Design of Vacuum- and Pressure-Compatible Optical and Thermal Camera Modules for Laser Powder Bed Fusion

Mumin Adhami[a], Mateo Garcia-Sandoval[a], Thienan Hoang[a], Matthew Whetham[a], Can Sun[a], Austin R.J. Downey[a,b], Yanzhou Fu[a], and Lang Yuan[a]

[a]Department of Mechanical Engineering, University of South Carolina, Columbia, USA
[b]Department of Civil and Environmental Engineering, University of South Carolina, Columbia, USA

ABSTRACT

Laser powder bed fusion additive manufacturing provides an efficient means of producing a wide range of complex designs. Welding performance is critical for component strength, print reliability, and dimensional accuracy. In-situ monitoring for such systems must be designed around the requirement of an atmosphere-controlled printing chamber and must not obstruct the welding laser or any print processes. This work presents the development of two custom open-source covers with integrated in-situ sensing systems for a laser powder bed fusion system. These modular covers are optical and thermal camera access modules that are interchangeable with the standard printing chamber cover of the Aconity MIDI laser powder bed fusion machine. Each module was engineered to provide sealed optical access while strictly maintaining an inert argon atmosphere and full functionality of the system. Design constraints included gas containment, compatibility with existing hardware, optical clarity, simplicity of assembly, and cost. Mounting configurations, sealing strategies, and laser safety measures were optimized with particular emphasis on argon gas leak prevention and the safety of sensor equipment during printer operation. Performance characterization included leak integrity testing, pressure stability evaluation, and in-process data acquisition during build operations. These modules successfully preserved the argon environment while enabling in-situ thermal imaging during active weld events and optical surface imaging between layer depositions. This demonstrates the feasibility of integrating sealed optical access modules into laser powder bed fusion systems without compromising chamber integrity or printer functionality.

Keywords: Additive manufacturing, Laser powder bed fusion, in-situ monitoring, optical imaging, thermal imaging, open-source hardware

1. INTRODUCTION

Additive manufacturing (AM) allows for the rapid prototyping of parts in less time and with greater precision than conventional manufacturing.[1,2] Laser bed powder fusion (LPBF) utilizes a laser to weld metal powder. The process involves spreading a thin layer of a pre-alloyed or mixed metal to be welded layer by layer, thus allowing for the fabrication of complex parts or components.[3] Such fabrications are often near-full-density-three-dimensional functional parts for various industrial applications. It also holds advantages such as reducing tooling costs, saving material resources, improving part reliability, and allowing design freedom for complex structures.[4,5]

Additive manufacturing (AM) is increasingly adopted across industries such as biomedical, automotive, and aerospace, where its ability to fabricate complex components offers significant advantages over conventional manufacturing.[6] In Laser Powder Bed Fusion, small variations in laser power, defocus, or print speed can significantly alter melt pool behavior, leading to defects such as porosity, lack of fusion, and spatter. Because these defects originate during melt pool evolution and solidification, they directly affect part density, dimensional accuracy, and mechanical performance. Ensuring consistent quality in production environments requires an improved understanding of process conditions during fabrication. Thus arises the need for in-situ monitoring techniques that improve understanding in terms of process parameters, defects, and other metallurgical phenomena.[7]

Further author information: (Send correspondence to Austin Downey)
Austin Downey: Email: austindowney@sc.edu

Traditional methods of ex-situ monitoring include non-destructive testing (NDT), x-ray microcomputed tomography for dimensional measurement and porosity analysis,[8] ultrasonic testing for identifying subsurface or surface discontinuities,[9] and destructive techniques such as cross-sectional metallography and mechanical pull or shear testing. While these approaches are effective in characterizing part integrity, they are typically performed after printing and on a sampled basis rather than for every build. Because these inspections occur offline, they do not provide real-time feedback during printing and cannot influence process parameters as defects form.

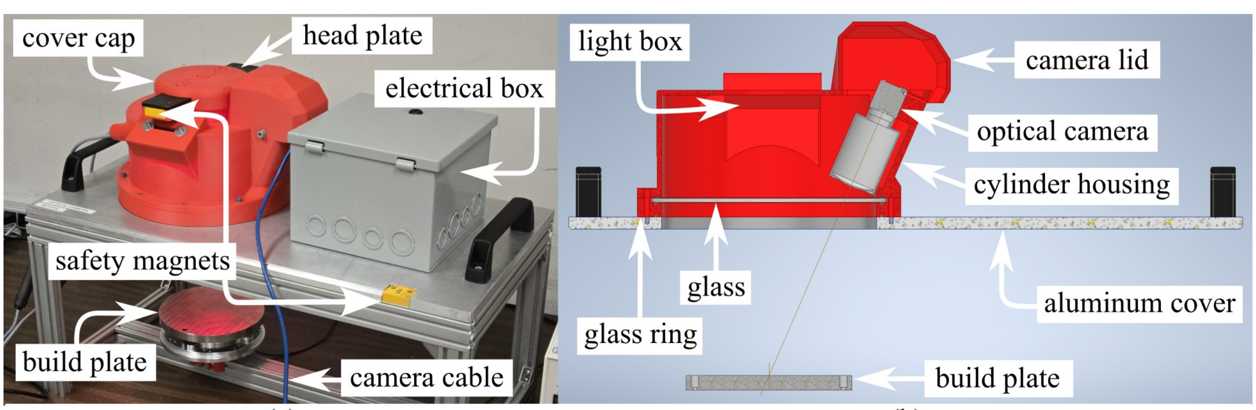
In-situ monitoring enables real-time observation of melt pool behavior and thermal history during fabrication, providing insight into process parameters and defect formation mechanisms.[10] The data acquired through optical and thermal sensing could be used in conjunction with machine learning algorithms[11] and artificial intelligence (AI) approaches[7] to identify defect patterns and support predictive modeling and digital twin development.[12]

This paper presents the design, fabrication, and integration of modular, sealed optical and thermal camera access modules for the Aconity MIDI Laser Powder Bed Fusion system. The work details the mechanical design, sealing strategy, and chamber interface required to maintain vacuum and pressurized build conditions while enabling in-situ imaging. Leak testing, pressure stability assessment, and in-process data acquisition were conducted to verify chamber integrity and imaging functionality. Complete CAD models and documentation are publicly available through a public GitHub repository.[13] The primary contributions of this work are: (1) the development of vacuum- and pressure-compatible optical access modules that preserve build chamber environmental control, and (2) the demonstration of integrated in-situ optical and thermal image acquisition without interference to standard printer operation.

The rest of the paper is structured as follows: Section 2 describes the system design and integration of the sealed optical and thermal camera modules. Section 3 presents the testing and demonstration of chamber integrity and in-situ imaging performance. Section 4 concludes the paper.

2. SYSTEM DESIGN AND INTEGRATION

The optical and thermal camera modules were designed as interchangeable replacements for the standard Aconity MIDI build chamber cover, providing sealed optical access without interfering with printer operation (Figs. 1 and 2). The optical module, shown in Fig. 1, includes an illumination system and bandpass-filtered camera for surface imaging between layer depositions, while the thermal module in Fig. 2 incorporates an infrared camera for in-situ imaging during active weld events. Each assembly consists of a custom housing mounted to a machined aluminum base plate to ensure structural rigidity and proper interface with the printer. Both designs utilize a telescoping cylinder interface that magnetically attaches to the welding laser head, allowing the cover assembly to be removed and reinstalled while maintaining alignment and chamber compatibility. The modular configuration preserves existing hardware and safety system functionality while enabling optical and thermal monitoring within the controlled build environment.



(a) (b)

Figure 1: The optical camera module, showing: (a) the assembled cover sitting on an experimental test frame and (b) a cross-section view of the module developed in CAD.

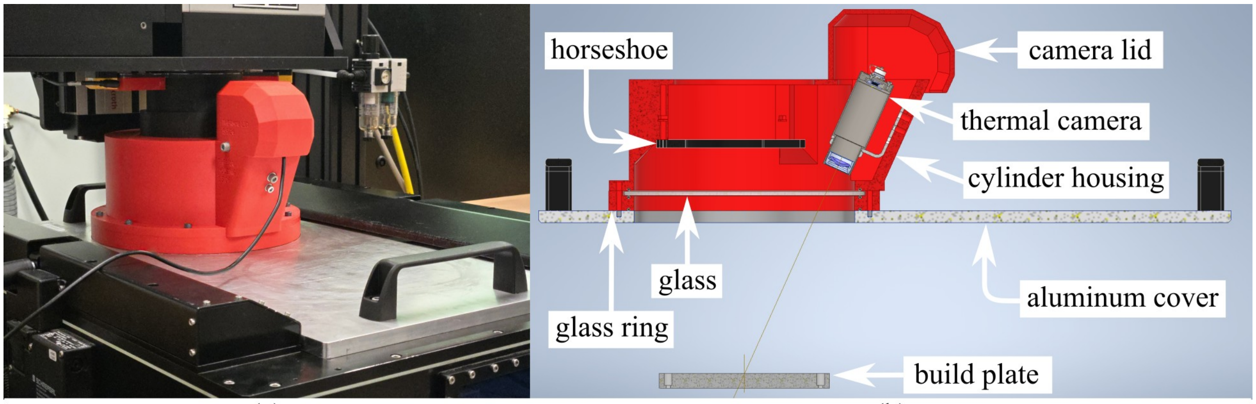


Figure 2: The thermal camera module, showing: (a) the assembled module installed on the Aconity MIDI Laser Powder Bed Fusion system and (b) a cross-section view of the module developed in CAD.

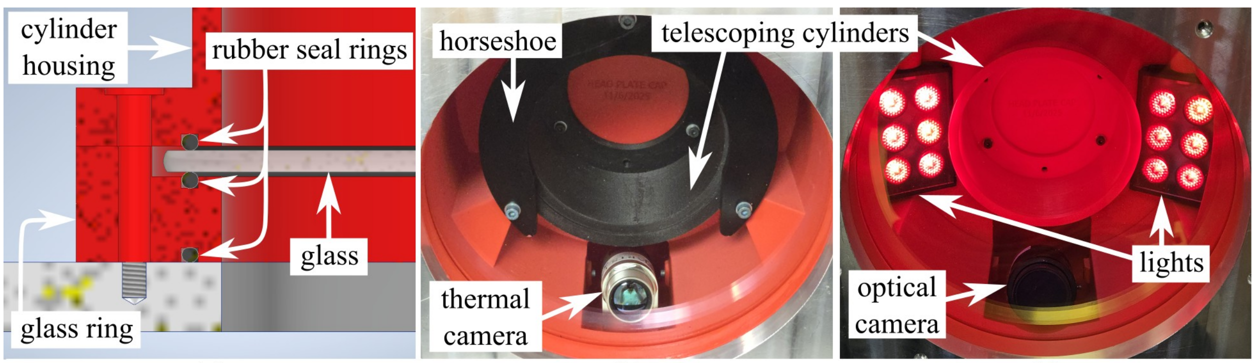


Figure 3: (a) cross-section view of glass seal installation and underside views of the (b) thermal camera cover and (c) optical camera cover assemblies with the anti-reflective glass.

Custom sensor housing components were designed using Autodesk Inventor Computer-Aided Design (CAD) software and exported as STEP files for fabrication. In-house fused filament deposition (FFF) printers were used to manufacture the components from glass-filled ABS, selected for its improved stiffness and thermal resistance compared to standard polymers. The printed parts were iteratively refined to meet geometric and mounting specifications. Each housing was mounted to a machined aluminum base plate to provide structural rigidity and ensure proper interface with the printer. As shown in Fig. 3, the assemblies incorporate a glass welding window retained within the housing structure and supported by a glass ring interface. Rubber o-rings were installed with silicone grease prior to final assembly to ensure proper mechanical seating of components.

Each completed module was installed on the Aconity MIDI system to assess mechanical integration and chamber compatibility (Fig. 4). Installation required disengaging the safety magnet sensors to allow removal of the standard chamber cover and attachment of the custom assembly. The head plate is connected to a telescoping cylinder interface that magnetically attaches to the welding laser head, enabling repeatable alignment during installation. The telescoping configuration differs slightly between modules to accommodate camera geometry and illumination components while maintaining proper standoff from the build surface. Chamber integrity was evaluated by executing a standard purge cycle in which oxygen was displaced with argon while continuously monitoring the oxygen concentration reported by the printer. Stable oxygen readings throughout the purge process confirmed that the installed assemblies preserved atmospheric containment. Mechanical compatibility was further verified by confirming that recoater motion and build platform movement were not impeded during operation.

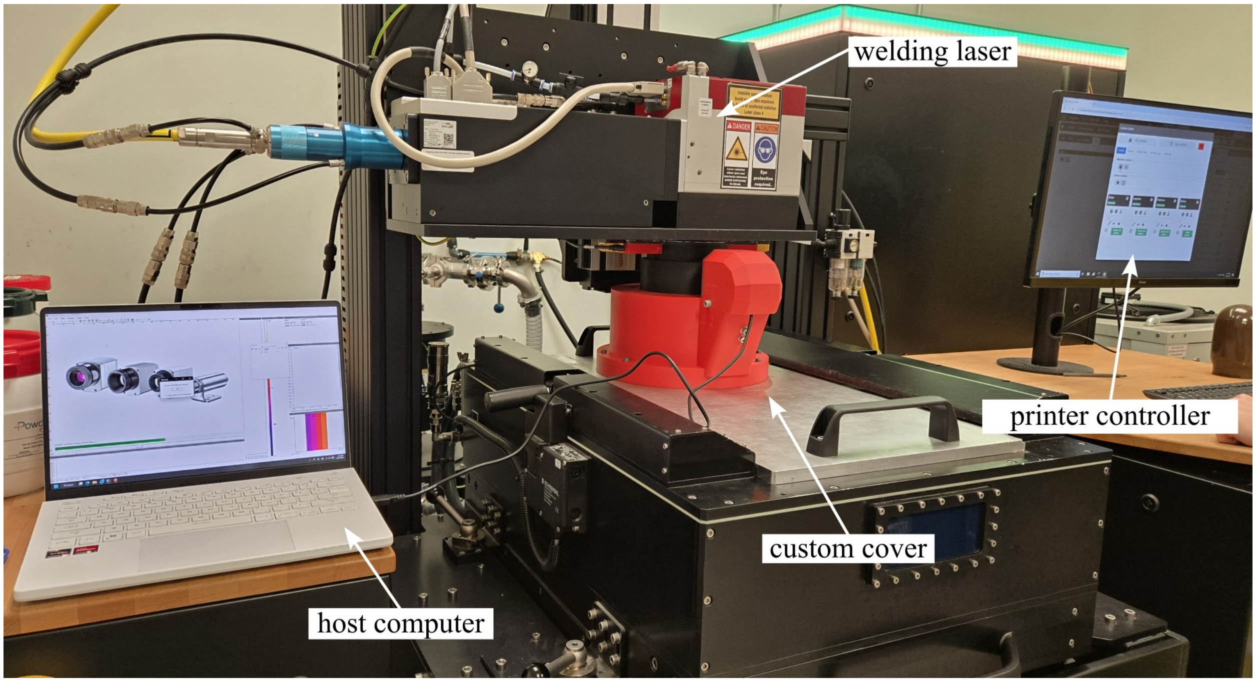


Figure 4: Test fitting and seal testing of a custom cover on the Aconity machine.

The platform was designed to be compatible with compact industrial imaging systems, specifically the Optris Xi Series thermal cameras and the FLIR Blackfly series optical cameras. For the present study, thermal imaging was performed using an Optris Xi 400 (OPTXI40LTF20T090, Optris GmbH), providing a resolution of 382×288 pixels at up to 80 fps with an $18° \times 14°$ field-of-view lens ($f = 20$ mm). Optical imaging was conducted using a FLIR Blackfly USB 3.0 camera (BFS-U3-200S6M-C, Teledyne FLIR), featuring a 20 MP monochrome sensor in a 1-inch format (IMX183, Sony). The monochrome optical configuration was paired with a fixed focal length lens (86573, 35 mm/F1.8 C Series, Edmund Optics), dark red LED illumination arranged in a 2×3 array (AL143-625IC, Advanced Illumination), and a bandpass filter (BP660-37, Midwest Optical Systems).

The optical and thermal configurations were designed with consideration of wavelength transmission and sensor protection (Fig. 5). The anti-reflective fused silica glass used in the cover assemblies is identical to that installed in the standard Aconity printing chamber cover and permits transmission of the 1070 nm welding laser.

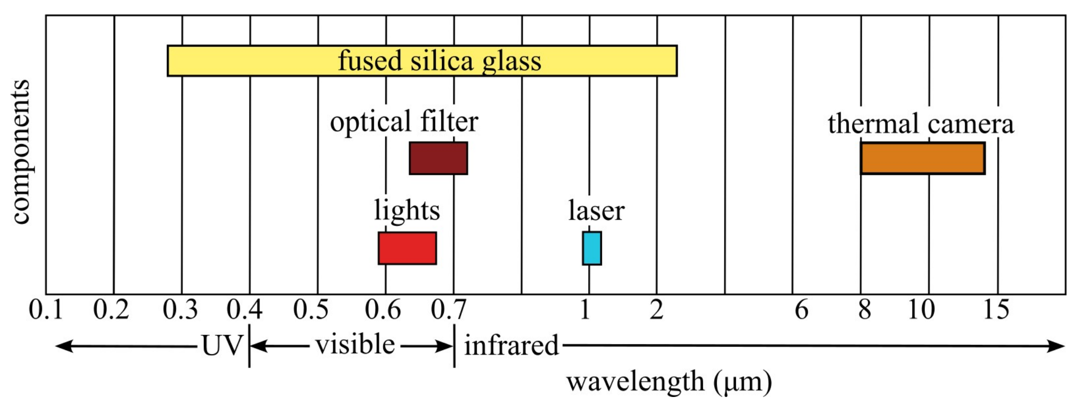


Figure 5: Wavelength spectra of the AL143-625IC lights and welding laser compared to the wavelengths allowed to pass through the Midwest Optical Systems dark red bandpass filter (BP660-37) and the anti-reflective coated fused silica glass.[14]

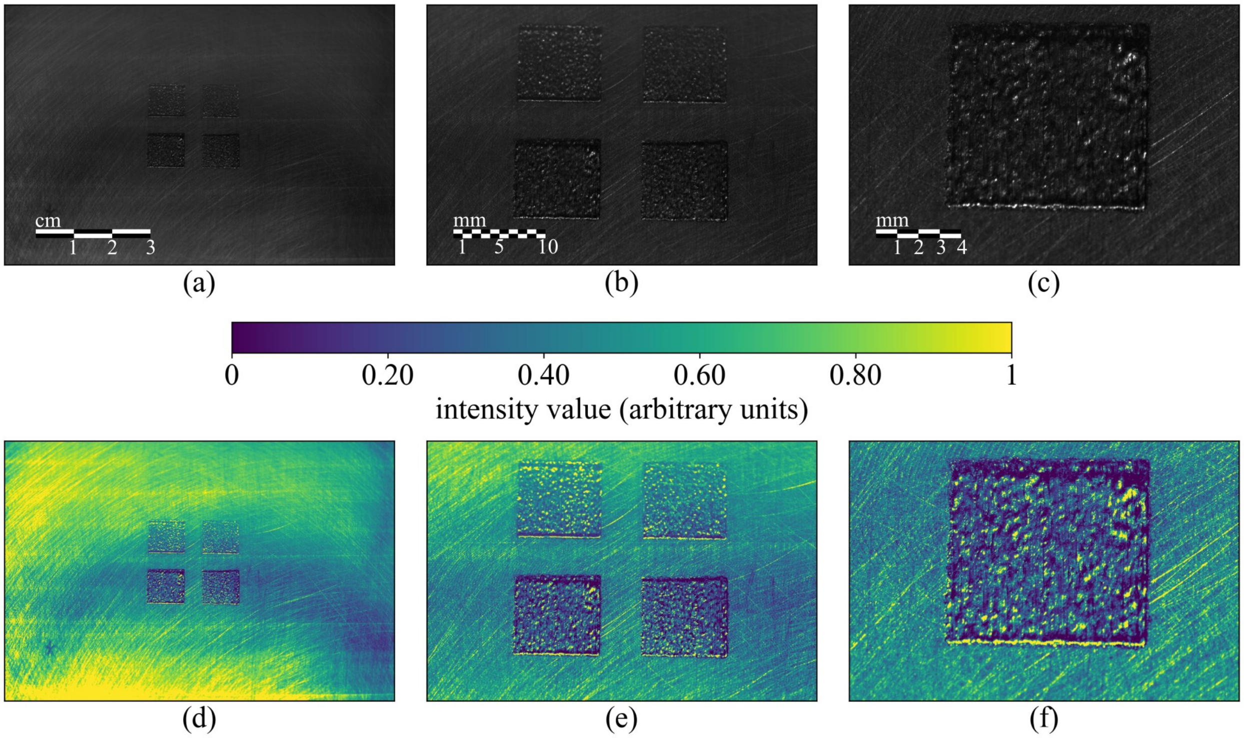


Figure 6: Representative in-situ optical images of the build surface. (a) Monochrome, uncropped RAW image, (b) zoomed view of four square samples, and (c) zoomed view of the bottom-left sample. (d–f) Corresponding colormap representations of (a–c) using a consistent intensity scale for enhanced visualization of relative intensity variations.

For optical imaging, chamber illumination was provided by 625 nm light sources, and a 660 nm bandpass filter was incorporated to ensure that the reflected illumination was captured by the camera sensor while preventing exposure to the welding laser. The thermal camera operates within a spectral range capable of detecting the energy peaks associated with weld events; however, the fused silica window introduces attenuation in portions of the long-wave infrared spectrum. Consequently, only qualitative intensity variations are achievable, rather than absolute temperature values.

3. TESTING AND DEMONSTRATION

Both modules successfully maintained the argon atmosphere within the Aconity MIDI printing chamber, with no observable increase in oxygen concentration reported during the purge cycle. These results indicate that the installed sealing interfaces did not compromise chamber integrity. Additional qualitative verification of seal performance was conducted by inspecting the perimeter of each module for leakage using lightweight tissue as an indicator to detect localized gas flow.

Representative in-situ optical data are shown in Fig. 6. Images were captured under controlled illumination using a bandpass-filtered optical configuration. The monochrome images (a–c) illustrate the as-acquired surface condition between layer depositions, while the corresponding colormap representations (d–f) provide enhanced visualization of relative intensity variations using a consistent color scale. The optical data demonstrate sufficient spatial resolution to distinguish surface features relevant to layer-wise monitoring.

Thermal imaging results are presented in Fig. 7, showing examples of slow cooling weld regions captured during active laser operation. Images show welding for a $0.15 \times 8 \times 100$ mm nickel strip onto a $0.6 \times 9.65 \times 85$ mm stainless steel base strip. Parameters for all welds were done at 45 mm/s, spot size was 150 µm, and laser power was set at 275W, 275W, 200W, and 225W for welds (a), (b), (c), and (d), respectively. The thermal

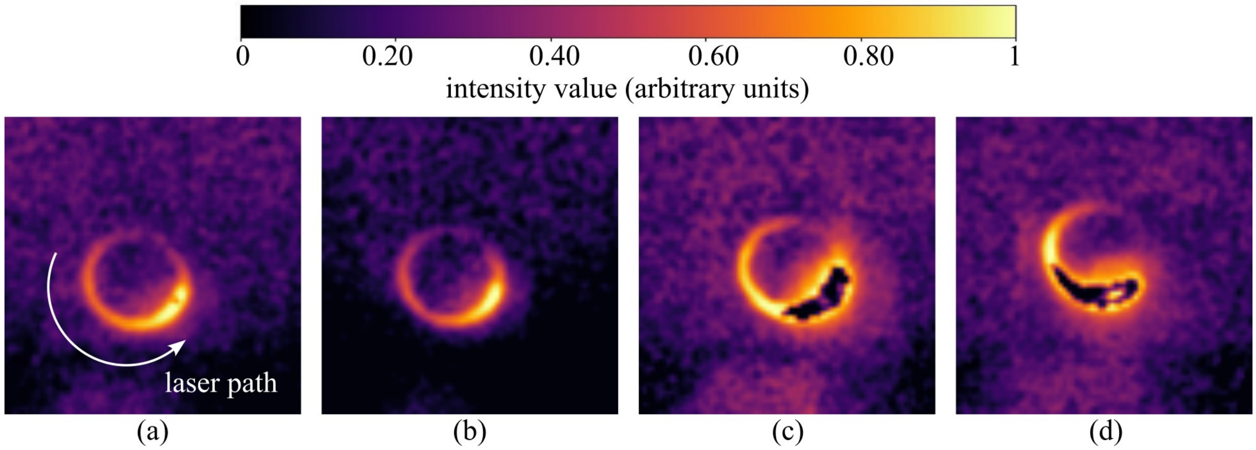


Figure 7: In-situ thermal images of weld regions captured during active laser operation. Welds containing slow cooling were chosen to validate image clarity, and image data was cropped around the region of interest. Temperature values are qualitative due to spectral attenuation through the fused silica viewing window.

camera detected relative differences in energy distribution and melt pool behavior; however, due to spectral attenuation introduced by the fused silica viewing window, absolute temperature measurements are not reliable. For this reason, the thermal data are interpreted qualitatively, and absolute temperature values were not used in the analysis. The images instead illustrate relative intensity variations associated with weld quality.

4. CONCLUSION

This paper presented the design, fabrication, and integration of vacuum- and pressure-compatible optical and thermal camera modules for a Laser Powder Bed Fusion system. The modules were developed as interchangeable build chamber covers capable of maintaining atmospheric containment while enabling in-situ imaging. Mechanical integration, sealing performance, and chamber compatibility were verified through purge testing and operational validation. Optical imaging between layer depositions and thermal imaging during active weld events were successfully demonstrated without interfering with standard printer functionality.

Design trade-offs were considered to balance cost and performance, including the use of fused silica in place of germanium for the thermal module, resulting in spectral attenuation that necessitates qualitative interpretation of thermal intensity data. Overall, the work demonstrates the feasibility of integrating sealed optical access modules into controlled-atmosphere additive manufacturing systems while preserving environmental control and imaging capability. Future work will focus on integrating the optical and thermal modules into a single unified system to reduce assembly complexity and overall cost.

5. ACKNOWLEDGMENTS

This research was supported by the United States' National Science Foundation (NSF), Grants Nos. CCF-2503055, and CPS-2237696. This work is also partially supported by the National Institute of Standards & Technology, United States, under grant number 70NANB23H030, as well as the South Carolina Space Grant Consortium under grants 21-117-RID RGP-SC-009, 25-073-REAP-SC-001, and 25-073-BTC-SC-001. Additional support is provided by the United States' National Science Foundation (NSF) through the NSF ASEE Fellowship. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation, the South Carolina Space Grant Consortium, or the National Institute of Standards & Technology.

REFERENCES

1. Kranz, J., Herzog, D., and Emmelmann, C., "Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4," *Journal of Laser Applications* **27** (Dec. 2014).
2. Lewandowski, J. J. and Seifi, M., "Metal additive manufacturing: A review of mechanical properties," *Annual Review of Materials Research* **46**, 151–186 (July 2016).
3. Abd-Elaziem, W., Elkatatny, S., Abd-Elaziem, A.-E., Khedr, M., Abd El-baky, M. A., Hassan, M. A., Abu-Okail, M., Mohammed, M., Järvenpää, A., Allam, T., and Hamada, A., "On the current research progress of metallic materials fabricated by laser powder bed fusion process: a review," *Journal of Materials Research and Technology* **20**, 681–707 (Sept. 2022).
4. Karunakaran, K., Bernard, A., Suryakumar, S., Dembinski, L., and Taillandier, G., "Rapid manufacturing of metallic objects," *Rapid Prototyping Journal* **18**, 264–280 (June 2012).
5. Thomas, D. S. and Gilbert, S. W., [*Costs and Cost Effectiveness of Additive Manufacturing*] (Dec. 2014).
6. Petrick, I. J. and Simpson, T. W., "3D printing disrupts manufacturing: How economies of one create new rules of competition," *Research-Technology Management* **56**, 12–16 (Nov. 2013).
7. Zolfagharian, A., Jin, L., Ge, Q., Liao, W., Díaz Lantada, A., Franco Martínez, F., Zhang, T., Liu, T., Wang, C. C. L., Mosallanejad, M. H., Ghanavati, R., Saboori, A., De Blas De Miguel, A., Solórzano-Requejo, W., Cai, Y., Dong, X., Qu, H., Samadiani, N., Huang, G., Downey, A., Fu, Y., Yuan, L., Lee, T. G., Baniya, A. A., Waseem, E., Sani, A. R., Kouzani, A. Z., Wu, Y., Nemitz, M. P., Shirzad, M., Oh, D., Nam, S. Y., Bonatti, A. F., Chiesa, I., Fortunato, G. M., Vozzi, G., De Maria, C., and Bodaghi, M., "Roadmap on artificial intelligence-augmented additive manufacturing," *Advanced Intelligent Systems* (Jan. 2026).
8. du Plessis, A., Yadroitsev, I., Yadroitsava, I., and Le Roux, S. G., "X-ray microcomputed tomography in additive manufacturing: A review of the current technology and applications," *3D Printing and Additive Manufacturing* **5**, 227–247 (Sept. 2018).
9. Hayajneh, A. J., "Diagnosis of surface and subsurface defects by using ultrasonic techniques," *Journal of Positive School Psychology* (2022).
10. Papatheodorou, A., Papadimitriou, N., Stathatos, E., Benardos, P., and Vosniakos, G.-C., "Recent advances in sensor fusion monitoring and control strategies in laser powder bed fusion: A review," *Machines* **13**, 820 (Sept. 2025).
11. Fu, Y., Downey, A. R., Yuan, L., Zhang, T., Pratt, A., and Balogun, Y., "Machine learning algorithms for defect detection in metal laser-based additive manufacturing: A review," *Journal of Manufacturing Processes* **75**, 693–710 (Mar. 2022).
12. Fu, Y., Downey, A. R., Yuan, L., Huang, H.-T., and Ogunniyi, E. A., "Simulation-in-the-loop additive manufacturing for real-time structural validation and digital twin development," *Additive Manufacturing* **98**, 104631 (Jan. 2025).
13. ARTS-Lab, "In situ monitoring of powder bed fusion additive manufacturing." Accessed: 2026-03-04 - https://github.com/ARTS-Laboratory/In-situ-monitoring-of-Powder-bed-fusion-additive-manufacturing.
14. Edmund Optics, "Understanding optical windows." https://www.edmundoptics.com/knowledge-center/application-notes/optics/understanding-optical-windows/ (2026). Accessed: 2026-03-04.