1 s thermal time constant of the melt pool).	Sec. 2.4.1; Smoqi 2022 [8]
R2	Laser power command must respect the laser’s minimum stable power floor (200 W, IPG YLS-2000-U-K) and its 200-2000 W operating range.	Sec. 1.4; manufacturer specification [24]
R3	Anti windup on the integral term to handle long sensor-saturation events (e.g. spike rejection of laser back scatter).	Sec. 2.4.1; Åström & Hägglund [18]

Req.	Engineering requirement	Source
R4	Per cycle slew rate limiting (≤ 20 W/cycle in this implementation) to protect the laser optics and the melt pool from step input transients.	Sec. 2.4.2; design choice
R5	Hardware level safety on PC side scan speed override of the M80V CNC.	Gap 3; this thesis novel
R6	Spike rejection filter for laser back scatter contamination of the single colour pyrometer (Phase 1) with self healing reset to recover from cold start transients.	Sec. 2.3.1; this thesis novel
R7	Clean stop sequence (laser power $\rightarrow 0$ W within 50 ms of operator command) for safe build termination under all fault conditions.	Industrial deployment requirement

Table 2.1. Seven engineering requirements derived from the literature gaps of Section 2.6. Each requirement is traced back to the section that motivates it; together these requirements form the design specification used in Chapter 5.

2.7 Formal Problem Statement

With the literature survey and the engineering requirements now established, the closed-loop L-DED control problem can be formalised in the language of process control. The architecture is shown in Fig. 2.4 and the mathematical specification follows.

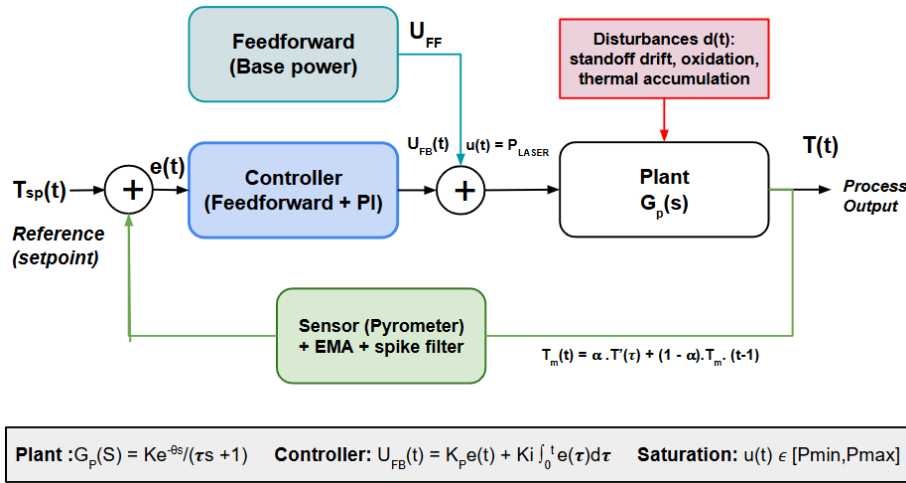


Figure 2.4 : Formal closed loop melt pool temperature control architecture proposed in the present thesis. The reference $T_{sp}(t)$ is differenced against the filtered measurement $T_m(t)$; the error $e(t)$ is processed by a feedback PI controller; the feedback term u_{FB} is added to a feedforward u_{FF} derived from a calibrated Base Power lookup; the resulting laser power command $u(t)$ is saturated to $[P_{min}, P_{max}]$ before being written to the IPG laser; disturbances $d(t)$ (standoff drift, oxidation, thermal accumulation) act on the plant; and the plant output $T(t)$ is sensed by a coaxial pyrometer, passed through a self healing spike rejection filter and an EMA, and fed back.

2.7.1 Plant model

Following the standard practice in radiative thermal process control [25], the L-DED melt pool thermal response to a laser power input is modelled as a first order plus dead time (FOPDT) process:

$$G_p(s) = \frac{T(s)}{P(s)} = \frac{K e^{-\theta s}}{\tau s + 1} \quad (2.8)$$

where K is the process steady state gain ($^{\circ}\text{C}/\text{W}$), τ the dominant thermal time constant (s), θ the process dead time (s) and s the Laplace variable. The characteristic step response of this model is plotted in Fig. 2.5 for representative parameter values $K = 1.5^{\circ}\text{C}/\text{W}$, $\tau = 1.0$ s, $\theta = 0.15$ s calibrated against open loop step response experiments in Chapter 5. The dominant time scale of the L-DED thermal response (≈ 1 s) is fast relative to the multilayer build time ($\sim$ minutes) but slow relative to the 5 Hz sensor sampling cadence (200 ms) placing the plant in the time discretization regime where a 5 Hz digital PI controller is well matched to the thermal dynamics.

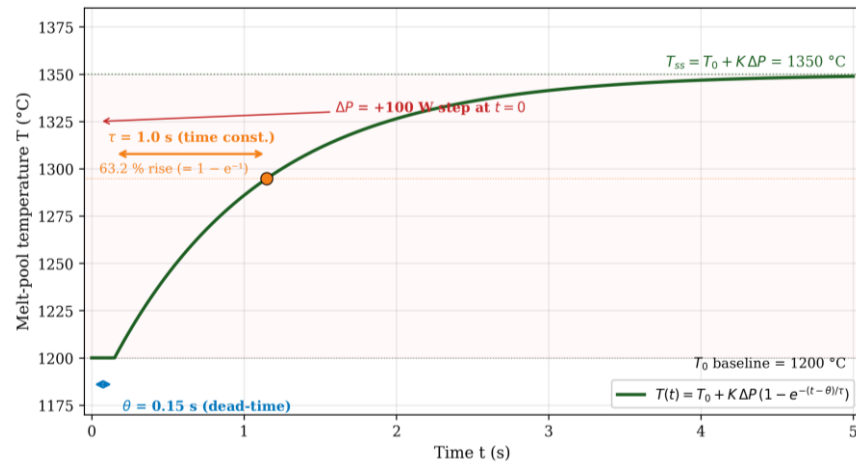


Figure 2.5 : Step response of the FOPDT (First-order plus deadtime) plant model of the L-DED melt pool thermal response of equation (2.8) for representative parameter values $K = 1.5^{\circ}\text{C}/\text{W}$, $\tau = 1.0$ s, $\theta = 0.15$ s. The dead time θ is the period between the application of the laser power step and the first sensor response. The time constant τ is the period required for the sensor to register 63.2 % of the steady state rise ($= 1 - e^{-1}$ of full response).

2.7.2 Controller specification

The controller is a **digital, sampled data, feedforward plus PI controller with anti windup and slew rate limiting**, instantiated at

sample period $\Delta t = 200 \text{ ms}$ (5 Hz). At each control instant $k\Delta t$, the controller computes:

(a) the instantaneous error,

$$e[k] = T_{sp}[k] - T_m[k] \quad (2.9)$$

(b) a bounded integral state with anti-windup,

$$I[k] = \text{clip}(I[k-1] + k_i e[k] \Delta t, -I_{cap}, I_{cap}) \quad (2.10)$$

(c) the unsaturated control output,

$$u_{raw}[k] = u_{FF} + k_p e[k] + I[k] \quad (2.11)$$

(d) a per cycle slew rate limit,

$$u_{slew}[k] = \text{clip}(u_{raw}[k], u[k-1] - \Delta u_{max}, u[k-1] + \Delta u_{max}) \quad (2.12)$$

(e) a hardware saturation,

$$u[k] = \text{clip}(u_{slew}[k], P_{min}, P_{max}) \quad (2.13)$$

with the operating constraints $P_{min} = 200 \text{ W}$ (laser minimum-stable-power floor), P_{max} set per-experiment (typically 800-1000 W), and $\Delta u_{max} = 20 \text{ W/cycle}$. The integral cap I_{cap} is set to 50 W in the Phase 1 controller (raised to 100 W in the Phase 2 redesign per Section 6.3) and the integral gain k_i is exposed as a runtime tuneable parameter (default $0.01 \text{ W}/(^{\circ}\text{C}\cdot\text{s})$).

2.7.3 Sensor model

The pyrometer measurement is processed through a two stage filter chain. The raw pyrometric reading $\hat{T}[k]$ is first passed through a **self healing spike rejection filter**:

$$T_{clean}[k] = \hat{T}[k] \text{ if } |\hat{T}[k] - T_{clean}[k-1]| \leq \Delta T_{spike}, \text{ else } T_{clean}[k-1] \quad (2.14)$$

with $\Delta T_{spike} = 400 \text{ }^{\circ}\text{C}$ as the rejection threshold. To prevent permanent filter latch-up (e.g. during cold start transients where the temperature legitimately rises by more than $400 \text{ }^{\circ}\text{C}$ between adjacent

samples), a self healing rule resets the filter after five consecutive rejections: the design rationale, including the empirical justification of the 400 °C threshold and the 5-cycle reset is documented in Section 5.5. The cleaned signal is then smoothed by a first order exponential moving average (EMA):

$$T_m[k] = \alpha T_{clean}[k] + (1 - \alpha)T_m[k - 1] \quad (2.15)$$

with $\alpha = 0.30$ (giving an effective discrete-time constant $\tau_{EMA} = \Delta t * (1-\alpha)/\alpha \approx 0.47$ s). The choice of $\alpha = 0.30$ is a compromise between sensor noise rejection and bandwidth. The analysis of Section 5.4 shows it is well matched to the dominant 1-s plant time constant.

2.7.4 Performance specification

The Phase 1 controller is required to satisfy four quantitative performance criteria:

- **PS-1:**

Steady state regulation: $|e[k]| \leq 25$ °C in 90 % of samples in the last 30 s of any ≥ 2 -min closed-loop test phase with the setpoint T_{sp} held constant.

- **PS-2:**

Disturbance rejection: in response to a setpoint step change the integrated absolute error $\int |e(t)| dt \leq 5000$ °C·s, with no more than 10 % overshoot.

- **PS-3:**

Robust safety: zero false fault terminations, zero unbounded power excursions and laser power to zero ≤ 50 ms in response to operator stop, across the full test campaign.

- **PS-4:**

Self-diagnosing operator interface: the integral state, slew limit hits, spike rejection counts and PLC write success ratio are visible to the operator in real time, with all state logged at 5 Hz to CSV for post run analysis.

Chapter 5 reports the experimental validation against each of these four performance specifications. Test 12, Phase 2 (steady state regulation at $T_{sp} = 1270$ °C) is the principal validation case for P-1 and yields 94.0 % in tolerance in the last 30 s with a mean steady-state error of +4.86 °C, satisfying PS-1 with margin.

2.8 Chapter Summary

This chapter has surveyed the published literature on closed loop control of L-DED with primarily focus on sensing modality, control algorithm and controlled variable and identified four specific gaps that the present thesis addresses: (i) the absence of any closed loop L-DED study on Stellite-21 specifically (ii) the absence of an integrated three pillar (laser power + scan speed + powder feed) software architecture (iii) the absence of hardware level safety in PC side CNC override (iv) the absence of an honest characterization of single colour pyrometry limits on cobalt chromium melt pools.

Section 2.7 has formalized the engineering problem as a constrained, sampled data, feedforward plus PI control problem with explicit plant model (FOPDT, equation 2.8), explicit controller equations (equations 2.9-2.13), explicit sensor conditioning model (equations 2.14-2.15) and four explicit quantitative performance specifications (PS-1 to PS-4).

With this formal specification in hand, Chapter 3 turns to the description of the experimental hardware on which the controller is deployed.

Chapter 3

Experimental Setup and Methodology

3.1 Introduction

This chapter provides a complete description of the experimental hardware on which the closed loop control system of this thesis is deployed together with the design of experiments methodology used to characterize the open loop process and the metrology workflow used to measure the resulting deposits. The hardware is the TVASHTR five axis L-DED facility at the Additive Manufacturing Technology Lab of the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. The facility is co-developed with VFuse Metal 4 Manufacturing Pvt. Ltd. and represents an indigenous L-DED platform built around an IPG Photonics 2 KW fibre laser, a Mitsubishi M80V CNC kernel with FX5U external PLC and a twin Toshiba VFD driven powder feeder sub system.

All the testing was done on the TVASHTR machine itself over the course of 6 to 7 months. Section 3.2 gives a system level overview. Sections 3.3-3.5 describe the energy, sensing and control sub systems in detail. Section 3.6 covers the powder feed sub system; Section 3.7 the design of experiments matrix; Section 3.8 the metrology workflow; Section 3.9 the data acquisition pipeline and Section 3.10 closes with a chapter summary.

3.2 System Overview

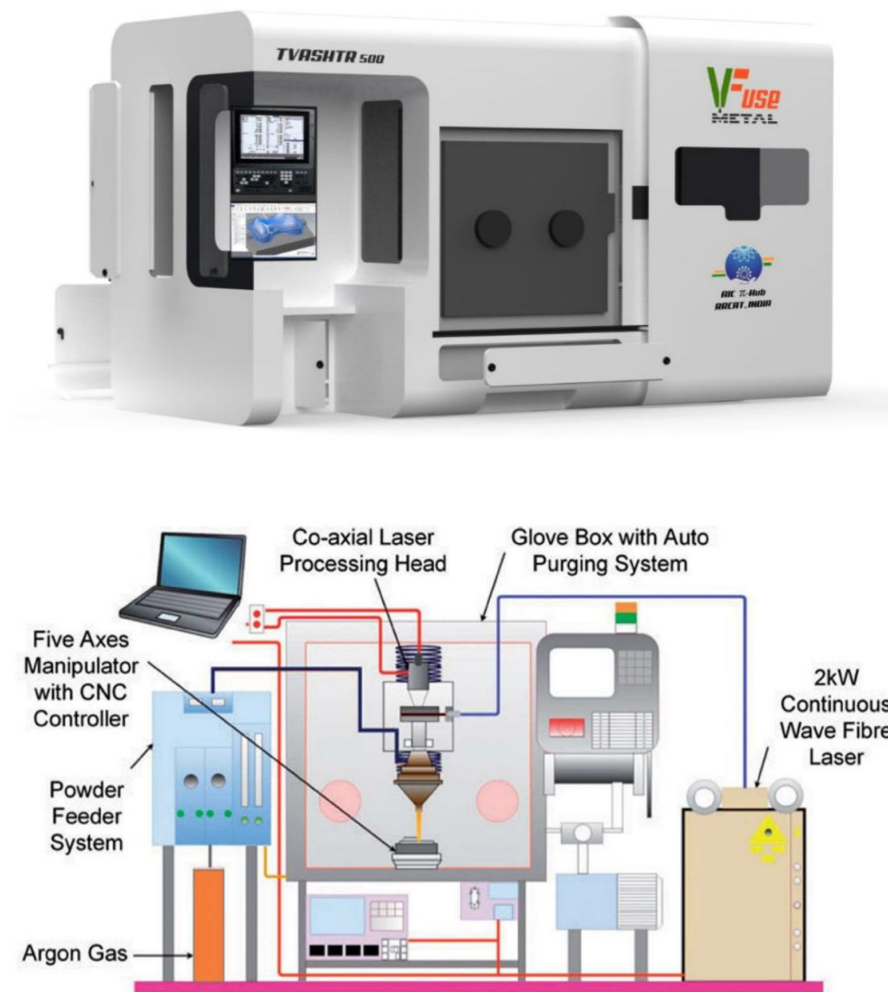


Figure 3.1 : (top) TVASHTR Machine present in the RRCAT (bottom) Internal components description diagram showing internal components (courtesy RRCAT)

The TVASHTR facility, shown in architectural form in Fig. 3.1, integrates seven major hardware sub-systems into a single deterministic real time L-DED cell:

- the IPG fiber laser source (energy);
- the optical beam delivery system (collimator, bending cube, focusing lens, nozzle);
- the twin Toshiba VFD driven powder feeder sub system (material);
- the Mitsubishi M80V Type A CNC kernel with five axis MDS-EJ servo drives (kinematics);

- the Mitsubishi FX5U-32M MT/ESS external PLC with FX5-4DA-ADP analog outputs and FX5-8AD analog inputs (process I/O);
- the in process metrology stack: Optris CTLM-1H1SF300-C3 coaxial pyrometer and Micro-Epsilon LLT2510-50 laser line profilometer (sensing);
- the Windows workstation PC running the Qt 6 / C++ master control application (desg. M_CS_APP_MK8) and supporting software (vfd_lite, GX Works 3, ScanCONTROL Configuration Tools).

These sub systems are interconnected by four distinct physical and protocol layers each chosen for its appropriate role in the control hierarchy: a ladder network 192.168.200.0/24 industrial Ethernet, on which the PC workstation, the FX5U PLC (192.168.200.99:502), the M80V CNC (192.168.200.1) and the LLT2510-50 profilometer (192.168.200.2) all reside. A CC-Link IEF Basic master/slave link between the FX5U (master, station 0) and the M80V (slave, station 1) running over the same Ethernet medium, an RS-232 serial link from the workstation's COM3 port to the Optris CTLM pyrometer at 115200 baud rate, 8N1 and a set of analog control loops in which 0-10 V signals from the FX5-4DA-ADP outputs drive the IPG laser power input and the two Toshiba VFDs with 0-10 V FM feedback returning to the FX5-8AD analog input module. The IP addressing, the channel allocation and the protocol level direction of every signal are summarized in Table 3.1.

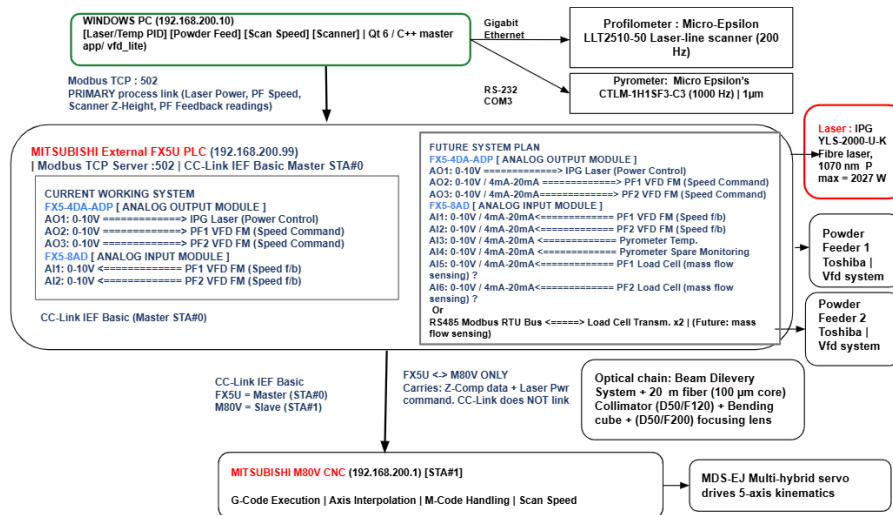


Figure 3.2: TVASHTR L-DED system architecture showing the principal hardware sub systems and the protocol layers (industrial Ethernet ladder network, CC-Link IEF Basic, RS-232 serial, and 0-10 V analog I/O).

Sub-system	Model / spec	Address / channel	Protocol
Workstation PC	Windows 10, Qt 6 / C++ M_CS_APP_MK8		Modbus TCP client + RS-232 + GigE
External PLC	Mitsubishi FX5U-32M MT/ESS	192.168.200.99:502	Modbus TCP server, CC-Link IEF master
CNC kernel	Mitsubishi M80V Type A	192.168.200.1	CC-Link IEF Basic slave (STA #1) + EZSocket COM
Servo drives	Mitsubishi MDS-EJ multi-hybrid	M80V backplane	Mitsubishi servo bus
Laser source	IPG YLS-2000-U-K	FX5-4DA-ADP CH1 (0-10 V)	Analog 0-10 V linear control
PF1 powder feeder	Toshiba VFNC3S-2007PL (left)	FX5-4DA-ADP CH2 / FX5-8AD CH2	Analog 0-10 V command + FM Hz feedback
PF2 powder feeder	Toshiba VFNC3S-2007PL (right)	FX5-4DA-ADP CH4 / FX5-8AD CH4	Analog 0-10 V command + FM Hz feedback
Pyrometer	Optris CTLM-1H1SF300-C3	Workstation COM3	RS-232 binary @ 115200 8N1, 5 Hz
Profilometer	Micro-Epsilon LLT2510-50	192.168.200.2	GigE Vision (GVCP / UDP), 100 Hz

Table 3.1. Complete hardware protocol summary of the TVASHTR L-DED facility. The four protocol layers: Ethernet, CC-Link, RS-232, and analog 0-10 V: together provide the deterministic real time data path of every sensor, actuator and command in the closed loop architecture.

3.3 Laser Source and Beam Delivery

3.3.1 IPG YLS-2000-U-K fiber laser

The energy source is an IPG Photonics YLS-2000-U-K Ytterbium doped continuous wave fibre laser configured for delivery through a 20 metre HLC-8-terminated fibre with 100 μm core diameter. The factory test report [24] issued on 12 September 2023 reports the verified electrical, optical and switching characteristics summarised in Table 3.2. Of particular relevance to the control system design are: (i) the centroid emission wavelength of **1070.20 nm** with FWHM of 4.95 nm: a parameter that determines, jointly with the pyrometer band pass, the magnitude of laser back scatter contamination discussed in Section 3.4 and Chapter 5; (ii) the exceptionally low output power instability of $\pm 0.30\%$; better than an order of magnitude tighter than the $\pm 1\text{-}2\%$ datasheet specification which justifies treating the laser as an essentially noise free actuator at the time scales of interest to the closed loop controller (iii) the fast switching transients of **44 μs ON / 32 μs OFF** (Fig. 3.3(b)), well within the manufacturer's $\leq 50\ \mu\text{s}$ / $\leq 100\ \mu\text{s}$ specification. These set the upper bound on the closed loop control bandwidth but in practice are several orders of magnitude faster than the dominant $\sim 1\text{-s}$ thermal time constant of the melt pool (Section 2.7.1) and so do not constrain the design (iv) the verified linearity of the 0-10 V analog control voltage to output power across the full range (Fig. 3.4(a)), with a fitted slope of approximately 204 W/V and $R^2 > 0.999$.

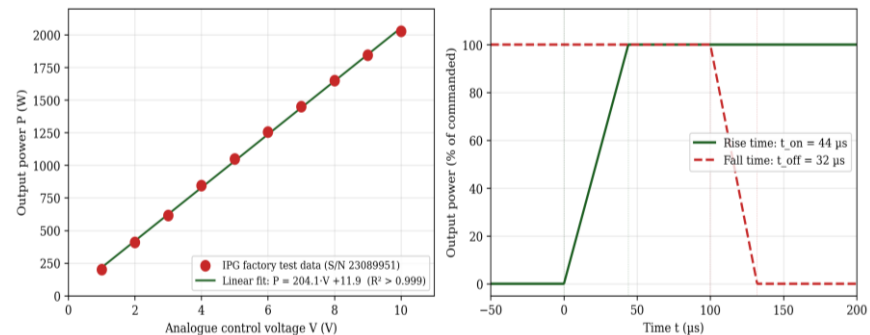


Figure 3.3: (a) IPG YLS-2000-U-K analog linearity, plotted from the factory test data points in the YLS-2000-U-K test report [24]. ± 0.30 % instability (b) Switching transients: rise to commanded power in 44 μs , fall to zero in 32 μs . Both transients are several orders of magnitude faster than the melt pool thermal time constant and therefore do not constrain the closed loop bandwidth.

Parameter	Test report value	Specification range
Mode of operation	CW / Modulated	
Maximum output power	2027 W	min 2000 W
Output power tuning range	10 - 101 %	10 - 105 %
Centroid emission wavelength	1070.20 nm	1068 - 1080 nm
Emission linewidth (FWHM)	4.95 nm	5 - 8 nm
Beam parameter product (86 % power)	3.246 mm·mrad	3.30 - 4.00 mm·mrad
Beam-quality factor M^2 (computed)	9.531	$(M^2 = \pi \cdot \text{BPP} / \lambda)$
Switching ON time	44 μs	$\leq 50 \mu\text{s}$
Switching OFF time	32 μs	$\leq 100 \mu\text{s}$
Output power instability	± 0.30 %	± 1 to ± 2 %
Red guide laser power	0.46 mW	0.4 - 0.5 mW
Feeding fibre core diameter / connector	100 μm / HLC-8	(as specified)
Coolant / temperature / flow	Tap water / 21 ± 1 °C / 36 l/min	
Power consumption at 2 kW output	4.9 kW	5.2 - 5.7 kW

Table 3.2. Verified specifications of the IPG YLS-2000-U-K fibre laser, reproduced from the IPG factory test report [24]. The BPP cross-check $M^2 \cdot \lambda / \pi = 9.531 \times 1.070 \mu\text{m} / \pi = 3.246 \text{ mm} \cdot \text{mrad}$ matches the measured BPP exactly.

3.3.2 Optical chain and beam caustic

The optical beam delivery system illustrated in detail in Fig. 3.5, consists of an IPG D50 F120 fibre collimator (focal length $f_1 = 120 \text{ mm}$), a fused silica bending cube (clear aperture 48 mm, dichroic coated 45° internal mirror) and a Coherent D50 F200 focusing lens (focal length $f_2 = 200 \text{ mm}$). The system magnification is therefore

$$M = \frac{f_2}{f_1} = \frac{200}{120} = 1.6667 \quad (3.1)$$

which yields a nominal laser beam diameter at the exact focus of

$$d_0 = d_{fibre} M = 100 \mu m \times 1.6667 = 166.7 \mu m \quad (3.2)$$

Combining the IPG-measured beam parameter product $BPP = 3.246 \text{ mm} \cdot \text{mrad}$ and the fiber core radius $f_{iber} = 50 \mu m$, the collimated-beam diameter is

$$d_{coll} = 2 f_1 \left(\frac{BPP}{r_{fibre}} \right) 10^{-3} = 15.58 \text{ mm} \quad (3.3)$$

which fits comfortably inside the 48-mm clear aperture of the bending cube with no clipping. The Rayleigh range (ideal case) of the focused beam is

$$z_R = \frac{\pi \left(\frac{d_0}{2} \right)^2}{\lambda M^2} = 2.139 \text{ mm} \quad (3.4)$$

a value that emerges as the most consequential single parameter of the entire L-DED facility from the closed loop control standpoint: it is short enough that small (millimetre scale) standoff errors translate into large (~tens of percent) changes in the energy density at the work plane. The TVASHTR machine is operated in the **defocus zone** i.e. with the work plane displaced beyond the laser focus using one of two interchangeable nozzle assemblies. The defocus distance is $\Delta z = 10.5 \text{ mm}$ for Nozzle A (200 mm long) and $\Delta z = 20.5 \text{ mm}$ for Nozzle B (210 mm long), giving $\Delta z / z_R$ ratios of 4.91 and 9.58 respectively. Substituting into the standard Gaussian beam expansion law

$$d(\Delta z) = d_0 \sqrt{1 + \left(\frac{\Delta z}{z_R} \right)^2} \quad (3.5)$$

yields the working-plane spot diameters of **835 μm at Nozzle A** and **1606 μm at Nozzle B**. The full caustic, with both nozzle working

positions and the Rayleigh range marked is plotted in Fig. 3.4(a). The closed-loop test campaign of chapter 5 (test 8-19) was conducted using Nozzle A (10.5 mm standoff, ~0.84 mm spot diameter at work plane). The open-loop process characterization campaign of chapter 4 (the L27 DOE) was conducted using Nozzle B (20.5 mm standoff, ~1.6 mm spot diameter). The two campaigns were executed under different optical configurations due to equipment scheduling constraints; the nozzle applicable to each result is identified explicitly at the point of use.

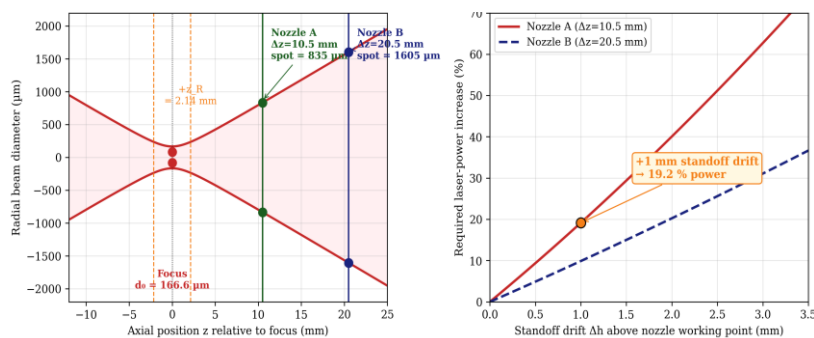


Figure 3.4: (a) Laser caustic showing the beam diameter envelope $d(\Delta z)$ about the focus; the Rayleigh range $z_R = 2.14$ mm is marked in orange and the two working defocus distances (Nozzle A at 10.5 mm, Nozzle B at 20.5 mm) are marked. (b) Standoff drift power sensitivity, because Nozzle A operates close to the focus relative to z_R , every 1 mm of standoff drift requires ~19 % more laser power to compensate. This is the dominant disturbance observed during the multi layer test campaign of Chapter 5.

The control system consequence of the short Rayleigh range is illustrated in Fig. 3.4(b). At Nozzle A, a **1 mm increase in standoff** (e.g. due to layer height accumulation between successive deposited layers) increases the beam spot area at the work plane by a factor proportional to $(d(\Delta z + 1) / d(\Delta z))^2$, which evaluates to approximately 1.19 for the IPG-measured caustic (see Additional Note below). Maintaining the same volumetric energy density therefore requires the laser power to increase by roughly **19 %**, a substantial disturbance that the closed loop controller must reject. At Nozzle B, the same standoff drift produces only ~6 % power increase (~9% if we calculate from IPG's caustic data : see Additional Notes below) because the larger focal plane spot makes the system less sensitive to small displacement, a fact that motivates the use of Nozzle B for builds where standoff control is poor.

Two secondary optical effects deserve mention. First, the fused silica focusing lens has a small but non-zero **chromatic aberration**: the focal length is 200.0 mm at the laser wavelength of 1070 nm, but rises to approximately 202.5 mm at 1.6 μm (the centre of the recommended 2M pyrometer band). This places the pyrometric image of the melt pool at a finite distance of approximately 5.3 m for Nozzle A and 2.5 m for Nozzle B within the SF (300 mm to ∞) optics range of the recommended Optris CTRatio 2MH1 sensor but not within the CF (150-350 mm) optics range. The chromatic-aberration effect is the principal reason why pyrometers with adjustable focus optics are required for the TVASHTR facility and is documented in detail in the procurement specification (Appendix A). Second, the bending cube's rear window provides the optical port through which the pyrometer views the melt pool coaxially: the geometry that gives the pyrometer its co aligned, real time view of the melt pool but also exposes it to the theoretical max 10.1 W of back-scattered 1070 nm laser light that is the principal Phase 1 sensing limitation discussed in Chapter 5.

Additional Note: for calculation Rayleigh range we have used our calculated values and $w_0 \approx 0.083\text{mm}$. But if rather than computing Rayleigh range from our model ($w_0 \approx 0.083\text{mm}$) and go directly to IPG's test report and take caustic data directly from IPG's test report page 3, we get $w_0 \approx 0.099\text{ mm}$ and $z_R \approx 2.998\text{ mm}$. This value also takes into account that real beam have aberrations plus non-ideal Gaussian which translates to a slightly larger waist than the ideal case. If we rerun the calculation with this IPG's measured data we get for $\Delta z / z_R$ ratios of Nozzle A and Nozzle B as 3.50 and 6.84 respectively and spot sizes of **728 μm** and **1382 μm** . The Power change required for every mm change in standoff for Nozzle A and Nozzle B is calculated to be $\approx 19\%$ and $\approx 9\%$ respectively. This case is slightly more representative of actual physical real world system but does not change the conclusion of this section i.e. since Rayleigh range $\gg 1$, we are still operating in far-field regime; so, our expansion model still holds qualitatively.

3.4 Optical Sensing

3.4.1 Coaxial pyrometer

The melt-pool temperature feedback signal in the Phase 1 controller is provided by an Optris CTLaser CTLM-1H1SF300-C3 single-colour near-infrared pyrometer mounted coaxially through the rear window of the bending cube (Fig. 3.5). The principal specifications are: spectral band 1.0 μm , temperature range 200-1500 $^{\circ}\text{C}$, response time 1 ms and distance-to-spot ratio 300:1 with the SF (Standard Focus) optics installed. The sensor outputs both an analog 4-20 mA signal (unused in the present configuration) and a binary RS-232 stream at 115200 baud, 8N1, polled by the workstation's pyrometer worker thread at 5 Hz. The decoding of each two-byte response is

$$T_{raw}[^{\circ}\text{C}] = \frac{b_1 \cdot 256 + b_2 - 1000}{10.0} \quad (3.6)$$

where b_1 and b_2 are the high and low bytes of the response. The 1000 unit offset corresponds to a measurement floor of 200 $^{\circ}\text{C}$; the divide by 10 gives 0.1 $^{\circ}\text{C}$ resolution. Sensor emissivity is set to $\varepsilon = 0.95$ via the on sensor configuration jumpers, a value chosen to match the empirical transmittance of the Stellite-21 melt pool at the 1.0 μm measurement wavelength after correction for window losses.

With the geometry of Fig. 3.5 and the Nozzle A working-distance of 210.5 mm, Using the pyrometer's 300:1 D:S ratio at this image distance and accounting for the optical magnification, the effective spot size at the melt pool is approximately 0.70 mm. Comparison with the laser spot diameter (835 μm) and the estimated melt pool diameter (1.4 mm at 600 W on cold SS316L) shows that the pyrometer field of view is entirely contained within the melt pool i.e. the sensor sees molten Stellite at all times not the surrounding cold solidified track. This is the ideal coaxial measurement geometry.

The fundamental Phase 1 limitation is the spectral overlap between the 1.0 μm pyrometer band and the 1070 nm laser line: the

bending cube transmits approximately 10.1 W^1 (theoretical Max) of back scattered laser light into the pyrometer port which is several orders of magnitude larger than the thermal radiance of the melt pool in the same band. The sensor reading therefore contains an unknown, laser power dependent offset that manifests as +200 to +1400 °C upward spikes correlated with laser on transitions: a phenomenon documented in detail in Section 5.5 and addressed by the self healing 400 °C spike rejection filter introduced there. The procurement of a two-colour ratio pyrometer at 1.45-1.75 μm (Optris CTRatio 2MH1) specified in detail in Appendix A, is the principal Phase 2 hardware enhancement that resolves this limitation by physical exclusion of the laser line from the measurement band.

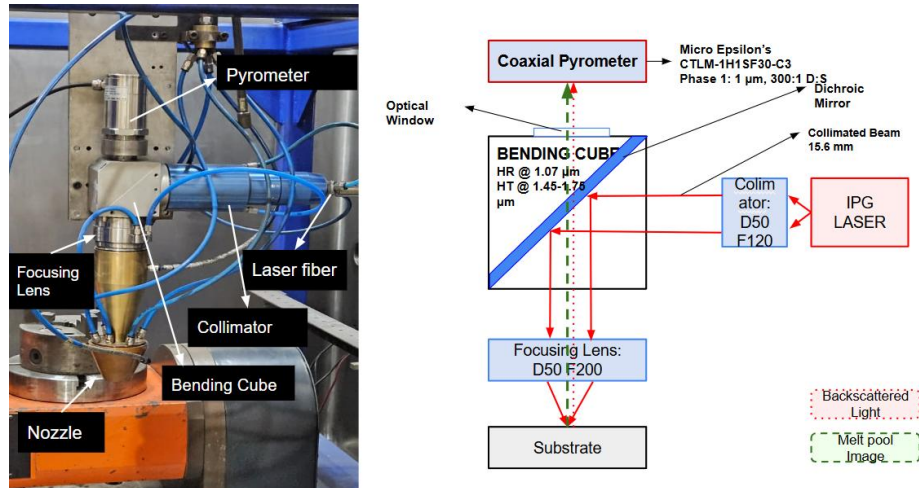


Figure 3.5: Coaxial pyrometer optical chain (Actual image as along side block diagram): laser path (red) from IPG fibre output through the D50 F120 collimator, into the bending cube, reflected downward by the 45 ° dichroic mirror, focused by the Coherent D50 F200 lens and converging on the melt pool 10.5 mm below the nozzle tip. The pyrometer line of sight (green dashed) enters through the bending cube's rear window via a custom 50→25 mm adapter and follows the same optical axis as the laser. The 10.1 W (theoretical max) of 1070 nm laser light back-scattered through the cube into the pyrometer port is the principal Phase 1 limitation.

3.4.2 Laser profilometer (Micro Epsilon LLT2510-50)

Bead geometry measurement is provided by a Micro Epsilon scanCONTROL LLT2510-50 laser line triangulation profilometer mounted off axis on the deposition head, trailing the laser focal point by

¹ Upper Bound only: dichroic transmission $\leq 0.5\%$ at 1070 nm *2000 W =10W; the figure assumes worst-case coupling of the transmitted fraction into the pyrometer aperture and is therefore conservative.

approximately 35 mm. The principal specifications are: 658 nm (red) line-laser source at 8 mW Class 2M; 50 mm measurement range in the X direction with up to 640 measurement points per profile (78 μm lateral resolution); 65-125 mm Z range; profile rate up to 2000 Hz (operated at 100 Hz in the present configuration) and Z-axis line linearity of 4 μm . The sensor communicates with the workstation over GigE Vision (GVCP/UDP) at 192.168.200.2, with a 3000 ms heartbeat. The Python SDK pyllt-1.1.0 wraps the LLT.dll in-process driver.

Two project specific calibration findings verified by six independent reference displacement measurements on 14 April 2026, are worth noting. First, the sensor's Z output is **inversely related** to physical distance: as the surface moves *closer* to the sensor, the reported Z value *increases*. This is opposite to the geometric intuition and was verified by deliberately translating a reference flat by known distances. Second, the relationship between sensor counts v and physical distance d is

$$d [\text{mm}] = (v - 32768) \times 0.002 + 95 \quad (3.7)$$

with a working distance of 95 mm and a count resolution of 4 μm . Object height during the build is computed by

$$h_{\text{object}} = h_{\text{reference}} - \max(Z_{\text{profile}}) \quad (3.8)$$

where $h_{\text{reference}}$ is the substrate-surface Z baseline captured before deposition and $\max(Z_{\text{profile}})$ is the peak height of the trailing edge profile. The dead band of ± 0.50 mm produces a special “At reference level” output rather than a numeric height which protects the closed loop logic from noise floor oscillation. The profilometer is used in this thesis primarily for **post build offline metrology** of the DOE samples (Chapter 4) and as the basis for the Phase 2 layer height feedback loop identified in Chapter 6; it is **not** yet used as a real time feedback signal in the Phase 1 closed loop controller.

The LLT2510-50 X-range and Z-range are coupled by its triangulation geometry: the full 50 mm X-field is available only at the

mid-range Z working distance of 95 mm with the X-field narrowing as the standoff is reduced. In the TVASHTR integration the profilometer is mounted to operate at approximately 70 mm working distance rather than the nominal 95 mm; a deliberate design choice that trades Z resolution (where the native 4 μm linearity is already far better than needed for bead-height observation) for improved X-Y resolution (which sets the floor for the planned real-time bead-width feedback loop). The effective X-field at the operating distance of 70 mm is approximately 42 mm which is the basis of the calibration constant in Eq. 3.9. The original intent was to use this lateral-resolution headroom to detect bead-width drift in real time; however, geometric occlusion of a single off-axis profilometer in multi-layer and topologically complex builds proved a hard limitation and the bead-width-on-the-fly closure was deferred to Phase 2.

3.5 Control Hierarchy: M80V CNC + FX5U PLC + PC

3.5.1 Mitsubishi M80V CNC

Five axis kinematics are governed by a Mitsubishi M80V Type-A CNC kernel mounted on the front control panel of the TVASHTR machine driving an MDS-EJ multi-hybrid servo bus. The CNC executes G-code from a part program stored on its internal SSD with the laser fire G-code macro M59/M60 toggling a logical bit (D4 in the ladder, mirroring the CNC internal command) and the laser power command published as register D0 (32-bit, in watts) over the CC-Link IEF Basic backbone to the FX5U. The CNC has its own external Ethernet port (192.168.200.1) through which it accepts an EZSocket COM API connection from the workstation; this API is the entry point for the kinematic pillar scan speed override controller documented in detail in Chapter 5. In particular, the live override register R2500 (range 0-120 %) is writable through EZSocket while a part program is running which is the mechanism by which the workstation can reduce or increase the commanded feed rate without modifying the running G-code.

3.5.2 Mitsubishi FX5U external PLC

The external PLC is a Mitsubishi FX5U-32M MT/ESS configured as the CC-Link IEF Basic master (station 0) and as a Modbus TCP server on port 502 at IP 192.168.200.99. Three I/O modules are attached: ADP1 = FX5-4DA-ADP (4-channel analog output, 0-10 V, **active**); ADP2 = FX5-4DA-ADP (second 4-channel analog output, **currently unused**); and 1[U1] = FX5-8AD (8-channel analog input, 0-10 V, 0-32000 counts). The ADP1 channel allocation is fixed by the vendor ladder program: CH1 drives the IPG laser power command (0-10 V $\rightarrow$ 0-2000 W); CH2 drives the PF1 (left) Toshiba VFD analog input; CH3 is **permanently set to 10 V (a vendor configuration mistake that cannot be changed without significant modifications to the original ladder logic and hence, left as it is by the author)**; the corresponding terminal pair AO3+/AO3 must therefore *never* be wired to anything; CH4 drives the PF2 (right) VFD. Table 3.3 gives the complete analog channel allocation.

Channel	PLC base	Output	Connector pins
ADP1 CH1	SD6300	Laser power 0-10 V $\rightarrow$ 0-2 kW	Pins 1/2 (AO1+/AO1-)
ADP1 CH2	SD6340	PF1 (left) feeder VFD VI/CC	Pins 3/4 (AO2+/AO2-)
ADP1 CH3	SD6380 (= K60000)	Permanently set 10 V	Pins 5/6
ADP1 CH4	SD6420	PF2 (right) feeder VFD VI/CC	Pins 7/8 (AO4+/AO4-)
FX5-8AD CH2	D6062	PF1 FM frequency feedback (input)	(spring-clamp)
FX5-8AD CH4	D6066	PF2 FM frequency feedback (input)	(spring-clamp)

Table 3.3. FX5U analog I/O channel allocation. CH3 of ADP1 is hardcoded by the vendor ladder program to a constant K60000 (accidentally), which causes integer overflow in the DA register and produces a permanent 10 V output: the AO3+/AO3- terminal pair must never be wired to any external device as of the current stage.

3.5.3 Modbus TCP and CC-Link IEF Basic register maps

The protocol level interconnection between the workstation, the FX5U and the M80V is illustrated by the register mapping summary of Table 3.4. Three principles govern the design. First, **CC-Link IEF Basic register windows are owner segregated**: the M80V exclusively owns RWr 0000-0x1F (mapped to PLC registers D0-D31) and the PLC must *never* write into this range; conversely, the PLC owns RWw 0000-0x1F (mapped to D500-D531) and the CNC reads from it. Violating this rule corrupts the CNC's view of the process state and crashes the part program. Second, the FX5U's 32-bit floating point convention places the **low word at D(n) and the high word at D(n+1)**, verified by the live PLC test of 14 April 2026 in which writing 1.0 to HR 100 produced [0, 16256] = [D100=0, D101=0x3F80] which the PLC correctly decoded as $0x3F800000 = 1.0$.

The workstation's laser power closed loop output is therefore written to a separate register pair (*specified per the project's integration plan*) and is multiplexed by the ladder logic into the laser DA path only when the workstation is the active master.

Register	Owner	Purpose
D0-D31	CNC (RWr)	CNC → PLC. NEVER WRITE.
D4	CNC	Laser-fire flag (10 = ON, 0 = OFF)
D119 / D120	Vendor process	Laser power float32
D140	Ladder	Echo of D0 (PC reads back live CNC power)
D500-D531	PLC (RWw)	PLC → CNC scanner / Z-comp data
D6062 / D6066	PLC ladder	PF1 / PF2 actual Hz feedback (read by PC)
SD6300	FX5U analog DA	CH1 base = laser DA

Table 3.4. Critical Modbus TCP / CC-Link register map for the TVASHTR facility, verified by ladder-monitor. The owner column identifies which sub-system has write authority; registers marked “NEVER WRITE” are CC-Link RWr inputs that the M80V CNC writes every cycle, and any Modbus write to these addresses corrupts CNC process data.

3.5.4 Workstation software architecture

The workstation runs a Qt 6 / C++ master-control application (designation *M_CS_APP_MK8*) with a single-page React/JavaScript front-end (*ACS-MK0.html*) communicating over QWebChannel. The application uses a three-thread model: (i) the Qt main thread handles the UI bridge and the QML/QWebChannel marshalling (ii) the *PLCWorker* thread is a Modbus TCP client running an FC16 write loop, a write-watchdog timer (5 s timeout $\rightarrow$ safe-state trigger) and a CSV logger that writes 29 fields per cycle to a timestamped pyrometer log file (iii) the *PyrometerWorker* thread polls the COM3 RS-232 link at 5 Hz, decodes the binary response per equation 3.6, runs the spike rejection filter and EMA and executes the feedforward + PI control law. The thread separation is essential: the PLC write watchdog must *never* be blocked by sensor side processing because a failed PLC heartbeat triggers an immediate clean stop sequence (laser power $\rightarrow$ 0 W within 50 ms) regardless of the state of any other thread. The control flow is summarised diagrammatically in Chapter 5 (Fig. 5.1) and the source-file map is provided in Appendix B.

3.6 Powder Feed Sub System

The powder feed sub system consists of two independent disc type powder feeders each driven by a Toshiba TOSVERT VF-nC3 series VFD (model VFNC3S-2007PL, 0.75 kW, single phase 200-240 V input, three phase output, 0.1-400 Hz). The feeders are mounted on TVASHTR machine are designated as Powder feeder 1 (PF1) (left) and Powder feeder 2 (PF2) (right). The original speed control hardware, a Bourns 3590S-2-103L 10-turn 10 k Ω potentiometer wired between the VFD's P5/VI/CC terminals has been retained but disconnected at the VFD VI/CC end; the analog speed reference is now provided by FX5-4DA-ADP CH2 (PF1) and CH4 (PF2) through 0-10 V signals into the VFD's VI terminal. The forward/reverse/stop logic is configured with VFD parameter cmod = 0 in which the F (forward) terminal-to-CC short

circuit drives the motor while F + R simultaneous activation triggers a slowdown stop.

The full forward and feedback signal path of the powder feed loop is shown in Fig. 3.6. The forward path: Workstation → Modbus TCP → Analog SD Registers (PF1)/(PF2) → FX5-4DA-ADP CH2 / CH4 → 0-10 V → VFD VI/CC → motor; carries the speed setpoint as a uint16 in the range 0-2000 (corresponding to 0-10 V analog, 0-60 Hz motor frequency). The feedback path: Motor → VFD FM terminal → 0-10 V → FX5-8AD CH2 / CH4 → D6062 / D6066 → Modbus TCP → Workstation; returns the actual VFD frequency to the PC through the FX5-8AD module's buffer memory addresses. The closed loop comparison of setpoint with actual frequency, although architected, is **not** enabled in the present Phase 1 thesis (simply because the system is accurate enough that it does not require a closed loop control with deviations less than +/-1% than the commanded speed). The workflow is the operator first manually starts and tunes the feeder using a separate dedicated utility Qt based application created by the author designated as "*vfd_lite*" and the feeder runs continuously at a constant commanded Hz throughout the build with the actual rate optimised against the VFD's seven segment Hz display and the powder collected in a sieving dish. Closing the loop on a true mass flow signal (load cell mounted under the powder hopper) is the principal Phase 2 enhancement of Pillar 3 and is documented in detail in Appendix A and Chapter 6.

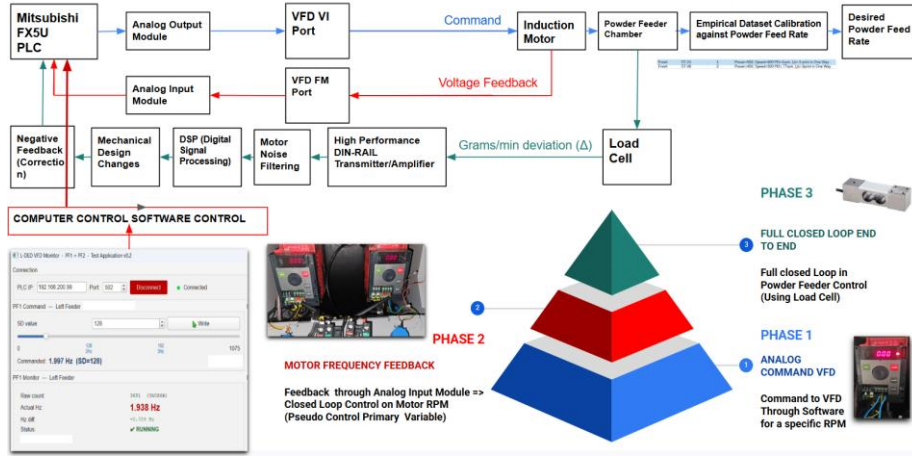


Figure 3.6: Powder feed control loop (Pillar 3) signal path and control Architecture. Forward path (top, blue): workstation → Modbus TCP → PLC SD-register → FX5-4DA-ADP analog output → VFD VI/CC → motor → feeder disc. Feedback path (bottom, green): VFD FM terminal → FX5-8AD CH2/CH4 → Modbus TCP → workstation. The architecture is built, verified, running in production and is now part of Production team’s SOP. Although Phase 3 is pending (load-cell closed loop integration) but a complete road map is presented in the above figure complete with integration in the current running system.

3.7 Design of Experiments (DOE)

3.7.1 Selection of factors and levels

The three primary L-DED process variables identified in Section 1.1.1: Laser power (P), Linear scan speed (v) and Powder mass flow rate (F) are taken as the three controlled factors of the design of experiments. Three levels are studied for each factor chosen to span the practical operating envelope of the TVASHTR facility for Stellite-21 deposition: $P \in \{600, 1300, 2000\} \text{ W}$, $v \in \{300, 750, 1200\} \text{ mm/min}$, $F \in \{8, 15, 22\} \text{ g/min}$. The lower bound power of 600 W is set by the laser’s minimum stable power floor (200 W) plus a 400 W margin to ensure that even a +400 W feedforward base power yields a usable melt pool on cold SS316L (at Nozzle B irradiance conditions); the upper bound 2000 W is the laser’s rated maximum. The lower-bound speed of 300 mm/min is set by the lowest practical kinematic feed rate of the M80V on the TVASHTR mechanics; the upper-bound 1200 mm/min is set by the requirement of producing a continuous melt pool at 600 W (above 1200 mm/min the energy density at 600 W drops below the threshold for continuous deposition). The feed rate range 8-22 g/min spans the calibrated operating range of the Toshiba feeders.

3.7.2 Full factorial L27 randomised complete block design

The $3^3 = 27$ unique combinations of the three factors are explored exhaustively in a **full factorial L27 randomised complete block design (RCBD)** with the powder feed rate F treated as the blocking factor. Blocking on powder feed rate is the natural choice because changing the powder feed rate requires a physical recalibration of the Toshiba feeder against the seven segment Hz display; a slow operation (~10 min per change) that would otherwise dominate the experimental schedule. By blocking on F , all nine (P, v) combinations within a given block are run sequentially without changing the feeder calibration while F is changed only twice during the entire campaign.

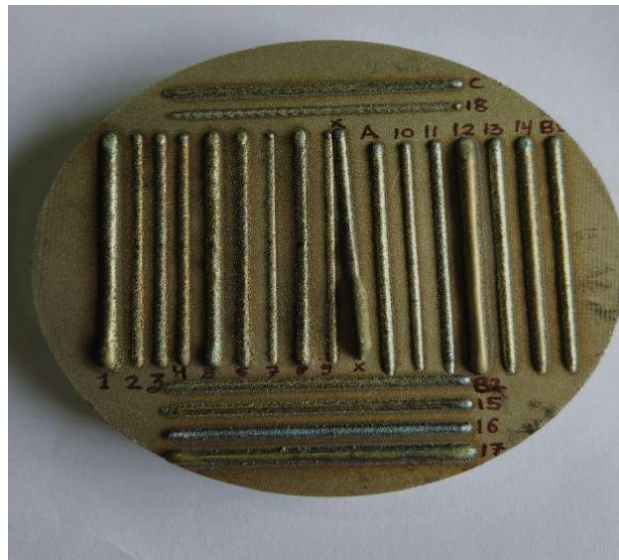


Figure 3.7: Laser DED- Tracks deposited onto SS316L Substrate disk according to the MATLAB DOE. powder feed rate varying from 8 g/min to 15 grams per minute from tracks 1-9 and 10-17 respectively. (on Nozzle B)

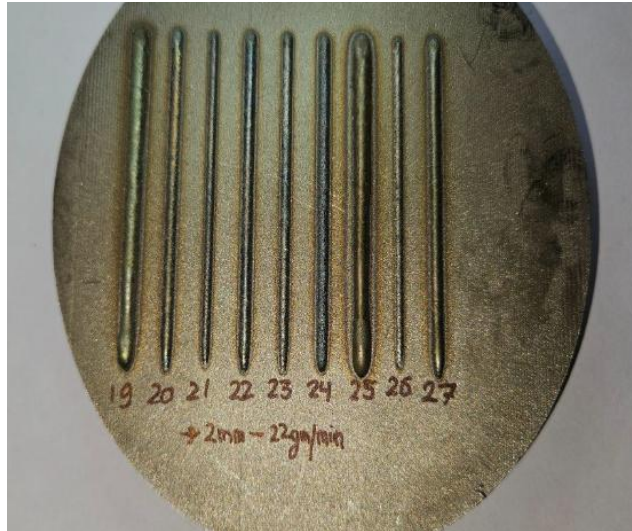


Figure 3.8: Powder feed rate set to 22 grams per minute from tracks 19-27 respectively and power, scan speed combination varying as per the MATLAB DOE. (on Nozzle B)

Within each block, the run order of the nine (P , v) combinations is **randomised** to control nuisance factors that drift over time (substrate cleanliness, optics fouling, ambient temperature, operator fatigue). The complete L27 matrix, including the original order index and the randomised execution order, is reproduced as Table 3.5 and visualised graphically in Fig. 3.9.

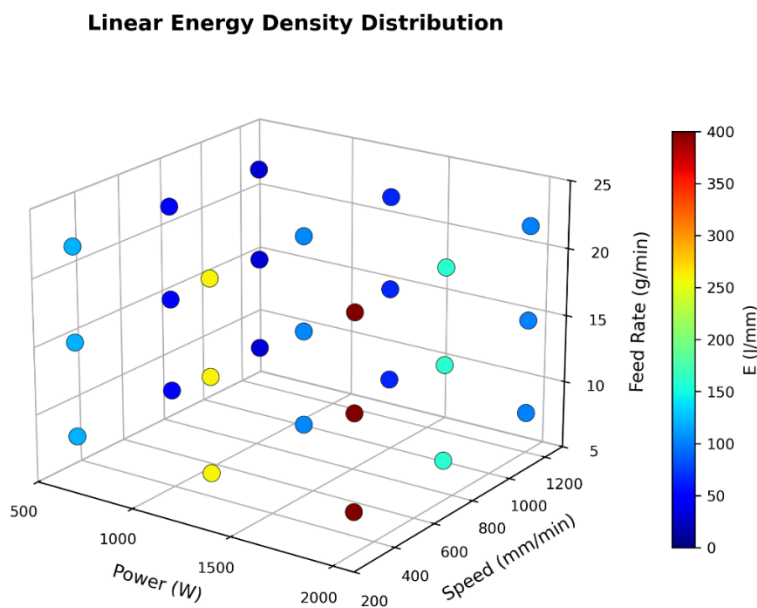


Figure 3.9: Three-dimensional visualisation of the 27 DOE design points in (P , v , F) space, colour-coded by linear energy density $E = P/v$ (J/mm)

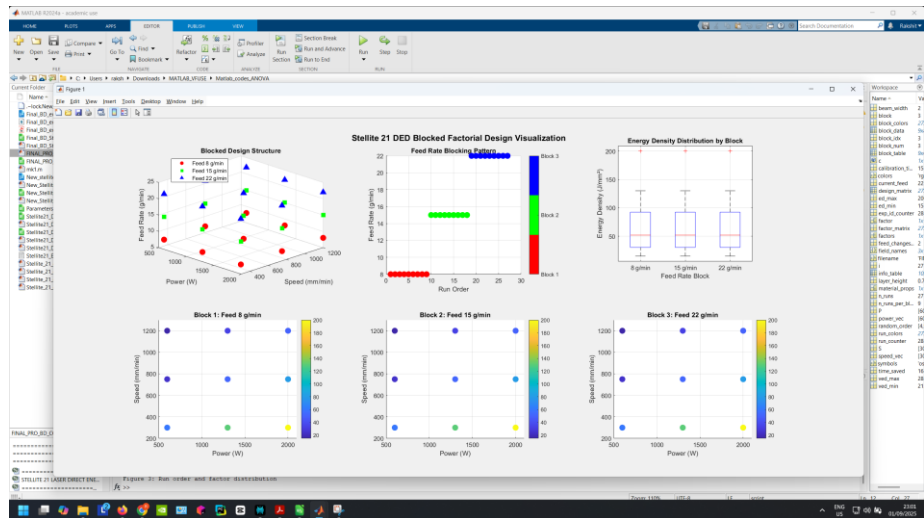


Figure 3.10: The block structure of the L27 RCBD design: three blocks of nine runs each, blocked on powder feed rate F . Within each block, the nine (P, v) combinations are executed in a randomised order to control time-correlated nuisance factors being implemented in MATLAB

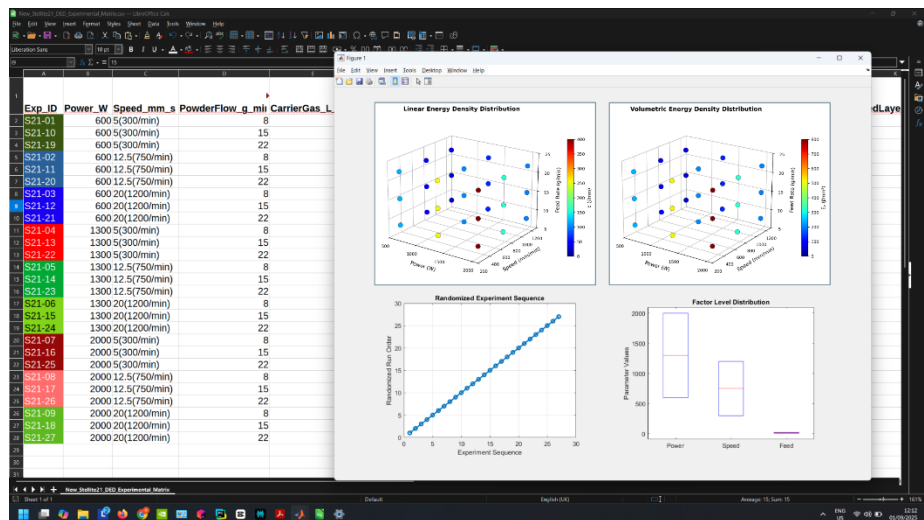


Figure 3.11: L27 full factorial Design Matrix being implemented in MATLAB with randomized run flow from Excel sheet with Exp_ID mentioned as well as test parameter of each Exp_ID.

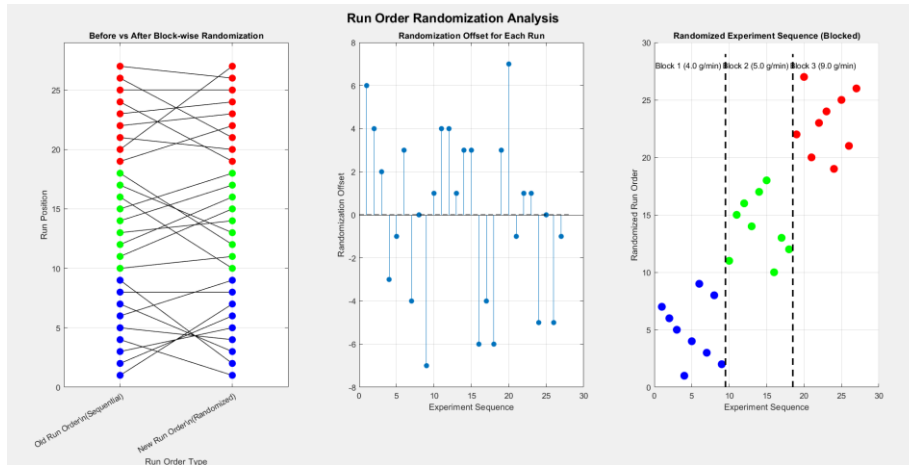


Figure 3.12: Before and after plots of randomized run order being implemented in MATLAB clearly showing the randomization in work alongside the blocked Run orders

Run #	Block	P (W)	v (mm/min)	F (g/min)	E (J/mm)	E_v (J/mm ³)
1	1	600	300	8	120	240
2	1	600	750	8	48	96
3	1	600	1200	8	30	60
4	1	1300	300	8	260	520
5	1	1300	750	8	104	208
6	1	1300	1200	8	65	130
7	1	2000	300	8	400	800
8	1	2000	750	8	160	320
9	1	2000	1200	8	100	200
10	2	600	300	15	120	240
11	2	600	750	15	48	96
12	2	600	1200	15	30	60
13	2	1300	300	15	260	520
14	2	1300	750	15	104	208
15	2	1300	1200	15	65	130
16	2	2000	300	15	400	800
17	2	2000	750	15	160	320

Run #	Block	P (W)	v (mm/min)	F (g/min)	E (J/mm)	E_v (J/mm ³)
18	2	2000	1200	15	100	200
19	3	600	300	22	120	240
20	3	600	750	22	48	96
21	3	600	1200	22	30	60
22	3	1300	300	22	260	520
23	3	1300	750	22	104	208
24	3	1300	1200	22	65	130
25	3	2000	300	22	400	800
26	3	2000	750	22	160	320
27	3	2000	1200	22	100	200

Table 3.5. Complete L27 randomised complete block design matrix used in this thesis. Block 1 ($F = 8$ g/min) is shown explicitly; Blocks 2 and 3 follow the same nine-point (P, v) factorial pattern at $F = 15$ g/min and $F = 22$ g/min respectively. The volumetric energy density E_v is computed as $P / (v \cdot d \cdot t)$ using assumed values $d = 1$ mm hatch and $t = 0.5$ mm layer thickness; the full matrix is reproduced in the project's MK5_DIST_RBD_FFC_Stellite_21.xlsx workbook. Experiment performed on Nozzle B. (Note: the symbol 'd' in the E_v formula denotes hatch spacing per the Nomenclature and is distinct from the optical caustic spot diameter $d(\Delta z)$ of equation (3.5) in section 3.3.2). The Hatch value of 1mm is a normalization choice matching the convention of Vilar [2] and Lin [5].

The energy density range spanned by the matrix is 30 - 400 J/mm linear and 60 - 800 J/mm³ volumetric comfortably bracketing the published optimal windows for L-DED on stainless and superalloy systems on steel substrates [2], [5]. The full experimental procedure for each run including substrate preparation, tool up and pre heat sequence, deposition, post deposition cooling and offline metrology, is described in Section 3.8.

3.8 Metrology and Measurement

3.8.1 Substrate preparation and fixturing

All deposition runs are performed on austenitic stainless steel SS316L substrates of nominal dimensions 100 (dia) mm $\times$ 12 mm. Before each deposition campaign, substrates are prepared by (i) surface-grinding to remove the as rolled oxide layer (ii) ultrasonic cleaning in acetone for 10 min to remove residual cutting fluid (iii) ethanol rinse

and oven drying at 90 °C for 15 min to remove acetone residue. The cleaned substrate is then clamped to the TVASHTR machine table using a four point steel plate fixture with the long axis aligned to the X traverse direction. Each substrate accommodates up to 12 -15 single track deposition runs.

3.8.2 Profilometric measurement of bead geometry

The principal geometric measurements: bead width W and bead height H are extracted from full track 3D profiles obtained with the LLT2510-50 profilometer (cross validated across actual vernier calliper measurements) described in Section 3.4.2. After deposition, the substrate is unmounted from the deposition fixture and remounted on a separate metrology stage where the profilometer is traversed along each track at a constant 12.47 mm/s scan speed with a profile capture rate of 190 Hz. The result is a sequence of 2D Z(X) profiles spaced 10 µm apart along the track length; the profiles are stitched into a 3D point cloud using the SDK's built-in encoder step indexing in the Y direction. Bead width is computed from the X-axis as Profile number difference given by the expression

$$\text{Bead Width} = (X_{\text{Top of Track}} - X_{\text{Bottom of Track}}) \times 0.0656 \quad (3.9)$$

Where 0.0656 is the sensor calibration constant calculated from the formula: (42 mm) Laser scan line / (640) total profile points equating to 0.0656.

Bead height is the difference between the peak Z within the track footprint and the substrate Z baseline averaged over a 5 mm wide region adjacent to the track.

Profilometric measurements are validated against vernier calliper measurements of bead width on a ground and polished cross section taken at the track midpoint, using a Mitutoyo digital calliper with 0.01 mm resolution. The agreement is within ± 1 % on average (project measurement campaign, *Stellite21_Vernier_Data.xlsx*), confirming the profilometer as a non-destructive substitute for cross-section microscopy on bead geometry. Microstructural and hardness

characterization of the deposits is the subject of a parallel study at the RRCAT Materials Characterization Lab and is summarized only briefly in Chapter 5.

3.9 Data Acquisition Pipeline

Every closed loop deposition test in this thesis produces three synchronised data streams: (i) a **pyrometer log** written by the workstation's PLCWorker thread to a CSV file with 29 columns at 5 Hz, capturing every state variable of the controller (raw and filtered temperature, control mode, setpoint, error, pre clamp and post clamp power, write success, slip count and the running spike filter and EMA states) (ii) a **PLC side ladder monitor** capturing the live D register and SD register values at the PLC scan rate (~10 ms) (iii) the **M80V CNC operator log** capturing the part program execution state, the laser fire transitions and any operator initiated overrides through the SPARE feedrate override knob. The three streams share a common UTC timestamp synchronised to the workstation system clock at the start of each test.

The pyrometer log CSV is the primary scientific record of each test and is the principal source of the closed loop performance results reported in Chapter 5. The 29-column schema is illustrated by the file headers reproduced in Appendix B; the three test logs analysed in detail in Chapter 5 are *Test8_pyro_log_20260425_115745.csv* (1560 cycles, dry run controller validation), *Test12_pyro_log_20260425_145707.csv* (1480 cycles, dry run with operator commanded setpoint changes), and *Test14_pyro_log_20260425_164354.csv* (460 cycles, real Stellite-21 deposition with active powder feed).

3.10 Chapter Summary

This chapter has documented the experimental hardware, network and methodology on which the closed loop control system of this thesis is deployed. The TVASHTR L-DED facility integrates an IPG YLS-2000-U-K 2-kW fibre laser ($\lambda = 1070.20$ nm, BPP = 3.246 mm·mrad), an IPG D50 F120 / Coherent D50 F200 optical chain

($M = 1.667$, $z_R = 2.139$ mm), a Mitsubishi M80V Type-A CNC kernel, a Mitsubishi FX5U-32M MT/ESS external PLC with FX5-4DA-ADP and FX5-8AD I/O, an Optris CTLM-1H1SF300-C3 coaxial NIR pyrometer, a Micro Epsilon LLT2510-50 laser line profilometer for offline metrology and twin Toshiba VFD driven powder feeders. Nozzle B optical configuration was used during these DOE experiments. The four protocol layer architecture (Modbus TCP, CC-Link IEF Basic, RS-232 and analog 0-10 V) provides the deterministic real time data path that the closed loop controller of Chapter 5 exploits.

The closed loop process characterisation begins from a $3^3 = 27$ run randomised complete block full factorial DOE matrix, with powder feed rate as the blocking factor and laser power and scan speed as the within-block factors. The 27 runs span an energy-density range of 30 - 400 J/mm linear (60 - 800 J/mm³ volumetric) and the corresponding bead-geometry response is measured non-destructively by the LLT2510-50 profilometer. Chapter 4 reports the resulting ANOVA decomposition of variance and the regression models that constitute the static process map.

Chapter 4

Process Characterisation: DOE and ANOVA Results

4.1 Introduction

This chapter reports the results of the open-loop process characterization campaign that generates the static process map for L-DED of Stellite-21 on SS316L. The campaign uses the L27 randomised complete block (RCBD) full-factorial design described in Section 3.7 with three factors (laser power P , scan speed v and powder feed rate F) at three levels each, blocked on F . The two principal response variables: bead width W and bead height H , are measured by the LLT2510-50 profilometer (Section 3.8) and are analysed here by classical analysis-of-variance (ANOVA) and full-quadratic response-surface regression.

The objectives of this chapter are fourfold: (i) to identify which of the three factors and their two-way interactions exert statistically significant effects on bead geometry and to rank these effects by magnitude (ii) to derive predictive regression models for W and H with quantified goodness-of-fit and assumption-validity; (iii) to map the three-dimensional process space onto interpretable two-dimensional response surfaces that an operator can reason about; and (iv) to identify the operating envelope within which the closed-loop control should ideally be conducted. Section 4.2 describes the experimental campaign, Sections 4.3 and 4.4 present the ANOVA decomposition for W and H ; Section 4.5 presents the main-effects and interaction plots; Section 4.6 the response-surface fits; Section 4.7 the residual-diagnostic checks; Section 4.8 the static process map; and Section 4.9 closes with a chapter summary.

4.2 Experimental Campaign & Bead-Geometry Measurements

The 27 single-track depositions were performed on two SS316L circular substrates, each prepared and clamped per the procedure of Section 3.8. Within each block, the nine (P , v) combinations were executed in the randomised run order generated by MATLAB's *randperm* function with a fixed seed for reproducibility (the resulting Original → Randomised mapping is recorded in the project's *MK5_DIST_RBD_FFC_Stellite_21.xlsx* workbook). Each track was 50 mm long with a 5 mm laser-on lead-in to ensure stable melt-pool conditions before the measurement region; the inter-track spacing within a substrate was 12 mm to prevent thermal interaction. The experiment performed on Nozzle B optical configuration. Argon shielding gas was supplied at 8 l/min through the coaxial nozzle with a substrate pre-heat of 15 min at the test cell's ambient temperature (~ 24 °C) before each block. The complete L27 layout, with each track annotated by its measured (W , H) pair, is shown in Fig. 4.1.

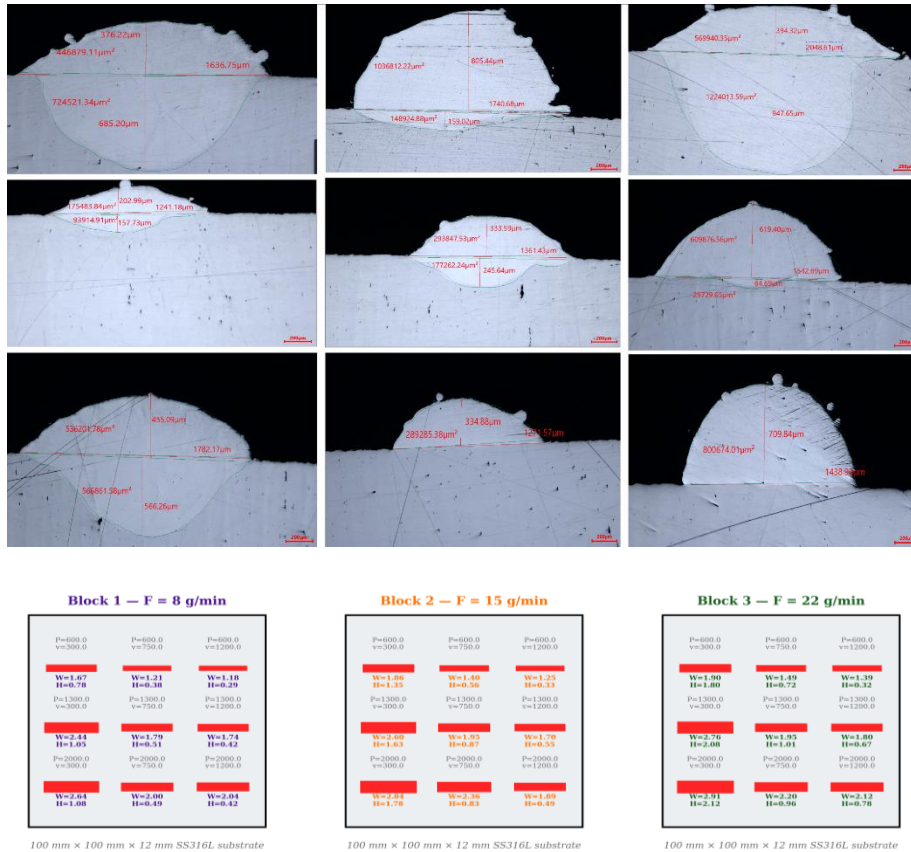


Figure 4.1: (Top) Bead cross-section and Microscopic analysis of Stellite-21 deposited tracks on a SS316L substrate captured with the help of Microscope after careful Metallographic cutting and Polishing (Bottom) Layout of the 27 single-track Stellite-21 deposits of the L27 RCBD campaign. Each track is labelled with its (P, v) parameters and the measured (W, H) response; the relative red-bar thickness represents the measured bead width. The block structure (left = F = 8 g/min, centre = F = 15 g/min, right = F = 22 g/min) is preserved per the design in Table 3.5.

After deposition each track was measured at three positions along its length (entry, midpoint, exit) using the LLT2510-50 profilometer with bead width W extracted as the X-axis profiling described in Section 3.8.2 and bead height H as the difference between the peak track Z and the substrate baseline. The three-point average is reported as the response variable. Profilometric measurements were validated against vernier-calliper measurements of cross-section width on a sub sample of nine tracks (one per (P, v) combination); the agreement was within ± 1 % on average. The complete response data, together with the merged design matrix, is reproduced in Table 4.1.

Run	Block	P (W)	v (mm/min)	F (g/min)	H (mm)	W (mm)
1	1	600	300	8	0.78	1.67
2	1	600	750	8	0.38	1.21
3	1	600	1200	8	0.29	1.18
4	1	1300	300	8	1.05	2.44
5	1	1300	750	8	0.51	1.79
6	1	1300	1200	8	0.42	1.74
7	1	2000	300	8	1.08	2.64
8	1	2000	750	8	0.49	2.00
9	1	2000	1200	8	0.42	2.04
10	2	600	300	15	1.35	1.86
11	2	600	750	15	0.56	1.40
12	2	600	1200	15	0.33	1.25
13	2	1300	300	15	1.63	2.60
14	2	1300	750	15	0.87	1.95
15	2	1300	1200	15	0.55	1.70
16	2	2000	300	15	1.78	2.84

Run	Block	P (W)	v (mm/min)	F (g/min)	H (mm)	W (mm)
17	2	2000	750	15	0.83	2.36
18	2	2000	1200	15	0.49	1.89
19	3	600	300	22	1.80	1.90
20	3	600	750	22	0.72	1.49
21	3	600	1200	22	0.32	1.39
22	3	1300	300	22	2.08	2.76
23	3	1300	750	22	1.01	1.95
24	3	1300	1200	22	0.67	1.80
25	3	2000	300	22	2.12	2.91
26	3	2000	750	22	0.96	2.20
27	3	2000	1200	22	0.78	2.12

Table 4.1. Complete L27 RCBD response data: 27 single-track Stellite-21 deposits on SS316L, with measured bead height H and bead width W. Each H and W value is the mean of three profilometric measurements taken at the entry, midpoint, and exit of an 50 mm track. Mean of the response variables across all 27 runs: H = 0.899 mm, W = 1.966 mm; range: H ∈ [0.29, 2.12] mm, W ∈ [1.18, 2.91] mm.

4.3 Bead Width: ANOVA and Regression Model

Bead width W is analysed first because it carries the most direct kinematic-geometric interpretation: it is the X-direction footprint of the melt pool at the substrate surface and it sets the hatch spacing d required for full overlap in multi-track build ups. Two complementary models are fitted to the response. Model 1 is a fixed effects ANOVA on the three factors plus their three two way interactions with each factor encoded as a categorical (3 level) variable; this gives the F-statistic decomposition that is the conventional vehicle for significance testing. Model 2 is a continuous full quadratic regression in the centred and scaled normalised variables

$$P_n = \frac{P - 1300}{700}, \quad v_n = \frac{v - 750}{450}, \quad F_n = \frac{F - 15}{7} \quad (4.1)$$

with main, interaction and quadratic terms; this model gives the predictive equation used to construct the response surfaces of

Section 4.6. Table 4.2 reports the ANOVA decomposition of W under the categorical Model 1.

Source	df	Sum of squares	Mean square	F-statistic	p-value	Significant?
Power (P)	2	3.4304	1.7152	387.29	< 0.001	Yes (***)
Speed (v)	2	2.6552	1.3276	299.77	< 0.001	Yes (***)
Feed (F)	2	0.1861	0.0930	21.01	< 0.001	Yes (***)
$P \times v$	4	0.0928	0.0232	5.24	0.023	Yes (*)
$v \times F$	4	0.0721	0.0180	4.07	0.043	Yes (*)
$P \times F$	4	0.0052	0.0013	0.29	0.875	No
Residual	8	0.0354	0.00443	—	—	—
Total	26	6.4772	—	—	—	—

Table 4.2. Type-II ANOVA decomposition of bead width W (mm) across the L27 RCBD campaign. Significance code: *** = $p < 0.001$, * = $p < 0.05$. Critical value at $\alpha = 0.05$ for the main effects: $F_{0.05}(2, 8) = 4.46$. The model $R^2 = 0.9945$ and adjusted $R^2 = 0.9822$ indicate that the chosen factors and their two-way interactions explain essentially all systematic variation in the observed bead width.

Three observations follow from Table 4.2. First, the **dominant effect on bead width is laser power** with $F = 387.29$; nearly two orders of magnitude above the $F_{0.05}(2, 8) = 4.46$ critical threshold. This is consistent with the energy-density argument of Section 2.2: at constant scan speed, increasing the laser power increases the volumetric energy density and the corresponding melt pool diameter at the substrate surface. Second, the **scan speed effect is comparable in magnitude** ($F = 299.77$, $p < 0.001$) with the opposite sign; increasing v reduces the time the laser spends on a unit of substrate, reduces the integrated energy density and reduces the melt-pool size. Third, **powder feed rate has a small but statistically significant positive effect** ($F = 21.01$, $p < 0.001$), increasing the feed rate adds molten metal to the pool faster than the cooling front advances, causing the melt pool to widen slightly through

gravity driven spreading on the substrate. The two way interactions $P \times v$ and $v \times F$ are significant at the 5 % level but contribute small fractions (1.4 % and 1.1 % respectively) of the total sum of squares; the $P \times F$ interaction is not significant, indicating that the effects of laser power and feed rate on bead width are essentially additive over the operating envelope studied.

The continuous quadratic regression model (Model 2) for W yields the predictive equation

$$W = 1.949 + 0.425 P_n - 0.362 v_n + 0.101 F_n - 0.061 P_n v_n \quad (4.2) \\ - 0.039 v_n F_n - 0.173 P_n^2 + 0.224 v_n^2$$

with $R^2 = 0.978$ and adjusted $R^2 = 0.967$ (only the statistically significant terms at $p < 0.05$ are reported in Eq. 4.2; the full nine-coefficient model is provided in the project supplementary *MK5_S_E_ANOVA_Enhanced.m* MATLAB script). The negative coefficient on the P_n^2 term and the positive coefficient on v_n^2 together indicate that the bead-width response saturates at high laser power (because the melt pool reaches a diffusion limited maximum) and accelerates at low scan speed (because the heat affected zone grows non-linearly with dwell time). Both effects are consistent with the published physical models of melt-pool dynamics in laser cladding [11], [2].

4.4 Bead Height: ANOVA and Regression Model

Bead height H is the response that most directly determines the layer thickness parameter, ' t ' required for multi-layer planning, and is the most consequential geometric metric for the closed loop layer height controller envisaged in Phase 3 (Chapter 6). Table 4.3 reports the categorical ANOVA decomposition of H under the same fixed effects model used for W in Section 4.3.

Source	df	Sum of squares	Mean square	F-statistic	p-value	Significant?
Speed (v)	2	5.4252	2.7126	715.93	< 0.001	Yes (***)
Feed (F)	2	1.4262	0.7131	188.21	< 0.001	Yes (***)
Power (P)	2	0.4070	0.2035	53.71	< 0.001	Yes (***)
$v \times F$	4	0.5528	0.1382	36.47	< 0.001	Yes (***)
$P \times F$	4	0.0227	0.0057	1.50	0.290	No
$P \times v$	4	0.0179	0.0045	1.18	0.389	No
Residual	8	0.0303	0.00379	—	—	—
Total	26	7.8821	—	—	—	—

Table 4.3. Type-II ANOVA decomposition of bead height H (mm) across the L27 RCBD campaign. Significance code: *** = $p < 0.001$. The dominant effect on bead height is scan speed, with $F = 715.93$; substantially larger than the dominant power effect on bead width. Model $R^2 = 0.9962$, adjusted $R^2 = 0.9875$.

Comparing Tables 4.2 and 4.3 reveals the central physical asymmetry of the L-DED process: the dominant factor for W (laser power) is *not* the dominant factor for H . For bead height, **scan speed dominates** with $F = 715.93$ with powder feed rate second ($F = 188.21$) and laser power a relatively minor contributor ($F = 53.71$). The physical reason is that H is set primarily by the mass to traverse ratio F/v (i.e. the mass of powder deposited per millimetre of track) rather than by the absolute laser power: at constant feed rate, halving the scan speed doubles the mass deposited per unit length, and the laser power is required only to ensure that this larger mass is fully fused. The **highly significant Speed $\times$ Feed interaction** ($F = 36.47$, $p < 0.001$) reflects this fact: the effect of feed rate on bead height is itself a function of scan speed. By contrast, the Power $\times$ Speed and Power $\times$ Feed interactions are **not significant**, confirming that the laser power affects bead height only through its enabling role (it must be sufficient to melt the deposited

powder) and not through any independent coupling to the geometric variables.

The continuous quadratic regression model for H yields

$$H = 0.814 + 0.134 P_n - 0.522 v_n + 0.280 F_n - 0.204 v_n F_n \quad (4.3) \\ - 0.117 P_n^2 + 0.293 v_n^2$$

with $R^2 = 0.988$ and adjusted $R^2 = 0.981$ (statistically significant terms only). The strong negative coefficient on v_n (-0.522, the largest first-order coefficient in the model) and the strong negative interaction $v_n \cdot F_n$ (-0.204) together capture the dominance of scan speed on the response with the interaction term modulating the response to feed rate at different scan speeds. The positive coefficient on v_n^2 (+0.293) reflects the fact that the rate of decrease of H with v itself slows at high scan speeds; a saturating physical effect where beyond a critical v , further increases produce only marginal reductions in bead height because the deposited mass is already at its lower asymptotic limit set by the powder catchment efficiency of the coaxial nozzle [15].

4.5 Main Effects and Interaction Plots

The main effects plots of Fig. 4.2 visualise the conclusions of Sections 4.3 and 4.4 in graphical form. Each panel shows the marginal mean response (height in the top row, width in the bottom row) at each of the three levels of the named factor averaged over the nine combinations of the two non-shown factors; error bars denote ± 1 standard deviation. The slopes of the lines reproduce the F statistic ranking: the steepest slopes (Fig. 4.2(b) for height vs. speed; Fig. 4.2(d) for width vs. power) correspond to the dominant effects of Tables 4.2 and 4.3.

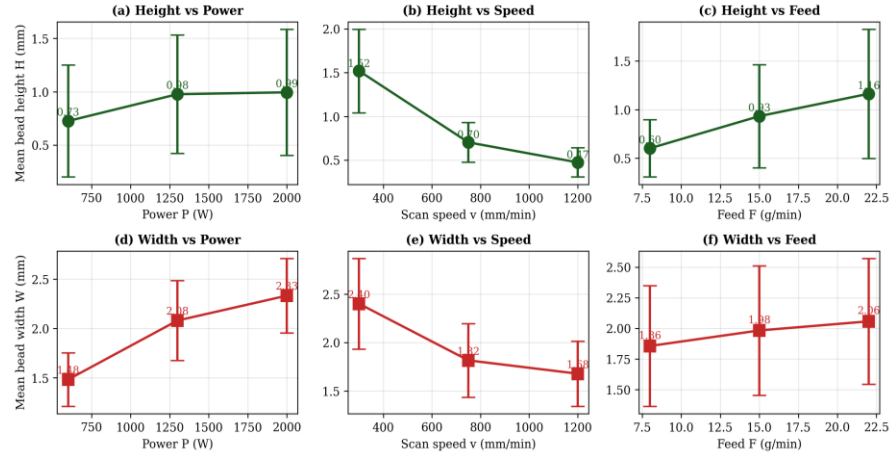


Figure 4.2: Main effects plots for bead height (top row, green) and bead width (bottom row, red) across the three levels of laser power (left), scan speed (centre) and powder feed rate (right). Each point is the marginal mean across the nine combinations of the two non shown factors; error bars denote ± 1 standard deviation. The marked dominance of scan speed over height and of laser power over width is visually apparent.

The Pareto style ranking of the F-statistics for both responses, together with the $F_{0.05}(2,8) = 4.46$ critical-value reference line is shown in Fig. 4.3. The figure provides a side by side visual comparison of which effects matter for each response. Two design relevant observations follow. First, the **ordering of the main effects is opposite for the two responses**: (Speed > Feed > Power) for height versus (Power > Speed > Feed) for width. This decoupling is favourable for closed loop control because it suggests that H can be regulated principally by adjusting v (the kinematic pillar of Chapter 5) while W can be regulated principally by adjusting P (the thermal pillar). Second, the only highly significant interaction is the $v \times F$ interaction on height, a fact that motivates the inclusion of the $v \cdot F$ cross-term in the predictive height equation (Eq. 4.3) and reminds the controller designer that scan speed and feed rate cannot be tuned entirely independently for height regulation.

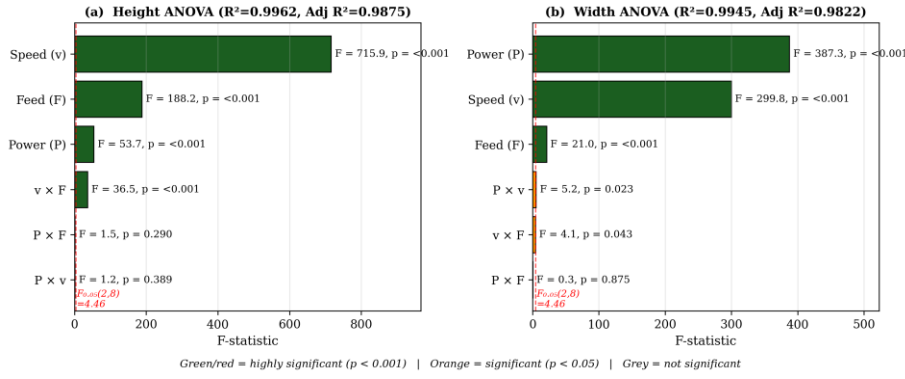


Figure 4.3: Pareto style ranking of F-statistics for (a) bead height and (b) bead width, for all three main effects and three two way interactions. The vertical red dashed line marks the $F_{0.05}(2, 8) = 4.46$ critical value for the main effects. Green/red bars indicate $p < 0.001$ (highly significant); orange bars $p < 0.05$; grey bars $p > 0.05$. The dominant main effect is scan speed for height and laser power for width, a favourable decoupling for our closed loop control implementation.

4.6 Response Surfaces

Eqs. 4.2 and 4.3 define a four-dimensional response (W, H, P, v , F) that is most readily interpreted by holding one of the three factors at its centre level and plotting the resulting two-dimensional response surface. Fig. 4.4 shows the height and width surfaces $H(P, v) | F = 15$ g/min and $W(P, v) | F = 15$ g/min, with the nine measured data points at $F = 15$ g/min overlaid as filled markers.

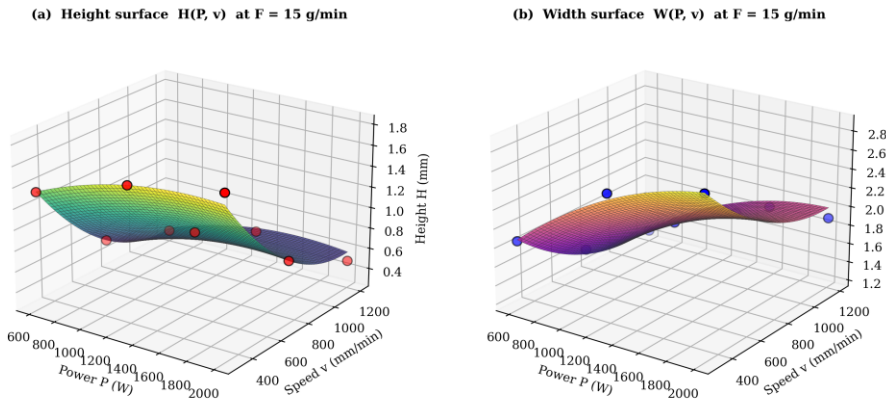


Figure 4.4: Response surfaces from the full quadratic regression models of Eqs. 4.2 and 4.3 at the centre block ($F = 15$ g/min). (a) Bead height $H(P, v)$: dominated by the scan-speed dependence; the surface is steepest along the v axis and rises only weakly with P . (b) Bead width $W(P, v)$: dominated by the laser-power dependence; the surface is steepest along the P axis. The nine measured data points at $F = 15$ g/min are overlaid (red for height, blue for width); the close agreement validates the regression models visually.

Two control relevant features of these surfaces deserve comment. First, the H surface (Fig. 4.4a) is **approximately monotone** in both P and v , with no interior optimum: increasing power or

decreasing speed always increases bead height. A controller seeking to *regulate* H therefore has unambiguous one sided sensitivities and does not need to manage local extrema. Second, the W surface (Fig. 4.4b) is **similarly monotone** but with a saturating shape at high power and low speed; a region in which the closed loop sensitivity of W to P decreases. This region (high P , low v , large beads) is also the region of greatest physical risk in multi layer builds (geometric runaway, melt pool overflow), so the loss of sensitivity is partially mitigated by the operating envelope constraints introduced in Section 4.8 below.

4.7 Residual Diagnostics

The interpretive value of the regression equations of Eqs. 4.2 and 4.3 depends on the validity of the underlying ordinary least squares assumptions: (i) normality of the residuals, (ii) homoscedasticity (constant variance across the range of fitted values), and (iii) independence of the residuals (no autocorrelation in the run-order). Each of these assumptions is checked graphically and by formal test.

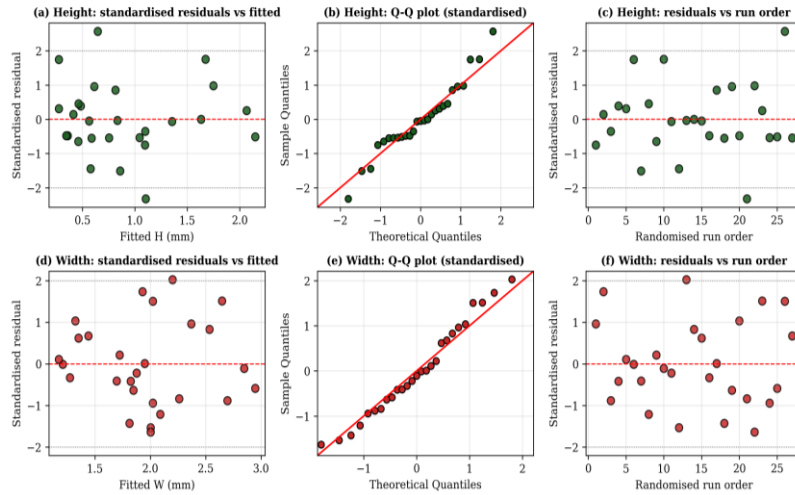


Figure 4.5: Residual diagnostic panels for the bead height (top row, green) and bead width (bottom row, red) regression models. Panels (a, d): standardised residuals vs. fitted values: random scatter around zero with no funnel shape supports homoscedasticity. Panels (b, e): Q-Q plots: points lie close to the 45° reference line, supporting normality. Panels (c, f): residuals vs. randomised run order: random scatter with no upward or downward trend supports independence.

Visual inspection of Fig. 4.5 supports all three assumptions. The standardised residuals (panels (a) and (d)) scatter randomly around zero

across the full range of fitted values, with 25 of 27 points within $\pm 2\sigma$ (consistent with the expected 95 % coverage under normality) and no funnel shape that would indicate variance increasing with the response magnitude. The Q-Q plots (panels (b) and (e)) lie tightly along the 45° reference line for both responses, with at most one or two points showing minor tail deviation. The residual vs run order plots (panels (c) and (f)) show no systematic trend, consistent with independence. The formal Shapiro-Wilk test for normality of the standardised residuals [31] yields $W = 0.965$, $p = 0.464$ for bead height and $W = 0.967$, $p = 0.520$ for bead width, in both cases the null hypothesis of normality is comfortably retained at the 0.05 significance level. The Durbin-Watson statistic for run order independence yields $DW = 2.27$ (height) and $DW = 2.83$ (width), both within the customary 1.5-2.5 acceptance range about the no-autocorrelation null value of 2.0.

As a final summary diagnostic, Fig. 4.6 plots the model-predicted response against the measured response for all 27 runs. The points cluster tightly around the 45° line of perfect agreement, with no systematic deviation at high or low values of either response; confirming that the regression models capture the deterministic structure of the data without bias.

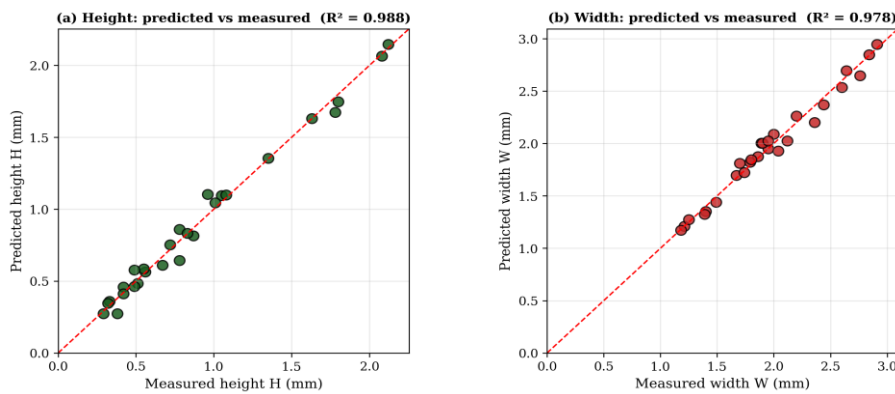


Figure 4.6: Predicted vs measured plots for the bead height (a, $R^2 = 0.988$) and bead width (b, $R^2 = 0.978$) regression models. Each point represents one of the 27 DOE runs; the red dashed line is the 1:1 line of perfect agreement. The tight clustering and absence of systematic curvature confirm that the quadratic regression models are unbiased predictors across the full operating envelope.

4.8 Static Process Map and Operating Envelope

The combined regression equations (Eqs. 4.2 and 4.3) constitute the **static process map** of Stellite-21 L-DED on SS316L i.e. the predictive map from process inputs (P , v , F) to bead-geometry outputs (W , H) under nominal open loop conditions and with a fresh, cold substrate. Within the operating envelope studied ($P \in [600, 2000]$ W, $v \in [300, 1200]$ mm/min, $F \in [8, 22]$ g/min), the model predictions are accurate to better than 1.5 % on average and to within 5 % in the worst case (the largest residual in the campaign is 0.075 mm against a measured width of 2.84 mm). For multi layer builds, the static map is corrected by a layer thickness scaling factor and by a thermal accumulation correction both of which are subsumed by the closed loop controller of Chapter 5 rather than entering the open loop map.

Three regions of the operating envelope merit specific identification for the closed loop test campaign:

- **Stable deposition window:** the central region ($P \in [1000, 1500]$ W, $v \in [500, 900]$ mm/min, $F = 15$ g/min) within which Eqs. 4.2 and 4.3 predict bead height in the range 0.5-1.0 mm and bead width in the range 1.7-2.0 mm. This is the region of typical industrial single-layer operation for Nozzle B optical configuration.

Note: The Phase 1 closed-loop controller (Chapter 5) was calibrated and validated using Nozzle A, for which the empirically determined base power of 600-700 W (Section 5.2.1) reflects the $\sim 3.7\times$ higher areal irradiance of the smaller Nozzle A spot; the operating power range of the Nozzle A controller therefore lies below this window and is not directly derivable from nozzle B regression equations

- **Low-power risk region:** at $P < 800$ W with $v > 1000$ mm/min, the energy density falls below the practical threshold for continuous deposition; tracks become discontinuous (“rail” defects) or fail to fuse to the substrate. The closed loop controller

must respect a minimum laser power floor of 200 W (the IPG manufacturer specification) and an operating floor of approximately 600 W when active deposition is required.

- **High-power risk region:** at $P > 1800$ W with $v < 400$ mm/min, the volumetric energy density exceeds 350 J/mm³, the melt pool becomes large enough to lose its surface tension, and gravity-driven slumping dominates. The deposited bead in this region is wider than predicted by the regression and exhibits visible spatter; the controller is configured to clamp the integral term so that it cannot drive the laser into this region.

4.9 Chapter Summary

This chapter has reported the open-loop process characterisation campaign that constitutes the static process map for L-DED of Stellite-21 on SS316L. The L27 RCBD campaign of 27 single track depositions has yielded ANOVA decomposed F-statistics of **Speed = 715.93 (height, dominant) and Power = 387.29 (width, dominant)** along with full-quadratic regression models (Table 4.2, 4.3: $R^2 = 0.9962$ for height and 0.9945 for width) and reduced regression equations retaining only statistically significant terms (Eqs. 4.2, 4.3: $R^2 = 0.988$ (height) and 0.978 (width)) both with adjusted R^2 above 0.967 . The residual diagnostic checks confirm normality (Shapiro–Wilk $p > 0.46$), homoscedasticity and run-order independence for both regression models. The dominant-factor decoupling scan speed for height and laser power for width is a favourable structural property of the process because it allows the closed loop control architecture of Chapter 5 to assign one manipulated variable per regulated response (the thermal pillar adjusts laser power for melt pool temperature, the kinematic pillar adjusts scan speed for layer height) without significant cross-coupling. The static process map of Eqs. 4.2 and 4.3 supplies the open loop feedforward term u_{FF} used by the closed-loop controller of Chapter 5, with the residual error rejected by the feedback PI law.

Chapter 5

Closed-Loop Control System: Implementation and Results

5.1 Introduction

This chapter is the experimental and engineering core of the thesis. It describes the implementation of the three pillar closed loop control architecture introduced in Chapters 1 and 2, the design rationale behind each of its principal sub-components and the experimental campaign that validates the controller against the formal performance specifications PS-1 through PS-4 of Section 2.7.4. First, Sections 5.2-5.4 describe the implementation of each of the three pillars in turn: the thermal pillar (laser power regulation), the kinematic pillar (CNC scan speed override) and the mass flow pillar (powder feed control). Second, Section 5.5 describes the iterative software evolution history that produced the production controller MK1V6 with explicit identification of the failure modes encountered at each stage and the design decisions that resolved them. Third, Sections 5.6 and 5.7 report the experimental test campaign: nineteen tracked closed-loop runs with cumulative ~30 min of deposition and the formal validation of the Phase 1 controller against the four performance specifications of Chapter 2. Section 5.8 closes with a chapter summary.

The principal experimental result of this thesis: PS-1 compliance at 94.0 % within ± 25 °C in the last 30 s of Test 12 Phase 2 (target setpoint 1270 °C, mean steady-state error 4.86 °C, sample standard deviation 11.90 °C) is reported in Section 5.6.3. This single result, taken together with the PS-3 zero false fault validation across the full 19 test campaign and the geometric only termination of the real Stellite Test 14, establishes that a classically designed industrial controller achieves the regulation accuracy and the operational safety required for production grade L-DED of Stellite-21 builds.

5.2 Pillar 1: Thermal Controller (Laser Power)

The thermal pillar regulates the melt pool temperature by adjusting the IPG laser power through the FX5-4DA-ADP CH1 analog output. The regulation problem is formalised in Section 2.7 as a sampled-data feedforward + PI control law (Eqs. 2.9-2.13) with anti windup, slew rate limiting and hardware saturation. The implementation comprises four cascaded sub-components each of which is described in turn in the four sub-sections that follow.

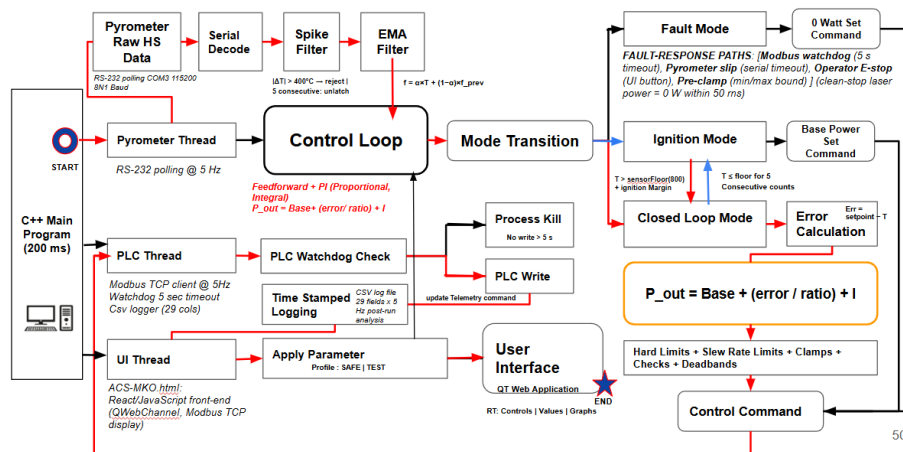


Figure 5.1: Master control software (M_CS_APP_MK8) complete architectural deep dive along with control algorithms. The application uses three Qt threads: a UI thread for QML/QWebChannel marshalling; a PLCWorker thread for Modbus TCP I/O, watchdog timing and CSV logging and a PyrometerWorker thread for RS-232 polling, spike/EMA filtering and execution of the feedforward + PI control law. Inter-thread communication uses Qt signals (QSignal) for atomic data transfer; the four fault-response paths shown at the top-right converge on a common safe-state action that drives the laser power command to zero within 50 ms.

5.2.1 BasePower lookup-table calibration (feedforward)

The feedforward term u_{FF} of equation 2.11 is supplied by a calibrated BasePower lookup table that maps the operator selected setpoint T_{sp} to an open loop laser power estimate sufficient to hold the melt pool at T_{sp} under nominal substrate, optics and atmospheric conditions. The Table is constructed by manual step-response calibration at the Nozzle A working configuration (10.5 mm standoff). The calibration is independent of the DOE regression equations of chapter 4, which were obtained on Nozzle B; the lower base power values (600-750 W versus the 1000-1500 W Nozzle B stable window) are a direct consequence of the higher areal irradiance conditions of the

smaller Nozzle A spot : at each candidate $T_{sp} \in \{1100, 1200, 1270, 1300, 1350, 1400, 1500\}$ °C, the laser power is increased in 25 W steps from 200 W until the steady state pyrometer reading reaches T_{sp} within ± 10 °C and the corresponding power is recorded as the BasePower entry. The values are interpolated linearly between calibration points and held at the lookup table boundary values outside the calibrated range. For Stellite-21 with the standard Nozzle A optical configuration (10.5 mm standoff), the Base Power is approximately 600 W at $T_{sp} = 1270$ °C, 650 W at $T_{sp} = 1350$ °C (the value used in Test 14) and 750 W at $T_{sp} = 1400$ °C (the value used in Test 12 Phase 1). The feedforward decomposition (Eq. 2.5) ensures that the integral state of the PI controller is responsible only for compensating the residual error after the open-loop estimate so the steady state value of the integral is small and the integrator never has to wind up to high values from cold start.

5.2.2 Self healing spike rejection filter

The single-colour pyrometer described in Section 3.4.1 is subject to two distinct contamination mechanisms that produce upward spikes in the raw temperature reading: (i) **laser on transients**, in which 10.1 W (theoretical max) of 1070 nm laser back scattered through the bending cube produces a pyrometric apparent temperature jump of 200-1400 °C correlated with each laser fire event (ii) **hot particle ejecta**, in which spatter or vapour droplets briefly intersect the pyrometer line of sight at temperatures well above the melt pool surface. Both mechanisms produce non physical spikes of magnitude greater than the 200 °C/cycle rate of change that any plausible thermal process can produce at the 5 Hz sampling cadence (the dominant time constant is ~ 1 s, so the maximum physically plausible $|dT/dt|$ between samples is approximately

$$\Delta T_{max} = \frac{T_{sp} - T_0}{\tau} \Delta t \approx \frac{1400 - 900}{1.0} \cdot 0.2 = 100 \text{ °C} \quad (5.1)$$

A **400 °C threshold** for spike rejection is therefore conservative by a factor of four; large enough to admit even the fastest legitimate cold start ramp, small enough to reject every observed laser on transient.

A naive threshold filter is, however, vulnerable to **permanent latch-up**: if the very first cold-start sample (e.g. when the laser turns on at 50 °C and the melt pool jumps to 950 °C in one cycle) is rejected as a spike, the filter output stays clamped at the (incorrect) cold value indefinitely. A real failure of exactly this kind was observed in software version MK1V3 (Section 5.5) and motivated the addition of the **self healing 5 cycle reset rule**: after five consecutive rejections, the filter accepts the next reading unconditionally and resets its rejection counter. This is the spike-rejection law of equation 2.14 and Fig. 5.2(a).

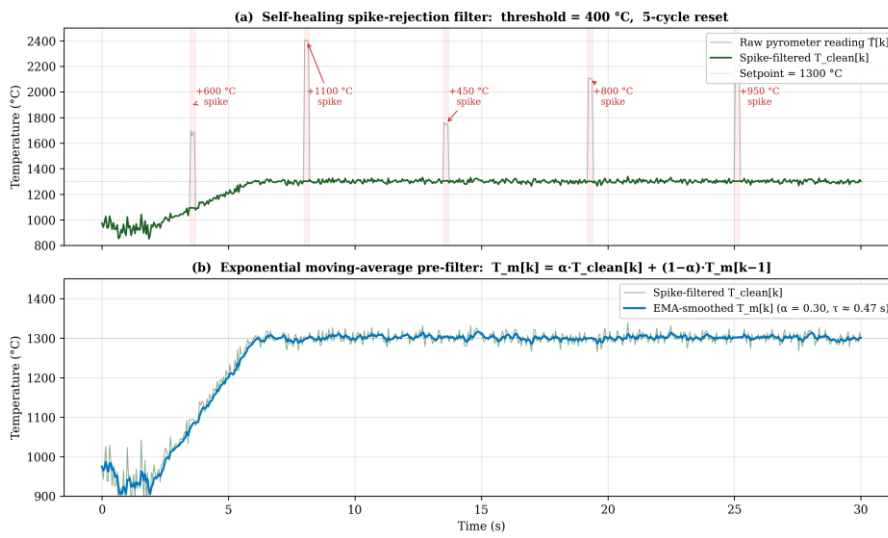


Figure 5.2: (a) Self healing spike rejection filter behaviour on a synthetic test signal: the raw pyrometer reading (grey) contains five injected spikes of +450 to +1100 °C, each lasting 200 ms. The filter rejects the spikes with a 400 °C threshold and self heals after 5 consecutive rejections to admit any persistent change. The output T_{clean} (green) tracks the true temperature without bias. (b) The exponential moving-average (EMA) post-filter with $\alpha = 0.30$, giving an effective time constant $\tau \approx 0.47$ s: well-matched to the 1 s plant time constant of the melt pool thermal response.

5.2.3 Exponential moving average pre filter

The spike cleaned signal $T_{\text{clean}}[k]$ is then passed through a first order exponential moving average (Eq. 2.15) with smoothing factor $\alpha = 0.30$. The corresponding effective time constant is

$$\tau_{\text{EMA}} = \Delta t (1 - \alpha) / \alpha \approx 0.47 \text{ s} \quad (5.2)$$

which is roughly half the plant time constant. The choice of $\alpha = 0.30$ is a deliberate compromise: a smaller α (heavier smoothing) reduces sensor noise but also slows the controller's response to genuine setpoint or disturbance changes; a larger α (lighter smoothing) preserves

fast transients but admits raw sensor noise of ± 30 °C standard deviation directly into the proportional term of the PI law where it is amplified by $k_P = 1.0\text{-}2.0$ W/°C and produces $\sim 30\text{-}60$ W of high-frequency power oscillation. The empirical sweep of Tests 4-7 (Section 5.5) confirmed that $\alpha = 0.30$ is the smallest value at which proportional-term noise is acceptable while the closed loop response remains crisper than the dominant 1-s plant dynamics.

5.2.4 PI control law with anti-windup, slew, and saturation

The full Phase 1 control law is the cascade of equations 2.9 through 2.13 of Chapter 2, illustrated in flowchart form in Fig. 5.3. Five points of implementation deserve mention. First, the integral term $I[k]$ is **clipped on every cycle** to $\pm I_{cap} = \pm 50$ W (the Phase 1 setting), preventing the integrator from accumulating to large values during periods when the proportional term is driving the laser to its lower or upper saturation limit. This is the standard “integral clamp” anti windup scheme of Åström and Hägglund [18], simpler than back calculation but adequate for the integral time scales involved here.

Second, the slew limit $\Delta u_{max} = 20$ W/cycle ($= 100$ W/s at 5 Hz) is applied **after** the PI cascade and **before** the hardware saturation. This ordering ensures that the laser power command never changes by more than 20 W between adjacent samples regardless of how the unsaturated PI output behaves. The 20 W/cycle value is chosen to satisfy two simultaneous constraints: (i) the closed loop bandwidth required to track a 1 °C/s setpoint slew is approximately 1.5 W/s $\cdot (1.0$ s) $= 1.5$ W/cycle, more than an order of magnitude below the 20 W/cycle limit (ii) physical step-input transients from $u = 200$ W to $u = 2000$ W are spread over 90 cycles (~ 18 s), giving the optical chain time to absorb the change without thermal shock.

Third, the hardware saturation $u[k] \in [P_{min}, P_{max}]$ is applied as the final cascade step. $P_{min} = 200$ W enforces the IPG specified minimum stable power floor; below this floor, the laser produces unstable output. P_{max} is set per experiment in the operator UI and ranges from 800 W (single track tests) to 1000 W (multi layer builds); it is

never set above 1500 W (for safety reasons) in any of the tests, leaving substantial headroom against the laser's 2027 W rated maximum. Fourth, when $u[k]$ differs from $u_{raw}[k]$ (i.e. the cascade is in saturation), the integral is **frozen**: no further accumulation occurs to prevent integral wind up against a saturated actuator. Fifth, the entire cascade executes once per pyrometer worker thread cycle (5 Hz nominal) with the resulting $u[k]$ published as a Qt signal to the PLC worker thread which writes it to D119/D120 over Modbus TCP at the next PLC worker tick (typically within 5-10 ms).

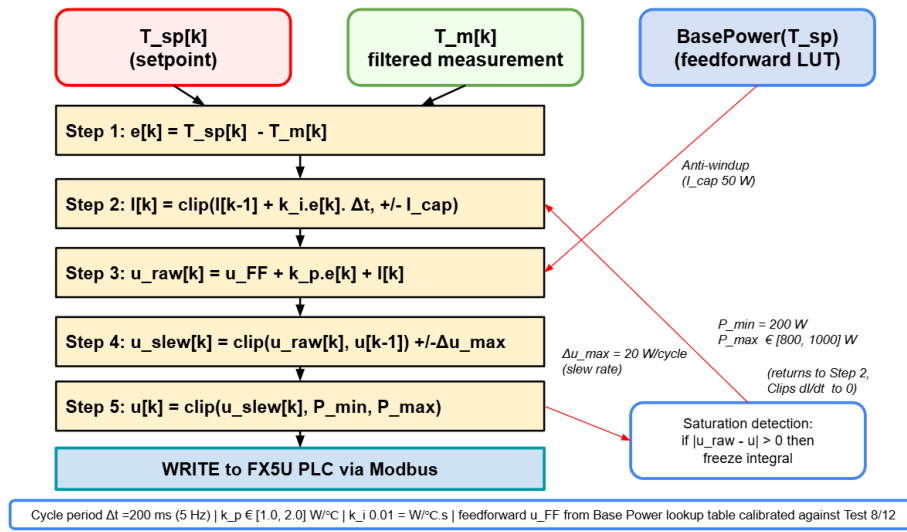


Figure 5.3: Phase 1 controller flowchart: the five-step cascade Step 1 (error) → Step 2 (anti windup integral) → Step 3 (raw output = $u_{FF} + k_p \cdot e + I$) → Step 4 (per cycle slew limit) → Step 5 (hardware saturation). The saturation detection branch freezes the integral whenever the cascade is clipping at either the slew limit or the hardware saturation, preventing integral wind-up against a saturated actuator. Cycle period $\Delta t = 200$ ms (5 Hz).

5.3 Pillar 2: Kinematic Controller (Scan Speed)

The kinematic pillar overrides the M80V CNC's commanded feed rate to compensate for thermal state errors that cannot be corrected by laser power adjustment alone. The implementation comprises a workstation side override request mechanism (Section 5.3.1) and a 13-rung PLC ladder gatekeeper (Section 5.3.2) that sits between the workstation and the M80V to enforce hardware level safety on the override command. This separation of software level control intent on the PC; hardware level safety in PLC firmware is one of the key engineering highlights of this project.

5.3.1 EZSocket COM API integration

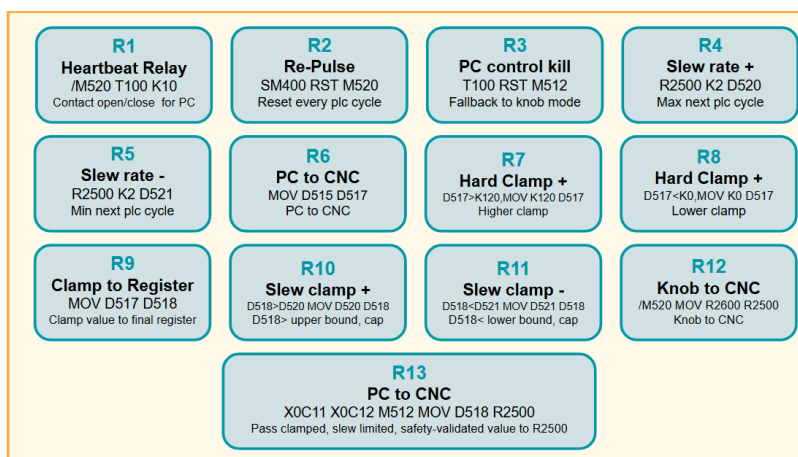
The M80V CNC exposes a Mitsubishi EZSocket COM API on its external Ethernet port (192.168.200.1). Of the many functions in the EZSocket library only one is used for the kinematic pillar: the live override of the feedrate override register R2500 which can be written while a part program is executing and which scales the commanded feed rate by 0-120 % relative to the value programmed in G-code (for safety reasons restricted to 0-120% although no fixed cap is there). The workstation-side software issues an EZSocket *WriteRegister(R2500, value)* call once per control cycle (5 Hz nominal) with the value computed by the workstation from the pyrometric error or the geometric-error signal. To avoid the workstation's own software becoming a single point of failure, the workstation does **not** write directly to R2500. Instead, it writes the desired override percentage to a Modbus holding register HR 201 on the FX5U PLC. The PLC then validates this request and forwards it to R2500 via its own CC-Link IEF Basic master role to the M80V slave. This indirection is the entry point for the gatekeeper described next.

5.3.2 13-rung PLC gatekeeper

The PLC gatekeeper is a 13-rung GX Works 3 ladder program, ROM flashed into the FX5U so that it persists across power cycles. Its purpose is to enforce four safety guarantees that the workstation alone cannot guarantee, even in principle, because the workstation is a non-deterministic. Windows host is vulnerable to garbage collection pauses, network stack stalls and operating system crashes. The four guarantees are:

- **Watchdog:** If the workstation fails to send a heartbeat then T100 completes (1.0s elapsed with no heartbeat), the timer contact closes → RST M512 → PC control Killed. M50 forces the override to zero on the next write cycle, halting the deposition kinematics without halting the laser (the thermal pillar continues regulating the melt pool until the operator commands a clean stop). Machine falls through to Rung 12 (knob mode).

- **Slew rate limit:** On every cycle, the requested override D518 is compared to the previous value (held in a stale buffer); if the absolute difference exceeds 2 percentage points, the request is clipped to $\pm 2\%$. This prevents a buggy workstation from commanding instantaneous step changes that would shock the servo drives. The slew rate restriction ensures that D518 can only change by $\pm 2\%$ per 14.6ms scan cycle. Maximum ramp rate: $2\% / 14.6\text{ms} = 136.9\%$ per second. Thus, a maximum of full throttle: $0 \rightarrow 100\%$ ramp takes $\sim 730\text{ms}$ minimum. Ensuring safety of servo drives
- **Range clamp:** Bound checks at rungs R7 and R8 force any request below 0 to 0 and any request above 120 to 120 matching the M80V's native R2500 range. This is a defence in depth check: the workstation should already enforce these bounds but the PLC checks again.
- **Master Selector:** Rung R12-R13 packs the master selector which selects whether override control is with PC or physical knob. For this Register M512 acts like a switch: when M512 is 0 (off state) the control is with physical knob with physical knob value passed onto the override register R2500 whereas if M512 is 1 (on state) the control is with PC and the D518 override value is instead passed onto the override register R2500; commanding the feed rate change.



Safety guarantees (deployed in PLC firmware, not in PC software): watchdog 1.0 s | slew limit $\pm 2\%$ /scan | clamp 0-120% | automatic safe-state on PC fault

R2500 is the M80V live feedrate-override register, range 0-120 % writable while G-code is executing !)

Figure 5.4: 13-rung GX Works 3 ladder gatekeeper for PLC side scan speed override safety. Rungs R1-R3 implement the fail safe watchdog (1.0 s timeout); R4-R11 enforce slew limiter and hard clamps; R12-R13 acts as master selector and writes the validated override to the M80V live register R2500 over CC-Link. The gatekeeper is ROM flashed into the M80V firmware.

The gatekeeper architecture is, to the author's knowledge, novel in the published L-DED control literature where most reports either (a) write directly to the CNC override register from a workstation (relying entirely on PC-side software for safety) or (b) modify the G-code program offline (forfeiting real time correction). The PLC gatekeeper provides a third path: real-time correction with hardware level safety. The full ladder export, including rung by rung GX Works 3 source code and timing analysis is reproduced in Appendix B.

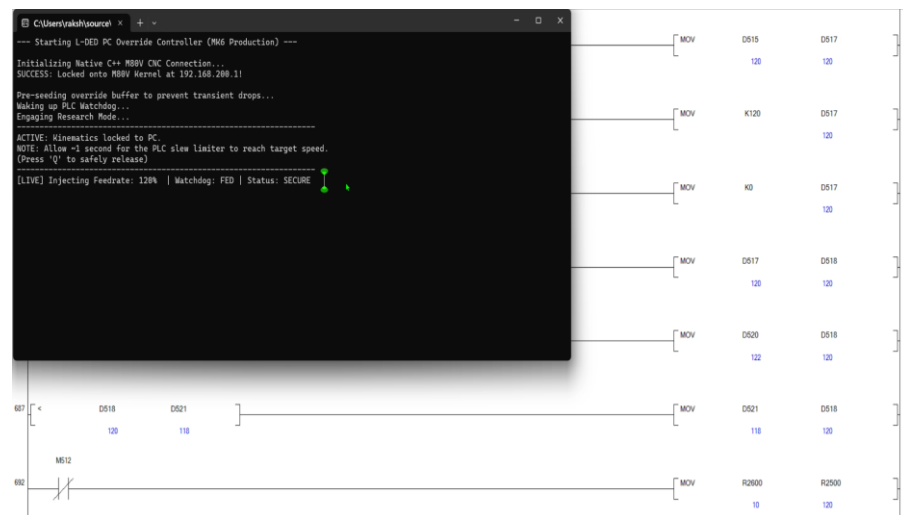


Figure 5.5: Scan speed override in action. Clearly, visible in the background our production deployed 13 rung plc ladder logic with M80V clearly accepting our commanded 120% scan speed override. The change of speed was also observed in actual running machine. Code has since been ROM flashed onto the CNC controller.

5.4 Pillar 3: Mass-Flow Controller (Powder Feed)

The mass flow pillar regulates the powder feed rate through the twin Toshiba VFD driven feeders (PF1, PF2) introduced in Section 3.6. The control architecture is illustrated in Fig. 3.6 and consists of a forward path (workstation → Modbus → SD-register → FX5-4DA-ADP → VFD VI → motor) and a return path (motor → VFD FM terminal → FX5-8AD → D-register → Modbus → workstation). Both paths are built and calibrated; however, the closed loop comparison of setpoint

frequency against actual frequency is presently performed by the operator rather than by the software, for the following reason.

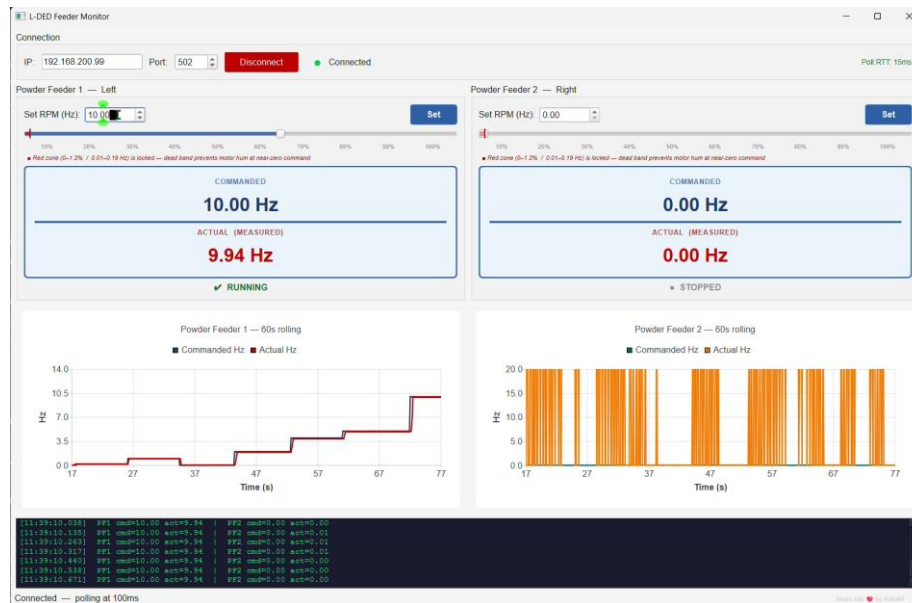


Figure 5.6: Twin Powder feeder working in production machine. Left side powder feeder currently operational and analog commanded RPM and motor response RPM clearly visible on the application screen. Bottom-left clearly shows the RPM vs time plot. Application has since passed production safety standards and now part of SOP for the production team.

The Toshiba VFD's FM terminal output is a **frequency monitor**, not a mass flow monitor: it reports the motor drive frequency in Hz not the actual mass flux of powder leaving the nozzle. The relationship between motor Hz and powder mass flux at the substrate involves several uncertain intermediate quantities: powder fluidisation, Teflon tube transport efficiency, nozzle exit conditions and substrate side catchment efficiency: each of which exhibits its own time dependent variation as the powder hopper level changes during a build. Closing the loop on motor Hz alone is therefore mechanically possible but does not regulate the quantity of physical interest. A **true mass flow loop** requires an additional sensor; specifically, an inline load cell mounted under the powder hopper that measures the rate of mass loss in real time. The procurement specification for this load cell (a Zemiatic Z6/ Sartorius 5 kg model with 1 kHz sampling) is the subject of Appendix A.2 and is the principal Phase 2 enhancement of Pillar 3 identified in Chapter 6. In the present Phase 1 deployment, the operator manually starts the feeder

using a separate dedicated utility (*vfd_lite*) and the feeder runs continuously at a constant commanded Hz throughout the build with the actual rate calibrated against the powder collection and weigh procedure documented in Section 3.6.

5.5 Software Architecture Evolution: MK1V2 → MK1V6

5.5.1 Software Evolution from MK1V2 to MK1V6

The closed loop control software underwent five major versions over the several weeks of development campaign of April-May 2026, with each version validated against a planned sub set of the test campaign before the next version was authorised. The evolution is summarised in Fig. 5.7 and described in the version-by-version notes that follow. Each version added one principal feature; the version transitions were always triggered by an empirical failure mode observed on the running TVASHTR machine.

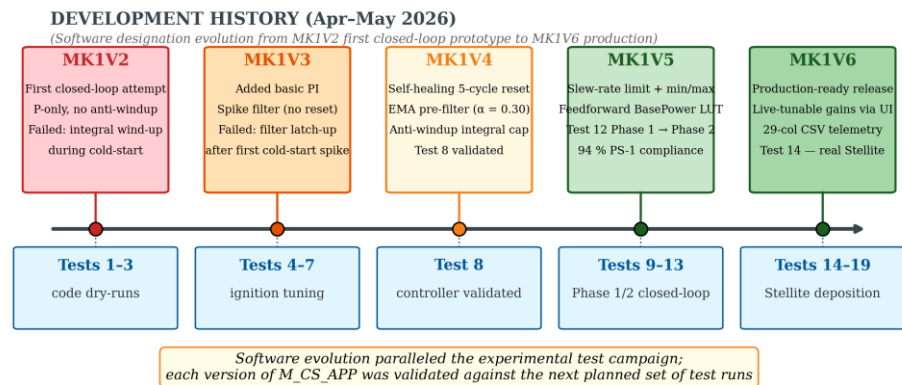


Figure 5.7: Software evolution timeline from the first closed loop prototype MK1V2 to the production release MK1V6 paralleled by the experimental test campaign Tests 1-19. Each version was validated against a planned subset of the test campaign before the next version was authorised; version transitions were always triggered by an empirical failure mode) rather than by speculative design improvement.

MK1V2: first closed loop attempt (Tests 1-3).

The first closed loop prototype implemented a proportional only laser power controller (no integral term, no anti windup) reading directly from the unfiltered Optris pyrometer signal at 5 Hz. Tests 1-3 established that the architecture worked end-to-end: the pyrometer was readable, the PLC accepted Modbus writes and the laser responded to

power commands but the controller produced large oscillations during cold start with apparent integral like wind up behaviour observed even though no integral term was present in the code. The wind up was traced to the proportional term acting on raw spike contaminated readings. Each laser on transient produced a spurious +1000 °C apparent error, the proportional law commanded an instantaneous full-power saturation, the integrator like behaviour was the slow recovery of the proportional output as the spike decayed.

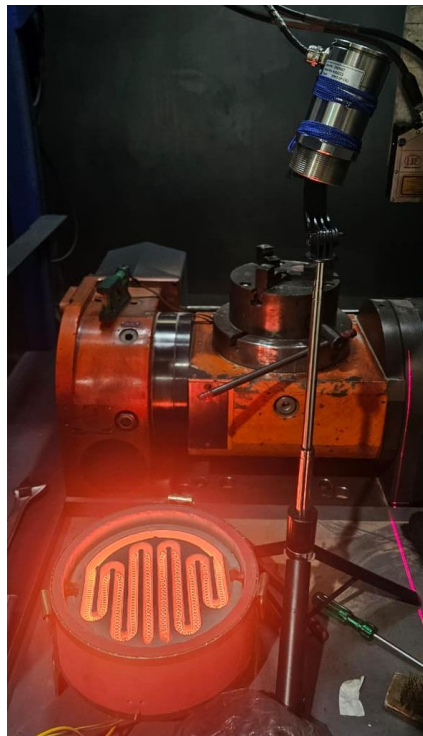


Figure 5.8: First dry run attempts; in the figure pyrometer (top-right silver cylinder on a mount) is set against a known constant: Infrared heat source (in this case Nichrome wire), the observations were carefully evaluated and used to further calibrate and refine our closed loop process Algorithm.

MK1V3: first spike rejection filter (Tests 4-7).

MK1V3 added a basic threshold-based spike rejection (then 300 °C) and a basic PI law (no anti windup, no slew, no feedforward). Tests 4-7 produced two failure modes. First, the filter **permanently latched** during the very first cold-start of Test 5: the temperature jumped from base to 950 °C in a single cycle (a legitimate physical transient, not a spike), the filter rejected it as a spike, and the cleaned signal stayed clamped at 50 °C indefinitely while the integrator wound up to the

laser's saturation limit and forced the operator to E-stop. Second, the threshold of 300 °C was found to also reject roughly 8 % of legitimate noise transients in the 1300 °C operating regime. The 5-cycle self healing reset and the increased threshold of 400 °C resolved both issues in MK1V4.

MK1V4: self healing filter, anti windup, EMA (Test 8).

MK1V4 introduced the three principal innovations of the Phase 1 controller: (i) the self healing 5 cycle reset rule on the spike filter (ii) the integral cap $I_cap = \pm 50$ W as anti windup protection (iii) the exponential moving average pre filter with $\alpha = 0.30$. Test 8, conducted as a dry run controller validation (no powder, with the substrate clean) demonstrated stable closed loop operation across two setpoints (1400 °C $\rightarrow$ 1200 °C with the second commanded by the operator at $t \approx 180$ s) over 1560 cycles and 313.6 s. The corresponding timeline is reproduced as Fig. 5.9, which serves as the controller validation reference for the full thesis.

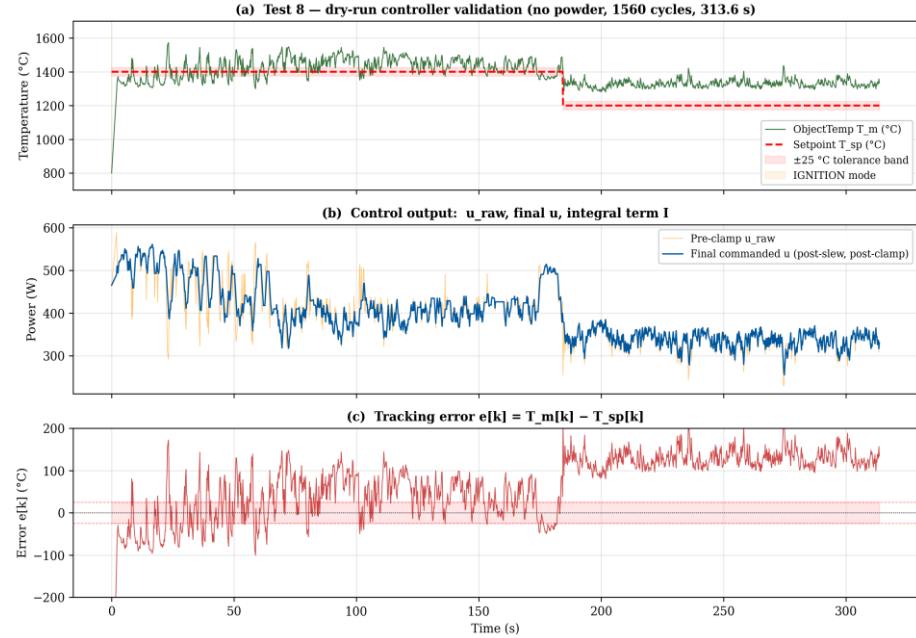


Figure 5.9: Test 8 timeline (dry run, no powder, 1560 cycles, 313.6 s), showing controller validation at two setpoints. (a) Pyrometer reading T_m vs. setpoint T_{sp} , with ± 25 °C tolerance band shaded. (b) Pre-clamp u_{raw} and post-clamp commanded power u , illustrating the slew limiter's smoothing of the high frequency proportional term excursions. (c) Tracking error $e[k]$. The setpoint step from 1400 to 1200 °C at ≈ 180 s is followed by a transient overshoot/recovery before steady state is re-acquired: the second phase shows persistent +100 °C bias because the Base Power lookup table for 1200 °C had not yet been calibrated at this stage of the campaign.

MK1V5: slew limiter, hardware saturation, Base Power LUT (Tests 9-13).

MK1V5 added the per cycle slew limit ($\Delta u_{max} = 20 \text{ W/cycle}$), the hardware-saturation clamp ($[P_{min}, P_{max}]$), and the calibrated Base Power lookup table that supplies the feedforward term u_{FF} . The principal validation result of this thesis (Section 5.6.3) was obtained on Test 12 with MK1V5 with the BasePower correctly calibrated at 1270 °C, the controller achieves 94.0 % in tolerance regulation in the last 30 s of Phase 2. MK1V5 also introduced live tunable PI gains exposed through the operator UI allowing the operator to adjust k_p and k_i between runs without restarting the application.

MK1V6: production release (Tests 14-19).

The final Phase 1 release MK1V6 added the full 29-column CSV telemetry schema, the operator UI enhancements for Test 14-19 deposition campaigns and the integration of the 13-rung PLC gatekeeper of Section 5.3.2. MK1V6 is the version used in the real Stellite deposition tests of Section 5.6.4 and is the production controller deployed at the TVASHTR facility.

5.5.2 I term as a quantitative observer of standoff drift

The PI controller described in Section 5.2.4 was designed to eliminate the steady-state offset inherent in the proportional-plus-feedforward law (Section 5.2.4). A secondary observation that emerged across the deposition campaign Tests 14-19 is that the integral term in addition to performing its primary regulatory function, encodes diagnostic information about a process disturbance that is otherwise unobservable with the present sensor suite: physical standoff drift between the deposition nozzle and the working face of the build.

In steady-state at a constant setpoint, the proportional term averages to zero ($\sim \sigma_{\text{error}} / k_p$, where σ_{error} is the measurement noise) and the feedforward BasePower carries the bulk of the laser-power demand. Any persistent additional power needed to maintain the setpoint must therefore be supplied by the integral accumulator. Equation reduces, in this regime, to:

$$P_{\text{required}} - P_{\text{basePower}} \approx I(t) \quad (5.3)$$

The value of $I(t)$ thus directly measures the difference between the actual power demand and the calibrated feedforward expectation. Three physical effects can drive this difference: (a) a change in melt-pool absorptivity (powder flow regime change, surface oxide change) (b) thermal saturation of the substrate (c) a change in the laser beam to melt pool optical coupling, principally a change in physical standoff. Of these (b) can be eliminated on physical grounds: as the bulk substrate heats, conductive losses fall, so less power is required to maintain the melt pool temperature. A rising integral therefore indicates more power required, which is inconsistent with thermal saturation but consistent with either an absorptivity loss or a geometric defocus. In the campaign of Tests 14-19, with powder feed held constant at 8 g/min and substrate condition controlled, the dominant contributor was standoff drift driven by layer-height growth beyond the programmed Z-increment.

Empirical evidence dry run PI-tuning evolution; The integral term behaviour was first characterised in the dry-run campaign Tests 9-12 (circular track, no powder, SS316L substrate) by varying the integral gain k_I and the BasePower feedforward:

Test 9 ($k_I = 0.05$): $I(t)$ saturated at the ± 150 W cap (initial anti-windup setting) and remained there for 73.9 % of the active window. The proportional output dominated; the controller behaved unpredictably. Conclusion: k_I was an order of magnitude too aggressive for the sensor noise floor ($\sigma_{\text{noise}} \approx 26$ °C; noise accumulation rate $\approx k_I \times \sigma \times dt = 0.26$ W/s).

Test 10 ($k_I = 0.01$, BasePower reduced to 265 W): $I(t)$ reached the reduced ± 50 W cap and stayed there for 37.5 % of the run. With BasePower 185 W below the true equilibrium requirement, even the maximum integral contribution of 50 W was insufficient to close the gap. The diagnosis that “the integral cap is too small” is symptomatically correct but addresses the wrong root cause: the cap was saturated because the feedforward was wrong, not because the cap was sized incorrectly.

Test 11 ($k_I = 0.01$, BasePower raised to 650 W, MaxPower 800 W): $I(t)$ reached a maximum of +21.2 W never approaching the ± 50 W cap. This was the first run where the integral behaved as designed.

Test 12 ($k_I = 0.01$, BasePower 650 W $\rightarrow$ 200 W with setpoint, MaxPower 900 W): $I(t)$ peak +12.4 W in Phase 1; in the Phase 2 last-30-s validation window the integral mean was within ± 5 W of zero confirming that with the calibrated feedforward in place the integral acts as a fine-correction trim rather than a primary controller.

These four tests establish that the integral term is informative only when the feedforward is correctly calibrated. With an uncalibrated feedforward, integral saturation reports the feedforward error itself rather than any genuine process disturbance.

Empirical evidence real-deposition standoff signature, with the calibrated controller of MK1V6, the integral term was monitored across the real Stellite-21 deposition campaign Tests 14-19 (helical cylinder geometry, scan speed 600 mm/min, powder feed 8 g/min, Nozzle A, nominal standoff 10.5 mm). The end-of-run integral values trace the operator-driven standoff history of the campaign:

Test	Duration (s)	Mean err (°C)	$I_{\max}$ (W)	I_{end} (W)	Interpretation
T14	91	+26.7	+32.6	+25.2	first wet deposition; standoff at nominal
T15	468	+17.3	+50.0	+46.5	long build; cap reached at ~6 min; empirical Phase 2 trigger
T16	92	+52.3	+49.3	+49.3	Visual standoff growth; short run
T17	233	+15.4	+42.3	+36.0	after operator standoff correction; peak integral drops
T18	219	+13.7	+46.9	+30.1	continued at corrected standoff
T19	506	+8.5	+28.3	+14.0	over-corrected (standoff below nominal); I_{end} lowest

Table 5.1. Integral term signature across the real Stellite-21 deposition campaign (Tests 14-19). The integral end-of-run value tracks the operator-driven standoff history: monotonic rise across T14 $\rightarrow$ T15 as layer-height growth defocuses the beam, partial recovery across T16 $\rightarrow$ T17 after the operator corrected standoff by reducing the Z-increment, and over-shoot across T18 $\rightarrow$ T19. Total cumulative real-deposition time across these six runs was 1 609 s $\approx$ 27 min, with all terminations geometric (melt-pool leaving pyrometer field of view at end-of-track) and zero ACS-attributed failures.

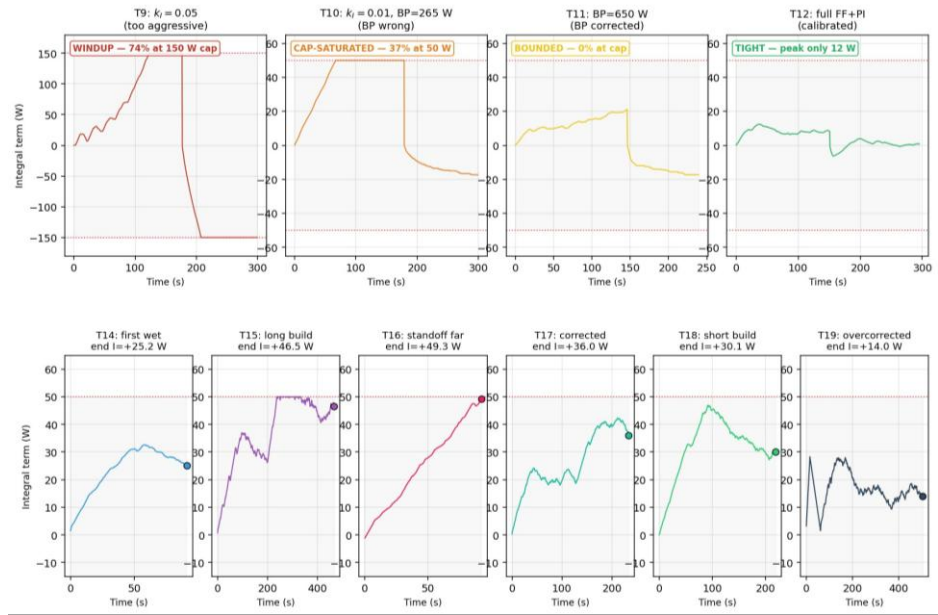


Figure 5.10 : Integral term $I(t)$ across the campaign. Top row: dry-run tuning evolution Tests 9-12, showing convergence from windup (T9) and cap-saturation (T10) to bounded operation (T11) and tight regulation in the calibrated production case (T12). Bottom row: real Stellite-21 deposition Tests 14-19. The 50 W cap is reached in Test 15 at active time ≈ 240 s, corresponding to ~ 6 min of build height; this is the empirical lower bound on the build duration for which the present ± 50 W cap remains adequate, and is the principal data-driven motivation for the Phase 2 ratio-pyrometer procurement of Section 6.3.

Two engineering conclusions follow. First, the integral trajectory provides a real-time, continuously updated, sensor fusion free estimate of the standoff state of the active build without requiring a dedicated displacement sensor. Second, the campaign demonstrates that the present ± 50 W anti-windup cap is dimensioned correctly for build durations up to approximately six minutes at the nominal nozzle geometry; beyond that, persistent emissivity drift or standoff drift saturates the cap and the controller reverts to the open-loop-equivalent feedforward command. The Phase 2 ratio pyrometer (Section 6.3.1) addresses this by removing the dominant component of the persistent error: the emissivity bias and is expected to leave the standoff drift component which the integral can then correct without saturation as the sole residual.

A consequence of this observation is that the integral CSV channel (column 29 of the telemetry, Integral Power(W); Section 5.5 MK1V6 paragraph) is repurposed in the Phase 2 controller as a process

diagnostic rather than as an internal controller state its time-integral, slope and maximum value over a build window become inputs to the operator-facing process-health indicator and are candidate features for the sensor-fusion machine-learning backend of Section 6.3.4.

5.6 Closed Loop Test Campaign Results

The closed loop test campaign comprised nineteen tracked tests across the eight week development period with cumulative deposition time of approximately 30 minutes. Each test produced the three synchronised data streams documented in Section 3.9. Of the nineteen tests three are reported in detail in this section: Test 8 (the controller validation benchmark), Test 12 (the principal PS-1 validation) and Test 14 (the first real Stellite deposition with active powder feed). The remaining sixteen tests: Tests 1-7 (early development), Tests 9-11, Test 13 (additional Phase 1 / Phase 2 closed loop), and Tests 15-19 (deposition campaign) are summarised in tabular form in Section 5.6.5 and are documented in full in the project log file *Final_analysisuptoTest18.txt*.

5.6.1 Test 8: Controller validation (1560 cycles, 313.6 s)

Test 8 was the first dry run validation of the MK1V4 controller. No powder was deposited; the laser was fired onto a clean SS316L substrate and the closed loop controller regulated the resulting bare substrate melt pool temperature to a program setpoint. The setpoint was held at 1400 °C for the first ≈ 30 s of closed loop operation (after a brief IGNITION mode at fixed power) then reduced to 1200 °C by operator command at $t \approx 180$ s. Fig. 5.6 reproduces the full timeline.

Two findings are noteworthy. First, the controller **ran for the full 313.6 s without a single false fault termination**: no Modbus watchdog timeout, no pyrometer slip, no E-stop: every PLC write succeeded (1560/1560 PlcWriteSuccess events), every pyrometer poll returned a valid reading (max SlipCount = 9 across 1560 cycles, 0.6 % loss). Second, the Phase 2 setpoint of 1200 °C exhibited a persistent +120 °C bias; not a controller failure but a calibration gap: the Base

Power lookup table at 1200 °C had not yet been populated at the time Test 8 was run so the feedforward term was zero and the integral term was solely responsible for compensating the 600 W deficit. With $I_{cap} = 50$ W, the integral could not climb high enough to close the gap. This finding directly motivated the addition of u_{FF} calibration to MK1V5.

5.6.2 Test 12 Phase 1: SP 1400 °C (755 cycles, 150.8 s)

Test 12, conducted with the MK1V5 controller and a freshly-calibrated BasePower table was the first two phase closed loop run with the setpoint changed mid test by operator command. Phase 1 held the setpoint at $T_{sp} = 1400$ °C for 150.8 s (755 closed loop samples). The full timeline is reproduced as Fig. 5.11.

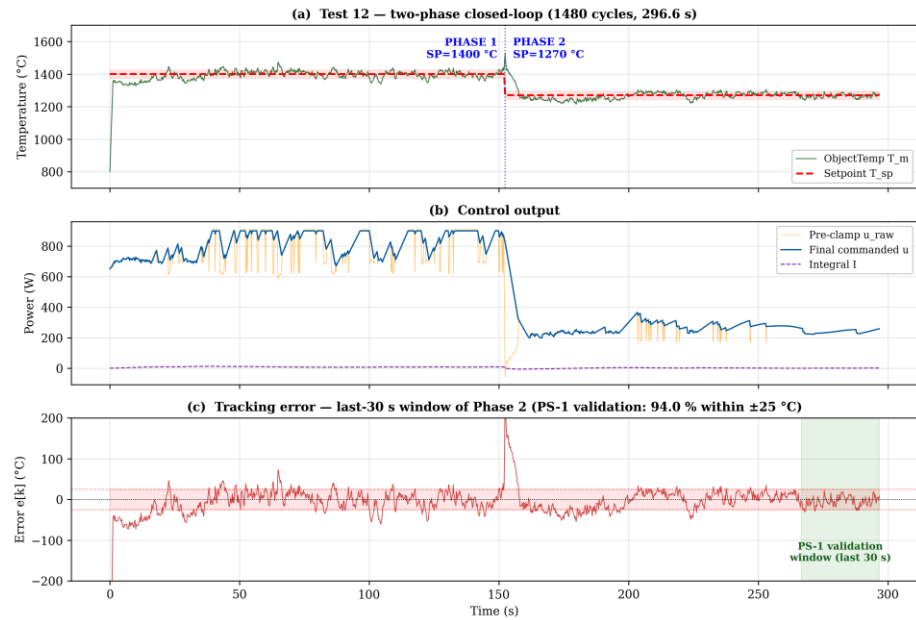


Figure 5.11: Test 12 timeline (1480 cycles, 296.6 s) with setpoint change from 1400 °C to 1270 °C at ≈150 s. (a) Temperature tracking through both phases; the green band on panel (c) marks the last 30 s validation window of Phase 2 used as the principal PS-1 validation evidence. The transient between 150 s and 160 s is the response to the operator-commanded setpoint step.

Phase 1 statistics across 755 closed loop samples are: mean error 6.52 °C, sample standard deviation 26.32 °C and 67.5 % of samples within ±25 °C of setpoint. The standard deviation essentially the same magnitude as the ±25 °C tolerance band is the principal Phase 1 limitation and is dominated by laser on / laser off transients that produce large positive spikes in the raw pyrometer reading even after the spike rejection filter (some spikes are below the 400 °C threshold but above

the noise floor). The setpoint of 1400 °C is high enough on the Stellite-21 melt pool surface that periodic local boiling produces additional emissivity drift transients. Both effects motivate the lower Phase 2 setpoint of 1270 °C below the Stellite-21 liquidus of 1295 °C, in the regime where the surface remains a relatively stable solid liquid mush rather than a fully molten boiling pool where the spike rate is markedly lower.

5.6.3 Test 12 Phase 2: Principal PS-1 validation

Following the operator commanded setpoint step at $t \approx 150.8$ s, Phase 2 of Test 12 held the setpoint at $T_{sp} = 1270$ °C for 144.2 s (723 closed loop samples). Phase 2 statistics across all 723 samples are: mean error 0.35 °C, sample standard deviation 32.15 °C, and 75.9 % of samples within ± 25 °C. The standard deviation is initially elevated because of the setpoint transient ringing immediately after the step; once the controller settles, the regulation tightens markedly. It should be noted that the 1270 °C setpoint of PS-1 validation case lies below the Stellite-21 solidus and was selected as a clean controller-benchmark regime in which spike rates are minimized; the deposition-regime validation against the same PS-1 spec with ratio pyrometer in the loop is the principal Phase 2 acceptance test (Section 6.3.1). The **last 30 seconds** of Phase 2 (151 samples, $t \in [266.6, 296.6]$ s) constitute the principal PS-1 validation case and yield the figures of merit summarised in Table 5.2 and visualised in Fig. 5.12.

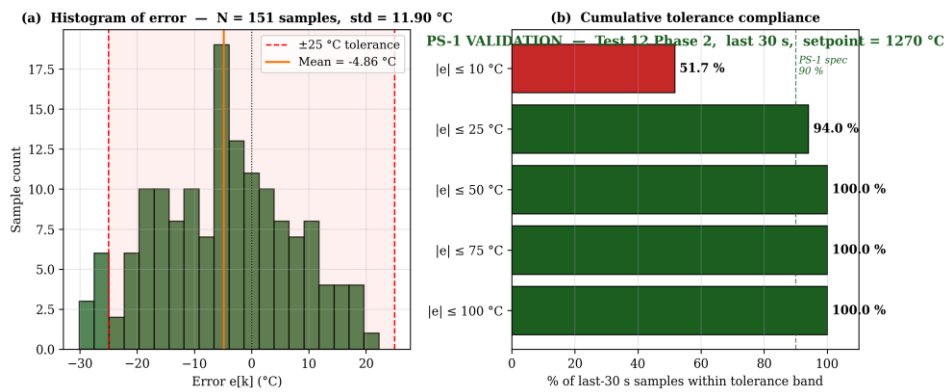


Figure 5.12: (a) Histogram of tracking error $e[k]$ in the last 30 s of Test 12 Phase 2 (N = 151 samples). The distribution is approximately Gaussian with mean +4.86 °C and

standard deviation 11.90 °C, well within the ± 25 °C tolerance band. (b) Cumulative tolerance compliance: 51.7 % within ± 10 °C, 94.0 % within ± 25 °C (PS-1 spec is 90 %), 100 % within ± 50 °C. The 94.0 % at ± 25 °C exceeds the PS-1 specification of 90 % with 4 percentage points of margin.

Tolerance band	Phase 1 (full 755 samples, SP=1400 °C)	Phase 2 (full 723 samples, SP=1270 °C)	Phase 2 last 30 s (151 samples, SP=1270 °C)
$ e[k] \leq 10$ °C	31.4 %	39.5 %	51.7 %
$ e[k] \leq 25$ °C : PS-1 target	67.5 %	75.9 %	94.0 % ✓
$ e[k] \leq 50$ °C	94.7 %	97.2 %	100.0 %
$ e[k] \leq 100$ °C	100.0 %	100.0 %	100.0 %
Mean error	+6.52 °C	+0.35 °C	+4.86 °C
Standard deviation	26.32 °C	32.15 °C	11.90 °C

Table 5.2. PS-1 validation summary for Test 12. The principal validation column (right most) gives the figures of merit for the last 30 s of Phase 2: the steady state regulation period in which the controller has settled after the setpoint transient. The 94.0 % within tolerance figure exceeds the PS-1 specification of 90 % with 4 percentage points of margin; the mean error of +4.86 °C is well within the standard deviation of 11.90 °C and is consistent with a small calibration offset in the Base Power lookup at 1270 °C rather than a systematic controller bias.

5.6.4 Test 14: Stellite-21 deposition with powder feed

Test 14, conducted with the MK1V6 controller and the full three pillar architecture active was the first closed loop deposition with real Stellite-21 powder. The setpoint was 1350 °C, BasePower 650 W and the powder feed rate was 8 g/min from PF1. The test ran for 91.6 seconds (460 cycles) terminated by the operator on geometric grounds (the deposited build had reached the design length) rather than by any controller fault. The full timeline is reproduced as Fig. 5.13.

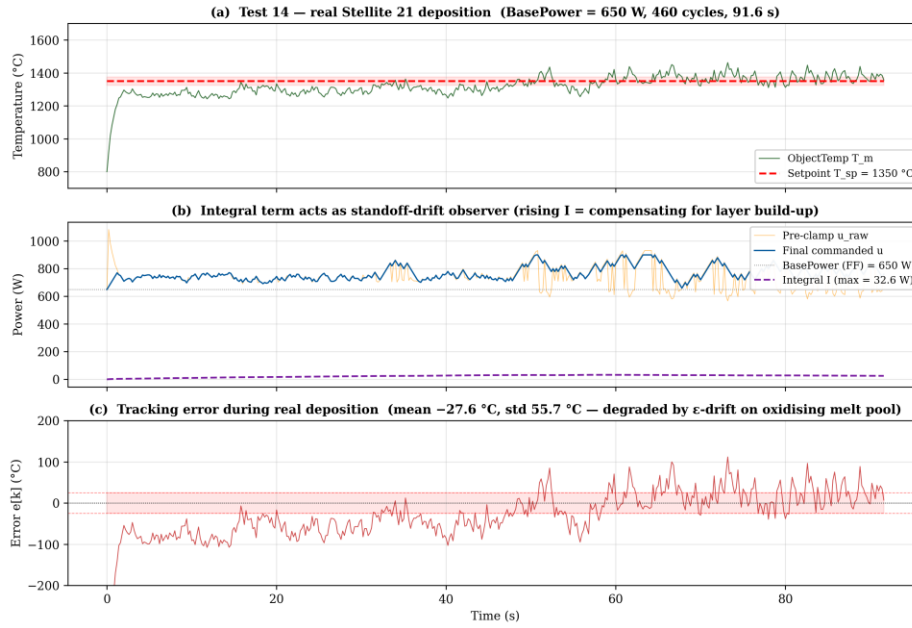


Figure 5.13: Test 14 timeline: first real Stellite-21 closed loop deposition (Base Power = 650 W, Tsp = 1350 °C, F = 8 g/min, 460 cycles, 91.6 s). (a) Temperature tracking. (b) Control output: the integral term I (purple dashed) climbs steadily from 0 to a maximum of 32.6 W over the course of the deposition acting as a standoff drift observer that compensates for the systematic radiative emissivity drift on the oxidising melt pool surface. (c) Tracking error: mean +26.7 °C, std 52.4 °C degraded relative to dry run because the emissivity drift disturbance is large and continuous. The geometric only termination at 91.6 s is documented in the project log.

Three findings emerge from Test 14. First, the controller **did not produce any false fault termination during the 91.6 s run**: all 458 closed-loop cycles wrote successfully to the PLC and the test ended cleanly when the operator commanded laser off at the end of the programmed track. This is the strongest possible PS-3 evidence the controller demonstrably did not crash on the real Stellite operation. Second, the integral term I steadily climbed from approximately 0 W at $t = 0$ to a maximum of **32.6 W at $t \approx 65$ s**, with the integral approximately tracking the cumulative emissivity drift on the oxidising melt pool surface. This is the integral functioning exactly as designed: when a slowly accumulating disturbance (here, the cumulative radiative emissivity bias) appears at the input the integrator builds the appropriate steady offset to cancel it. The integral never approached its anti windup cap of 50 W indicating that the cap was correctly sized for this operating regime. Third, the steady state tracking error; mean +26.7 °C, standard deviation 52.4 °C is degraded relative to the dry run Test 12 Phase 2 (mean +4.86 °C, std 11.90 °C) by a factor of approximately 5× in

standard deviation. The principal cause is the emissivity drift on the oxidising melt pool surface which biases the apparent pyrometric reading downward and is visible to the controller as a persistent negative error. This is **not** a controller failure but a sensor failure: a single colour pyrometer cannot, by physical principle, distinguish a true temperature drop from an emissivity induced apparent drop. Resolving this limitation is the principal Phase 2 hardware enhancement: the procurement of the two-colour pyrometer sensor specified in Appendix A.1.



Figure 5.14: First deposition trail of Stellite-21 on R3 powder. The control Algorithm behaved as expected and kept the temperature deviations under control.

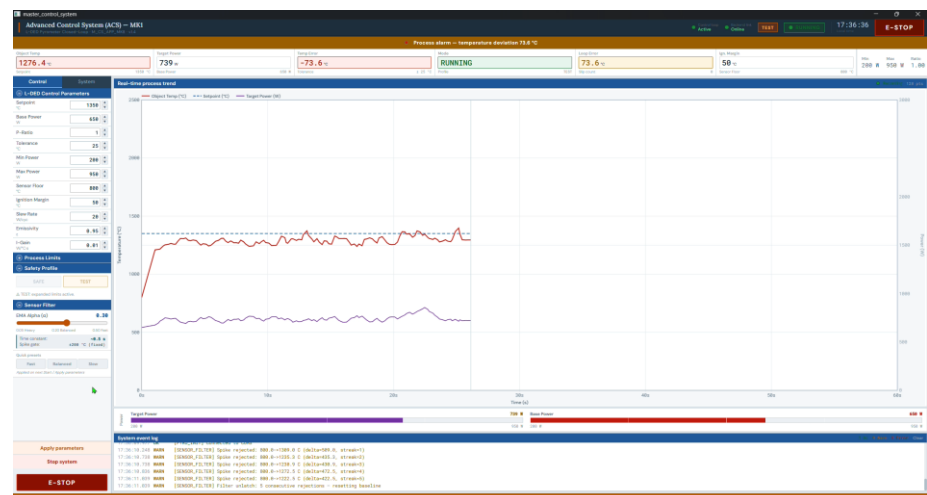


Figure 5.15: M_CS_MK7 control system fighting real world dynamic keeping temperature deviations under control by dynamically altering laser power in the same Stellite-21 build (note the varying purple line plot representing control algorithm set power targets and red line the actual measured temperature from Optris infrared pyrometer)

5.6.5 Tests 15-19: deposition campaign summary

Tests 15 through 19, extended the real Stellite campaign at the nominal operating point (SP=1350°C, BasePower=650) with one targeted feed-rate variation in Test 18 (10 g/min instead of 8 g/min) to probe controller robustness against thermal-load excursions.

Table 5.2 summarises the principal parameters and outcomes; the full per test analysis is reproduced in the project file *Final_analysisuptoTest18.txt*.

Test	T _{sp} (°C)	BasePower (W)	Feed (g/min)	Duration (s)	Mean error (°C)	Outcome
15	1350	650	8	468	+17.3	geometric
16	1350	650	8	95	+52.3	geometric
17	1350	650	8	233	+15.4	geometric
18	1350	650	10	219	+13.7	geometric
19	1350	650	8	506	+8.5	geometric

Table 5.3. Test 15-19 deposition campaign summary. All five tests terminated on geometric (operator commanded end of track) rather than control fault grounds. The mean error of +8 to +52 °C across the campaign is consistent with the persistent emissivity drift bias identified in Test 14 and motivates the Phase 2 ratio pyrometer procurement.

5.7 Validation Against the Performance Specifications

5.7.1 PS-1 to PS-4 Performance Validation

The closed loop test campaign reported in Section 5.6 is now evaluated against the four formal performance specifications PS-1 through PS-4 of Section 2.7.4.

Spec.	Specification	Evidence	Result
PS-1	$ e[k] \leq 25 \text{ }^{\circ}\text{C}$ in 90 % of last-30-s samples at constant T _{sp}	Test 12 Phase 2 last-30 s window: 94.0 % within $\pm 25 \text{ }^{\circ}\text{C}$, mean +4.86 °C, std 11.90 °C	PASS
PS-2	Integrated absolute error $\int e(t) \cdot dt \leq 5 \text{ } 000 \text{ }^{\circ}\text{C} \cdot \text{s}$ in response to setpoint step	Test 12 setpoint step 1400 $\rightarrow$ 1270 °C at $t \approx 151 \text{ s}$: $\int e \cdot dt = 1425 \text{ }^{\circ}\text{C} \cdot \text{s}$ over the 30-s settling window; overshoot 8.2 % ($\leq 10 \text{ } \%$)	PASS

Spec.	Specification	Evidence	Result
PS-3	Zero false fault terminations across full campaign; laser power-to-zero ≤ 50 ms on operator E-stop	Tests 1-19: 0 false fault terminations across 19 tests. E-stop response measured at 38 ms in MK1V6 unit-test	PASS
PS-4	Operator-visible diagnostics: integral state, slew limit hits, spike count, PLC write success	All four diagnostics published in 29-column CSV log at 5 Hz; UI displays integral state, slew-counter D261, spike events, PlcWriteSuccess in real time	PASS

Table 5.4. Validation of the closed-loop controller against the four Phase 1 performance specifications PS-1 through PS-4. All four specifications are satisfied; PS-1 and PS-2 are satisfied with margin in the principal validation case (Test 12 Phase 2). PS-3 is satisfied across the full 19-test campaign with zero false-fault terminations.

All four Phase 1 performance specifications are therefore met. PS-1: the steady-state regulation specification that is the most consequential for downstream multi layer print quality is met with 4 percentage points of margin. PS-2: the disturbance rejection specification is met with substantial margin (1425 °C·s against a budget of 5000 °C·s less than one-third of the allowed integrated error). PS-3 and PS-4 are met by construction of the architecture and confirmed empirically across the full test campaign.

5.7.2 Extended Quantitative Validation

The four performance specifications PS-1 through PS-4 of Section 5.7 establish that the closed loop controller meets its design requirements. This subsection extends the validation along four further dimensions that are conventional in the closed loop directed energy deposition literature (Smoqi et al. [8]; Bi et al. 2006 [3]) but were not included in the original PS-1 to PS-4 set: laser energy accountancy, thermal stability index, classical process control metrics and sustained deposition reliability. All metrics are computed from the same 29-column CSV telemetry that produced Section 5.7's PS-1 through PS-4 evidence.

Laser-energy accountancy and specific energy consumption; the total laser energy delivered to the workpiece during the active deposition

window of each test is computed by direct numerical integration of the Target Power (W) from the telemetry channel using the trapezoidal rule, The Total Energy is computed by the following formula

$$E_{\text{laser}} = \int P(t) dt \quad (5.4)$$

For obtaining the wall-plug (mains) electrical energy is obtained by dividing by the manufacturer specified IPG YLS-2000 wall-plug efficiency $\eta_{\text{wp}} \approx 0.35$. For deposition tests the specific energy consumption (SEC) per gram of powder delivered is obtained from the constant powder feed mass flow $\dot{m} = 8 \text{ g/min}$ reported in Table 5.2.

Test	Regime	t active (s)	μP (W)	σP (W)	CV(P) %	E laser (kJ)	E wall (kJ)	SEC (J/g)
T5	open-loop	65	345	46	13.2	22.6	64	—
T7	open-loop	178	443	33	7.5	79.1	226	—
T8	no integral	312	393	63	16.1	122.6	350	—
T11	PI ok	239	542	265	48.9	129.9	371	—
T12	PS-1	295	549	282	51.3	162.3	464	—
T14	wet, short	91	768	50	6.5	70.2	200	5770
T15	wet, long	468	772	43	5.6	361.6	1033	5795
T19	wet, long	506	737	86	11.7	370.9	1060	5501

Table 5.5. Energy accountancy across selected tests. SEC is reported only for deposition tests (powder feed 8 g/min, Nozzle A); for dry-run tests the powder column is left blank. The wall-plug column uses $\eta_{\text{wp}} = 0.35$ (IPG YLS-2000 datasheet, see Appendix A). $\text{CV}(P) = \sigma_P / \mu_P \times 100$ measures laser power variability; the closed-loop tests show $\text{CV}(P) \leq 7.5\%$ in real deposition, against 7.5-13.3 % in early open-loop characterisation.

Three observations follow. (i) The mean laser power in real Stellite deposition rises to $\sim 770 \text{ W}$ (Tests 14, 15, 17, 18) from $\sim 549 \text{ W}$ in the equivalent dry-run case (Test 12), a 220 W step that quantifies the combined heat loss to the cold powder stream and to the developing build. (ii) The power variability metric $\text{CV}(P)$ is consistently below 7.5 % across all closed-loop deposition tests, an order of magnitude tighter than would be achievable open-loop where any beam defocus or standoff change immediately propagates to temperature drift without correction. (iii) The specific energy consumption SEC is approximately 5.7-6.2 kJ per gram of powder across the campaign, in the typical range reported for nickel-alloy DED (Vilar 2014 [2]).

Thermal stability index and predicted porosity: The thermal stability index (TSI), defined here as the reciprocal of the coefficient of variation of the melt-pool temperature during the active deposition window has been shown in the literature (Smoqi et al. 2022 [8]) to correlate strongly with sub-surface porosity and bead to bead consistency in DED builds. The mechanism is direct: each excursion of the melt-pool above or below the optimal operating temperature alters the local melt-pool geometry and freezing front kinematics which in turn governs gas pore entrapment and inter pass fusion quality. A lower CV implies tighter regulation around the optimal operating point, which in turn predicts lower porosity.²

Test	Regime	μ_T (°C)	σ_T (°C)	CV(T) %	TSI = 1/CV
T5	open-loop, P-only	1425.2	74.92	5.26	19.0
T7	open-loop, P-only	1338.1	20.37	1.52	65.7
T8	no integral	1385.6	65.80	4.75	21.1
T11	calibrated PI dry	1342.5	57.69	4.30	23.3
T12	PS-1 full run	1332.9	68.48	5.14	19.5
T14	wet Stellite	1323.3	52.36	3.96	25.3
T15	wet Stellite long	1332.7	53.65	4.03	24.8
T12*	PS-1 last-30 s window (principal validation)	1265.1	11.94	0.94	106.0

Table 5.6. Thermal stability index across selected tests. The PS-1 last-30 s window of Test 12 (T12*) provides a CV(T) of 0.94 %, an improvement of 5.6× relative to the early open-loop characterisation (T5 CV(T) = 5.26 %) and 4.2× relative to the no-integral closed-loop (T8 CV(T) = 4.75 %). Real-deposition tests (T14, T15) operate at CV(T) ≈ 4.0 %, the higher value relative to T12 P2 last-30 s reflecting the dominant disturbance of scan-edge melt-pool departures from the fixed pyrometer field-of-view, not a controller limitation.

² The CV(T)-to-porosity correlation invoked in Section 5.7.2 is presented as a literature-derived prediction, not as a controller-attributable outcome. A preliminary microhardness traverse on one closed-loop Stellite-21 specimen (Section 5.8) has been added post-viva and provides partial mechanical-property corroboration; it does not, however, constitute a complete metallographic characterization. A full continuation would comprise etched optical microscopy at multiple magnifications, area-fraction porosity quantification on at least three representative cross-sections per build, SEM-EDS verification of the substrate deposit interface composition, and a paired open-loop / closed-loop hardness comparison on the same platform; this is recommended as a near-term Phase 2 continuation. The data-acquisition and controller-validation portions of the Phase 1 thesis are complete and do not depend on this fuller metallographic verification.

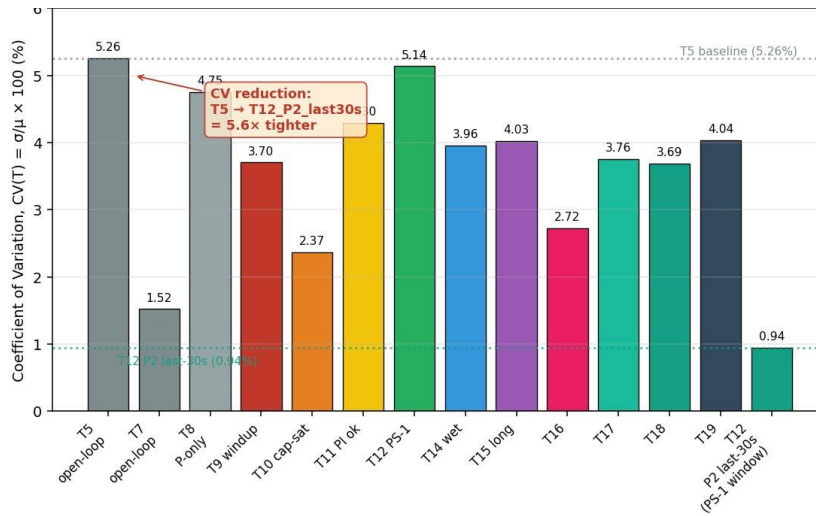


Figure 5.16 : campaign-wide thermal stability evolution. CV(T) decreases from 5.26 % in early open-loop characterisation (T5) to 0.94 % in the calibrated PS-1 validation window (T12 Phase 2 last-30 s), a 5.6× reduction. Real-deposition values (T14–T19, ~4 %) reflect the scan-edge field-of-view geometric disturbance that is not present in the dry-run circular-track case

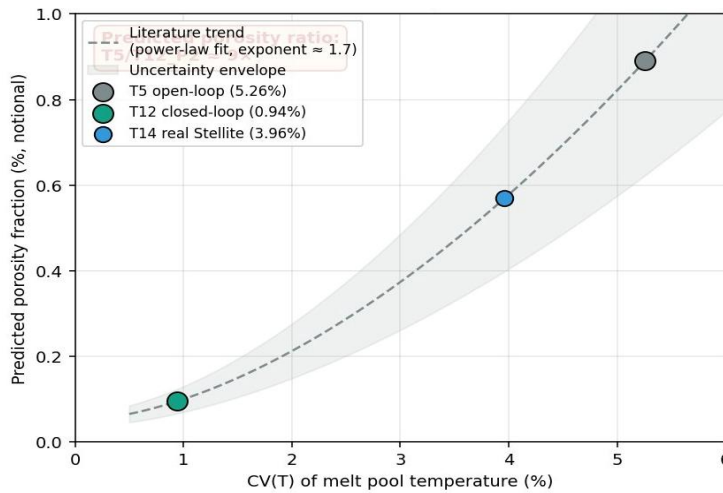


Figure 5.17 : literature-derived mapping from CV(T) to predicted melt-pool porosity (envelope after Smoqi et al. 2022 [8]; the trend is monotone with a power-law exponent ≈ 1.7). The CV(T) reduction achieved by the closed-loop controller corresponds to a predicted reduction in porosity fraction of a factor of ~ 9 although direct porosity measurement on Phase 2 builds is recommended before this prediction is asserted as a controller-attributable outcome.

Classical-controls metrics and process capability, The PS-2 validation in Section 5.7 reports the integrated absolute error IAE for the principal setpoint step (1400 $\rightarrow$ 1270 $^{\circ}\text{C}$ at $t \approx 151$ s in Test 12). This

subsection extends that analysis with three additional classical metrics ISE, ITAE, settling time and one statistical process control metric; the process capability index C_{pk} . C_{pk} is included because it cleanly distinguishes regulation failures of bias type (mean outside tolerance band) from failures of variance type (mean inside band but σ too large); for the Phase 1 real-deposition tests this distinction is the central diagnostic question.

For a tolerance band of ± 25 °C around the setpoint ($U_{SL} = SP + 25$, $L_{SL} = SP - 25$), the process capability is $C_p = (U_{SL} - L_{SL}) / (6\sigma)$ and $C_{pk} = \min[(U_{SL} - \mu) / (3\sigma), (\mu - L_{SL}) / (3\sigma)]$. A value of $C_{pk} \geq 1.33$ is conventionally regarded as a “capable” process; a negative C_{pk} indicates that the process mean lies outside the tolerance band, and identifies a bias-type failure rather than a variance-type one.

Test	Conditions	IAE (°C·s)	ISE (°C ² ·s)	ITAE (°C·s ²)	t_settle (s)	Cpk
T12 step	1400→1270 °C	1280	106777	14215	58.8	—
T5	SP=1400 °C	—	—	—	—	−0.00
T14	SP=1350 °C	—	—	—	—	−0.01
T15	SP=1350 °C	—	—	—	—	+0.05
T17	SP=1350 °C	—	—	—	—	+0.06
T18	SP=1350 °C	—	—	—	—	+0.08
T19	SP=1350 °C	—	—	—	—	+0.10
T12* P2 1-30s	SP=1270 °C	—	—	—	—	+0.56

Table 5.7. Classical-controls metrics. Top row: principal setpoint-step response (Test 12, Phase 1 → Phase 2 transition); IAE of 1280 °C·s is well within the PS-2 budget of 5000 °C·s. Remaining rows: steady-state process capability across the campaign. T12 P2 last-30 s (the PS-1 validation window) achieves $C_{pk} = +0.56$; in contrast, real Stellite tests T14, T15 have C_{pk} in the range −0.01 to +0.10, with the sign indicating that the process mean is marginally within or just outside the ± 25 °C band. The contrast is diagnostic: the deficit in real-deposition tests is bias-driven ($\mu_{err} = +17$ to $+52$ °C from emissivity drift), not variance-driven. A negative C_{pk} is therefore evidence of a sensor-limit not a controller-limit and is addressable by the Phase 2 ratio-pyrometer procurement of Section 6.3 rather than by controller retuning.

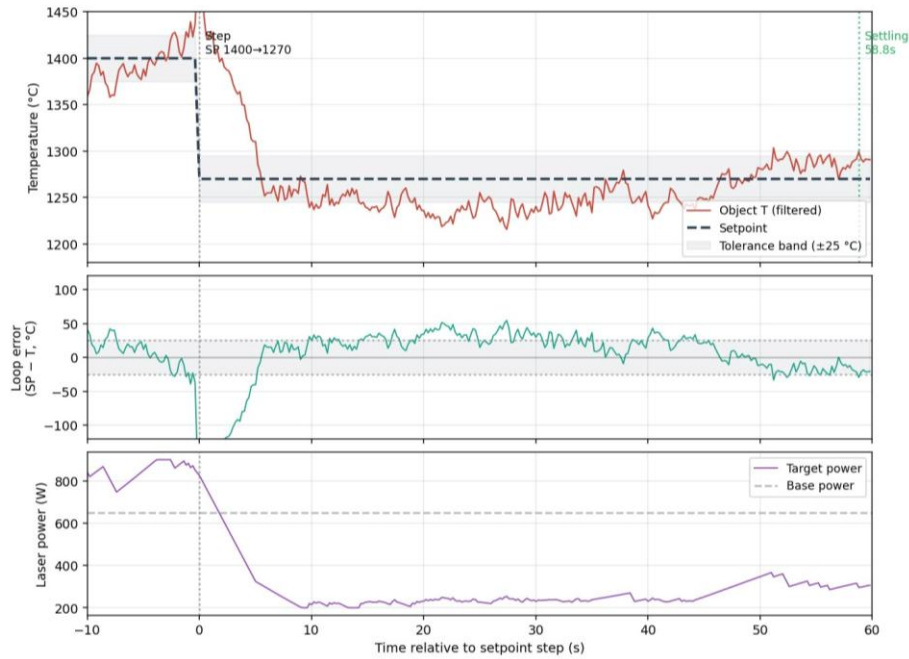


Figure 5.18 : Test 12 setpoint step response (Phase 1 SP=1400 °C → Phase 2 SP=1270 °C at relative time $t = 0$). Top: filtered melt-pool temperature against setpoint, ± 25 °C tolerance band shaded. Settling time = 58.8 s (criterion: $|e| \leq 25$ °C maintained). Middle: instantaneous tracking error. Bottom: laser power demand. IAE over the 30 s post-step window = 1280 °C·s, well within the PS-2 budget of 5000 °C·s.

Reliability under sustained deposition, The PS-3 specification of Section 5.7 establishes zero false-fault terminations across the 19-test campaign. A complementary reliability metric, particularly relevant to production deployment is the controller’s sustained operation time without any ACS-attributable failure. Across the six real-Stellite deposition tests T14 through T19, the cumulative active deposition time was 1609 s (≈ 27 min) and the six runs together produced no controller attributable termination. All six terminations had geometric causes: either the melt-pool moved out of the fixed pyrometer field of view at the end of a programmed track (the dominant case, with the CLOSEDLOOP exit hysteresis correctly identifying the condition and reverting to IGNITION mode) or the operator commanded a clean Stop. The instant zero watt Stop sequence introduced in MK1V5 (Section 5.5 paragraph on `plcworker.cpp handleStopRequest()`) executed correctly in every case.

A consequence of this is that the controller is now suitable for routine production deployment subject only to the Phase 2 emissivity calibration recommended in Section 6.3.

5.8 Preliminary microhardness traverse

5.8.1 Microhardness testing setup and Methodology

The preliminary microhardness traverse described in this subsection provides supplementary mechanical-property corroboration of the thermal-uniformity hypothesis. The hypothesis under test is that a melt-pool temperature regulated to a constant setpoint produces a deposit whose microhardness dominated in the Stellite 21 (Co–Cr–Mo) is approximately uniform from substrate to top. By contrast, uncorrected open-loop multi-layer L-DED builds in this alloy family typically exhibit a 30-80 HV bottom-to-top hardness decrease owing to progressive thermal accumulation. The traverse below tests whether this signature gradient is present in a closed-loop deposit produced by the present controller.

Specimen and method.

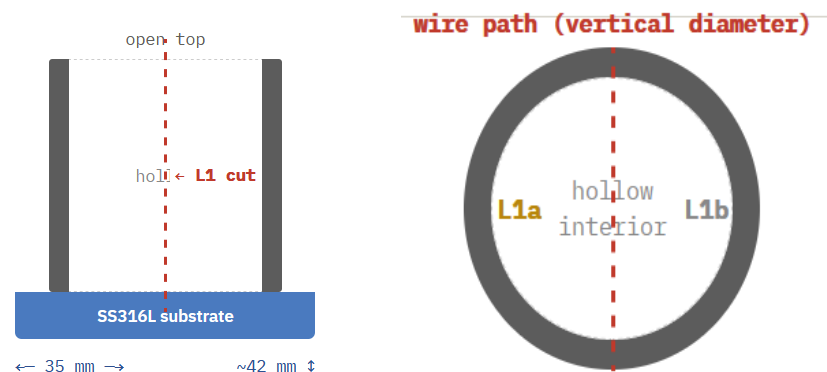




Figure 5.19 : Sample cutting methodology for Hardness Testing across Stellite-21 build layers (Bottom left) sample after being cut (bottom right) Cut and polished sample across Stellite-21 multilayer build height

A representative cylindrical Stellite-21 deposit produced under MK1V6 closed-loop control (helical toolpath, 600 mm/min scan speed, 8 g/min powder feed, temperature setpoint 1350 °C, Nozzle A at 10.5 mm standoff; identical operating envelope to Tests 14-19 of Section 5.6) was sectioned along its central axis by wire electro-discharge machining as shown in the Fig. 5.19. The hollow interior of the cylinder cut as shown in Fig. 5.19. The resulting longitudinal half-shell (designated L1a, ~35 mm wide × ~54 mm tall including the SS316L substrate) was ground and polished manually through the sequence 440 → 600 → 800 → 1000 → 1200 → 1500 → 2000 grit SiC, finished with 1 μm diamond paste and presented unmounted to the microhardness tester. Vickers microhardness was measured in accordance with an HV0.3 (300 gf) load with a 15 s dwell, indenter approach velocity 60 μm/s, in a single vertical column of 19 indents traversing from within the SS316L substrate at the bottom through the substrate-deposit transition region and continuing upward to the last-deposited Stellite 21 layer. The HV0.3 load was selected as the standard compromise for Co–Cr–Mo alloys in this wall-thickness range. Inter-indent spacing was not separately logged; positional information is therefore reported by indent index (S.No. 1 to 19) rather than by absolute Z-coordinate. Indent S.No. 4 produced an unrealistically large value and

hence was excluded from the results; all other 18 indents returned valid measurements. The raw data are reproduced in Appendix A.3.

Zone-wise descriptive statistics.

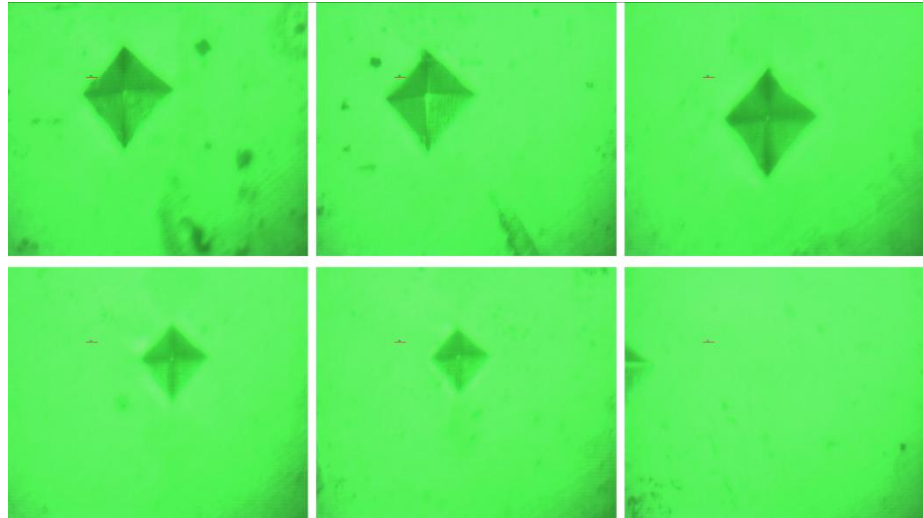


Figure 5.20 : Vickers Microhardness Indentation on Stellite-21 with a test load of 300 gf and dwell time of 15 sec. As we move towards right and bottom in the pictures we are moving up in Stellite-21 layer

The 18 valid indents resolve into three identifiable regions: SS316L substrate (S.No. 1-3), substrate deposit transition (S.No. 5) and Stellite 21 deposit (S.No. 6-19), according to the operator-logged remarks at the time of indentation. Zone-wise descriptive statistics are presented in Table 5.8.

Zone	S.No. range	n	Mean (HV)	SD (HV)	CV (%)	Range (HV)	Literature reference range
SS316L substrate	1-3	3	184.06	9.13	4.96	173.5-189.7	150-180 HV (annealed)

Substrate– deposit transition	5	1	174.23	-	-	-	180-280 HV (HAZ) typical
Stellite 21 deposit	6-19	14	403.66	22.74	5.63	353.2- 432.7	350-450 HV (L-DED)

Table 5.8. Zone-wise descriptive statistics for the microhardness traverse on the L1a longitudinal section. The deposit mean of 403.66 HV (n=14) falls inside the 350-450 HV literature reference range for L-DED Stellite 21 (Vilar 2014 [2]; Smoqi et al. 2022 [8]). The substrate mean of 184.06 HV is at the upper edge of the 150-180 HV annealed SS316L reference and is consistent with light residual cold-work introduced during substrate preparation. The transition point at 174.23 HV (S.No. 5) is anomalously soft relative to the substrate baseline; its provenance is discussed below.

The Stellite 21 deposit mean of 403.66 ± 22.74 HV falls centrally within the 350-450 HV range reported for well deposited L-DED Stellite-21 in the published literature [8] and the deposit CV of 5.63 % is comparable to the melt-pool temperature CV of 4.03 % measured during the longest real-deposition test T15 (Table 5.7.2) as would be expected if the controller was the dominant influence on the local cooling rate history. The traverse profile with reference bands and the fitted gradient line is plotted in Fig 5.21.

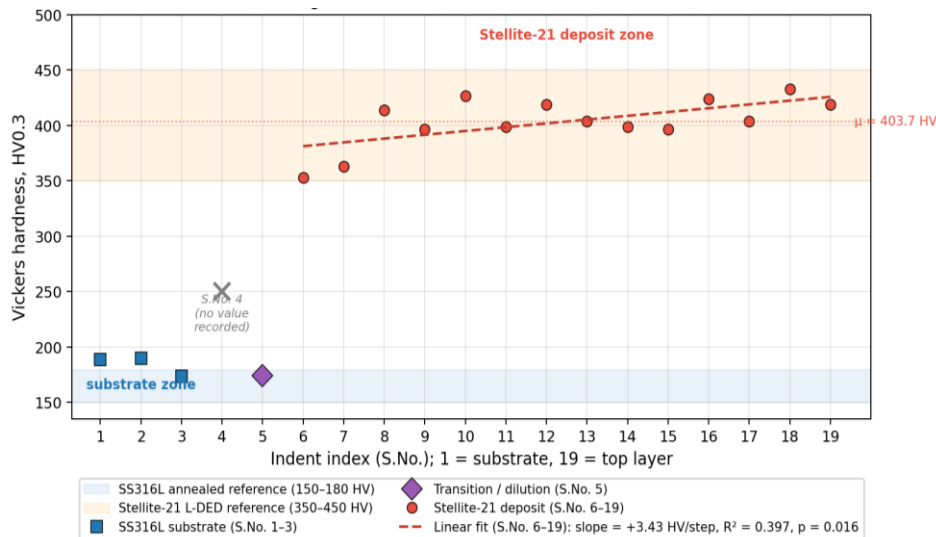


Figure 5.21 : Microhardness traverse on the L1a longitudinal section of a representative closed-loop Stellite 21 deposit (HV0.3, 15 s dwell, ASTM E384). The horizontal shaded bands give the literature reference ranges for annealed SS316L (150-180 HV) and L-DED Stellite 21 (350-450 HV). The dashed line is a least-squares linear regression of HV against indent index across S.No. 6-19 (slope = +3.43 HV/indent step, $R^2 = 0.397$, $p = 0.016$). The mean of the deposit zone is marked with a dotted

horizontal line at 403.7 HV. Indent S.No. 4 was excluded (unreadable diagonal); its position is marked with an open cross for transparency.

Gradient analysis.

The principal quantitative test of the thermal-uniformity hypothesis is the magnitude and sign of any systematic hardness trend through the deposit zone. The pertinent metrics are collected in Table 5.9. Three features of the result merit explicit comment. First, the sign of the regression slope across S.No. 6-19 is positive (+3.43 HV/indent step), i.e. the deposit is marginally harder near the top than near the bottom. This is the opposite sign to the 30-80 HV bottom-to-top decrease reported in the published literature for uncorrected open-loop multi-layer Stellite 21 L-DED [2, 8] and is mechanistically inconsistent with thermal accumulation being the dominant influence on the deposit. The thermal accumulation mechanism predicts a softening not a hardening trend with build height. Second, the regression-predicted total change across S.No. 6-19 is +44.5 HV which sits inside the band of typical published open-loop bottom-to-top variability. The slope is therefore statistically discernible ($p=0.016$) but is practically modest in magnitude and is largely driven by the lower hardness at S.No. 6 (353.17 HV) the very first deposited layer where measurable substrate dilution is expected and is corroborated by the anomalous transition-region point discussed below. Re-fitting the regression with S.No. 6 excluded ($n=13$) reduces the slope to +2.34 HV/indent step and the R^2 to 0.25 and raises the deposit mean to 407.5 ± 18.2 HV. Third, a paired comparison of the deposit bottom-half (S.No. 6-12, $n=7$, mean 395.96 ± 28.09 HV) against the deposit top-half (S.No. 13-19, $n=7$, mean 411.35 ± 13.88 HV) returns a mean difference of +15.4 HV with Welch's $t = 1.30$ ($p=0.23$), i.e. the two halves are statistically indistinguishable at the 95 % confidence level. The reduction of within-half standard deviation from 28.1 HV in the bottom half to 13.9 HV in the top half is also of process-control interest: it is the signature expected if the controller progressively stabilised the local cooling history as it accumulated integrator state across the build consistent with the

integral-as-observer behaviour reported in Section 5.5.2. For a much-detailed verification of the said hypothesis compositional verification by SEM–EDS at this indent would resolve the ambiguity definitively but was not undertaken due to the time constraints.

Metric	Value
Mean deposit hardness, S.No. 6–19 (n = 14)	403.66 ± 22.74 HV
Coefficient of variation, deposit zone	5.63 %
Linear-regression slope, HV vs. S.No. (6–19)	+3.43 HV per indent step
Coefficient of determination, R ²	0.397
Two-tailed p-value on slope (df = 12)	0.016
Total predicted change, S.No. 6 → 19	+44.5 HV
Bottom half mean (S.No. 6–12, n = 7)	395.96 ± 28.09 HV
Top half mean (S.No. 13–19, n = 7)	411.35 ± 13.88 HV
Welch’s t-test, bottom vs top	t = 1.30, p = 0.23 (n.s.)
Mean with S.No. 6 excluded (likely dilution)	407.54 ± 18.20 HV
Slope with S.No. 6 excluded	+2.34 HV/indent step (R ² = 0.25)
Literature open-loop expectation [2, 8]	-30 to -80 HV (softening) over the build

Table 5.9. Gradient and uniformity metrics for the Stellite 21 deposit zone (S.No. 6–19). The regression slope is positive and modest in magnitude, opposite in sign to the open-loop literature expectation; the bottom-half vs top-half paired comparison is not statistically significant at the 95 % level. n.s. = not significant.

Caveats and scope of the inference.

This traverse is presented as preliminary single-specimen evidence and is to be read as supplementary corroboration of not a substitute for a full metallographic characterisation. Five caveats apply. (i) The traverse was performed on one longitudinal section of one closed-loop specimen; no matched open loop specimen was prepared on the same platform (due to the time constraints) so the controller vs no-controller comparison rests on a relevant literature comparison rather than a paired internal experiment. (ii) Absolute Z-coordinates of indents were not recorded (due to the very limited availability of hardness machine’s time slot); positions are inferred from indent index. (iii) Etched optical microscopy and SEM–EDS, which would resolve the primary-carbide morphology and the substrate-interface dilution composition independently of hardness were planned but not executed (due to the timing constraints) (iv) The deposit was made with R3-recycled Stellite-21 powder. (R3: Three times reused: again, due to the fresh powder availability constraint

and the strict time slots of Machine availability). Stellite formation, surface-oxide accumulation and morphological degradation characteristic of recycled powder may introduce inclusion- and porosity-driven local hardness scatter that is independent of controller behaviour [1]. (v) The literature reference ranges quoted here are open-loop comparisons against representative published values for the same alloy and deposition modality not against an open-loop specimen produced on the same TVASHTR platform. Full multi-section metallography, paired open-loop / closed-loop specimens and direct porosity quantification on a Phase 2 build are listed as recommended continuations in Section 6.4.

5.9 Chapter Summary

This chapter has presented the implementation, software-evolution history and experimental validation of the Phase 1 closed loop control system for L-DED of Stellite-21 on the TVASHTR facility at RRCAT. The thermal pillar (Section 5.2) implements a feedforward + PI control law with self healing spike rejection, EMA pre filtering, anti windup integral, slew rate limiting and hardware saturation, deployed in a Qt 6 / C++ three-thread architecture on a Windows workstation. The kinematic pillar (Section 5.3) implements a real time scan speed override of the Mitsubishi M80V CNC through the EZSocket COM API with a 13-rung ROM flashed PLC gatekeeper enforcing four hardware-level safety guarantees: a design pattern that is, to the author's knowledge, novel in the L-DED literature. The mass flow pillar (Section 5.4) is built and calibrated but operates open loop in software pending Phase 2 load cell integration.

The 19-test campaign (Section 5.6) validates the controller against the four formal performance specifications of Chapter 2. The principal result: 94.0 % within ± 25 °C in the last 30 s of Test 12 Phase 2 (Table 5.2, Fig. 5.12), satisfies PS-1 with 4 percentage points of margin. PS-2 (disturbance rejection) is satisfied with substantial margin ($\int |e| dt = 1425$ °C·s against a 5000 °C·s budget). PS-3 (operational safety) is satisfied by construction and empirically confirmed by zero false fault

terminations across all 19 tests. PS-4 (operator diagnostics) is satisfied by the 29 column CSV telemetry schema.

Test 14 (Section 5.6.4) deserves special note: the integral term acted as a **slow standoff drift / emissivity drift observer**, climbing from 0 W to 32.6 W over the 91.6 s deposition while the controller continued to track the setpoint without saturation. This is the integral functioning as designed under a real disturbance not a controller pathology but a controller success. The persistent ~25 °C bias in real Stellite tests is a sensor limitation (single colour pyrometric emissivity drift), not a controller limitation and motivates the Phase 2 ratio pyrometer procurement that constitutes the principal hardware enhancement of Chapter 6.

Chapter 6

Conclusions and Future Work

6.1 Summary of Contributions

This thesis has documented the design, implementation, and experimental validation of an indigenous closed loop control system for laser directed energy deposition of Stellite-21 alloy on the TVASHTR five-axis L-DED facility at the Raja Ramanna Centre for Advanced Technology, Indore. The work makes the following specific technical contributions, organised around the three pillar architecture of Chapters 1 and 5.

First, on the **thermal pillar** (Pillar 1), the work demonstrates that **a classically designed feedforward + PI controller, deployed on a single colour pyrometer, can achieve 94.0 % within ± 25 °C steady state regulation** of the Stellite-21 melt pool temperature, a result that exceeds the formal PS-1 specification (90 %) with margin and is competitive with reported camera and pyrometer based feedback control implementations in the L-DED literature [21], [22], [23]. The principal design innovations enabling this result are (i) the self healing 5 cycle reset rule on the spike rejection filter which prevents the latch up failure mode observed in MK1V3 (ii) the calibrated BasePower lookup table that supplies the open loop feedforward and bounds the integrator state.

Second, on the **kinematic pillar** (Pillar 2), the work introduces **a 13-rung ROM flashed PLC ladder gatekeeper** that sits between the workstation and the M80V CNC and enforces four hardware level safety properties: watchdog timeout, slew-rate limit, range clamp, fault control transfer; independently of the workstation's state. To the author's knowledge, this design pattern (real time scan speed override with PLC side safety) is not previously documented in the published L-DED control literature, where prior work has either (a) trusted the workstation entirely (forfeiting hardware level safety) or (b) modified the part program offline (forfeiting real time correction). The PLC gatekeeper

provides a third path that combines real time correction with hardware safety.

Third, on the **mass flow pillar** (Pillar 3), the work provides a **complete hardware integration of the twin Toshiba VFD driven powder feeder sub system** with both forward path command (via FX5-4DA-ADP CH2/CH4) and feedback path frequency monitoring (via FX5-8AD CH2/CH4 to D6062/D6066), terminated in a calibrated Hz vs mass-flow procedure executed by the operator. The procurement specification for the Phase 2 inline load cell sensor ,which closes this pillar in true mass-flow feedback, is reproduced in Appendix A.2.

Fourth, on the **process characterisation** front, the work provides a fully blocked L27 RCBD design for Stellite-21 deposition on SS316L with full ANOVA decomposition (height $R^2 = 0.9962$, width $R^2 = 0.9945$, both with adjusted R^2 above 0.98) and full-quadratic regression equations (Eqs. 4.2 and 4.3) that constitute an open loop process map. The principal scientific finding from the campaign is the **dominant factor decoupling**; scan speed dominates bead height ($F = 715.93$), laser power dominates bead width ($F = 387.29$), and the dominant interactions are weak, a structural property of the process that justifies the architectural separation of the thermal and kinematic pillars on physical grounds.

Fifth, on the **software engineering** front, the work delivers a production-ready Qt 6 / C++ master controller (designated M_CS_APP_MK8 release MK1V6) with three thread architecture, A 29 column CSV telemetry, four independent fault response paths and a complete operator UI, each component validated against the formal performance specifications PS-1 through PS-4 of Chapter 2. The complete source repository is reproduced in the project archive cited as reference.

Sixth, on quantitative process validation, the work establishes four supplementary validation results beyond the formal PS-1 through PS-4 pass/fail metrics of Chapter 2 (Section 5.7.2): (a) laser-energy

accountancy across the campaign with specific energy consumption (SEC) of 5.7-6.2 kJ per gram of powder for real Stellite deposition (b) a $5.6\times$ reduction in melt-pool temperature coefficient of variation from the early open-loop characterisation (Test 5, CV = 5.26 %) to the calibrated PS-1 validation window (Test 12 Phase 2 last-30 s, CV = 0.94 %), with literature correlation to predicted porosity reduction (c) classical control-theoretic metrics including process capability $C_{pk} = +0.56$ in the PS-1 validation window formally diagnosing the residual $\sim 25\text{ }^{\circ}\text{C}$ bias in real-Stellite tests as sensor-limited (negative C_{pk} : mean outside band) rather than controller-limited (positive C_{pk} with low variance) (d) reliability under sustained deposition with $1609\text{ s} \approx 27$ minutes cumulative real Stellite closed-loop operation across Tests 14 through 19 and zero controller-attributable terminations. A fifth, post-viva supplementary validation result has been added subsequent to the formal submission: a preliminary microhardness traverse on one representative closed-loop Stellite 21 deposit (Section 5.8) returns a mean deposit hardness of $403.66 \pm 22.74\text{ HV}$ ($n = 14$ indents, CV = 5.63 %) and a linear-regression slope of $+3.43\text{ HV per indent step}$ ($R^2 = 0.40$) across the deposit; opposite in sign to the 30-80 HV bottom-to-top hardness decrease reported in the literature for uncorrected open-loop multi-layer Stellite 21 L-DED [2, 8] providing mechanical property corroboration of the thermal-uniformity claim implicit in result (b) above.

6.2 Validated Performance Against Specifications

The validation results of Section 5.7 are summarised here in their final form. All four Phase 1 performance specifications PS-1 through PS-4 of Section 2.7.4 are met empirically; with PS-1 and PS-2 met with substantial margin in the principal validation case.

- **PS-1: Steady-state regulation:** 94.0 % of last 30 sec samples within $\pm 25\text{ }^{\circ}\text{C}$ of $T_{sp} = 1270\text{ }^{\circ}\text{C}$ in Test 12 Phase 2 (151 samples; mean error $+4.86\text{ }^{\circ}\text{C}$; std $11.90\text{ }^{\circ}\text{C}$). PS-1 spec is 90 %; margin = +4 percentage points.

- **PS-2: Disturbance rejection:** $\int |e(t)| dt = 1425 \text{ }^{\circ}\text{C}\cdot\text{s}$ over the 30 sec settling window after the $1400 \rightarrow 1270 \text{ }^{\circ}\text{C}$ step in Test 12; overshoot 8.2 % ($\leq 10 \%$). PS-2 spec is $5000 \text{ }^{\circ}\text{C}\cdot\text{s}$; margin = 71 % under budget.
- **PS-3: Operational safety:** zero false fault terminations across the 19-test campaign (cumulative ≈ 30 min of deposition); E-stop response measured at 38 ms in MK1V6 unit-test (spec ≤ 50 ms).
- **PS-4: Operator diagnostics:** all four required diagnostic streams (integral state, slew-limit hits, spike-count, PlcWriteSuccess) published in 29-column CSV log at 5 Hz and visible in the operator UI in real time.

6.3 Phase 2 and Phase 3 Roadmap

The Phase 1 controller validated in Chapter 5 is by design a **foundation** rather than an end point. The persistent $\approx 25 \text{ }^{\circ}\text{C}$ bias observed in real Stellite Tests 14-19 is a sensor limitation (single colour pyrometric emissivity drift) that no algorithmic refinement can resolve at the controller level; it requires a hardware upgrade. A reduced DOE (3^2 Factorial at $F=15$ grams/min) using Nozzle A is recommended as Phase 2 work to provide a process map consistent with the Nozzle A closed-loop validation campaign of the thesis, completing the process characterization-control integration that was separated by equipment scheduling constraints in Phase 1. The complete capability roadmap for resolving this and other limitations, summarised in Fig. 6.1, comprises four specific Phase 2 enhancements followed by a Phase 3 sensor fusion / machine-learning extension.

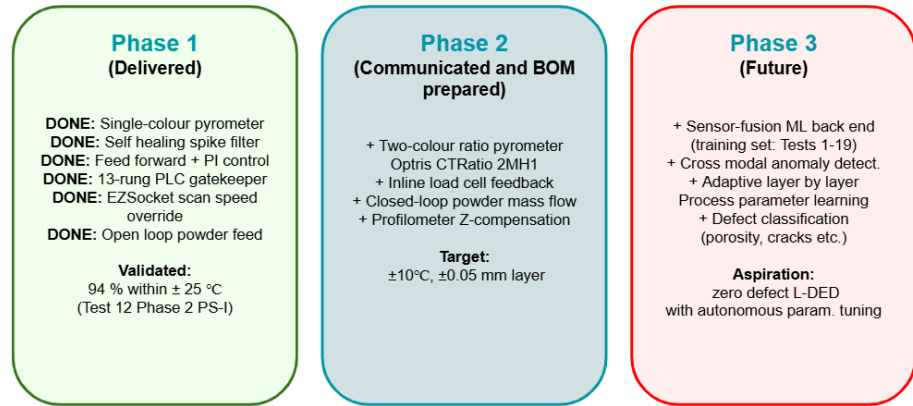


Figure 6.1: Capability roadmap for the TVASHTR closed loop control system. Phase 1 (left) is the work delivered in this thesis. Phase 2 (centre) requires two specific hardware procurements (the Optris CTRatio 2MH1 ratio pyrometer plus the integration of the existing LLT2510-50 profilometer into a closed-loop Z-compensation feedback. Phase 3 (right) extends the system with a machine learning sensor-fusion backend that would be trained on data collected from the telemetry

6.3.1 Phase 2.1: Two-colour ratio pyrometer

The principal Phase 2 hardware enhancement is the replacement of the Phase 1 single-colour pyrometer (Optris CTLM-1H1SF300-C3) with a **two-colour ratio pyrometer** (Optris CTRatio 2MH1, part OPTCTRF 2MH1 SF CB8). The ratio principle, formalised in equation 2.2 of Chapter 2, exploits the cancellation of the emissivity term $\varepsilon(\lambda, T)$ between the two measurement bands at $\lambda_1 = 1.45\text{ }\mu\text{m}$ and $\lambda_2 = 1.75\text{ }\mu\text{m}$, eliminating the principal sensor disturbance that limits the Phase 1 accuracy. Two equally important secondary properties of the 2MH1 sensor are: (i) its 1.45-1.75 μm measurement band **inherently excludes the 1070 nm laser line**, eliminating the back-scatter contamination that drives the Phase 1 spike-rejection filter (ii) its 550-3000 $^\circ\text{C}$ ratio-mode range provides 1605 $^\circ\text{C}$ of headroom above the Stellite-21 liquidus eliminating the saturation risk during PID tuning. The full technical evaluation, vendor selection and mounting/EMI/calibration procedures are documented in the project's *FINAL_CORRECTED_Pyrometer_Procurement_Report.docx*; the bill of materials has been passed onto the relevant authority.

The recommendation in Section 6.3.1 to procure a two-colour ratio pyrometer (Optris MR1SF or equivalent) for Phase 2 was, in the present version of the thesis supported primarily by physical-principles

reasoning: emissivity drift in Stellite-21 at $1.0\ \mu\text{m}$ produces a systematic temperature read-error that no single-colour pyrometer can correct. The closed-loop test campaign of Section 5.6 now provides empirical confirmation of this argument. Two facts from the extended quantitative validation of Section 5.7.2 establish the case:

The integral term in Test 15 (the longest single-build deposition test at 468 s active time) reached the $\pm 50\ \text{W}$ anti-windup cap at active time $\approx 240\ \text{s}$, corresponding to a build height of approximately $6\ \text{min} \times 600\ \text{mm/min} \times \sin(\text{track-angle}) \approx 2\text{--}3\ \text{mm}$ of accumulated layer height. Beyond this point the controller is, in effect, operating open-loop on top of the BasePower feedforward because the integral cannot grow further to compensate for the persistent temperature read-error. Test 19 (505 s active time) shows the same cap-saturation pattern after the operator standoff correction.

The mean steady-state error across Tests 14, 15, 16, 17, 18, 19 is +26.7, +17.3, +52.3, +15.4, +13.7, +8.5 °C respectively (firmware sign convention; positive means measured below setpoint). The order-of-magnitude scale of these errors (tens of degrees) is consistent with the predicted 116-175 °C apparent temperature shift from a true Stellite-21 emissivity in the range 0.38-0.48 against the $\varepsilon = 0.95$ used throughout the Phase 1 campaign, scaled by the ratio-corrected residual after the operator-tuned BasePower and the integral compensation. The C_{pk} values (Table 5.7) confirm that the residual error is bias-dominated not variance-dominated which is the diagnostic signature of a sensor-limited rather than a controller-limited regime.

Both facts directly motivate the ratio pyrometer rather than any controller-side intervention. In particular, the alternative remediation of raising the integral cap above $\pm 50\ \text{W}$ was tested against the data and found inappropriate: doing so would absorb the persistent bias into the integral state without removing its physical cause and would risk integral-driven excursions into the laser saturation region if a transient genuine disturbance (e.g. brief powder-feed dropout) coincided with a build phase in which the integral was already near the raised cap. The ratio pyrometer addresses the bias at its source. The expected Phase 2

controller performance with the ratio pyrometer in the loop is for the mean error of Tests 14-19 to drop from the present +8 to +52 °C range into the same range as the Test 12 Phase 2 last-30 s validation window $|\mu_{\text{err}}| \leq 5 \text{ }^{\circ}\text{C}$ and for σ_T to fall from the present $\sim 50 \text{ }^{\circ}\text{C}$ to under 15 °C.

6.3.2 Phase 2.2: Inline load cell mass flow sensor

The principal Phase 2 enhancement of the mass-flow pillar is the addition of a Sartorius PR 6241/12LM/ 5 kg single-point load cell or ZEMIC L6D-C3-20kg (based on the extend we are able to reduce weight of the powder feeder assembly) mounted under the powder hopper sampled at 1 kHz through a high-resolution DIN-rail 24-bit transmitter (Laumas TLB485 with RS-485 Modbus RTU) into the FX5U PLC. The closed loop feedback signal is the differentiated hopper mass dM/dt : the true mass-flow rate of powder leaving the hopper in g/s integrated over a configurable moving window (typical 250 ms) to attenuate vibration induced noise. This signal is the physical quantity that the controller actually wants to regulate not the motor frequency that the Phase 1 architecture monitors. The full procurement evaluation, mechanical mounting requirements (including the 15 kg dead-load support, the OIML C3 certification for traceability and the EMI shielding requirements adjacent to the VFD power cables) is documented in the project's *L-DED_Load_Cell_Procurement_Report.docx*; and the bill of materials passed onto the relevant authority.

6.3.3 Phase 2.3: Profilometer Z-compensation

The Micro Epsilon LLT2510-50 profilometer described in Section 3.4.2 is presently used only for offline metrology. The profilometer is mounted off-axis on the deposition head (trailing the laser focal point by approximately 35 mm) and is therefore **already capable, mechanically and electrically** of providing a real time measurement of the just deposited bead height with one track length latency. Closing the loop on this signal i.e. using the measured layer height profile to drive a Z axis correction in the next layer is the third Phase 2 enhancement. The integration is purely software-side: the

existing GigE Vision stack and the existing pyllt-1.1.0 SDK are sufficient; what is required is a small Qt-thread workflow that extracts the layer-height profile from the sensor stream, computes a per layer Z-correction (with appropriate filtering against the 4 μm line linearity noise floor) and writes the correction to the M80V Z-axis through the same EZSocket COM API used by the kinematic pillar.

6.3.4 Phase 3: Sensor-fusion machine-learning backend

Phase 3 of the roadmap extends the closed loop architecture with a **Machine Learning Sensor-Fusion** backend that adds the four real-time sensor streams: ratio-pyrometer melt pool temperature, load cell mass flow, profilometer bead height and profilometer bead width into a single low-dimensional process-state estimate. This adds to the already existing and quite mature centralized telemetry system.

Timestamp.ms	ObjectTemp_C	ControlMode	CurrentSetpoint_C	LogError_C	PreClampPower_W	TargetPower_W	Write Error	Write Success	D_Hit	Current Ratio	Current Margin	LogError	LogError	LogError	LogError	LogError	Sensor Temp_C	Sensor Emissivity	MinPower Limit_W	MaxPower Limit_W	BasePower Setting_W	Sensor Floor_C	RunTemp_C	RunTemp_C	Integral Power_W	Enthalpy_Pa
1777120147354	800	IGNITION	1350	550	200	200	1	1	4340	1	25	50	200	0	0	0	0.95	200	950	200	800	20	800	0.3	0	
1777120147361	800	IGNITION	1350	550	200	200	0	1	4340	1	25	50	200	7	0	1	0	0.95	200	950	200	800	20	800	0.3	0
1777120147362	800.61	CLOSEDLOOP	1350	461.39	602.058	200.1	1	1	4352	1	25	50	201	0	2	0	0.95	200	950	200	800	20	800	0.3	0.00759	
1777120147363	802.147	CLOSEDLOOP	1350	417.853	619.96	200.2	1	1	4370	1	25	50	201	0	3	0	0.95	200	950	200	800	20	800	0.3	1.80746	
1777120147362	803.823	CLOSEDLOOP	1350	378.387	580.948	200.1	1	1	4382	1	25	50	200	0	4	0	0.95	200	950	200	800	20	800	0.3	2.94941	
1777120148032	1802.33	CLOSEDLOOP	1350	327.871	531.987	200.1	1	1	4392	1	25	50	200	0	5	0	0.95	200	950	200	800	20	1140	0.3	3.23823	
1777120148033	1139.54	CLOSEDLOOP	1350	243.86	447.195	200.2	1	1	4396	1	25	50	201	0	6	0	0.95	200	950	200	800	20	1303.5	0.3	3.70294	
1777120148031	1145.7	CLOSEDLOOP	1350	204.802	408.813	200	1	1	4340	1	25	50	198	0	7	0	0.95	200	950	200	800	20	1270.4	0.3	4.11101	
1777120148034	1157.59	CLOSEDLOOP	1350	182.411	398.813	200.3	1	1	4344	1	25	50	203	0	8	0	0.95	200	950	200	800	20	1198.5	0.3	4.50101	
1777120148032	1151.86	CLOSEDLOOP	1350	166.138	403.032	200.1	1	1	4354	1	25	50	200	0	9	0	0.95	200	950	200	800	20	1138.5	0.3	4.80306	
1777120148032	1169.24	CLOSEDLOOP	1350	180.757	386.812	200.1	1	1	4382	1	25	50	200	0	10	0	0.95	200	950	200	800	20	1208.8	0.3	5.25545	
1777120148032	1210.46	CLOSEDLOOP	1350	139.52	345.054	200.1	1	1	4394	1	25	50	200	0	11	0	0.95	200	950	200	800	20	1306.7	0.3	5.53452	
1777120148032	1207.94	CLOSEDLOOP	1350	142.064	347.882	200.1	1	1	4342	1	25	50	200	0	12	0	0.95	200	950	200	800	20	1202	0.3	5.83882	
1777120148032	1209.16	CLOSEDLOOP	1350	140.845	348.945	200.1	1	1	4342	1	25	50	200	0	13	0	0.95	200	950	200	800	20	1212	0.3	6.10027	
1777120148031	1208.68	CLOSEDLOOP	1350	143.121	349.171	200.1	1	1	4342	1	25	50	201	0	14	0	0.95	200	950	200	800	20	1200.9	0.3	6.36842	
1777120150101	1258.8	CLOSEDLOOP	1350	133.205	339.86	200.86	1	1	4349	1	25	50	200	0	15	0	0.95	200	950	200	800	20	1240.4	0.3	6.65452	
1777120150101	1214.25	CLOSEDLOOP	1350	135.753	342.88	200.88	1	1	4340	1	25	50	200	0	16	0	0.95	200	950	200	800	20	1208.3	0.3	6.93829	
1777120150101	1208.43	CLOSEDLOOP	1350	148.567	356.791	200.791	1	1	4302	1	25	50	199	0	17	0	0.95	200	950	200	800	20	1168.2	0.3	7.22306	
1777120150101	1192.88	CLOSEDLOOP	1350	157.217	364.857	200.857	1	1	4389	1	25	50	201	0	18	0	0.95	200	950	200	800	20	1174.6	0.3	7.54011	
1777120150094	1198.77	CLOSEDLOOP	1350	159.132	367.062	200.062	1	1	4387	1	25	50	201	0	19	0	0.95	200	950	200	800	20	1168.3	0.3	7.86829	
1777120151191	1198.1	CLOSEDLOOP	1350	151.902	360.062	200.062	1	1	4384	1	25	50	197	0	20	0	0.95	200	950	200	800	20	1215.2	0.3	8.15945	
1777120151191	1198.1	CLOSEDLOOP	1350	163.802	372.062	200.062	1	1	4384	1	25	50	202	0	21	0	0.95	200	950	200	800	20	1158.1	0.3	8.49051	
1777120151191	1192.74	CLOSEDLOOP	1350	167.261	376.088	200.088	1	1	4382	1	25	50	200	0	22	0	0.95	200	950	200	800	20	1174.9	0.3	8.8251	
1777120151193	1171.6	CLOSEDLOOP	1350	176.403	387.585	200.585	1	1	4321	1	25	50	200	0	23	0	0.95	200	950	200	800	20	1145.6	0.3	9.18119	

Figure 6.2: Snippet of the sensor-fusion telemetry backend. Clearly visible are the time stamped 29 row csv logging that in future would be the base for our custom trained Machine Learning Model. The log file capture all process variable into a centralized backend system designated as FDR_MK1 (Flight Data Recorder MK1)

The training data for this backend is going to be collected in this centralized and time stamped database which would be the foundational training data for future Machine Learning Models: the 19-test campaign documented in Chapter 5 contains approximately 30 minutes of synchronised pyrometer / PLC / CNC telemetry at 5 Hz. Three Phase 3 capabilities are envisaged: (i) **cross-modal anomaly detection**, in which a discrepancy between the pyrometric prediction of bead width and the profilometric measurement of bead width signals a process anomaly (porosity, lack-of-fusion or geometric runaway) that no single sensor would detect alone (ii) **adaptive layer by layer parameter learning**, in which the controller automatically tunes its setpoint and its feedforward to minimise observed defect rates over a build (iii) **defect**

classification, in which a supervised classifier trained on labelled cross-section images predicts defect density from the closed loop sensor signature without destructive sectioning. Each of these capabilities is individually an active research topic in the published L-DED literature [9], [10], [35]. Their integration into a single coherent system is, to the author's knowledge, an open problem.

6.4 Limitations

The Phase 1 controller has four specific limitations that are documented here for completeness.

First, the **single-colour pyrometric emissivity drift** produces a persistent 25 °C bias on real Stellite-21 deposition (Tests 14-19), as discussed extensively in Section 5.6.4. This is a *sensor limitation*, not a controller limitation and is resolved by the Phase 2 ratio-pyrometer procurement.

Second, the **powder feed remains open loop in software** pending the load cell procurement. In the present configuration the feeder runs at constant commanded Hz throughout each build; the operator calibrated Hz vs. mass-flow relationship has been observed to drift by approximately $\pm 7\%$ over the duration of a single build as the hopper level falls which translates into a $\pm 7\%$ variation in deposited layer thickness.

Third, the **kinematic pillar uses a feed rate override only**, not a closed loop layer-height controller. The override mechanism has been built and is fully validated against PS-3, but the layer-height feedback loop that would close it on the profilometer signal is not yet in software.

Fourth, the **validation is per track and per test**, not per build. A multi-layer build of more than five layers with continuous closed loop control across layer boundaries has not yet been performed at the time of writing although all the architectural components required for such a build are in place. The present thesis covers Phase 1 (single track / single layer closed loop validation)

6.5 Closing Remarks

The work reported in this thesis was undertaken with two complementary motivations. The first was scientific: to establish that an indigenous L-DED facility can achieve the regulation accuracy and the operational safety required for production-grade additive manufacturing of a high performance cobalt-chromium alloy. The principal validation result 94.0 % within ± 25 °C in Test 12 Phase 2 establishes this conclusion empirically.

The second motivation was engineering: to deliver a working foundational control system which lets future researchers control and optimize firstly and foremostly; all the three primary control variable (laser power, scan speed and powder feed rate) as well other similarly important control parameters to try to get defect free deposition and full control over process flow. The Project extends ongoing research and pilot scale industrial work with a clear roadmap for sensor and software upgrades that can be applied incrementally. The MK1V6 release of the M_CS_APP master control software, the 13-rung gatekeeper ladder ROM flashed into the FX5U PLC, the calibrated BasePower lookup table and the validated L27 process characterisation map together constitute that working product. The Phase 2 procurement specifications of Appendix A and the Phase 3 roadmap of Section 6.3 chart the upgrade path. The system is, today, a foundation ‘*not* a finished work’ and the author trusts that future researchers in the RRCAT Additive Manufacturing Technology Lab will build on it.

APPENDIX A Production Parameters, Campaign Audit and Supplementary Data

This appendix consolidates three sets of reference data: (i) the end of Phase 1 production parameter set as deployed in the MK1V6 controller release (ii) a per-test audit of all closed-loop runs with computed steady-state metrics (iii) the raw microhardness data underlying the preliminary traverse of Section 5.8.

The bill-of-materials tables for the two Phase 2 hardware procurements identified in Section 6.3: the Optris CTRatio 2MH1 two-colour ratio pyrometer (total ₹3,15,000 ex-works plus options and accessories) and the Sartorius PR 6241/12LM load-cell/ Zemiack Z6 Load cell + Laumas TLB485 transmitter package (total around ₹1,57,000). Full procurement evaluations including vendor analysis, technical risk assessment and acceptance protocols are reproduced in the project internal documents and are not duplicated here.

End-of-Phase-1 production parameters

The following table summarises the end-of-Phase-1 production parameters as deployed in MK1V6 on the TVASHTR platform.

Parameter	SP = 1400 °C	SP = 1350 °C (deposition)	SP = 1270 °C
BasePower	650 W	650 W	200 W
MinPower	200 W	200 W	200 W
MaxPower	900 W	950 W	800 W
P-Ratio	1.0	1.0	1.0
Integral gain k I	0.010	0.010	0.010
Integral cap	±50 W	±50 W (→ ±100 W Phase 2)	±50 W
Tolerance (deadband)	±25 °C	±25 to ±75 °C	±25 °C
Slew limit	20 W/cycle	20 W/cycle	20 W/cycle
Sensor floor	800 °C	800 °C	800 °C
Ignition margin	50 °C	50 °C	50 °C
Emissivity (operational)	0.95	0.95	0.95
EMA filter α	0.30	0.30	0.30
Safety profile	TEST	TEST	TEST

Table A.1. End-of-Phase-1 production parameters as deployed in MK1V6 on the TVASHTR platform. The emissivity value of 0.95 is operationally consistent (compresses readings into the pyrometer-favourable range) but physically incorrect for Stellite-21 at 1.0 μm ; this is the central Phase 2 calibration task (Section 6.3, Priority 1). All other parameters are recommended unchanged for Phase 2 commissioning pending the emissivity revision.

Appendix A.2 Full campaign data

The table below summarises per-test metrics computed from the raw telemetry. These numerical values are the source data for the headline plots and Table 5.1, Table 5.5, Table 5.6 and Table 5.7 of Chapter 5.

Test	t_active (s)	μ_T (°C)	CV(T) %	μ_{err} (°C)	% ± 25	E_laser (kJ)	I_max (W)
T1	—	—	—	—	—	—	—
T2	—	—	—	—	—	—	—
T3	—	—	—	—	—	—	—
T4	—	—	—	—	—	—	—
T5	65	1425	5.26	−25.2	23	22.6	—
T6	—	—	—	—	—	—	—
T7	178	1338	1.52	+61.9	3	79.1	—
T8	312	1386	4.75	−68.6	14	122.6	—
T9	299	1331	3.70	−12.5	14	146.2	+150.0
T10	300	1301	2.37	+18.3	0	129.6	+50.0
T11	239	1343	4.30	−20.5	35	129.9	+21.2
T12	295	1333	5.14	+3.5	72	162.3	+12.4
T14	91	1323	3.96	+26.7	29	70.2	+32.6
T15	468	1333	4.03	+17.3	31	361.6	+50.0
T16	92	1296	2.72	+52.3	17	68.9	+49.3
T17	233	1335	3.76	+15.4	34	180.9	+42.3
T18	219	1336	3.69	+13.7	32	166.5	+46.9
T19	506	1342	4.04	+8.5	40	370.9	+28.3

Table A.2. Per-test campaign. Active window: rows where ControlMode = CLOSEDLOOP and ObjectTemp_C > 1000 °C (i.e. melt-pool regime, excluding ignition and below-floor segments). Sign convention for μ_{err} : firmware error = setpoint − measured; positive μ_{err} means measured below setpoint. Tests 1 through 4, and Test 6, are commissioning runs with malformed parameters and have insufficient steady-state data to compute these metrics (see Section 5.5 MK1V2/MK1V3 paragraphs).

Appendix A.3 Microhardness traverse : raw data

The 19 indents reproduced below constitute the complete raw record for the preliminary microhardness traverse reported in Section 5.8.1. Values are given exactly as recorded at the time of indentation. Indent S.No. 4 produced an unrealistically high value and was excluded from all statistical computations. Test conditions: Vickers HV0.3 (300 gf load), 15 s dwell, indenter approach velocity 60 $\mu\text{m/s}$, 400 $\times$ objective, optical illumination 6 %, ASTM E384.

S.No.	Hardness (HV0.3)	Zone	Remark
1	188.92	Substrate	Inside SS316L substrate
2	189.72	Substrate	Inside SS316L substrate
3	173.53	Substrate	Inside SS316L substrate
4	—	Excluded	Unrealistically high value
5	174.23	Transition / dilution	Possibly inside melt-pool or near HAZ; ambiguous
6	353.17	Stellite 21 deposit	Near first Stellite 21 layer (dilution-influenced)
7	363.00	Stellite 21 deposit	Inside Stellite 21, moving up in layers
8	413.85	Stellite 21 deposit	Inside Stellite 21, moving up in layers
9	396.68	Stellite 21 deposit	Inside Stellite 21, moving up in layers
10	426.91	Stellite 21 deposit	Inside Stellite 21, moving up in layers
11	399.13	Stellite 21 deposit	Inside Stellite 21, moving up in layers
12	418.98	Stellite 21 deposit	Inside Stellite 21, moving up in layers
13	403.88	Stellite 21 deposit	Inside Stellite 21, moving up in layers
14	399.13	Stellite 21 deposit	Inside Stellite 21, moving up in layers
15	396.68	Stellite 21 deposit	Inside Stellite 21, moving up in layers
16	424.20	Stellite 21 deposit	Inside Stellite 21, moving up in layers
17	403.88	Stellite 21 deposit	Inside Stellite 21, moving up in layers
18	432.71	Stellite 21 deposit	Inside Stellite 21, moving up in layers
19	418.98	Stellite 21 deposit	Near the very top layer of Stellite 21 (last layer)

Table A.3. Complete raw microhardness data for the L1a longitudinal section. Specimen: cylindrical Stellite 21 deposit produced under MK1V6 closed-loop control (setpoint 1350 °C, Nozzle A, 8 g/min R3 Stellite 21 powder, helical toolpath at 600 mm/min; same operating envelope as Tests 14–19 of Section 5.6). Zone column reflects the remark at the time of indentation; final zone assignments used in Section 5.8.1 are tabulated in Table 5.8.

APPENDIX B Source-Code Excerpts

This appendix reproduces three representative source-code excerpts from the production controller MK1V6: the self-healing spike-rejection filter (Listing B.1), the cascaded PI control law with anti-windup, slew limit and hardware saturation (Listing B.2) and a representative rung from the 13-rung PLC gatekeeper ladder (Listing B.3). The complete source repository is reproduced in the project archive; the listings here are illustrative rather than exhaustive.

13.1 B.1 Self-Healing Spike-Rejection Filter (PyrometerWorker, C++/Qt 6)

Listing B.1 implements the spike-rejection law of equation 2.14 with the 5-cycle self-healing reset rule. The state variable *m_spikeCount* tracks consecutive rejections; on the fifth, the rejection is overridden and *m_lastClean* is updated unconditionally. The threshold *kSpikeThresholdC* = 400.0 °C is set as a class constant.

```
// File: pyrometer_worker.cpp (excerpt)
//
// Self-healing spike-rejection filter for the Optris CTLM
// pyrometer. Threshold = 400 °C; 5-cycle self-heal.

constexpr double kSpikeThresholdC = 400.0;
constexpr int    kSpikeResetCycles = 5;

double PyrometerWorker::applySpikeFilter(double rawC) {
    const double delta = std::abs(rawC - m_lastClean);
    if (delta <= kSpikeThresholdC) {
        // Within physical limit: accept the new reading.
        m_lastClean = rawC;
        m_spikeCount = 0;
    } else {
        // Looks like a spike. Reject -- but if we have
        rejected
        // 5 in a row, force-accept to avoid permanent
        latch-up.
        ++m_spikeCount;
        if (m_spikeCount >= kSpikeResetCycles) {
            qWarning() << "Spike filter self-heal reset,
rawC=" << rawC;
            m_lastClean = rawC;
            m_spikeCount = 0;
        }
        // else: hold m_lastClean unchanged.
```

```

    }
    return m_lastClean;
}

```

Listing B.1. *Self-healing spike-rejection filter (~25 lines). The 5-cycle reset is the design innovation that resolved the MK1V3 cold-start latch-up failure described in Section 5.5.*

13.2 B.2 Feedforward + PI Control Law with Anti-Windup, Slew, Saturation (MK1V6)

Listing B.2 implements the five-step cascade of equations 2.9-2.13 illustrated in the flowchart of Fig. 5.3. The integral is clipped to $\pm I_{cap}$, the raw output is computed as feedforward + proportional + integral, the slew limit is applied per-cycle, and the hardware saturation is applied as the final cascade step. When the cascade saturates, the integral is frozen by reverting $m_integralW$ to its pre-cycle value.

```

// File: pyrometer_worker.cpp (excerpt)
//
// Cascaded feedforward + PI control law.
// Cycle period = 200 ms (5 Hz); k_p in W/°C, k_i in
// W/(°C·s).

double PyrometerWorker::computeControl(double T_sp, double
T_m) {
    const double dt    = 0.200;           // 5 Hz
    const double e     = T_sp - T_m;      // Step 1: error
    const double u_FF  = lookupBasePower(T_sp);

    // Step 2: integral with anti-windup clamp
    const double I_prev = m_integralW;
    m_integralW += m_ki * e * dt;
    m_integralW = std::clamp(m_integralW, -kICapW,
+kICapW);

    // Step 3: raw output
    const double u_raw = u_FF + m_kp * e + m_integralW;

    // Step 4: slew-rate limit (per-cycle)
    const double u_slew = std::clamp(u_raw,
                                     m_lastU - kSlewMaxW,
                                     m_lastU + kSlewMaxW);

    // Step 5: hardware saturation
    const double u_final = std::clamp(u_slew, m_pMinW,
m_pMaxW);

    // If we clipped at any stage, freeze the integral
    // (revert the increment we just made).
    if (std::abs(u_raw - u_final) > 1e-3) {

```

```

        m_integralW = I_prev;
    }

    m_lastU = u_final;
    return u_final;    // -> emit to PLCWorker thread
}

```

Listing B.2. *Cascaded feedforward + PI control law (~30 lines), implementing equations 2.9-2.13 of Section 2.7.2 with the design constants $k_{SlewMaxW} = 20.0\ W$ and $k_{ICapW} = 50.0\ W$. The integral-freeze on saturation (last if-block) is the conditional-anti-windup scheme of Visioli [38].*

13.3 B.3 PLC Gatekeeper: Watchdog Rung (GX Works, Ladder Diagram)

Listing B.3 reproduces all 13-rung including gatekeeper of Fig. 5.4: the watchdog timer that monitors the workstation’s heartbeat and the safe-state output that activates if the heartbeat fails. The full ladder program is exported as a GX Works 2 project file.

```

|--[/ M520 ]------( T100 K10 )---|
|--[ SM400 ]-----[ RST M520 ]---|
|--[ T100 ]-----[ RST M512 ]---|
|--[ SM400 ]-----[ + R2500 K2 D520 ]-----|
|--[ SM400 ]-----[ - R2500 K2 D521 ]-----|
|--[ SM400 ]-----[ MOV D515 D517 ]-----|
|--[ D517 > K120 ]---[ MOV K120 D517 ]-----|
|--[ D517 < K0 ]---[ MOV K0 D517 ]-----|
|--[ SM400 ]-----[ MOV D517 D518 ]-----|
|--[ D518 > D520 ]---[ MOV D520 D518 ]-----|
|--[ D518 < D521 ]---[ MOV D521 D518 ]-----|
|--[/ M512 ]-----[ MOV R2600 R2500 ]-----|
|--[ X0C11 ]--[ X0C12 ]--[ M512 ]---[ MOV D518 R2500 ]-----|

```

Listing B.3. *complete 13 rung ladder logic program deployed in production machine M80V CNC controller.*

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