Accelerating Qualification of Additively Manufactured Metal Parts

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Lawrence Livermore National Laboratory and General Electric Research Center
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Overview

Project Title: Accelerating Qualification of Additively Manufactured Metal Parts

Timeline:

Project Start Date: 05/01/2019

Budget Period End Date: 04/30/2020

Project End Date: 04/30/2021

Project Budget and Costs:

Budget	DOE Share	Cost Share	Total	Cost Share %
Overall Budget	$750,000	$750,000	$1,500,000	50%
Approved Budget (BP-1&2)	$750,000	$750,000	$1,500,000	50%
Costs as of 3/31/19	$14,000	$14,000	$28,000	50%

Barriers and Challenges:

Development of fast-running, reduced-order finite element models may prove to be a challenge	Implement efficient algorithms based on local geometry features and sensor data.
Thermal imaging sensors are not fast enough to capture the process	Rely on high speed photodiode technology
IFF produces inconsistent improvements	Return to high-fidelity modeling to understand missing physics

Project Team and Roles:

- Ibo Matthews (Lead) – Manage project, engage industry partner and potential sponsors
- Clara Druzgalski (Technical Lead & Modeling) – Coordinate project with ongoing IFF projects and lead modeling efforts
- Ava Ashby (Modeling) – Support modeling efforts, run Diablo code, scan path optimization
- Gabe Guss (Hardware) – Modify machine controller and develop handshaking protocols for various file formats
- Maria Strantza (Experimentation) – Operate laser powder bed machines, post process built parts, analyze part performance and material quality
- Wayne King (Consultant) – Coordination with broader AM community, technical reviewer

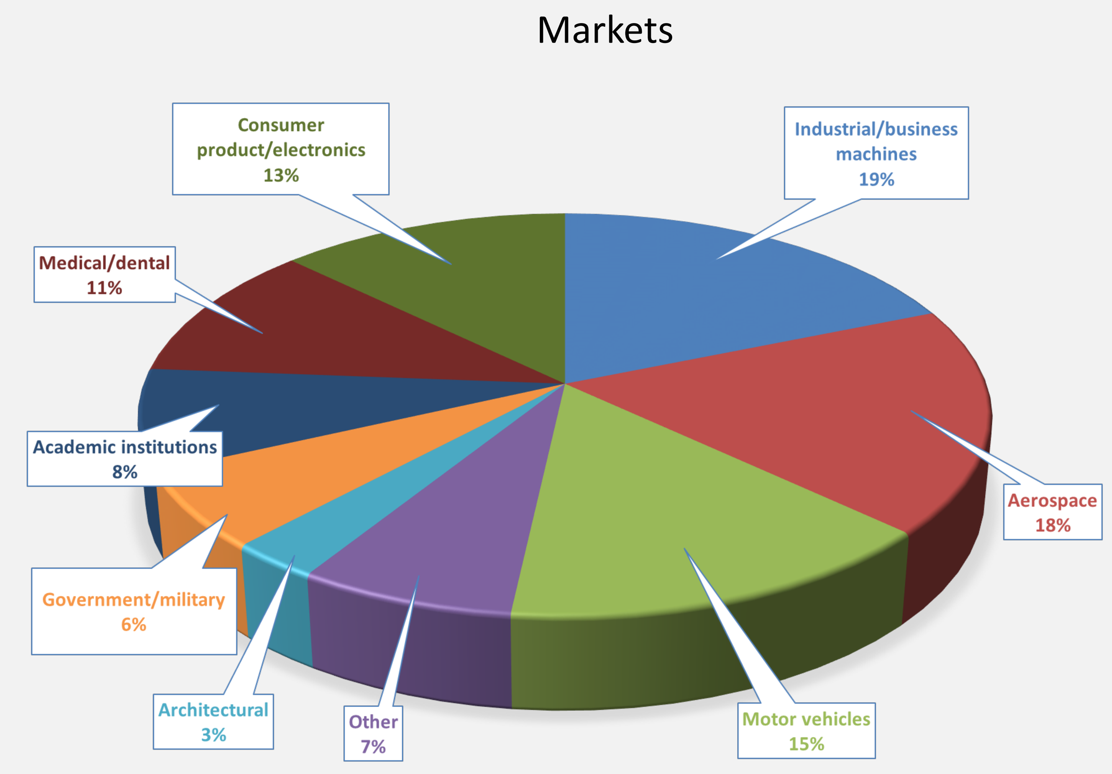
AMO MYPP Connection:

- AMO MYPP Area(s) being addressed - Smart Manufacturing (sensors/modeling), Additive Manufacturing.

- **Additive manufacturing (AM)** holds the potential to transform manufacturing, and one of the newest areas of AM involves efforts to **automate production** of metal parts via AM.
- However, according to a survey of manufacturers conducted by Additive Manufacturing for Aerospace and Space, 56% of manufacturers indicated that **uncertain quality of the final product** was a barrier to adoption of additive manufacturing.
- It can be costly and time intensive (up to two years) to qualify **complex parts** for critical applications, such as jet engines.
- Today's manufacturers demand an AM approach that can take advantage of the **speed, versatility, and adaptability** of AM, while still ensuring the quality of parts produced.
- This proposed work aims to address these challenges, offering a novel process that replaces the approach presently used to produce complex metal parts with a **science-based, automated AM approach** that can be easily implemented on the factory floor.

Project Objective(s)

In this two-year project, **LLNL** will partner with the **GE Global Research Center and GE Additive** to jointly develop an IFF hardware/software package for existing and future GE metal AM machines. If successful, we will then test and evaluate the use of **IFF on a GE metal AM machine**. Our goal is to demonstrate that IFF can enable **effective production of complex metal parts**, regardless of the feedstock, machine, or part geometry. IFF is expected to **reduce the number of iterations** required to produce a high-quality part and offer "right every time" part production.

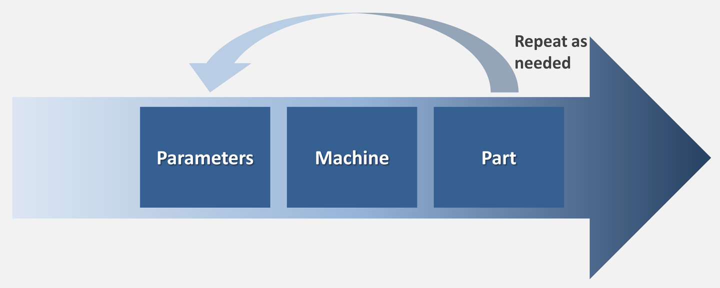


Technical Innovation

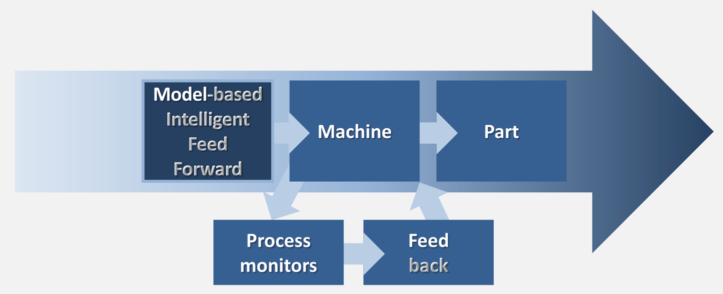
- Today, before building a part via AM, engineers use extensive, iterative experimentation to optimize the part's parameters, such as the laser power, speed, and beam size.
- Achieving the needed geometry-specific process control throughout a build requires control of the input parameters. The vision of achieving a ***precise, optimized 3D map of input parameters*** is referred to as *a priori*, geometry-based scan parameter adaption, look ahead, or **intelligent feed forward (IFF) control**.
- Applying the IFF methodology, we will use data generated from process simulation and in-situ sensors to ***optimize*** the process parameters through ***reinforcement learning***.

Closing the AM process loop with Intelligent Feed Forward (IFF)

Traditional (experience-based) approach for AM:



IFF (science-based) approach for AM:



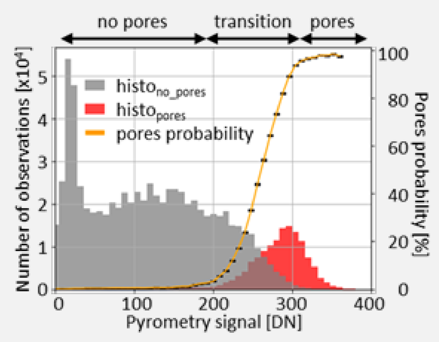
IFF puts a narrow band on parameters and approaches "First time right, every time right"

Technical Approach

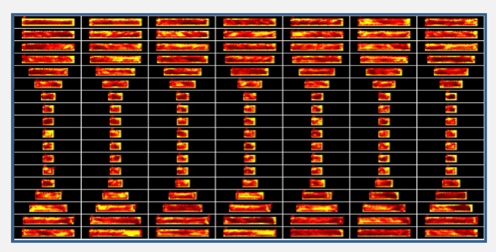
Geometry features within a part are prone to different types of defects.

Overhang: Dross formation — Overhang: Balling — Bulk: Pore formation — Thin wall: Warping

In-situ sensor data can be used to optimize the laser power strategy for challenging geometry features. In particular, it has been shown that pyrometry data is correlated with pore formation. Pyrometry data collected during the print can be used in conjunction with reinforcement learning algorithms to learn an optimal laser power.

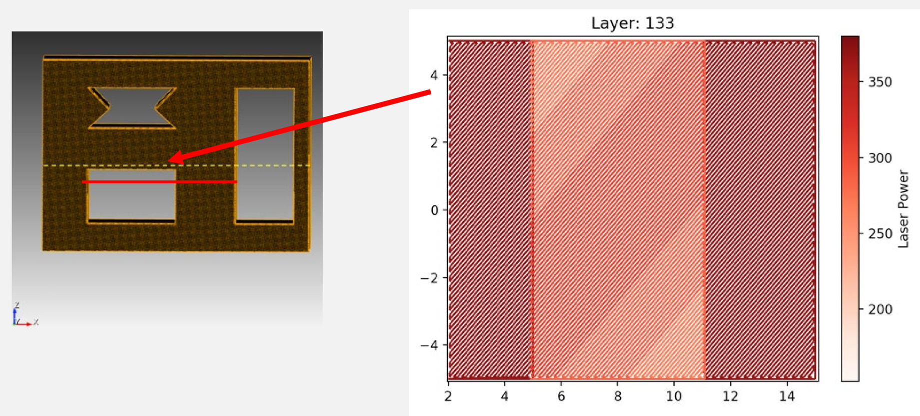


Pyrometry signal is correlated with pore formation



Pyrometry signal from dog-bone geometries

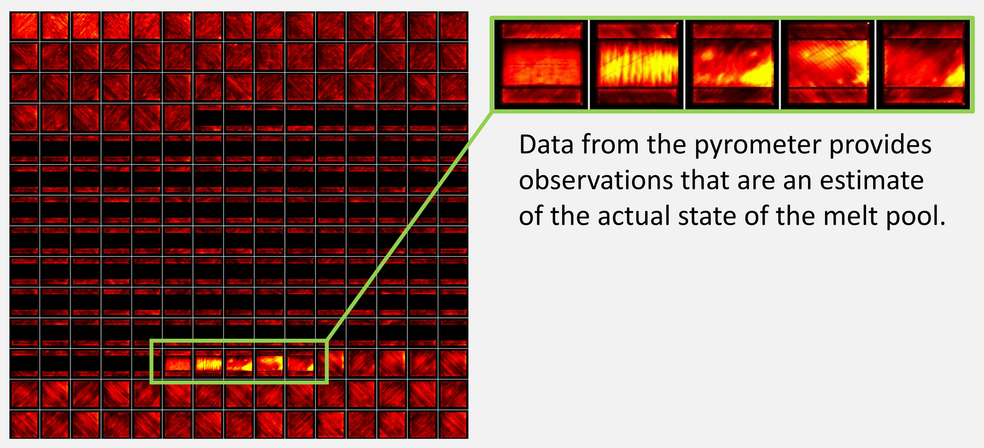
Results from the pyrometry data can be used to inform the Intelligent Feed Forward (IFF) Framework, which applies geometry feature specific corrections to the laser power



The IFF Framework is fast, can handle large geometries, and has a straightforward file workflow shown below:

XML files → Algorithm → XML files → Machine

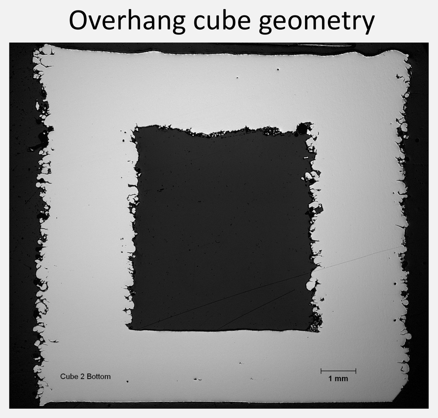
Technical Approach

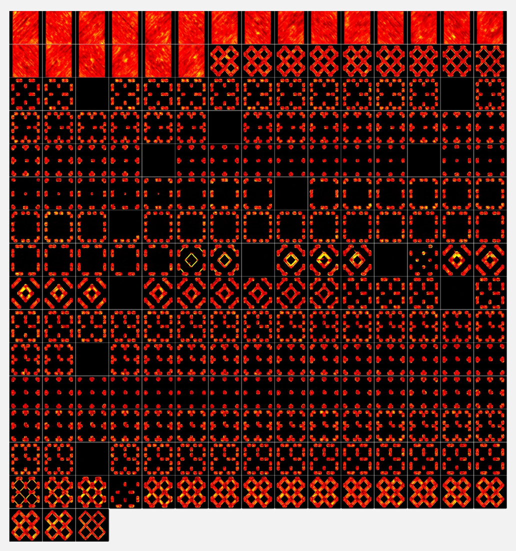


Data from the pyrometer provides observations that are an estimate of the actual state of the melt pool.

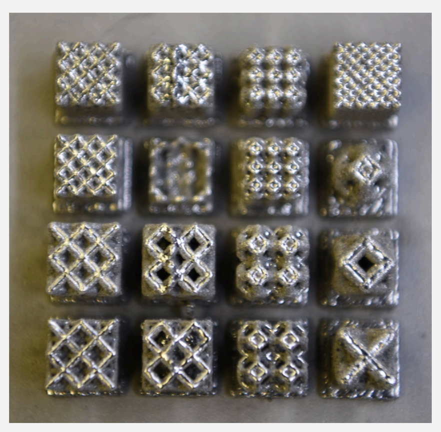
This montage shows the pyrometry signal on different slices of an overhang cube. The pyrometer signal is particularly high at the overhang, where defects are likely to occur.

Overhang cube geometry





Pyrometry data has been recorded during builds of complex geometries such as lattice structures.



Pyrometry provides high frequency samples. At every time step a distribution on the state can be estimated and fed into a Linear Quadratic Regulator (LQR). This is a low cost method to control a dynamical system with indirect, noisy observations of its state.

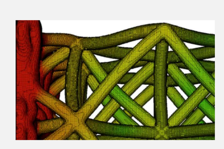
Results and Accomplishments

- Kick off meeting at Advanced Manufacturing Laboratory at Lawrence Livermore National Laboratory held on May 1, 2019
- IFF Framework presented and discussed between GE and LLNL. Latest product offerings from GE are being analyzed for adaptation to new technologies arising from joint collaboration.
- Down-selection of materials has been made, resulting in Ti-6Al-4V and Steel 316L being of mutual interest to both GE and LLNL.

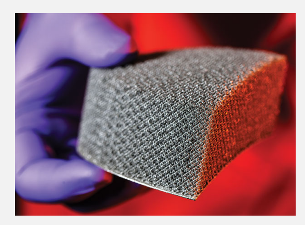
Transition (beyond DOE assistance)

- IFF technology will mature to a point where IP is generated and jointly-developed systems will become product at GE
- With coordination with US Navy's Quality Made program, IFF technologies developed in this project can potentially off-ramp into the Navy program
- Internal DOE investments (NNSA) are expected to benefit and further adopt the technology

GE/ConceptLaser M2 Cusing



Metal micro-lattices



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