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DESIGN, DEVELOPMENTS, AND RESULTS FROM THE NIST ADDITIVE MANUFACTURING METROLOGY TESTBED (AMMT)

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Abstract

The National Institute of Standards and Technology (NIST) is developing a facility titled the Additive Manufacturing Metrology Testbed that will enable advanced research into monitoring, controls, process development, and temperature measurement for laser powder bed fusion additive manufacturing and similar processes. This system provides an open control architecture as well as a plethora of sensor systems and calibration sources that are primarily radiance-based and aligned co-axially with the laser beam and focused on the laser interaction zone. This paper briefly reviews the system requirements, and details the current progress of the facility design and construction. Mechanical, optical, and control systems designs are detailed with select highlights that may be relevant to additive manufacturing researchers and system developers. Recent experimental results from the prototype laser control and in-situ monitoring system are also highlighted.

Introduction

Vlasea et. al. described the proposed construction of an additive manufacturing metrology testbed at the National Institute of Standards and Technology (NIST) that would provide a fully controlled research-oriented laser powder bed fusion (LPBF) system to enhance research capabilities in additive manufacturing (AM) and materials research [1]. This system is primarily designed to serve two different but supporting research endeavors by NIST's Engineering Laboratory (EL) and Physical Measurement Laboratory (PML), which require well-controlled and characterized high laser energy input applied to solid metals, metal powders, or other materials, and simultaneous measurement from a plethora of primarily optically-based metrological instruments. For EL's use, the system is given the moniker Additive Manufacturing Metrology Testbed (AMMT), and for PML's use, the system is named Temperature and Emittance of Melts, Powders, and Solids (TEMPS).

Overarching goals for the system are as follows:

1. Build an open-platform LPBF testbed instrumented for fundamental process study and optimization, as well as optical metrology (AMMT).
2. Research the measurement science of various real time monitoring and control methods for measuring and improving AM build quality (AMMT).
3. Establish new emittance measurement capability for materials in various stages of aggregation over solid and liquid-phase temperatures (TEMPS).
4. Develop new NIST calibration services and standard reference data on polymers, ceramics, high temperature alloys, composites, and coatings (TEMPS).
5. Develop capacity to accurately measure temperature distribution across the melt pool under laboratory conditions (common goal).
6. Study methods for real-time process thermometry in the production environment (common goal).

Since the previous report [1], the concept has progressed from definition of goals and conceptual design, to near final mechanical and optical design, and initialization of the research facilities construction, system control architecture, and mechanical fabrication and assembly. In addition, initial controller programming and laser scanning tests on a prototyping system have been performed. The focus of this paper is to provide a general update on this progress. A comprehensive description of all design aspects would be too lengthy, so an ‘overall’ system design concept is provided here. Highlights are provided regarding ideas and results that may be pertinent to the additive manufacturing research community. While the TEMPS-based operations and design concepts will support additive manufacturing research, the focus of this paper is primarily on aspects pertaining to AMMT operation.

Design Functionality

Vlasea et al. described the general dual-functionality of AMMT/TEMPS system as operating in either build mode or radiance-based metrology mode [1]. In build mode, which is the primary mode for AMMT operation, the system is a fully controllable LPBF machine, with fully definable and controllable build parameters including but not limited to laser power, scan speed, layer thickness, and scan strategy. Primary focus of AMMT metrological research will be on radiometric measurements using optical instruments in a co-axial configuration, that is, aligned with the laser and monitoring dynamically changing radiant emission from the melt pool. Design flexibility also allows for staring configurations (as opposed to co-axial) for imaging or other radiometric sensors, which are either mounted within the vacuum chamber or externally mounted looking through viewports. These two configurations, allowing for melt pool monitoring or layer-wise imaging, are already being incorporated into commercial LPBF systems [2]. The advantage brought by the AMMT, apart from full process control, characterization, and reconfiguration flexibility, is that radiometric calibration sources will be located adjacent to the build bed, allowing for rapid in-situ calibration. In addition, processes and instrumentation composing the TEMPS systems will provide additional references and comparison.

In radiance based metrology mode, which is the mode for TEMPS-based operation, the system is reconfigured such that other optical beam lines and instrumentation are accessed. Similar to the co-axial configured instruments used in AMMT operation, the TEMPS-based operation will utilize emitted radiation from the heat affected zone transmitted to co-axially aligned optics and instruments. However, unlike in AMMT operation, which utilizes visible and near-infrared spectrum, TEMPS operation is broad band (visible to long-wave infrared), and thus requires special reflective or broadband optics [3].

This operation mode is intended to extend current capabilities at NIST for material optical property measurement [4], and allow measurement at higher temperatures, operation in vacuum or high purity inert environment, measurement at shorter wavelengths, and measurement of material phases other than solids. These extended phase measurements primarily focus on powders and liquids, but availability of high laser energy densities may allow for vapor and plasma characterization as well. One of the measurement procedures, titled the DYnamic Meltpool Emissometry (DYME) method, essentially replicates procedures used at NIST for spectral emissivity characterization of solid material samples [5]. However, the DYME method utilizes the moving melt pool (or non-liquid, laser heated spot) as a target, statically held in the field of view of the co-axial optical system, rather than a statically heated sample. This method, compared to previous methods using larger, isothermally heated samples, reduces oxidation, contamination, and/or evaporation due to the small area of the heat affected zone. These measurements have direct application to LPBF process monitoring and research, and details of the TEMPS-specific system design, operation, and measurement procedures will be provided in separate publications.

System Modules and Mechanical Design

Although complex, the overall system allows expanded flexibility for researchers to reconfigure subsystems individually by providing a modular and separable design. Figure 1 shows an external view of the computer aided design (CAD) assembly, in which the carriage is pulled out of the vacuum chamber onto the transfer dolly. The figure highlights the five main system modules. The removable carriage allows researchers to have better access to assemble, reconfigure, and clean subsystems on the carriage externally from the vacuum chamber.

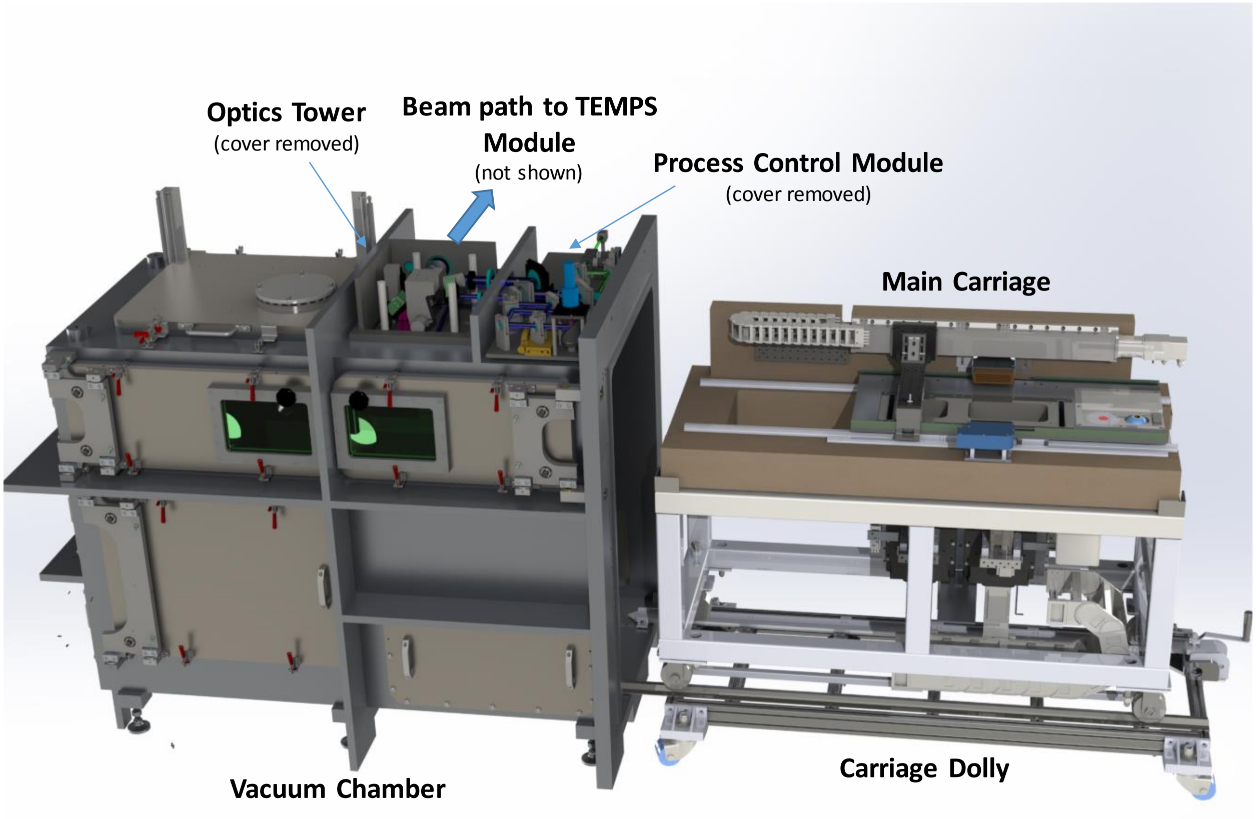

Figure 1: Solid model assembly of the AMMT/TEMPS system with the main carriage removed from the vacuum chamber. Not shown are the TEMPS module, which is positioned behind the vacuum chamber, and various cables and plumbing.

The *main carriage* is the main mechanical system built around a stainless steel frame and granite base, and houses the build bed, powder feed, recoating mechanisms, and most major mechanical and motion components. The carriage frame can be removed from the vacuum chamber by rolling along caster wheels on vee and flat tracks, and onto the external, mobile *carriage dolly*, which has similar tracks. The carriage dolly includes a winch and strap that connects to the main carriage to pull the carriage out of the vacuum chamber.

The *vacuum chamber*, designed for medium vacuum (0.1 Pa or 10^{-3} torr) operation, provides vacuum purging prior to backfilling with nitrogen or argon inert gas. This provides faster means to reduce oxygen levels compared to simply purging with inert gas. The vacuum chamber also provides access panels on all sides for cable and hose feedthroughs and user access to the build area and carriage underside. This also provides flexibility for incorporating future custom panels with ports or feedthroughs for newer or varying instrumentation or research projects.

The *optics tower* contains the main optical components to control and guide the heating laser, and divert back-emitted melt pool radiation to different modules. Pulling vacuum on the chamber will cause it to deflect, therefore the optics tower and fixed optical components are mechanically de-coupled from the chamber, and coupled to the granite by sitting on the optics tower bridge (not shown in Figure 1). The optics tower and internal components are vacuum compatible and can be purged, however a broadband window can be inserted between the optics tower and main chamber to isolate the optics tower from vacuum. The optics tower contains the galvanometric (galvo) scanner mirrors, removable beamsplitter/reflector (RSR), mirrors etc. for the laser delivery path, the process monitoring path, or the metrology beam path. The back-emitted radiation from the melt pool is switched between the process control module or the TEMPS module by a manually swapped, kinematically mounted RSR accessed by opening the top lid of the tower. Either a broadband reflector, or laser-line reflector is exchanged in the RSR position to switch operation between the process control module, or the TEMPS module. The optics tower is kinematically mounted to the optics bridge, which is rigidly attached to the granite base, however it is mechanically isolated from the vacuum chamber through a sealed, vacuum gasket flange.

The *process control module* sits atop the chamber adjacent to the optics tower, and is the heart of the AMMT process monitoring for additive manufacturing research. This module is essentially an enclosed optical breadboard which contains the laser fiber, beam expander, negative lens, and other bending mirrors or windows for the laser injection beam path to the optics tower. When the broadband reflector (700 nm to 1100 nm) is installed in the RSR position within the optics tower, this module also receives the back-emitted radiation from the melt pool which is further filtered to the 700 nm to 900 nm range with another beamsplitter. This 700 nm to 900 nm bandwidth can then be further split to various optical sensors, including high speed imagers or photodetectors. The process monitoring module provides extra space for these different optical configurations and instruments to use the back-emitted light for researching various co-axial melt pool monitoring methods.

The *TEMPS module* (not shown in Figure 1) contains the toroidal mirror, folding mirrors, mirrored field stop, and other components to support spectral emissivity and reflectance measurements. The mirrored field stop allows back emitted radiation to pass through an aperture to various instruments, while reflecting the surrounding image to a high speed thermal imager. This allows the imager to 'see' the thermal field around the aperture, and help discern the relative location on or near the melt pool that is passed through the aperture to the sensors. TEMPS instruments include Fourier transform infrared (FTIR) spectrometer, visible array spectrograph, and filtered radiometers. Although not in the same physical location as the TEMPS module located behind the chamber but not shown in Figure 1, an in-situ hemispherical reflectometer (also not shown in Figure 1) used only for TEMPS operation will be incorporated within the build chamber, and be automatically placed on or removed from the build plane.

Structural/Metrology Loop

Ultimate positional and mechanical tolerance requirements of commercial LPBF systems may be dictated by the size of metal powder used (10 s of micrometers). However, as a metrological instrument, AMMT structural design aimed to not only reduce potential sources of geometric error in AM builds, but to ensure stability and repeatability of measurements. Rules and concepts from precision machine design are apt for incorporation into AM machine design. Analysis of a manufacturing system with respect to the structural/metrology loop(s) enables a systematic approach to error identification and tabulation. A guiding principle in precision machine design dictates that a smaller, less complex, and closed structural/metrology loop provides improved precision [6].

The structural loop, shown in Figure 2, consists of the mechanical coupling of rigid structures from the build layer to the scanner mirrors and laser beam path back to the build layer, with the granite base forming the central reference structure. As mentioned in the previous report

[1], the build bed, powder feed bed, and calibration sources are suspended in a gantry-type assembly from two rails on the granite base, and can be positioned along the X-direction with respect to the granite base using a ballscrew mechanism (not shown on the back side of the main carriage in Figure 1). This allows either the build bed or the calibration sources located within the carriage to be positioned directly under the optics tower, and accessed via the laser or co-axially aligned instruments. Using the CAD assembly, size and location of the carriage components were arranged to ensure the calculated center of mass is close to the mechanical center of the rails as possible. As previously mentioned, the optics tower is mechanically decoupled from the vacuum chamber, but rests upon kinematic mounts on the optics tower bridge, which is then coupled to the granite base.

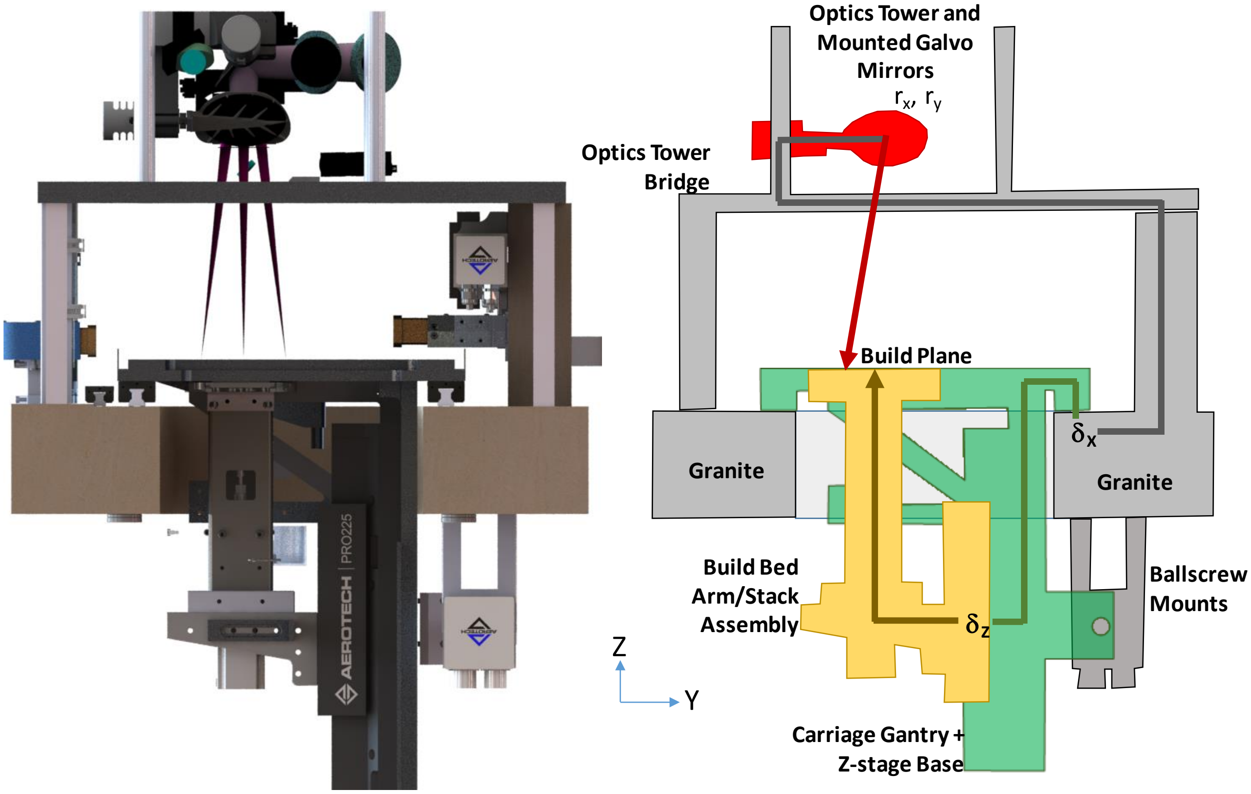

Figure 2: Mechanical linkage and metrology loop. Left: Solid model assembly view (multiple components hidden for clarity). Right: Schematic showing rigid structures, relative motion between rigid structures, and the metrology loop.

Though concepts from precision machine design were incorporated into the structural design of the AMMT system, many concepts were not directly transferable, and there is room for further research into the combination of machine tool metrology and optical system metrology for AM systems, especially when process monitoring instrumentation is considered. The AMMT, apart from the research objectives outlined above, will also act as a platform for researching the effects of machine components on part quality, and identify methods and requirements for error compensation and error budgeting.

Build Bed and Recoater Alignment

The designs of two subsystems on the carriage are detailed here, which differ from common commercial LPBF system configurations. Quality LPBF builds require consistent, smooth, and level powder layers, and thus require accurate alignment between the recoating plane and the build surface. The edge of the recoater blade forms a line in free space, and defines a plane when the recoater arm moves in the X-direction, shown in Figure 3 left. For uniform powder layer thickness, this recoater blade plane must be as parallel as possible to the build plate plane. Build layer thickness is then defined by the δz motion of the build arm motion stage. To parallelize two planes in free space requires two rotational adjustments with respect to one another. Many LPBF machines parallelize the build/recoater planes by implementing two rotational adjustments on the build plate, whereas we choose to separate the adjustment. Figure 3 left, demonstrates the relative motion and angular adjustments of the build plate and recoater blade. Not shown are the plate heating element, ceramic standoffs, or spring/felt seal assembly. The recoater blade is adjusted by a differential screw on one end, which rotates the blade about pivot bearings (angular flexures) on the other end. The recoater arm is positioned in δx by a motorized linear stage attached to the vertical wall on the granite, and held by an outrigger ball rail on the opposite side, also attached to the horizontal face of the granite.

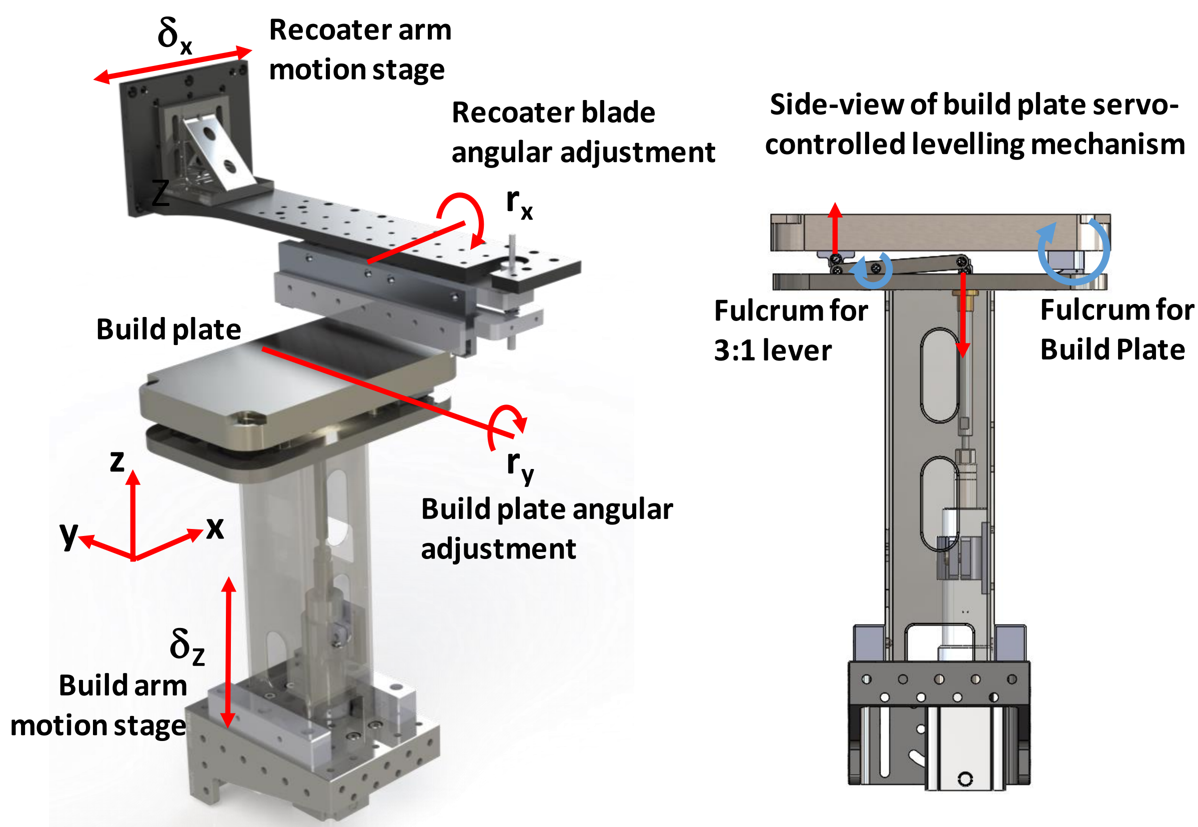

Figure 3: Left: Build plane and recoater plane parallelization adjustment coordinates. Note that some stiffening brackets and the outrigger ball rail connection are not shown. Right: Cutaway view of build arm showing internal linkage assembly for the automated build plate adjustment. An actuated pushrod rotates a 3:1 lever arm, which rotates the build plate's free edge about a pivot bearing fulcrum.

Provided the tight working space, an automated levelling mechanism was incorporated to align the build plate, shown in Figure 3 right. Again, certain elements such as the plate heater, standoffs, and spring/felt seal assembly are not shown. The five bar linkage mechanism transfers a linear displacement from a stepper motor with worm and rack gearbox, through a 3:1 lever arm (for mechanical advantage and improved positioning precision), to a pivoting build plate which rotates about the y-axis (r_y). Based on an estimated maximum distributed load, calculated design considerations included overall build plate stiffness, stiffness and strength of the pivot bearings, and detent torque of the motor.

Optical System Design

The driving design criteria for the process monitoring path is to create a 1:1 imaging system in the near infrared (NIR) which co-axially aligns an imager with the laser injection path, thus creating a stationary image of the melt pool. The 1:1 magnification was chosen so that a nominally 100 μm to 200 μm wide melt pool can be resolved between 10 pixels to 50 pixels, where typical Silicon (Si) based detector pixels are commonly between 4 μm to 10 μm. The near infrared spectrum was chosen for two reasons. Silicon based detectors, which are sensitive to visible and NIR, are less expensive and have a wider range of commercially available options. Another reason NIR was chosen, as opposed to visible spectrum, is so lower melt pool temperatures near the expected nickel or steel alloy melt pool solidus temperatures (around 1500 °C) can be better detected, since the maximum greybody radiant emission at this temperature is approximately 1.6 μm. However, choosing longer wavelengths is limited by the Si detector sensitivity cutoff at approximately 1200 nm, and the need to avoid the 1070 nm laser wavelength, which would potentially damage the detector. For the optical design, an imager sensitivity at 850 nm was chosen.

Multiple other sensor options and capabilities can be made possible within the process monitoring module. However, it was known early on that design requirements for the imager were most stringent and higher priority, and other sensors may be incorporated using various turning mirrors, beam splitters, and or hot/cold mirrors. Provided an imaging system with adequate spatial and spectral resolution is available, incorporation of other single-point detectors such as filtered photodetectors or pyrometers is trivial.

Optical Modeling and Optimization of the Process Monitoring Path

The optical system consists of laser injection and process monitoring paths co-located and sharing some components, shown in the Figure 4 schematic. The laser delivery fiber is terminated with a 60 mm focal length collimator producing collimated light at approximately 1070 nm. This light is reflected by the wavelength separator, whose coating is designed to reflect 1070 nm light in a narrow band, and transmit light in the NIR. The reflected laser light propagates through a Linear Translating lens (LTZ), through the window and Converging Lens Pair (CLP), and is then reflected by the mirrors in the scanner and converges to a focused spot onto the build plane. In the reverse direction, NIR light emitted from the build plane reflects off the mirrors in the scanner, through the CLP and window, through the LTZ, through the laser reflector, and is then directed through Custom Imaging Lenses (CIL) that forms an image for a camera to view. Fold mirrors and/or a custom relay lens can be used to direct the beam to be imaged to a more convenient location as needed.

The laser injection path is required to generate a focused spot having a full-width half-max (FWHM) of approximately 100 µm at an arbitrary location within a 100 mm x 100 mm square area below the scanner. It is the function of the LTZ to maintain the focus by compensating for the optical path length change resulting from the scanner mirrors' direction of the laser beam to the desired build plane locations. Commercial-off-the-shelf (COTS) parts for the LTZ and CLP are very good at maintaining this focus, but they were designed to work only over a very narrow wavelength band about 1070 nm. COTS parts are inadequate because of two requirements: 1) it is desired to monitor and image light from a 12 mm region at the build plane emitted in the NIR with the best possible image quality (the "diffraction limit") and 2) a focused, high power laser spot needs to be generated on the build plate at 1070 nm wavelength.

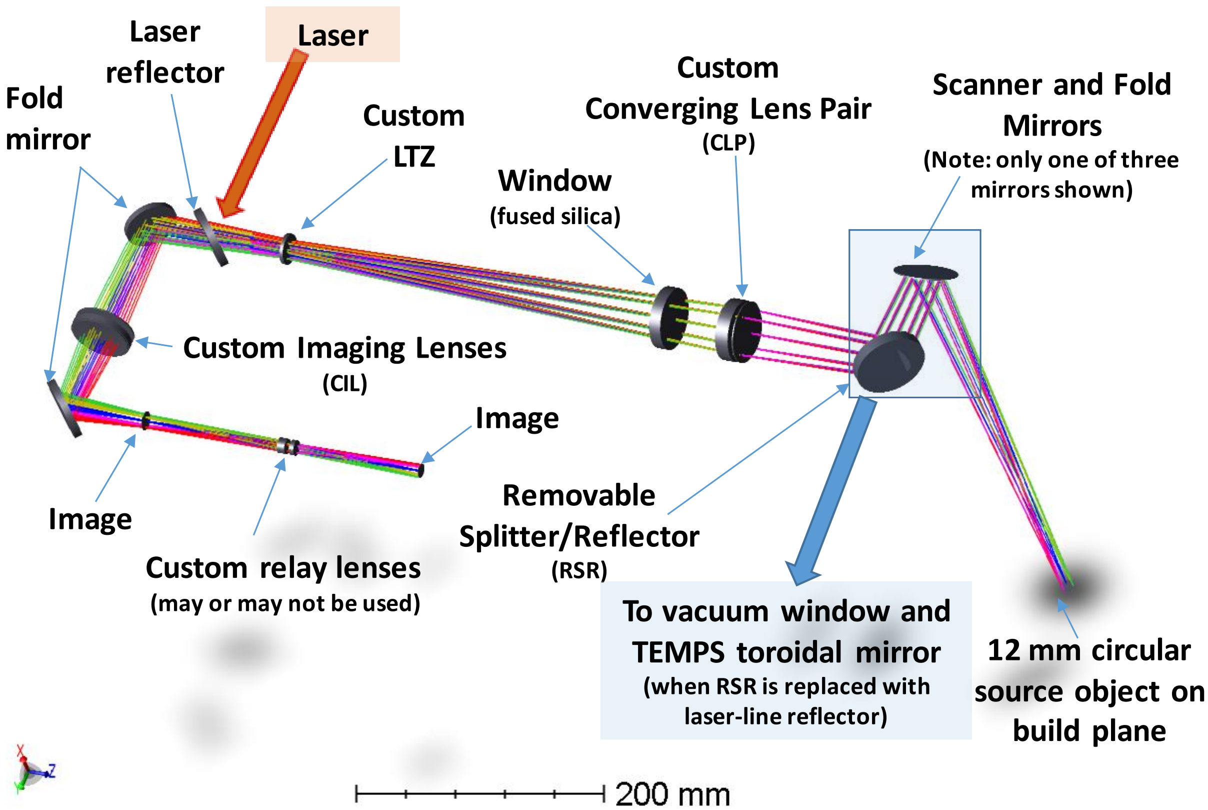

Figure 4: Schematic of ray tracing model used to optimize components for 1:1 imaging in process monitoring beam path. Current beam paths shown are for AMMT operation, where the laser-line reflector is in the RSR position.

To achieve diffraction-limited imaging performance in the NIR with 1:1 magnification in one direction as well as a focused laser beam at 1070 nm in the opposite direction, an "achromatic" solution is necessary, and custom LTZ, CLP, and CIL lenses are required. The lens surface curvatures and glass types were optimized using the ray-tracing optical design software based on a set of design criteria. The required operating wavelength bands, field-of-view, component temperature, and magnification all are included as constraints in the optimization routine. During the optimization process, the software automatically adjusts lens curvatures, glass types, and separation distances (the variables), and all within specified boundary constraints, resulting in simulated imaging performance characteristics (the objective functions).

The result of the optimization process yields a solution for the imaging having the performance shown in Figure 5. On the left-hand side, a laser beam directed to a point located on the build plane at (30,30) mm is shown. In the middle of Figure 5, spot diagrams for light at 850 +/- 25 nm emitted by a point at (30,30) and (30, 24) mm are shown. A spot diagram is an analog of the geometrical Point Spread Function (PSF) and diffraction effects are ignored. It illustrates the geometric image blur for a point source. Superimposed on each spot diagram is the "Airy disk", a contour whose radius represents the limit to the resolution when effects of diffraction are taken into account. Imaging can be no better than the diffraction limit. The radius of the Airy disk is a function of wavelength and system f-number (F/#) (Airy radius = $1.22 \cdot \lambda \cdot F/\#$) and is shown to be about 16 μm in Figure 5. The geometric spot diagram shows that the extent of the blur for a point source lays within the Airy disk and thus the performance of the imaging is diffraction-limited. Another way to express the performance of the imaging is in terms of the Modulation Transfer Function (MTF), shown at the right-hand side in Figure 5. MTF is a direct measure of how well details in the object are reproduced in the image. Since the imaging is 1:1, linear coordinates on the build plane are unscaled at the image plane and the MTF plot directly represents the spatial resolution at the build plane. MTF is widely accepted as the most important criterion for judging image quality and is typically specified in terms of spatial frequency as "line pairs per mm" or "cycles per mm". Diffraction effects limit the value of the MTF as the spatial frequency increases. As can be seen, the performance of the custom system results in an MTF that overlays the diffraction-limited MTF.

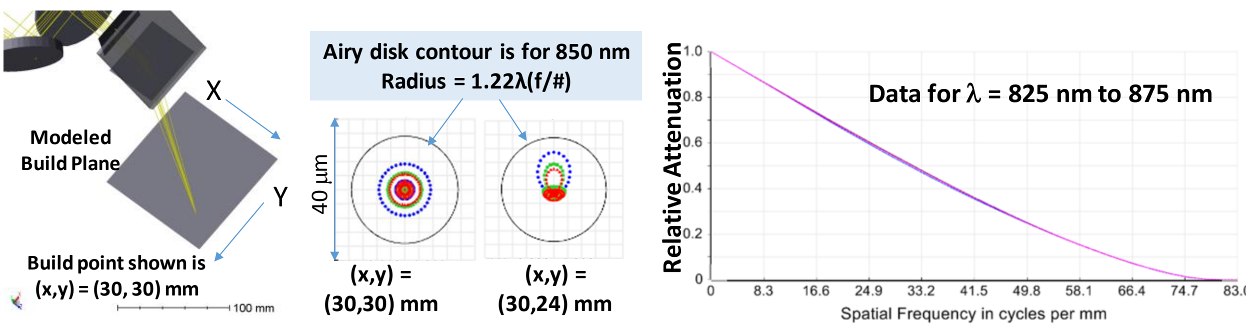

Figure 5: Optical modeling and optimization results for 1:1 imager resolution. Left: Schematic of physical model showing laser spot position coordinates. Center: Example spot diagrams showing point spread function (PSF) is encircled by Airy disk (thus diffraction limited performance) at center and 6 mm from center. Right: Modulation transfer function (MTF) showing spatial resolution.

Build Process and Environment Control

The AMMT control system design is process oriented and layer structured. The typical processes involved in AMMT can be divided into five major categories as shown in block diagram in Figure 6, and described as follows:

1. Laser control – laser power and gating, scan path (galvo position) and LTZ control.
2. High speed monitoring – in situ process monitoring, experiment data acquisition, and real time feedback.
3. Powder bed – build plate, powder feed, powder spread, and carriage motion and positioning.

4. Environment control – Build chamber preparation through vacuum purge, backfill, and inert gas circulation.
5. Environment monitoring – oxygen level, humidity, temperature, pressure, etc. monitoring.

Processes 1-3 are related to the building and build monitoring processes and realized using National Instrument (NI PXIe) and Aerotech systems, with main operations programmed in LabVIEW. Processes 4-5 are environment related and implemented by an Allen Bradley Programmable Logic Controller (PLC), programmed in Studio 5000 by ladder logic. The NI and PLC systems communicate to each other through an Open Platform Communications (OPC) server, where parameters in the PLC are published as global variables, read and written by Labview through the Datalogging and Supervisory Control (DSC) module.

The PLC is constantly monitoring and will shut down the system, in particular the laser, and trigger an alarm in cases such as abnormal high temperature, high O_2 level inside or low levels outside the chamber, chamber doors or panels open, etc. Since the PLC runs independently from building process control (NI controller), this provides a secondary guard against potential safety hazards.

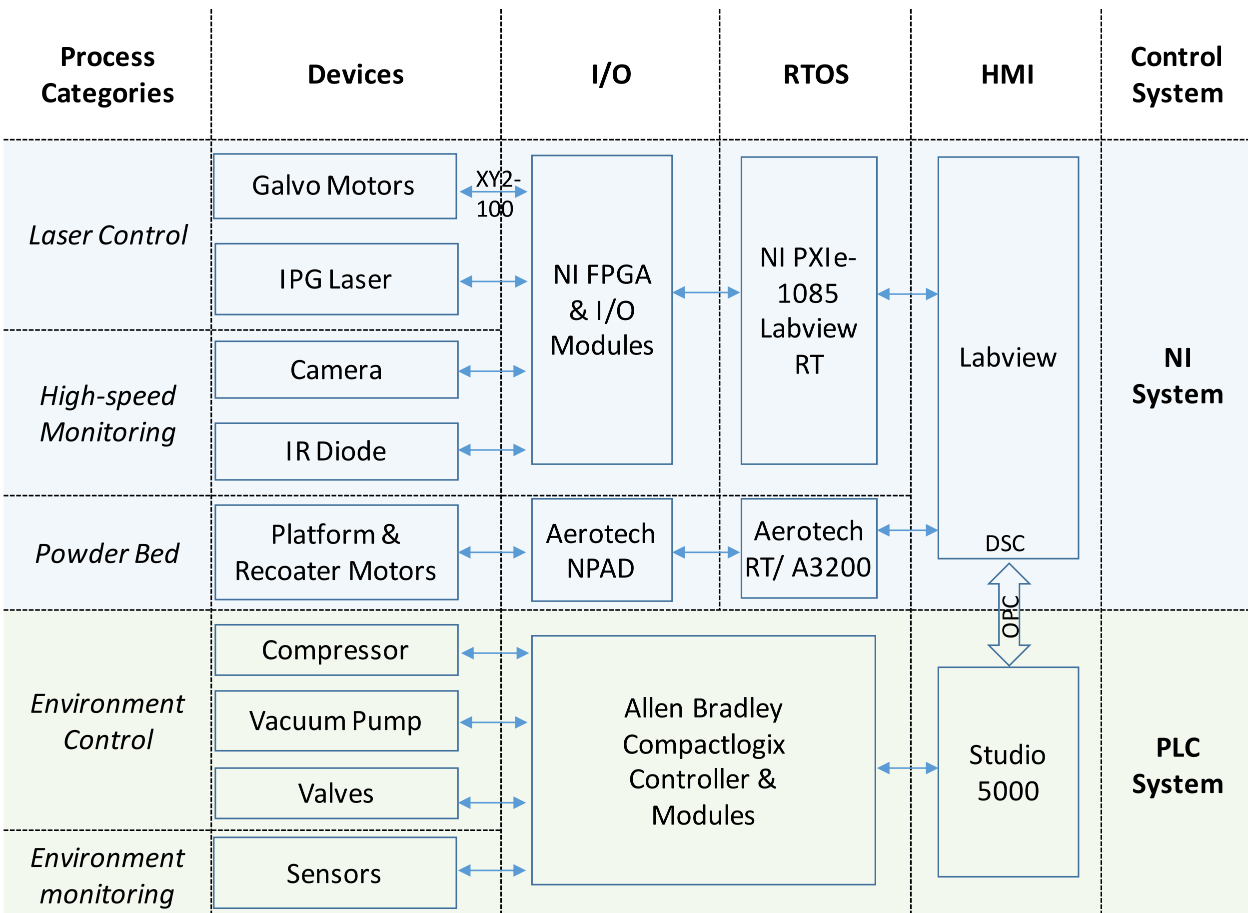

Figure 6: Overview of the NIST AMMT control architecture.

The block diagram is based on hardware, and much simplified and presented here to explain the architecture for AMMT control. Figure 6 can also be viewed as a layered structure from left to right.

1. Device – Individual hardware to perform the tasks listed in process categories.
2. I/O – Input / Output. This is a heterogeneous system and in general this layer refers to the interface between system controller and individual hardware device or driver.
3. RTOS – Real Time Operation System. NI PXIe-based system runs NI Linux Real-Time operating system, which also runs A3200 motion control Aerotech RTOS. On the RTOS, the PLC scans through all ladder logic in one clock cycle.
4. HMI – Human Machine Interface, which can also be referred to as the application layer. A Windows-based personal computer (PC) is used, with Labview and Studio 5000 installed. The user interface (UI), developed in Labview, also resides on this PC. All data, including process feedback and environment monitoring, are eventually logged here.

Environment Control Process

A build process starts with build chamber preparation. The chamber is first vacuumed to the preset level (0.1 Pa or 10^{-3} torr), then back filled by inert gas (argon or nitrogen). The experiment can also be conducted directly in vacuum if required. Refill is controlled by the PLC proportional-integral-derivative (PID) loop formed by proportional valves and pressure sensors. After the desired pressure is reached, the oxygen level is checked and if it is higher than the desired value, the vacuum-backfill (inert gas) process is repeated until the O_2 level is below the setpoint. The build cycle can then start.

The build cycle (powder feed, spread, and laser melting) can be started with vacuum purge, or inert gas recirculation. The circulation is powered by a 4 kW compressor, inert gas is pumped out of the chamber, filtered, cooled, and fed back into the chamber through three different ports into the chamber: 1) the air blanket, which is a custom-designed laminar flow nozzle directed right above the build plane, intended to uniformly remove vapor or melt pool ejecta, 2) the air knife, which is a high speed, thin flow layer located right below the scanner optics, intended to protect from contamination or deposition, and 3) the optics tower inlet, which maintains temperature of the mirrors and optics.

After the build process finishes, the inert gas is pumped out, and the chamber is back filled with dry air. The oxygen level warning sign will turn green only after the oxygen level reaches above 19.5%, to indicate it is safe to open the chamber door.

Laser Control

For LPBF AM, the laser beam is directed to the powder bed by a pair of mirrors driven by galvo motors. The galvos are limited rotational direct current (DC) motors with very fast response time, but are also very sensitive to noise. To eliminate transmission noise, an industrial standard digital communication protocol *xy2-100* is used to transfer control signal (position) from the field programmable gate array (FPGA) to the galvo driver. The *xy2-100* packages each position into a 20 bit ‘word’ and transmits it at 100 kHz per word (2 Mbps). Figure 7 shows the scheme for AMMT laser control. The scan path is generated on the controller PC together with laser power level according to the predefined scan strategies, and converted into *xy2-100* format on the FPGA. The digital signal is transmitted as differential pairs and converted back to analog voltage by the digital to analog (D/A) receiver. It is then fed into the galvo driver as command signal, and form a closed-loop control with the position feedback from the galvo encoder.

The standard *xy2-100* protocol is only for positions (x, y, and z axis). The z-axis is typically relegated for controlling an LTZ lens. However, the AMMT utilizes this axis for laser power control to ensure high speed synchronization, as shown in Figure 7. The laser power level is also updated at 100 kHz, and is synchronized to each scanning step by introducing a constant, calibrated delay (laser response is much faster than galvo). Since the LTZ position strictly depends on galvo x-y position values, and not on commands from the controller PC, it is controlled through a lookup table programmed on the FPGA, which is based on angular measurements determined from optical ray tracing. This lays down the foundation for laser path planning and power control strategies.

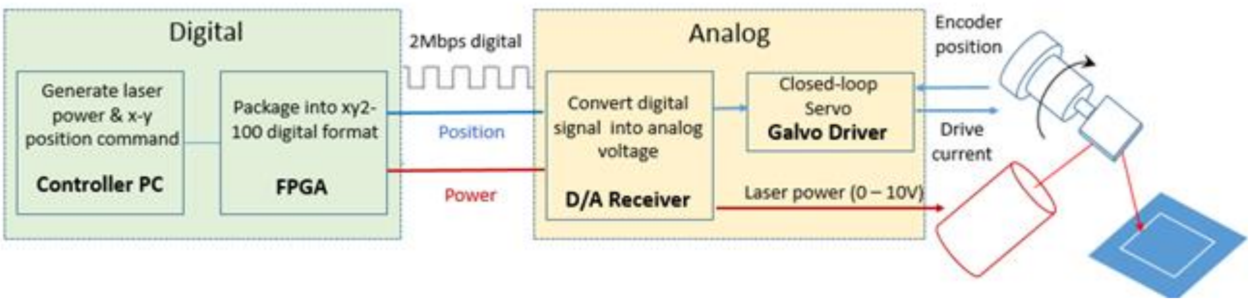

Figure 7: Laser path and power control.

Prototyping System

Certain design considerations for the AMMT/TEMPS required physical testing and evaluation of components, in particular to determine attributes that cannot be modeled using ray tracing software. In addition, the anticipated complexity of the monitoring and control system warranted attention prior to final system construction. In order to conduct these tests and initiate controller programming, the *prototyping system* was built which incorporates the laser, optics for the laser injection, galvo mirrors and driver system, and similar COTS components that will go into the process control module. Figure 8 shows a solid model schematic of the prototyping system with highlighted beam paths. Grantham et al. described several initial characterization tests, including laser spot size measurements, temporal laser control, and thermal load testing of various components to determine heating rates due to continual laser operation [3]. In the final AMMT/TEMPS facility, a prototyping system will exist along-side the full AMMT system with replicate components and similar capabilities to allow various testing and development before implementation on the AMMT.

Multiple other tests are currently being performed on the prototyping system, and are published elsewhere in this conference proceedings. These include system performance and control tests to evaluate the scan speed, acceleration, laser on/off timing, and positional accuracy of the laser spot. Results from these tests determined that the COTS galvo controller and command software were inadequate for our purposes, which initiated development of a custom design. Other tests include basic process mapping tests of single weld tracks, and simple scan patterns to provide qualitative comparison to commercial LPBF systems.

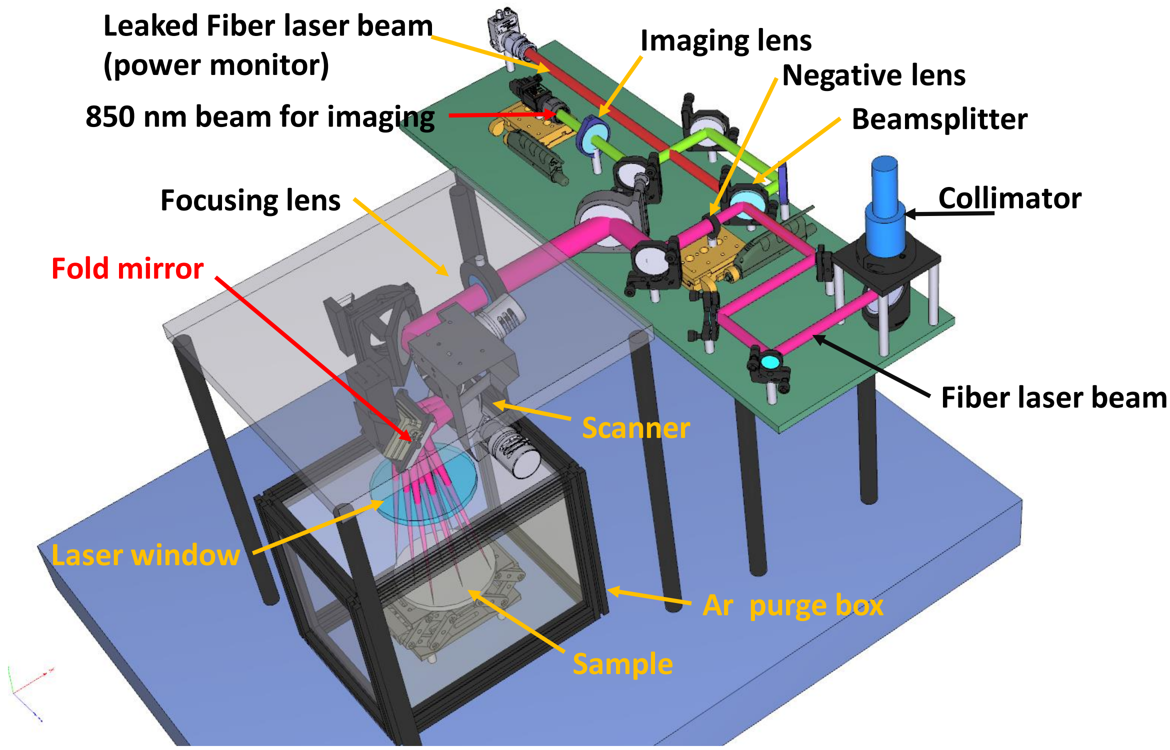

Figure 8: Schematic showing physical location of components within the prototyping system. The prototyping system is built on an optical table surrounded by a laser safety curtain.

One of the more important tests was to determine the level of optical throughput initiating from an incandescing melt pool and passing to the co-axially aligned sensors. Although one can calculate the expected optical throughput, adequate knowledge of the true melt pool temperature and emittance is very limited, therefore physical testing was necessary. Essentially, these tests were to determine at what integration time could the imager 'see' the melt pool. Though the custom optics for optimized resolution were not yet available, comparable signal from final optical design throughput is well approximated by the prototyping system.

The imager tested had 5.5 μm/pixel pitch, quantum efficiency of 63% (measured at 545 nm), and used the 850 +/- 25 nm bandpass filter. While scanning on bare 17-4 stainless steel (no powder) at 800 m/s scan speed and 200 W laser power, the center of the melt pool just saturated the imager (reached 4096 digital levels at 12-bit A/D) at an integration time of 100 μs, shown in Figure 9. During the 100 μs, the melt pool traveled 80 μm, or the approximate equivalent of 15 pixels. However, given the fact that the melt pool is stationary within the image, any motion blur will stem from perturbations in the melt pool size or intensity rather than its motion. Although the true melt pool size (defined by the liquidus/solidus boundary), approximated temperature, or other absolute measures cannot yet be determined, these tests indicate that there is adequate signal level to move forward.

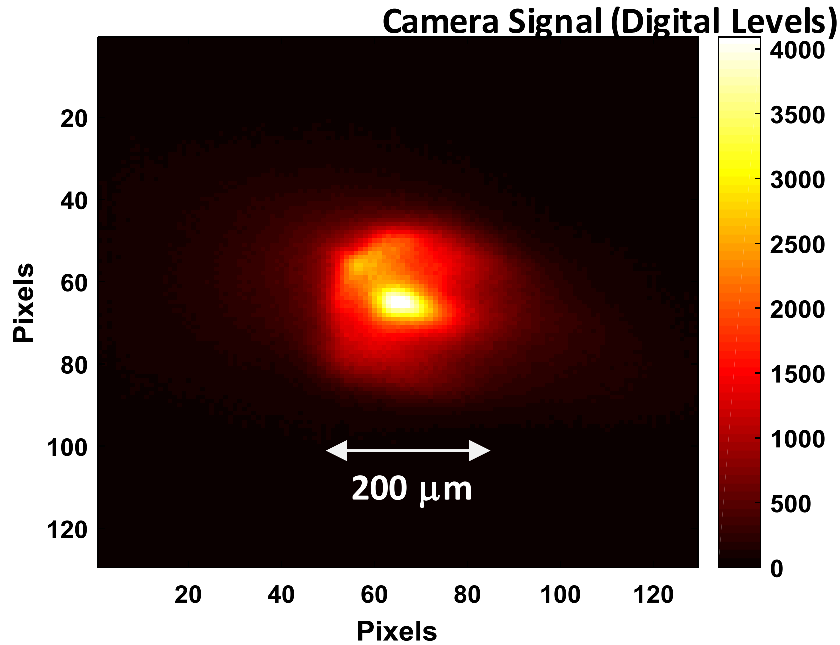

Figure 9: Melt pool image from co-axial imager in the prototyping system. Initial imaging tests were used to determine imager signal level vs. integration time.

Conclusions

This report reviewed the higher-level design of the AMMT/TEMPS system currently being constructed and tested at NIST. The system is essentially an LPBF additive manufacturing system, with a plethora of primarily optically-based sensor systems to enable high fidelity and well-characterized analysis of the melt pool and heat-affected zone. The two overarching purposes (additive manufacturing and materials optical property research) meet the combined interests of the NIST Engineering Laboratory (AMMT) and Physical Measurement Laboratory (TEMPS), respectively. The overall design applies concepts of modularization and accessibility to allow users to work to more easily on the instrument, and access and configure various modules separately from the main system. In addition, overall design flexibility and reconfigurability allow new experiment designs to be more easily incorporated, or various optical beam paths to be accessed for material property characterization, or AM monitoring and control. Foremost, full controllability and characterization enable users to fully define the LPBF process parameters to a high precision, and know how the system responds.

References

[1] Vlasea M, Lane B, Lopez F, Mekhontsev S E and Donmez M A 2015 Development of powder bed fusion additive manufacturing test bed for enhanced real time process control Proceedings of the Solid Freeform Fabrication Symposium (Austin, TX) p 527

[2] Dunsky C 2014 Process monitoring in laser additive manufacturing *Ind. Laser Solut.* **29**

[3] Grantham S, Lane B, Neira J, Mekhontsev S, Vlasea M and Hanssen L 2016 Optical design and initial results from NIST's AMMT/TEMPS facility vol 9738p 97380S–97380S–9

[4] Hanssen L, Kaplan S, Mekhontsev S, Khromchenko V, Burnett J and Zeng J 2015 Status Update of the NIST Infrared Optical Properties of Materials Program *Conf. Charact. Radiom. Calibration Remote Sens. CALCON*

[5] Hanssen L M, Mekhontsev S N and Khromchenko V B 2004 Infrared spectral emissivity characterization facility at NIST vol 5405pp 1–12

[6] Slocum A H 1992 *Precision Machine Design* (Englewood Cliffs, N.J.: Society of Manufacturing)