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Integrating Systems Engineering and Materials Science in a Cross-Disciplinary Capstone Project on Additive Manufacturing System Design

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This Work-in-Progress paper describes an interdisciplinary capstone project that integrates systems engineering (SE) principles with materials science and mechanical engineering practice. The project focuses on the iterative improvement of a student-designed direct energy deposition additive manufacturing system used to fabricate solid metal and ceramic components from powder precursors. Joint oversight by systems engineering and materials-focused faculty provides an authentic context for applying requirements flow-down, interface definition, baseline management, and verification planning within an undergraduate capstone environment.

Introduction

Modern engineered systems increasingly require coordinated integration of mechanical, electrical, software, and process subsystems. Systems engineering offers a structured approach for managing this complexity, yet SE methods are often weakly represented in discipline-specific capstone projects. This is even though it has been shown that multidisciplinary capstone projects involving systems engineering are very well suited to preparing students for engineering careers in the current industry [1]. Additionally, it has been shown that multidisciplinary capstone projects lead to enhanced student understanding of concepts, particularly when those projects are hands-on in nature [4, 7]

This paper presents an interdisciplinary capstone model in which systems engineering practices are embedded within a multidisciplinary capstone project involving materials science, mechanical engineering, and electrical engineering to enhance an additive manufacturing research project. The project is co-led by two faculty members, one in the area of systems engineering and one with expertise in materials and engineering. The project detailed in this work provides students with exposure to real-world constraints including in-situ problem, evolving requirements, and multiyear system development.

Project Context and Objectives

The capstone project centers on a direct energy deposition system designed to convert metal and ceramic powder materials into fully dense solid components using a laser energy source. A schematic diagram of the entire system identifying each of the subsystems is shown in Figure 2. The project began as a program enhancement grant designed to provide students with the opportunity to design and build laboratory equipment. That original idea transitioned from student prototype at the end of the first capstone project into a feasible laser-DED system capable of preliminary basic research. After additional work undertaken by summer research students, the system now supports an active faculty research investigation focused on novel material development. As a result, the platform operates under authentic operational constraints, including uptime requirements, configuration stability, and experimental reproducibility.

Educational objectives include: (1) fostering collaboration between systems engineering and non-SE faculty; (2) integrating real-world SE challenges—such as requirements allocation, interface management, and configuration control—into the undergraduate curriculum; and (3) providing an interdisciplinary capstone experience that emphasizes system-level performance rather than isolated component optimization.

Systems Engineering Challenges in a Multiyear Capstone

Students encounter challenges characteristic of complex engineered systems. The platform integrates mechanical powder handling hardware, electrical actuation, and computer-based control, requiring explicit interface definition across subsystems. Figure 1 shows a schematic of the requirements hierarchy. The team employed iterative requirements decomposition. This process began with stakeholder-defined needs (research-grade deposition defined by <10% variability in final part density) and allocating these to subsystem specifications. For example, the deposition uniformity requirement drove derived requirements for flow control of ±0.1L/min. This requirements allocation is shown in Figure 1, showing the decomposition from system-level objectives down to subsystem specifications to component-level design parameters

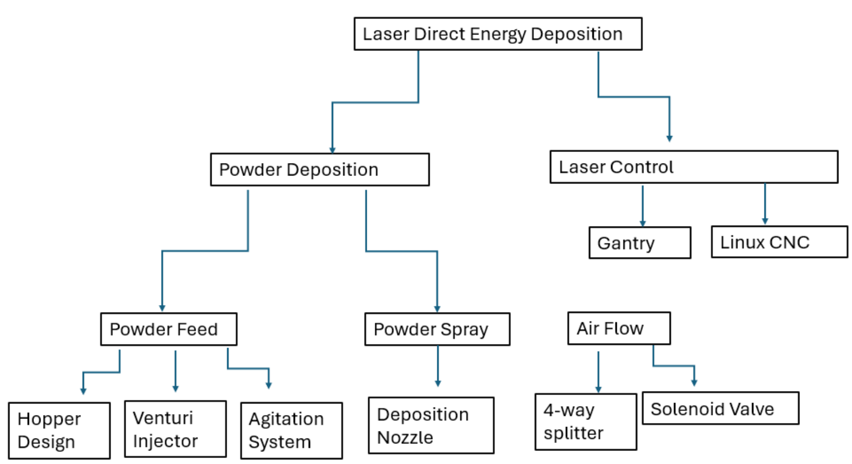

Figure 1: Requirements hierarchy showing decomposition from system-level research objectives (top) through subsystem requirements to component specifications (bottom)

The project spans multiple academic years, with each cohort inheriting a system baseline established by prior teams. To mitigate regression and knowledge loss, students apply configuration management practices including baseline documentation consisting of an operating manual containing CAD models, electrical schematics, component specifications, and procedures), version-controlled design artifacts, and structured design reviews with external reviewers. This document was built up and modified as necessary as new components were added and procedures changed. Rigorous documentation is necessary for a successful transition between teams, which is often difficult to integrate into more traditional projects [5,6, 7, 11].

Additional challenges arise from the dual instructional and research role of the system. Design modifications must be staged to minimize disruption to ongoing experiments, reinforcing the importance of incremental upgrades, risk management, and verification prior to operational release. This aspect becomes particularly challenging to communicate. Intended design improvements have the potential to enhance the system's capability greatly offering the promise of improved results. However, that must be weighed up against delays in implementing those upgrades. These risks have been mitigated by testing individual systems on isolated hardware to ensure suitability and function before integrating into the final system. This approach limits downtime to only actual time required to physically install the hardware.

Technical Improvements and System Evolution

Students have implemented several engineering improvements to enhance system performance and robustness. Several subsystems have been identified as areas of improvement including the powder deposition system, flow control, and control system.

The original powder deposition system involved filling a conical hopper located directly on top of a venturi injective valve. While this approach had limited success, results were inconsistent. The powder would often become clogged in the hopper or air lines and not flow to the laser head. The powder would flow through air lines to a single nozzle aimed at the focal point of the laser. This nozzle again showed the potential to clog and led to excess powder flow that would deposit on the inside of the system.

The redesigned powder deposition subsystem incorporates several key improvements. The first is an agitated hopper to reduce powder bridging and improve flow consistency. The agitated hopper design separates the conical hopper from the venturi injector directly, allowing for a more consistent feed of powder to the injector. A vibration motor was also added to the hopper to reduce clogging. Next, a four-nozzle powder delivery architecture was introduced to improve deposition uniformity.

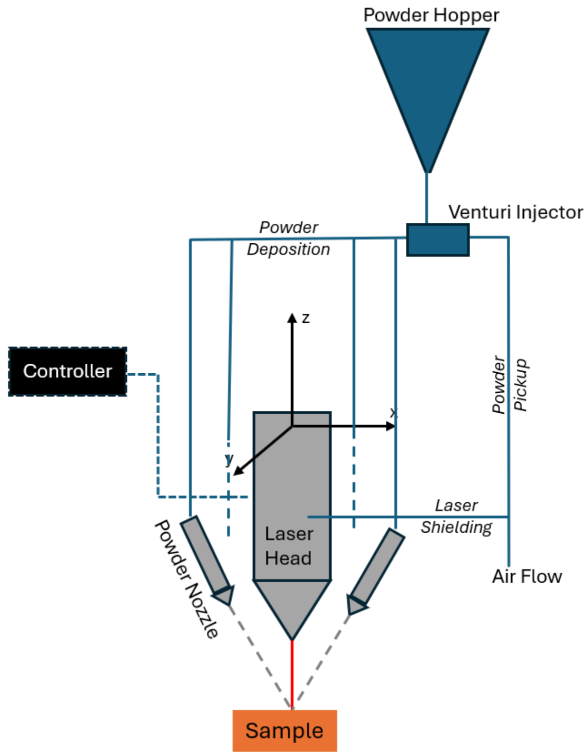

Figure 2: Schematic Diagram of the Direct Energy Deposition system designed and built by capstone students spanning several project cycles

The powder delivery nozzle marked an improvement in powder on target but led to additional challenges of splitting one airline into four and maintaining even powder distribution throughout each of the lines. Students optimized the airflow distribution manifold responsible for splitting a single supply line into four nozzle feeds. Design iterations reduced flow imbalance and turbulence, improving repeatability during operation. These improvements were implemented while experimental printing trials continued in parallel, reinforcing the importance of controlled configuration changes.

Another key modification of the system is to implement an automated powder flow control. The current system relies on the user to simultaneously manually opening the air line via flow control valve, turn on the hopper agitator, and fire the laser. Practically it is impossible for a single user to accomplish this. As a result, running experiments relays on the availability of two or three trained operators being available at a time. Automatic controls are being developed through integration of a solenoid valve within the compressed air supply. The solenoid valve will be controlled by LinuxCNC, which is the control software for the laser. Not only will the system be automated, but the solenoid valves will also allow much more control of the airflow, which in turns will offer improved precision of powder mass on target. Regulating airflow through a venturi-based transport mechanism enables indirect control of powder feed rate while maintaining compatibility with existing hardware. Verification activities include repeatability testing and comparison to prior system baselines. An evolution of the progression of the system evidenced by sample results is shown in Figure 3.

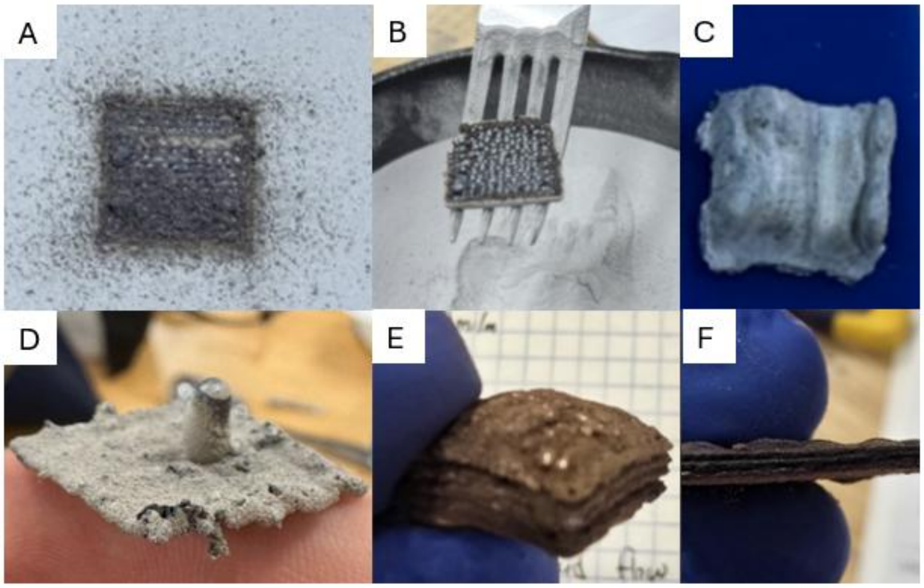

Figure 3: Images of samples showing the progression of capability of the 3D printer A)Single layer of stainless steel powder exposed to layer but did not densify into a stable structure B) Single layer of stainless steel powder densified into layer C)Al2O3 sample created from a single layer D) Al2O3 created from powder deposition E) Copper structure created by powder deposition showing individual layers F) Copper sample showing improved layer cohesion

An additional next step will be to tie the hopper agitation motor into LinuxCNC control software as well so that the entire system will be controlled via software commands.

Preliminary Outcomes

The implemented improvements have led to more stable and repeatable printing performance. Compared to earlier system configurations, students observed reduced variability in part geometry and density across repeated builds. This indicates improved process consistency and subsystem integration. While formal statistical analysis is ongoing, these trends support the effectiveness of system-level design and verification practices.

Mapping to Systems Engineering Frameworks

Project activities align closely with the systems engineering V-model as shown in Table 1. Early phases emphasize stakeholder needs identification through collaboration with research faculty. System requirements definitions were based on research operational constraints. The design continues with functional decomposition and detailed subsystem specification, with explicit interface definition across mechanical, electrical, and software sections. Implementation corresponds to the lower portion of the V-model, while verification occurs through both subsystem testing (e.g., airflow distribution uniformity measurements) and integrated system demonstrations (e.g., multi-layer deposition trials). Validation is achieved through successful operation of the system in its intended research environment. This preliminary success has been evidenced by stable experimental results producing pure copper samples. This structured approach provides students with authentic experience in requirements-driven design and systematic verification practices essential to complex engineered systems.

Table 1: Systems Engineering V-Model Mapping to Capstone Project Activities

V-Model Phase	Project Activities	Key Deliverables	Responsible Party
Concept of Operations	Faculty research needs analysis; identification of uptime requirements and experimental reproducibility constraints	Stakeholder interviews; ConOps document; initial operational scenarios	Faculty advisors + incoming student team
System Requirements	Definition of powder deposition uniformity targets; automated control specifications; safety and environmental constraints	System Requirements Specification (SRS); requirements traceability matrix	SE student lead with materials faculty review
High-Level Design	Functional decomposition into subsystems (powder delivery, flow control, laser control, motion control); interface identification	System architecture diagram; interface control documents (ICDs); functional block diagrams	Full student team

V-Model Phase	Project Activities	Key Deliverables	Responsible Party
Detailed Subsystem Design	4-nozzle powder delivery design; solenoid valve integration; airflow manifold optimization; LinuxCNC control logic	Detailed design drawings; CAD models; software specifications; bill of materials	Subsystem leads (mechanical, electrical, software)
Implementation	Fabrication of hardware components; LinuxCNC programming; solenoid integration; wiring and assembly	As-built documentation; fabricated hardware; control software v1.x; assembly procedures	Full student team
Subsystem Verification	Airflow distribution testing; powder feed rate repeatability measurements; solenoid timing validation; hopper agitation effectiveness	Subsystem test reports; performance data; test procedures; acceptance criteria checklists	Testing subteam with SE oversight
System Integration & Verification	Integrated system testing; end-to-end powder deposition trials; multi-layer print demonstrations	Integration test reports; system performance baseline; configuration audit results	Full student team
System Validation	Successful execution of faculty research experiments; material sample quality assessment; MRS conference paper acceptance	Validated operational capability; stakeholder acceptance sign-off (in progress)	Faculty research use with student support

Systems Thinking in Practice

The project provides students with concrete experience applying systems thinking concepts essential to complex engineering practice. Students accomplished reliable additive manufacturing capability from the coordinated interaction of subsystems rather than from any single component's performance. For example, improved layer cohesion (Figure 3F) resulted not from consistent airflow alone, but from the synergistic integration of consistent powder feed (hopper agitation), uniform spatial distribution, and stable laser focus via motion control. This emergent property cannot be predicted by analyzing subsystems in isolation, reinforcing the need for system-level verification.

Design modifications in one subsystem frequently affected the entire system. The transition from single-nozzle to 4-nozzle powder delivery illustrates this principle. Improved deposition uniformity introduced airflow distribution challenges requiring manifold optimization. This, in turn, affected powder transport velocity. Students learned to anticipate these ripple effects through interface analysis and structured impact assessment before implementing changes. Early design iterations revealed the limitations of component-level thinking. Students applied systems thinking to identify the optimal operating point that balanced multiple competing objectives across subsystems fundamentally different approach than optimizing each component independently.

The venturi-based powder transport mechanism creates a feedback relationship. Air flow rate affects powder feed rate, which influences powder density in the airstream, which in turn affects transport efficiency. Students learned to understand these system dynamics relationships and design control strategies that account for coupled behavior rather than treating variables as independent.

Future Assessment Plan

Planned assessment includes rubric-based evaluation of system documentation, requirements traceability matrices, and design reviews; pre- and post-project student surveys measuring confidence in systems thinking and interdisciplinary collaboration; and artifact analysis of configuration records and verification reports. This data will inform future refinement of the capstone structure and instructional approach.

Discussion and Work in Progress

As a Work-in-Progress, this paper reports early technical and educational outcomes rather than summative assessment results. The improvements made to the system have shown documented improvements in system performance measure by controllability and reliability. The system has produced results that have been awarded funding and have been accepted to the Materials Research Society annual spring meeting for 2026.

Future work will expand closed-loop control capabilities, strengthen documentation handoff between cohorts, and refine assessment instruments. The authors propose this model as a scalable approach for embedding authentic systems engineering practice within non-SE disciplinary capstones, particularly when projects intersect with active research infrastructure.

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