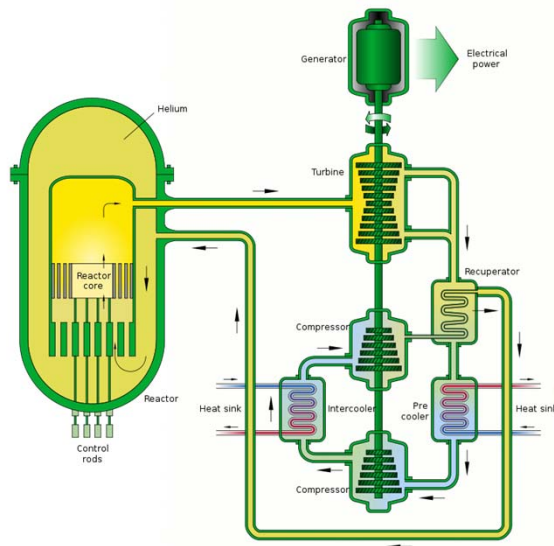
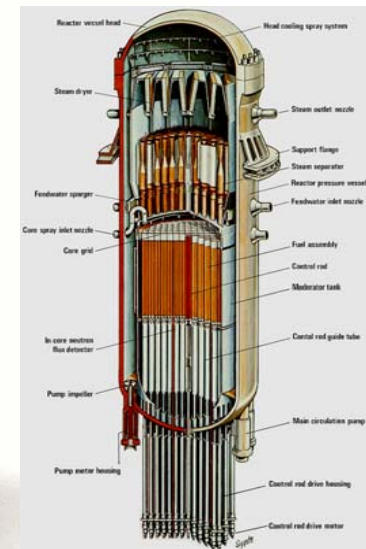


Intelligent System Development



Contact Information
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Small Modular Reactor (SMR)

December 17, 2019

AMM Technical Review Meeting

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Innovating 3D Manufacturing

Company Strengths: Vertically Integrated



Laser expert;
Process innovation;
System solution.

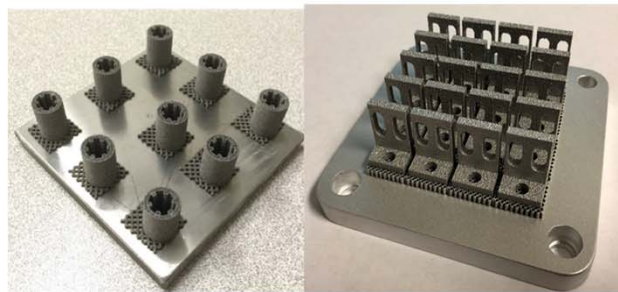
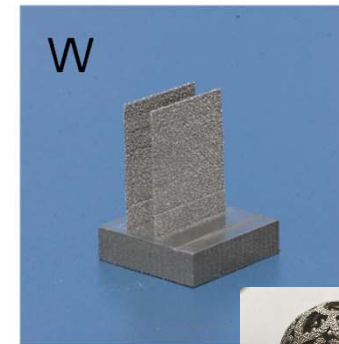
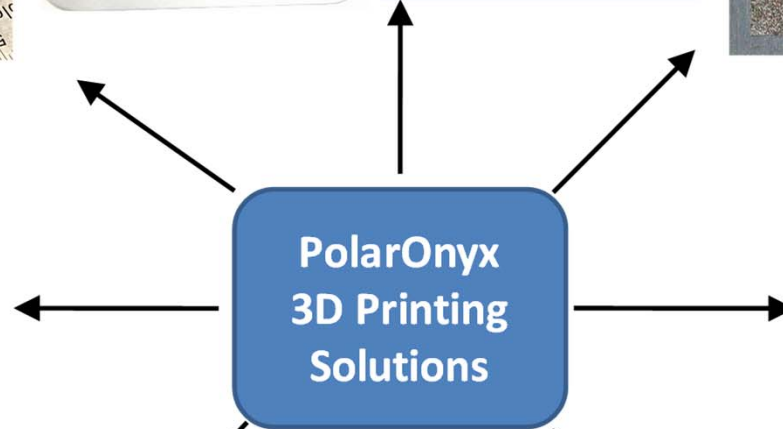
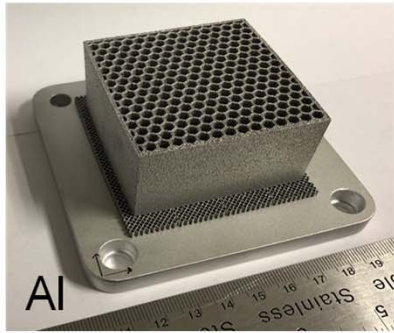
- Pioneer in ultrafast laser Additive Manufacturing (AM)
- Laser AM and subtractive manufacturing (SM) system integration
- SM is integrated for complex 3D part
- Patent pending technology for ultrafast laser AM & SM
- In house expertise in laser R&D and manufacturing
- Internal AM & SM process development
 - Best quality of service

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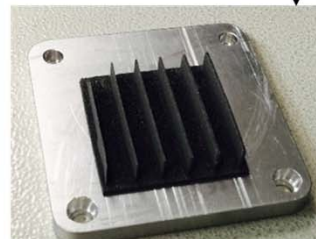
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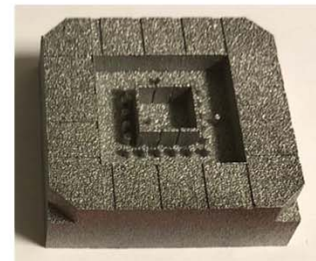
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Excellent Uniformity



Metal/Ceramic



Mold



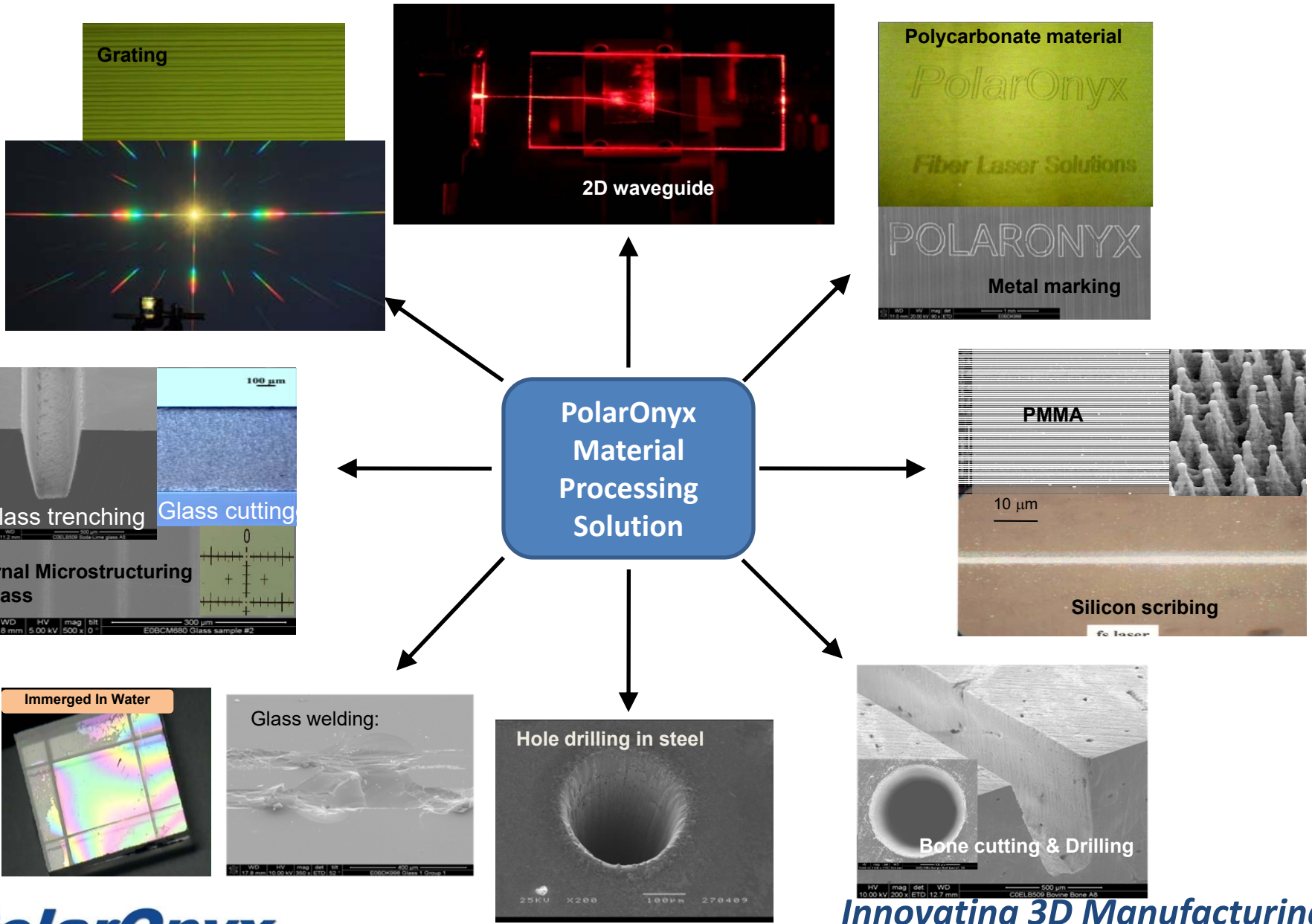
Structured parts

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Outline

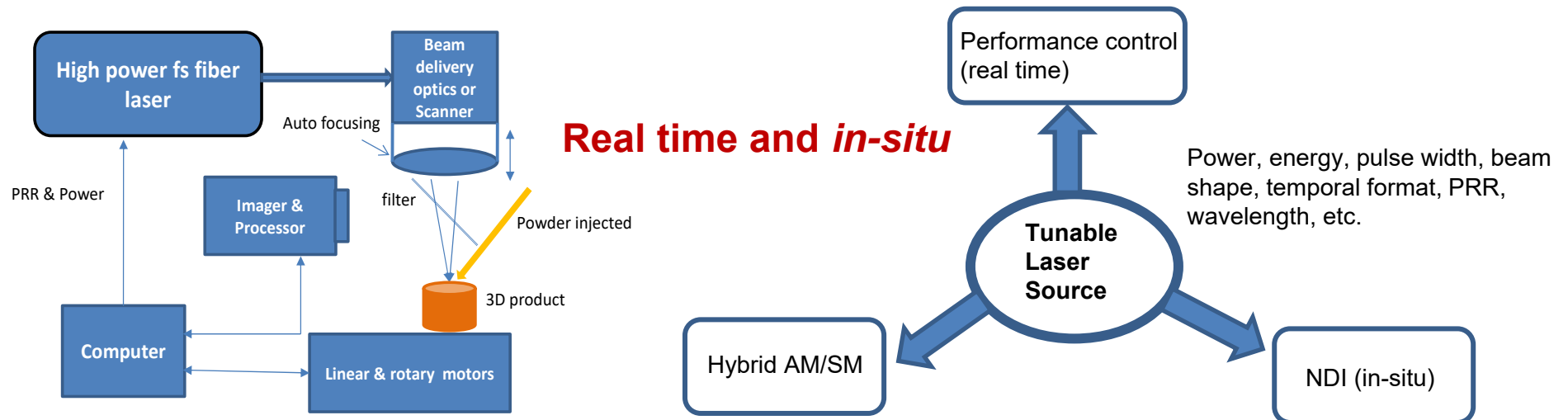
- Phase I motivation, tasks and schedule
- Phase I results
- Next plan

DOE SBIR Phase I (DE-SC0018826)

Controllable 3D Manufacturing System

July 2, 2018-April 1, 2019

- All-in-one system by including AM and SM in a single unit and share one laser
- Tuning of laser parameters (power, pulse width and PRR) to control melting pool temperature and microstructure
- In-process characterization (Thermal imaging, LIBS or plasma spectroscopy)
- Post-process characterization (LT: Laser Topography.)
- SS 316L and Inconel 718 parts making



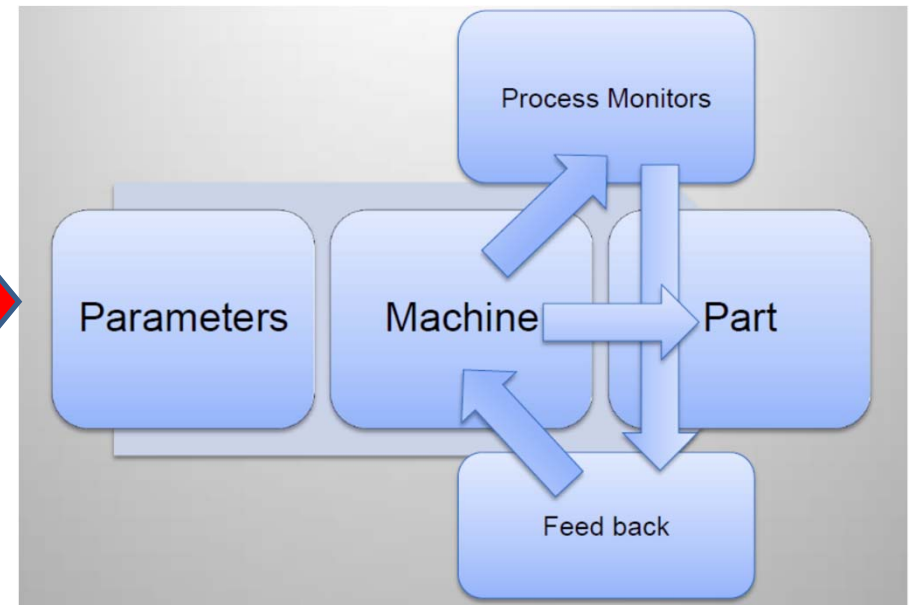
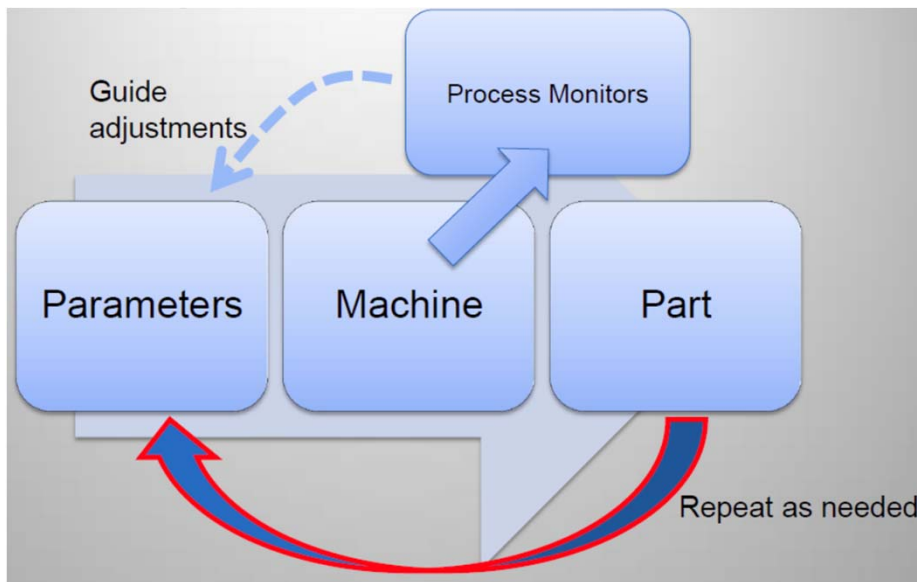
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AM Process Control



Many iterations needed for qualifying parts

- Machine dependent
- People dependent
- Vendor dependent

AM control in layer level to make less human intervention and iterations

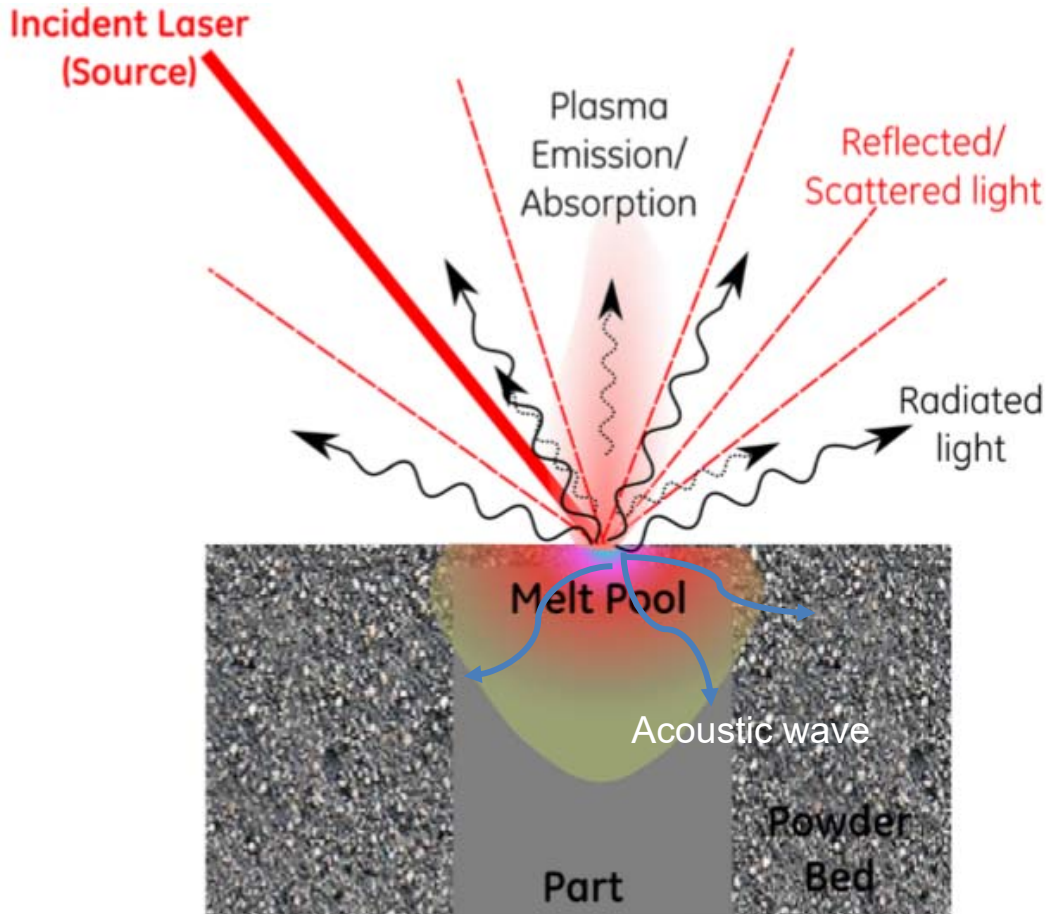
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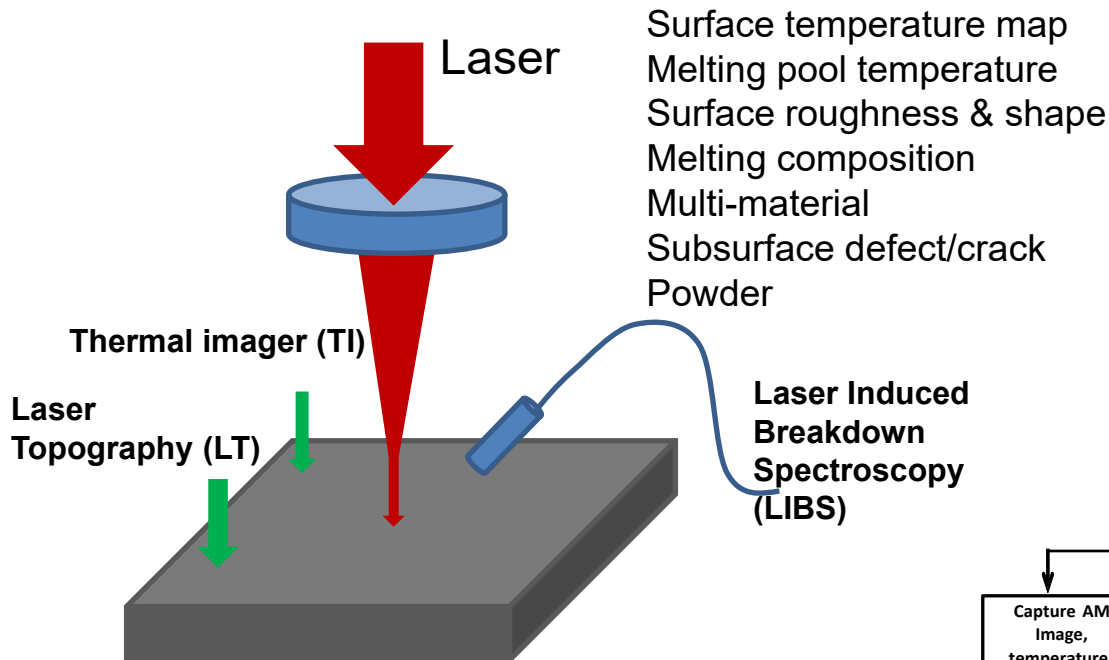
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Laser-Material Interaction

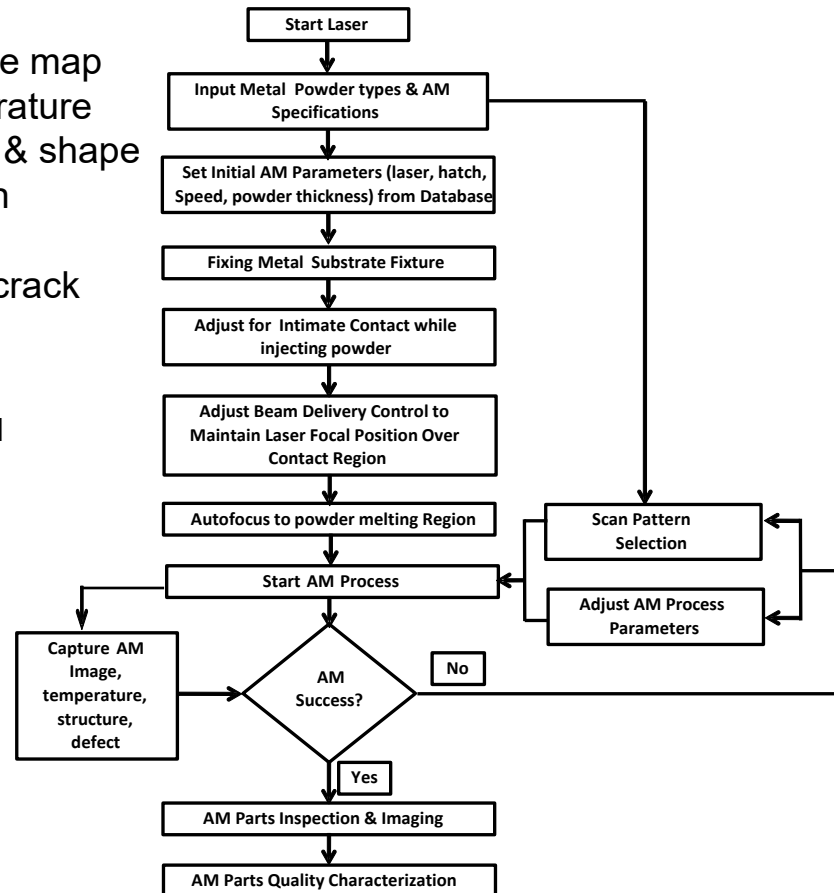


- ng pool temperature
- ace roughness
- emperature distribution
- ng composition & Phase
- material
- urface defect/crack
- der size and shape
- ...

Intelligent AM Process Control



Real time detection and feedback



Phase I Technical Tasks

- Develop control protocol (hardware and software algorithm) for the smart hybrid system
- Validates LIBS to measure elements and melting pool temperature.
 - Co-linear configuration
 - flat surfaces
- Proves that the LT can measure (parts) surface roughness and shape.
- Proves that the LT and TI can measure (parts) temperature distribution and defects.
- Correlates the measurements with powder (size/shape), temperature, defects, cracks, etc.

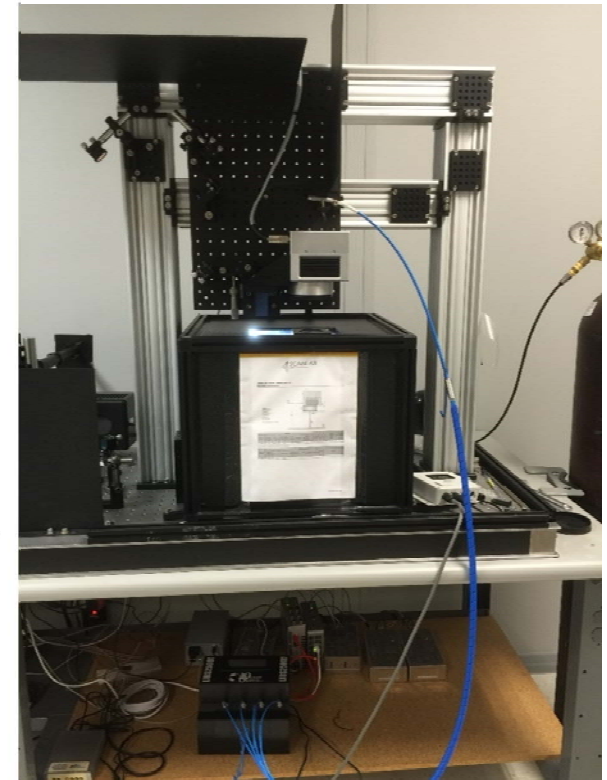
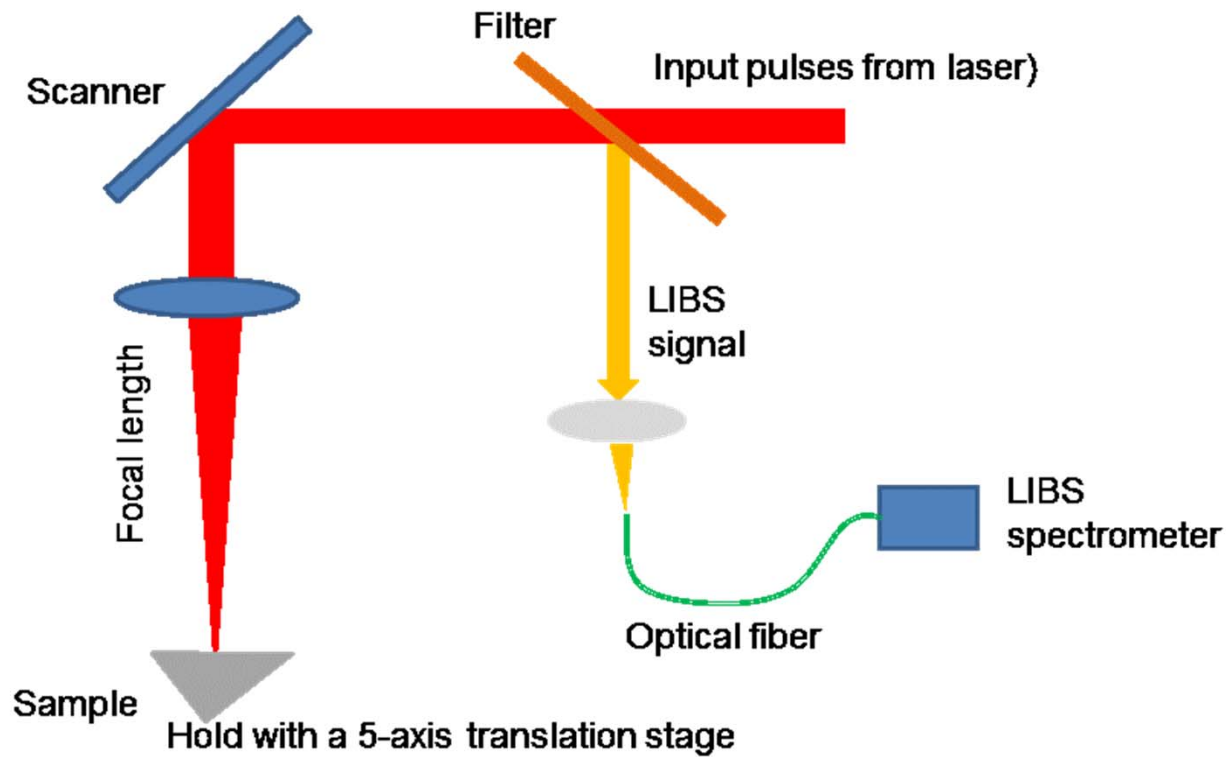
Outline

- Phase I motivation, tasks and schedule
- **Phase I results**
- Next plan

Phase I Accomplishments

- NDI in-situ Sensing (experimental proof of concept)
 - Breakthrough true temperature distribution measurement with thermal imager (TI) and surface roughness (emissivity) correction with visible camera (LT)
 - LT characterization and correlation with surface roughness and geometrical shape
 - filed one patent, [Jian Liu “Method and Apparatus for Real Time, In Situ Sensing and Characterization of Roughness, Composition, Defects, and Temperature in Three-Dimensional Manufacturing Systems” Application number 16378485, April 9, 2019.](#))
 - Thermal distribution correlates with residual stress and defects
 - Systematically studied feature LIBS spectral peak & contrast vs variation of elements (SS316L) and powder impact
- Laser Control and Process Optimization
 - Developed laser manipulation of PRR and pulse format
 - Optimal overhand parts making with feedback control.
- Control Mechanism
 - Developed control hardware and software layout and algorithm
 - Defined control parameters and feedback featured parameters

LIBS Validation



- Co-linear configuration
- Curved surfaces
- Powder characterization

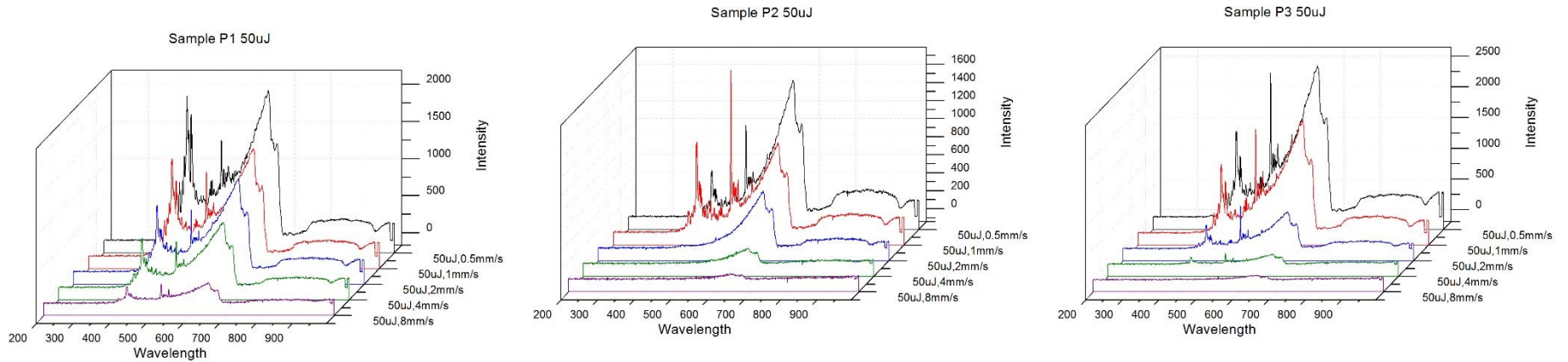
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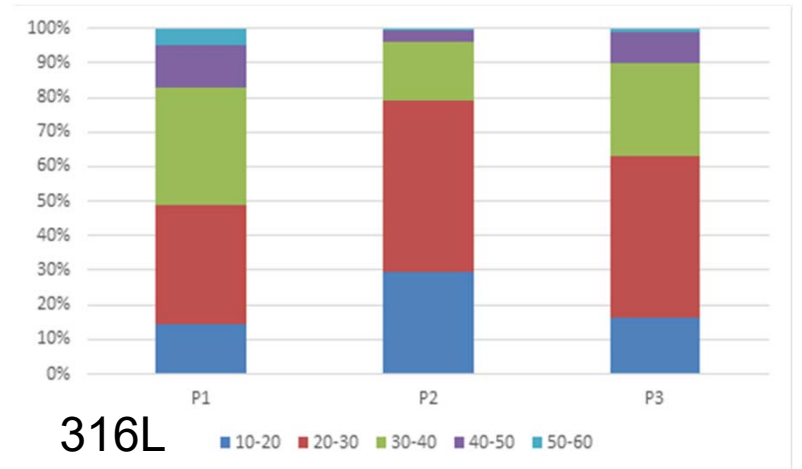
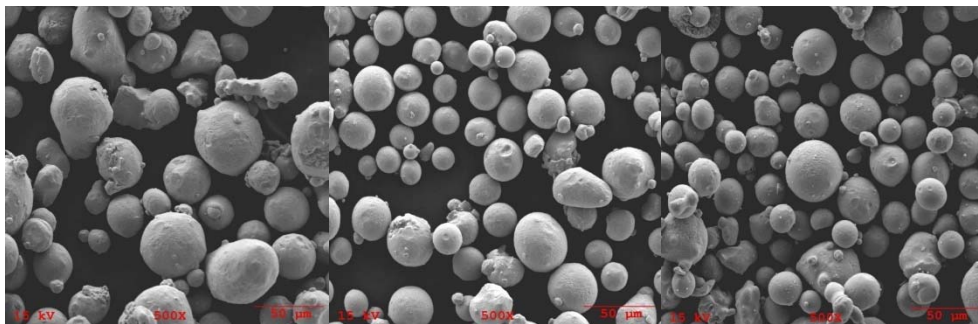
LIBS Validation (Powder)



P1-EOS

P2-concept laser

P3-CNPC



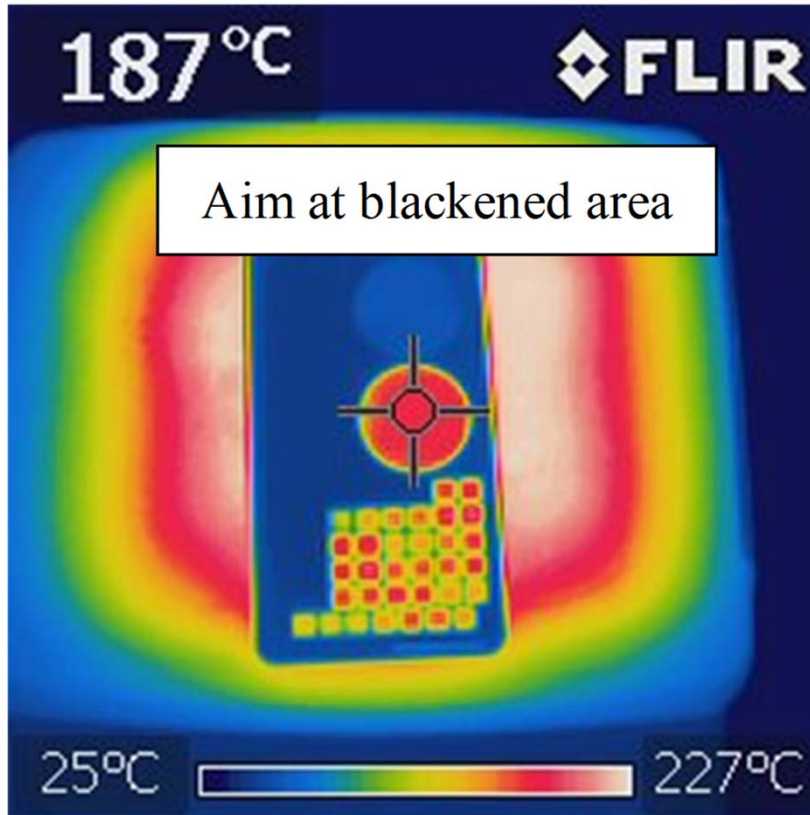
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Thermal Imaging Can Fool



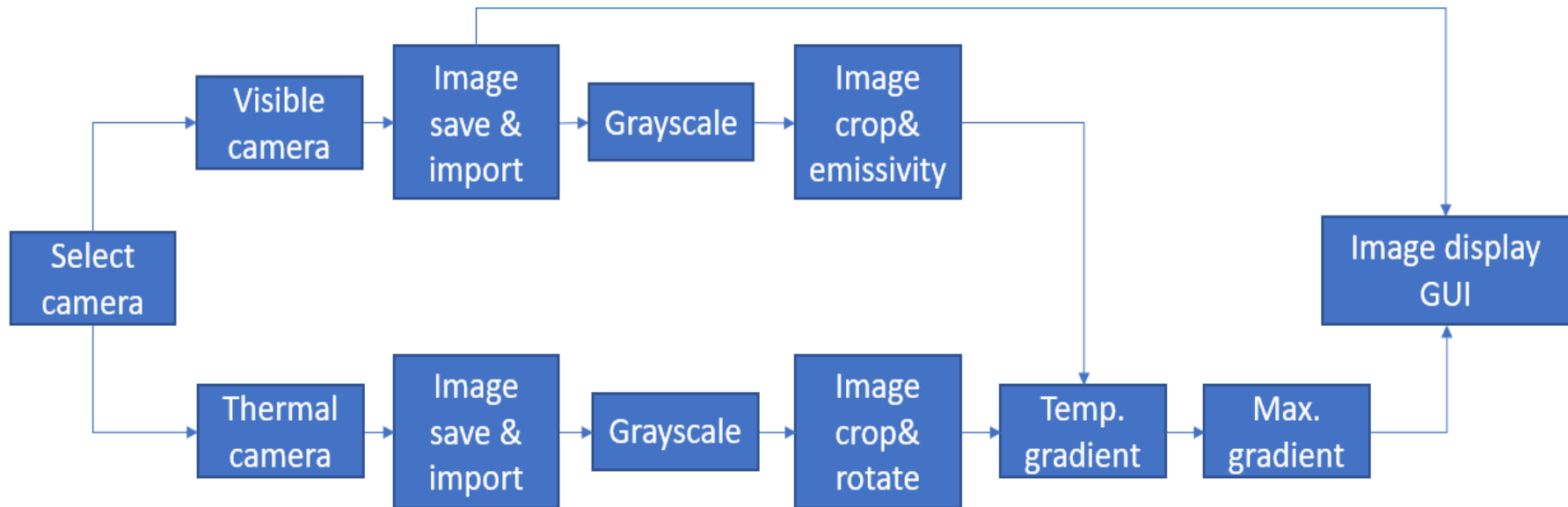
H Huang, LM Yang, S Bai, J Liu "Blackening of Metals Using Femtosecond Fiber Laser," Applied Optics, 54 (2), pp. 324-333 (2015).

Temperature is highly dependent on surface structures.

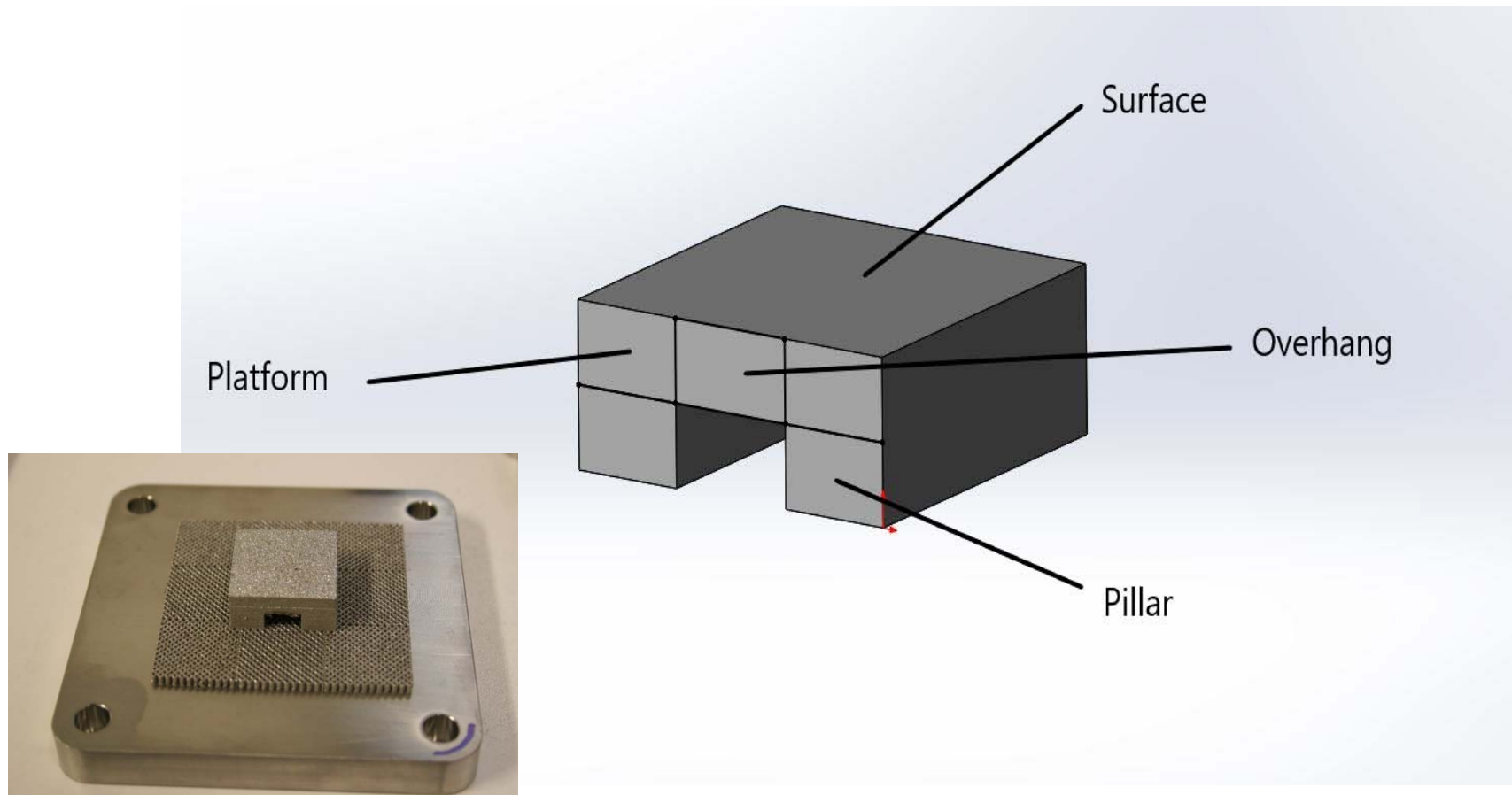
Thermal accumulation /dissipation speed varies largely!

Calibration for thermal imaging with varying structure is very challenging!

System Control Implementation

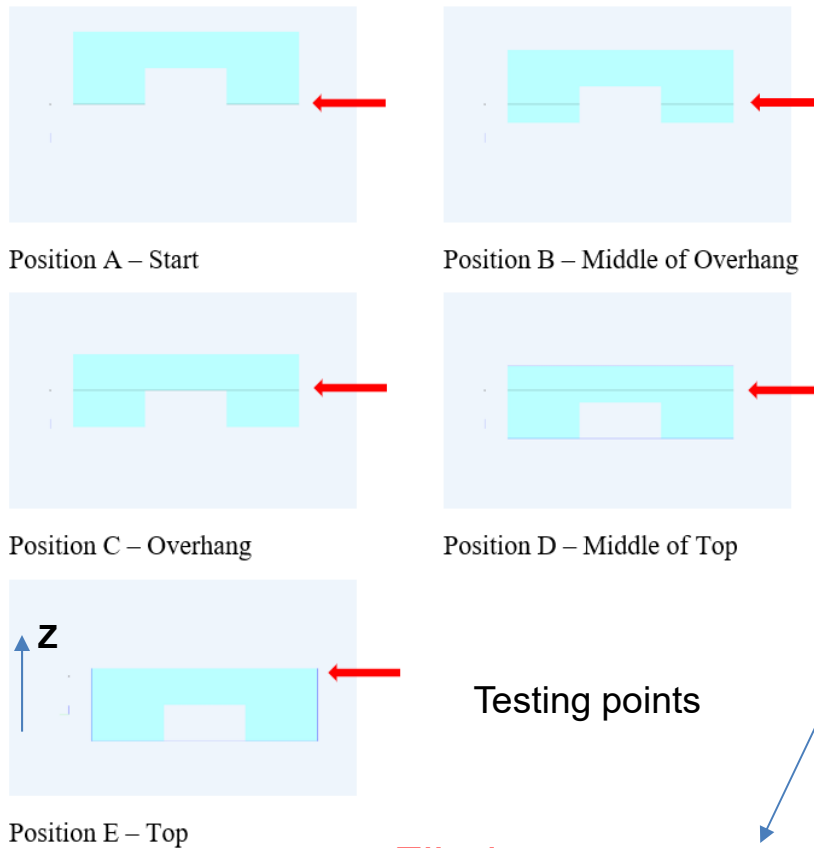


Overhang Definition

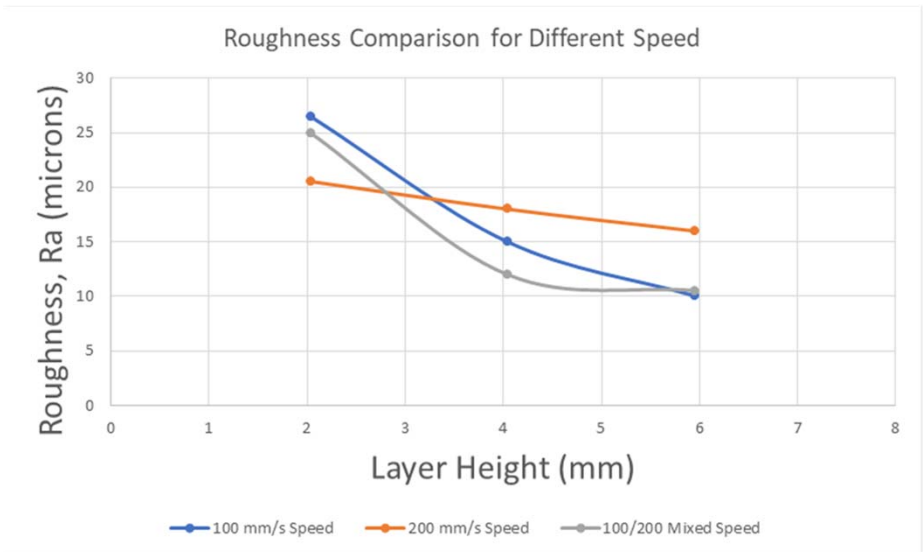


Emissivity is calibrated with roughness and temperature

Thermal Distribution



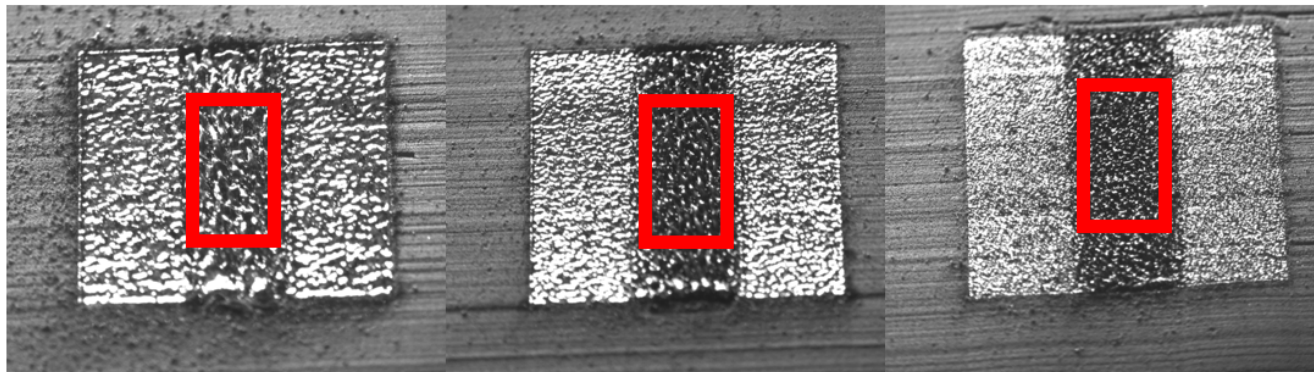
Filed one patent



- Roughness characterization
- Temperature distribution with roughness and temperature calibration
- Feedback control of process to make flat and high density overhang structure
- Density comparison

Position C (Overhang)

Position C. Overhang Layer 1 - Middle



A. 100mm/s speed

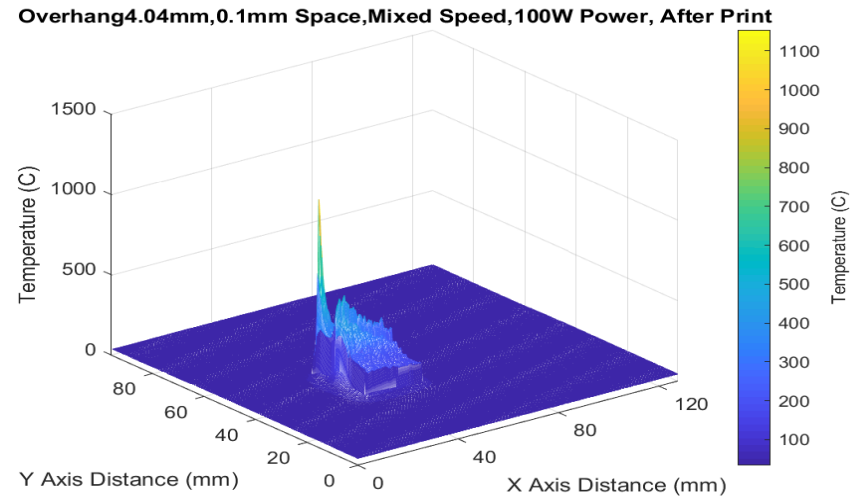
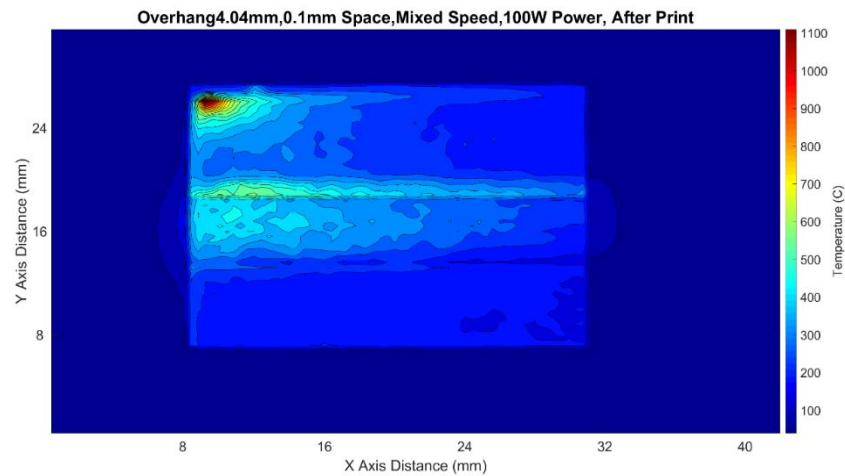
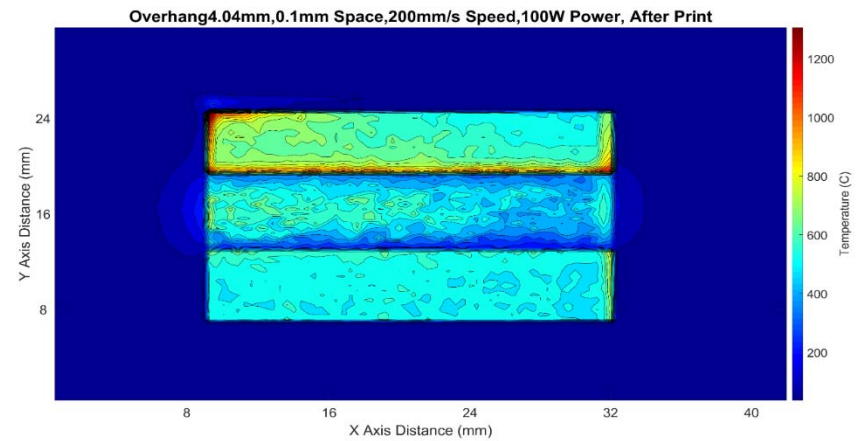
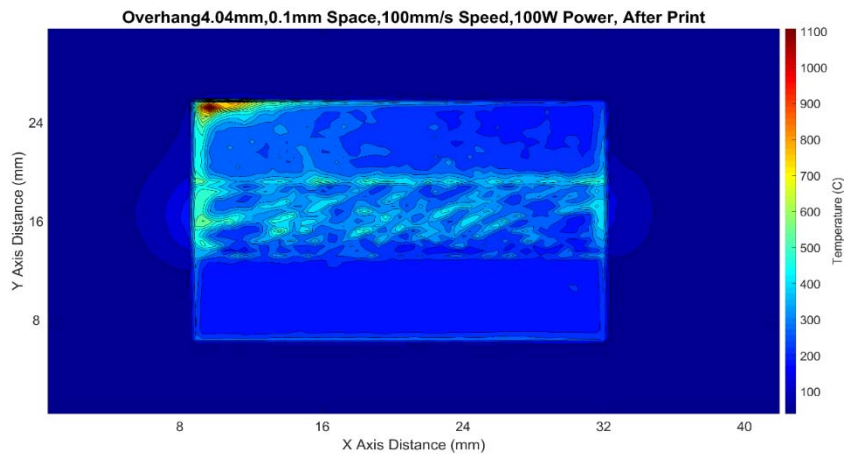
B. 200mm/s speed

C. Mixed speed (200mm/s)

Print	Percent of White Pixels	Roughness (Ra)
A	-	Out of range
B	-	Out of range
C	-	Out of range

Too large roughness

Thermal Distribution (Overhang 1st Layer)



Density Characterization(Overhang)

	1	2	3	4	5	Average	
B e s t	Mixed Speed Surface	99.758	99.774	99.12	99.545	99.434	99.526%
	Mixed Speed Pillar	99.36	99.091	99.294	96.459	98.807	98.602%
	Mixed Speed Overhang	96.775	98.497	97.463	96.62	94.782	96.827%
	Mixed Speed Platform	98.539	98.462	98.67	98.747	94.498	97.783%
	100mm/s Surface	99.357	98.308	97.922	99.221	99.339	98.829%
	100mm/s Pillar	97.781	98.296	97.228	97.795	97.217	97.663%
	100mm/s Overhang	96.132	96.528	96.897	95.326	91.078	95.192%
	100mm/s Platform	97.539	99.326	98.094	97.906	94.432	97.459%
	200mm/s Surface	60.938	77.912	64.563	71.900	81.534	71.369%
	200mm/s Pillar	90.855	93.981	94.568	90.887	93.478	92.753%
	200mm/s Overhang	86.003	92.847	91.518	93.126	80.626	88.824%
	200mm/s Platform	93.658	95.639	74.768	81.233	89.959	87.051%

Feedback control gives control of thermal distribution to obtain highest density.

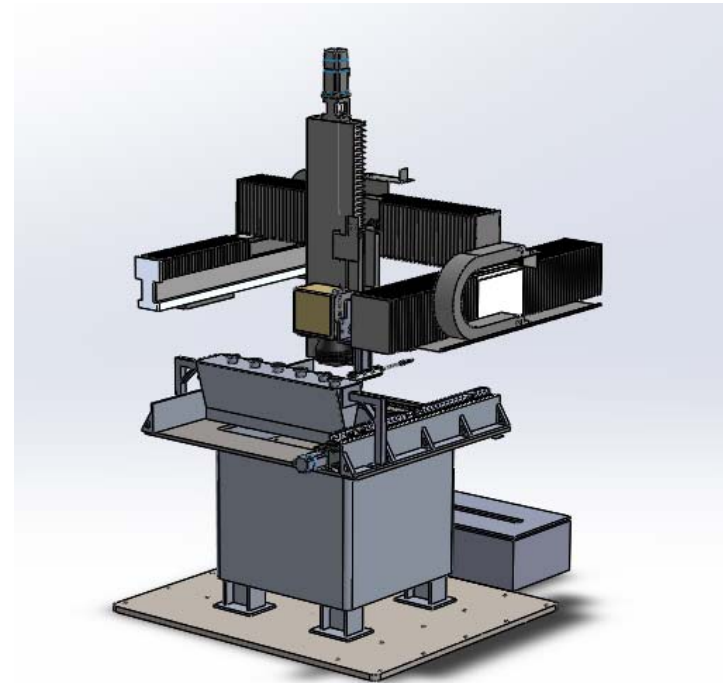
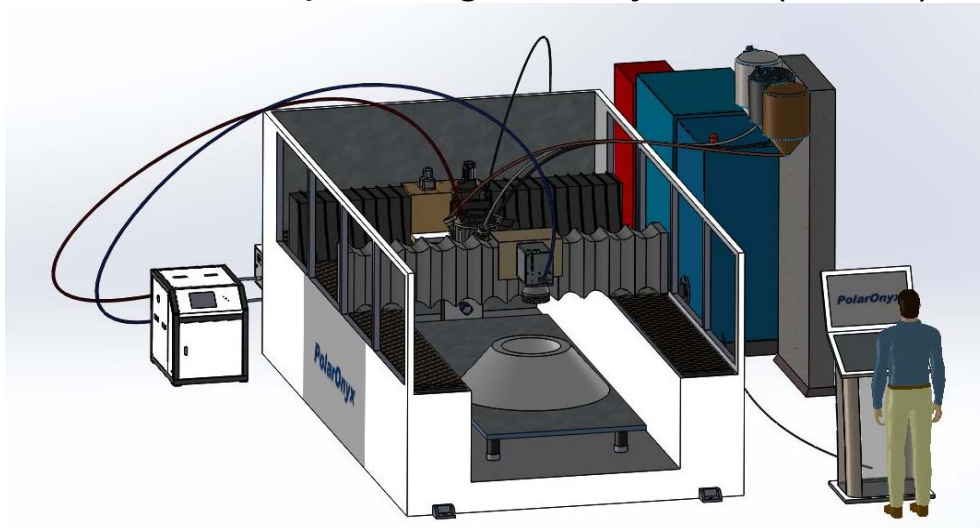
Outline

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SLAM System (600x600x600 mm)

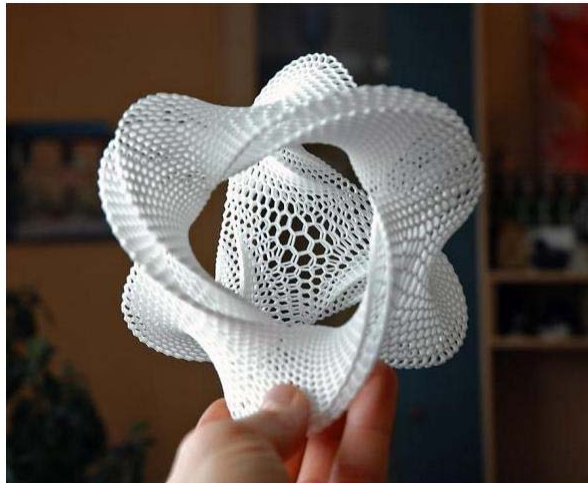
System development capability is essential to make high quality AM parts

Super Large AM system (SLAM)



Finished design stage and negotiating with vendors.

Thank You Very Much!



The future is in our hand!

Welcome to visit us in Silicon Valley!

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