In-Situ Process Monitoring for Metal Additive Manufacturing

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Abstract – A potential growth opportunity for KLA-Tencor is to leverage existing technology and experience to serve new markets. One such opportunity we are exploring is the development of an in-situ process monitoring module for metal additive manufacturing. Current post-build quality assurance and lack of in-situ process monitoring capability is costly and limits adoption of metal AM in its most promising markets. Here we describe a joint development project recently started with a metal AM equipment manufacturer and briefly discuss highlights of the conceptual design to address this gap using optical inspection technologies.

I. Introduction

A. Metal Additive Manufacturing

Additive Manufacturing (AM, or 3D printing), a method of fabricating objects in a layer-wise, generative manner, offers manufacturing advantages such as reduced cost of complexity, efficient use of raw materials, and in some cases cost efficiencies. Selective Laser Melting (SLM), one AM variant produces nearly fully dense metal parts by melting patterns on layers of metallic powder using a scanned laser spot.

Adoption of metal AM has largely occurred in the aerospace and biomedical fields, with applications such as jet engine fuel nozzles, turbine blades, and orthopedic implants leading the way. Movement from prototyping to direct part production has resulted in 3 year CAGR of more than 30% [1].

B. In-Situ Process Monitoring

Current quality assurance techniques such as micro-CT scanning and extensive destructive testing limit widespread adoption of metal AM. The need for in-situ process monitoring capability is a gap for high-end, critical parts [2, 3]. Today's metal AM machines require advanced users, finely tuned build parameters, and highly-constrained materials. Under the status-quo the hyper growth forecasted by most analysts is doubtful; however, we believe it is likely that metal AM machines will become smarter so they can be operated with less training and with fewer materials and recipe constraints. Here we describe a project kicked off in February 2015 to explore the possibility to leverage KLA-Tencor technology for enabling a new level of AM in-situ process monitoring, and hopefully lead into a new business opportunity for the company.

II. Investigation Scope and Module details

A. Problem Statement and Challenge

To form each layer in SLM, a ~200 µm melt pool is driven at a velocity of 0.5–3 m/s in a random access pattern by a laser spot of size ~50–100 µm. The laser spot is scanned over the 275x275 mm powder bed by a galvo mirror pair and formed through an f-theta lens with a working distance of typically 500 mm.

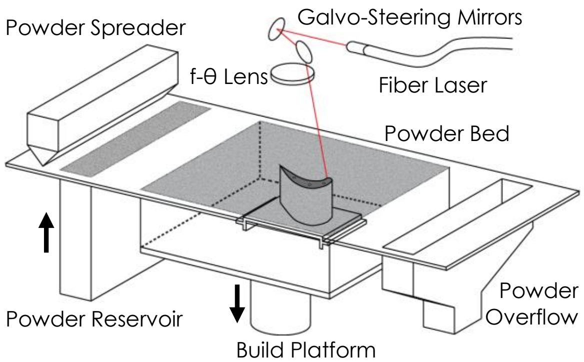

Fig. 1. A diagram illustrating metal AM operating principle. Metal powder is melted in select locations of the powder bed with a scanned laser beam. After each layer's melting pattern is completed, the build platform is lowered; new powder is introduced and then spread over the powder bed. The build process proceeds by melting subsequent layers.

In metal AM, a part and the material structure—including any defects—are formed in-situ. In this context, defects include voids, micro-cracks, and microstructural inconsistencies. The root cause(s) of these defects is mostly unknown, but originate from the part's thermal history, melt pool physics, and thermally induced mechanical stresses. From what we have learnt in our investigation and more recently confirmed with our partner, many of these defects can be managed through feed-forward control of the melting parameters. Random voids, however, are a persistent defect type for which size and concentration impact adoption for high-end applications. According to our partner it would be of great value to be able to map the presence of critical voids (which they have estimated to be >20 µm).

There are numerous challenges for an optical in-situ monitoring system of the SLM. First, the relative size of the melt pool and defects of interest to the powder bed size would require a large pixel count sensor for global monitoring. Additionally, the fast beam velocities and random access nature of the scan pattern require >10 kfps readout. In order to monitor melt pool dynamics, even faster acquisition rates, such as 100 kfps, have been motivated by our partner, which goes way beyond what they and other players have been able to attempt of their own. Last but not least, the smoke and spatter emitted by the melt pool can hurt imaging optics. For these reasons, the preferred and likely most effective optical monitoring setup is coaxial with the laser beam. In this configuration, the thermal radiation from the melt pool can be imaged. Other channels such as pyrometers, a brightfield (BF) channel, and spectrometers are also considered in our concept.

The coaxial configuration has several significant challenges remaining. One is the thermal light budget, which is hindered by a small numerical aperture (NA ~ 0.03), and black-body radiation spectra at longer wavelengths than most available fast Si-based camera sensors can capture. Another challenge is that the front-end f-theta lens and scanner optics and coatings are optimized for the 1070 nm Ytterbium fiber laser line and will require customization for broadband monitoring. Finally, build times of 10–100 hrs and Gpix/s camera rates will require handling significant quantities of data well beyond those typically used in AM. While these challenges don't make the direct detection and mapping of ~20 µm voids an easy task, the difficulty is what makes solving this problem a potential match with KT technology and engineering horsepower and enabled us to secure a valuable and experienced partner in the field.

B. Project Description

This project was preceded by a market and technology investigation in FY15 initiated by Candela. That investigation concluded that a significant market opportunity for process monitoring of nearly $1B exists for in-situ in the high-end metal segment by 2025. The investigation also identified a metal AM equipment maker to partner with on a Joint Development Project.

The varied and novel challenges posed by this project are best addressed by leveraging expertise throughout KLA-Tencor. For that reason we are employing an organizational structure we are calling Core+. The project is managed by an engineering lead and subsystem leads from Candela, while each subsystem team includes experts throughout the company. We believe that this structure will be a lightweight and effective way to leverage the best talent for this and similar projects in the future.

The project Mission is to produce an in-situ process monitoring system integrated onto a commercial metal AM machine by January 2016. This unique system will be used as an experimental setup to prove technical feasibility, better understand requirements, and to start testing market needs. The successful experiment will then result in a Phase 1 exit, which if successful would be followed by a Phase 2 towards an effort to commercialize a market probe.

C. Brief Description of Subsystem Requirements and Conceptual Designs

In order to capture anomalous melt pools with extended tails in random directions, we will design for a field of 1x1 mm for thermal imaging in the 800–1000 nm spectral band, which allows us to use two fast commercial CMOS cameras interleaved effectively yielding 100 kfps acquisition. Initial light budget calculations support feasibility of imaging the melt pools of steel-like materials down to solidification, and even below solidification for the hotter melting Titanium alloys (our first priority). In addition to this main fast imaging channel we are planning to add a brightfield channel illuminated around 780 nm, as well as a longer IR band imaging channel (1100–1700 nm, InGaAs sensor) for observing the resolidified landscape and cooling rates. These may help capture as-formed defects, while the 100 kfps channel picks-up fastest dynamics and instabilities in the hotter regions. The BF and IR channels will have a larger 2x2 mm field of view. To balance optical sampling with acquisition speed, the camera sensors will be windowed to 100x100 pixels for the NIR channel, 200x200 for the IR, and 400x400 for the BF. Fig. 2 shows a concept layout of the various optical channels and their associated wavelength bands.

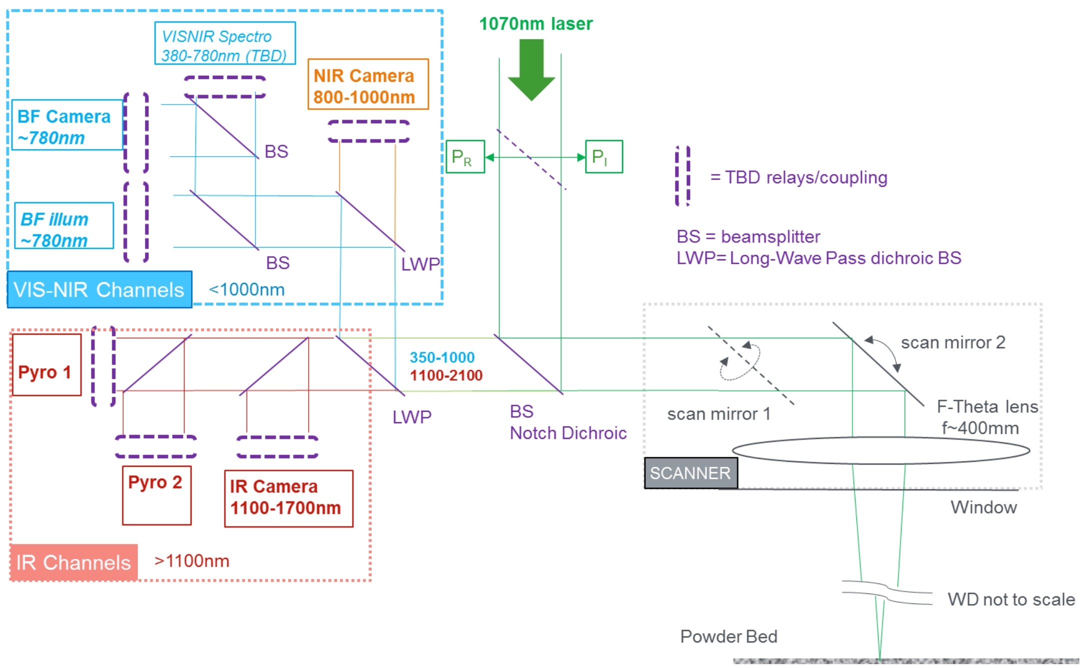

Fig. 2. Conceptual optics layout.

Because of the exploratory nature of this project, algorithm design and possibly sensor inputs may change as we learn; therefore, flexibility and quick time to implementation are critical, especially for the Image Computer (IMC) subsystem. The chosen IMC architecture utilizes proven KT solutions to provide the flexibility, lower risk, and possibility of quick implementation. Flexible and proven infrastructure is taken from Surfscan (previously from EBEAM). The hardware interface code for the Matrox frame grabbers is reused from EBEAM. Datapath from acquisition to compute node is the same as SP7, but with lower bandwidth requirements. Saving of raw data reuses a software solution from Surfscan utilizing a generic file format and hardware from WIN. The host solution is taken largely from Surfscan.

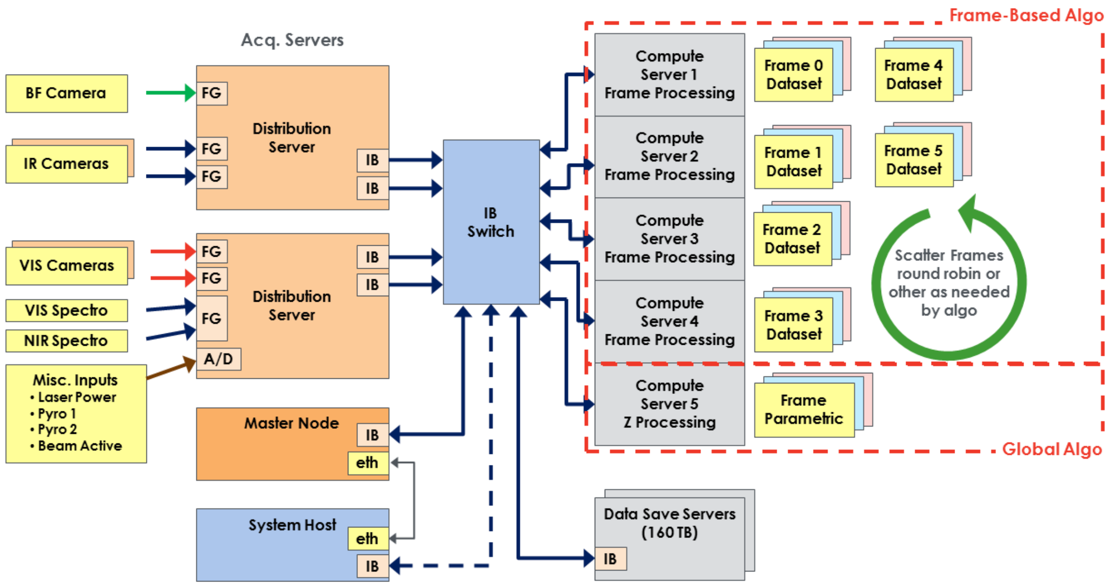

Fig. 2. Conceptual Image Compute Architecture.

In addition to leveraging the reliability of the above proven solutions, this architecture is extremely flexible. Because jobs take named buffers, datapath can be very easily changed or dynamic based on recipe. Transparent to the user, jobs are scheduled as data becomes available and can be distributed across nodes automatically or optionally by node, socket, or CPU core. Finally, the solution is cross-platform, leverages numerous open-source technologies, and provides accessibility to multiple clients (C++, Java, Python).

Our main goal is to relate collected melt pool signals with defects in the final metal object. This requires the collection and analysis of hundreds of TB of data, which must then be reviewed in 3D. For visualization of melt pool parametrics and defect candidate sites in 3D, we chose to modify open-source 3D volume scientific visualization software with rich scripting capability by adding custom defect selection and review capability.

III. Conclusion

This manuscript describes a joint development project with metal AM equipment maker to develop an in-situ optical process monitoring module. While led by Candela, this project is enabled and accelerated by leveraging talent and expertise throughout the company. Highlights of the conceptual design, key challenges, and technology solutions unique to this problem are discussed; we anticipate seeing our first melt pool images as early as September 2015.

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Bibliography

[1] T. Wohlers, Wohlers Report 2014, Fort Collins, Colorado: Wohlers Associates, Inc., 2014.

[2] W. E. Frazier, "Metal Additive Manufacturing: A Review," *Journal of Materials Engineering and Performance*, vol. 23, no. 6, pp. 1917-28, 2014.

[3] National Institute of Standards and Technology, "Measurement Science Roadmap for Metal-Based Additive Manufacturing," 2013.