NORTHERN ILLINOIS UNIVERSITY

College of Engineering and Engineering Technology

Bridging Theory With Practice.

Additive Manufacturing in the Aviation Industry

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College of Engineering & Engineering Technology

DMDII ROCKFORD CHAPTER

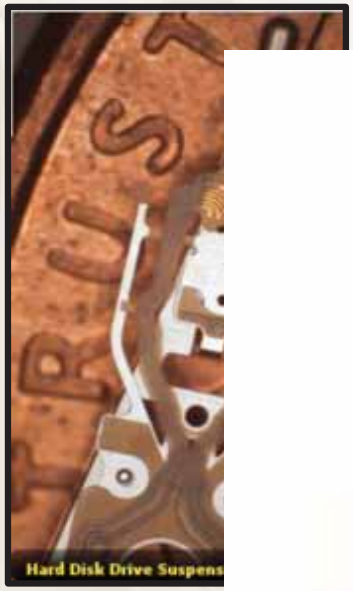
NORTHERN ILLINOIS UNIVERSITY EIGERlab Innovation Network

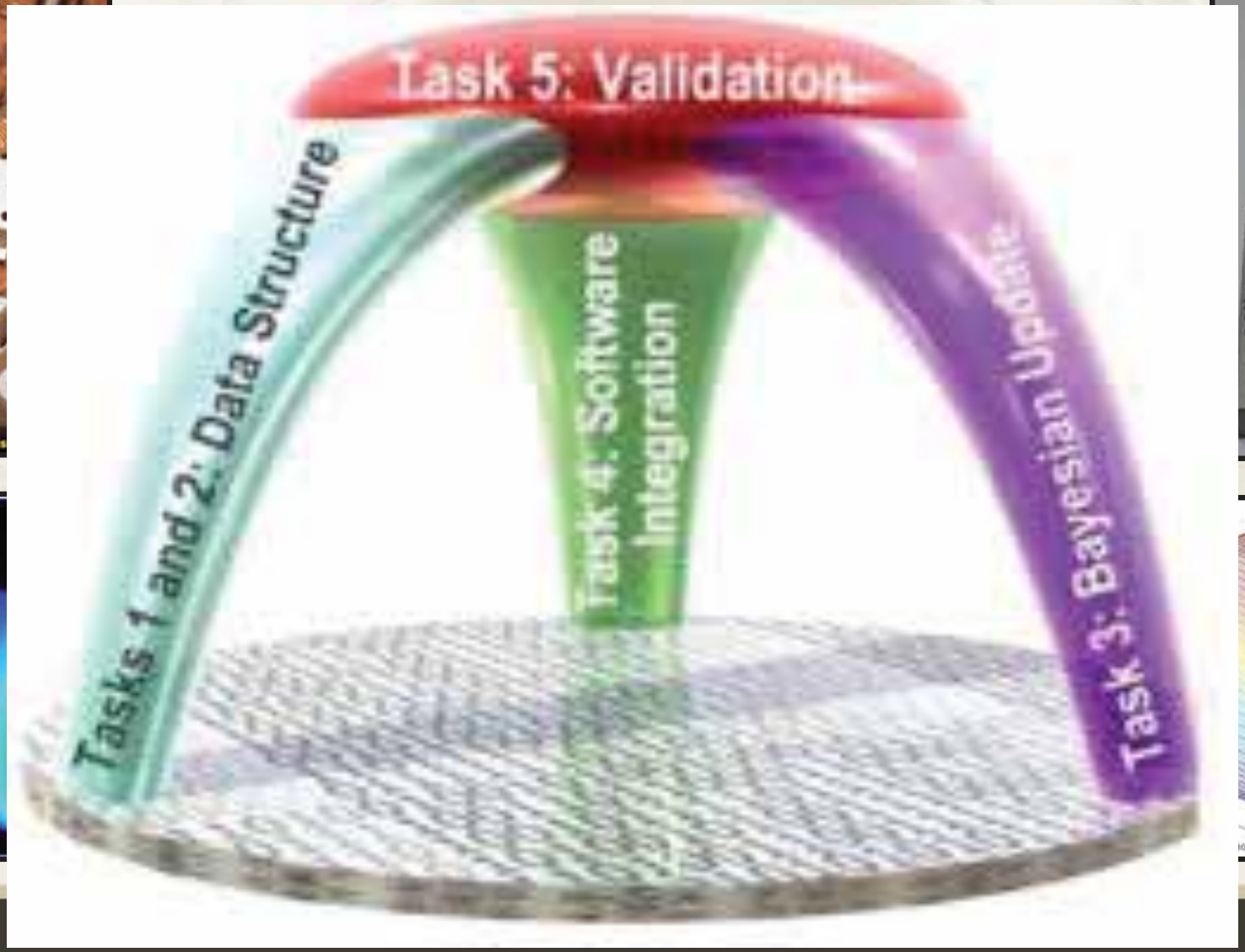
Innovation, Acceleration and Product Development

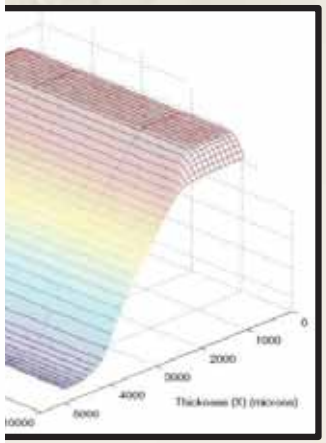
America Makes

National Additive Manufacturing Innovation Institute

DMDII Project Vision for Rapid Process Certification and Verification for High-Value-Added and Low-Volume Production







Seven forms of Additive Manufacturing

Additive manufacturing technologies

TECHNOLOGY	MATERIALS	TYPICAL MARKETS	RELEVANCE FOR METAL
Powder bed fusion – Thermal energy selectively fuses regions of a powder bed	Metals, polymers	Prototyping, direct part	●
Directed energy deposition – Focused thermal energy is used to fuse materials by melting as the material is deposited	Metals	Direct part, repair	◑
Sheet lamination – Sheets of material are bonded to form an object	Metals, paper	Prototyping, direct part	◔
Binder jetting – Liquid bonding agent is selectively deposited to join powder material	Metals, polymers, foundry sand	Prototyping, direct part, casting molds	◔
Material jetting – Droplets of build material are selectively deposited	Polymers, waxes	Prototyping, casting patterns	○
Material extrusion – Material are selectively dispensed through a nozzle or orifice	Polymers	Prototyping	○
Vat photopolymerization – Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Photopolymers	Prototyping	○

AM technologies for metal objects

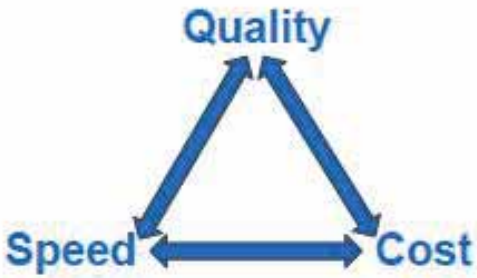
Slide source: Roland Berger

AM Pays When:

1. Conventional methods fail
   - Buy-to-fly ratio is high
   - Too thin or intricate to cast, machine, or forge
2. Assemblies can be replaced with single parts
3. Tooling costs are not acceptable
   - Required quantities are low
   - Time is critical
   - Each part is different

Additive Manufacturing
Value Proposition

- Considerations
  - Application / Material Properties
  - Part Quality
  - Lead Time
  - Production Volume / Quantity
  - Part Cost
  - Tooling Cost



FDM	SLS	Rapid Cast	Billet	Production Cast
Lead Time - 8 hours	Lead Time - 3 Days	Lead Time - 4 weeks	Lead Time - 4 weeks	Lead Time - 2 Months
Cost - $50	Cost - $2500	Cost - $2000	Cost - $1500	Cost - $5

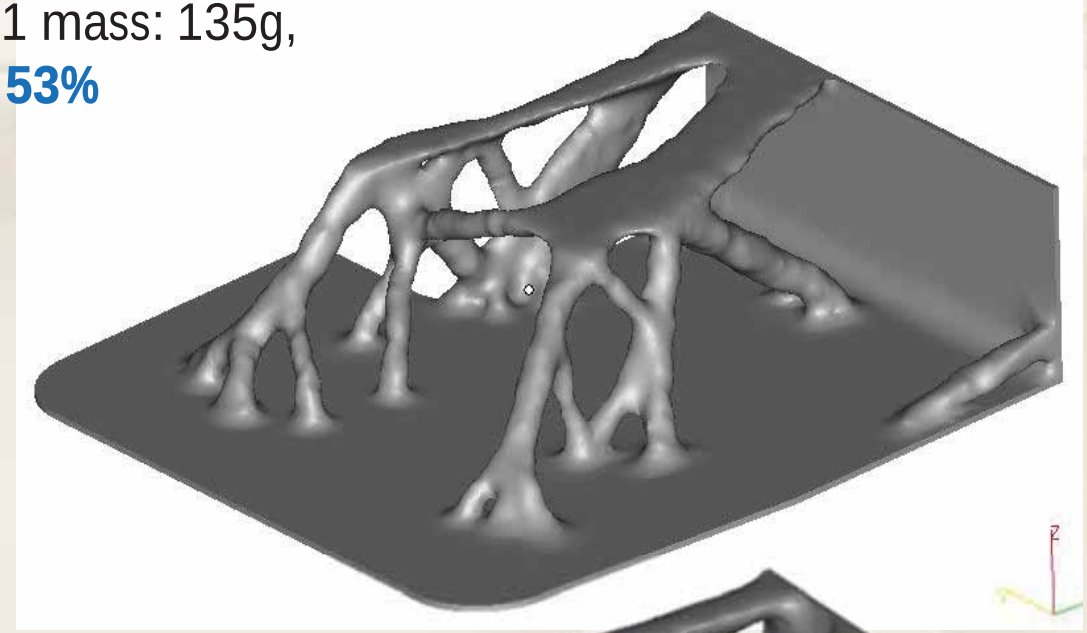
Lead Time

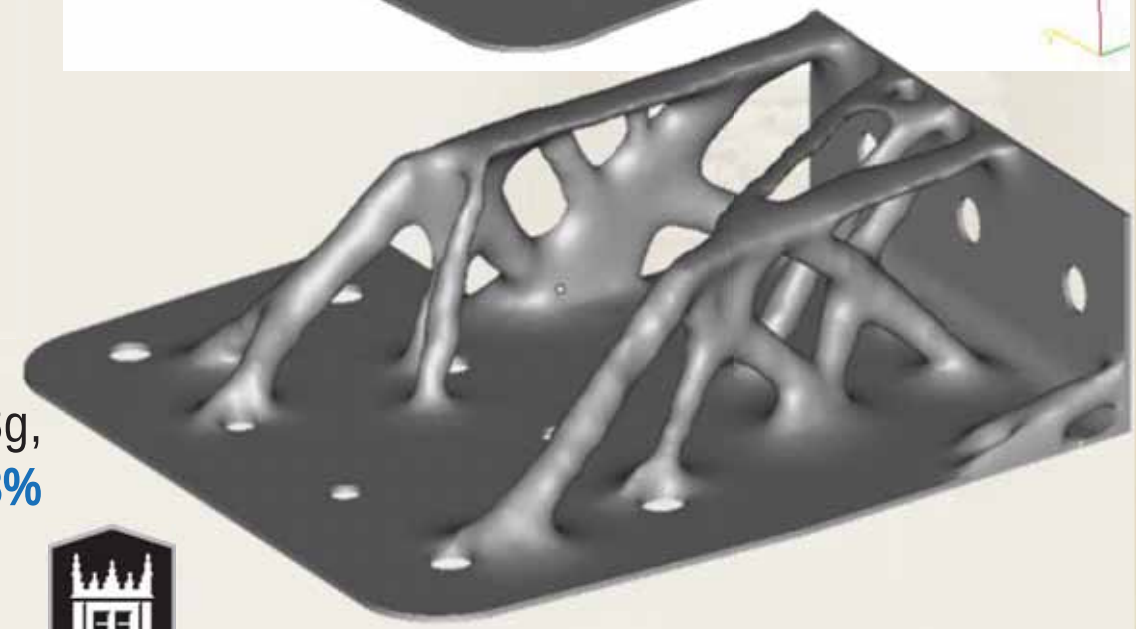
Cost

The Additive Manufacturing Advantage

Optimised 1 mass: 135g,
reduction: 53%

Original
mass: 285g

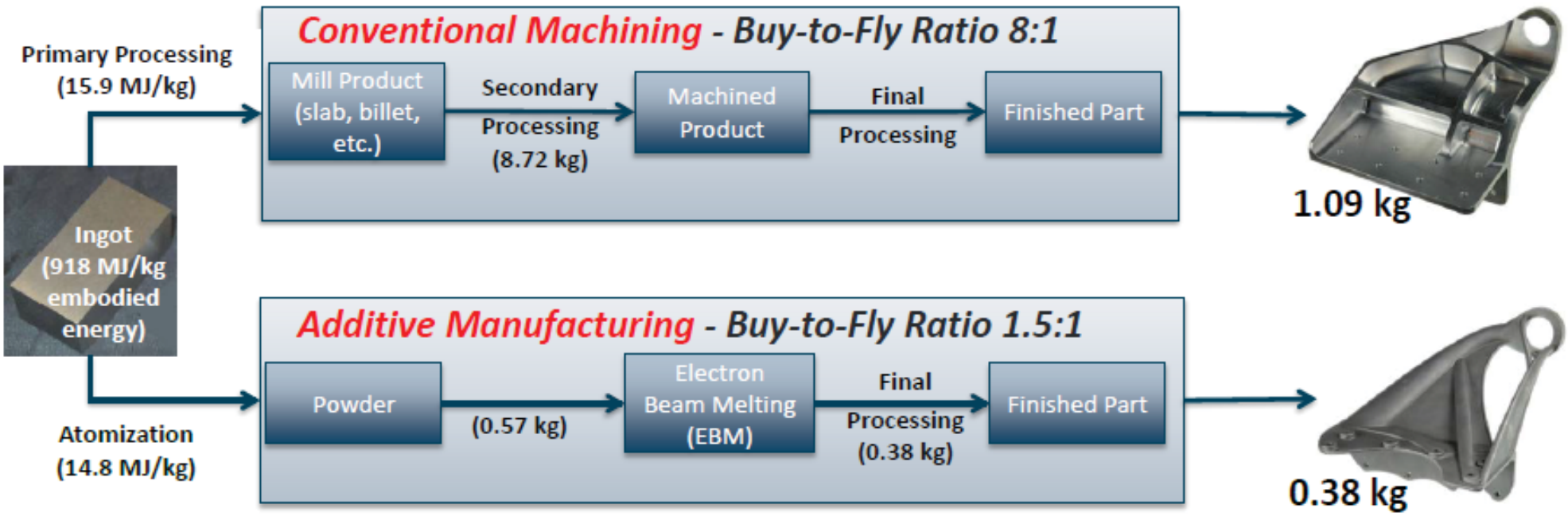




Optimised 2 mass: 148g,
reduction: 48%

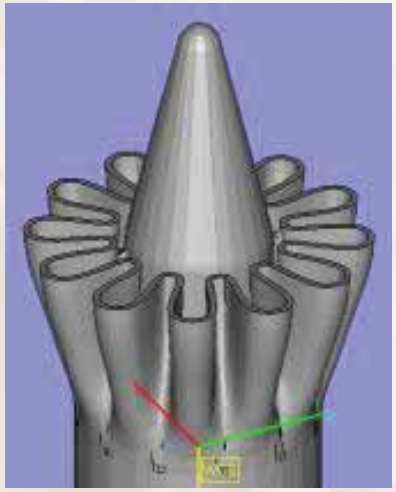
Courtesy: Boeing work done at
Univ. Of Nottingham

Higher performance parts: Ex. Aircraft Bracket



Process	Final part (kg)	Ingot consumed (kg)	Raw mat'l (MJ)	Manuf (MJ)	Transport (MJ)	Use phase (MJ)	Total energy per bracket (MJ)
Machining	1.09	8.72	8,003	952	41	217,949	226,945
EBM (Optimized)	0.38	0.57	525	115	14	76,282	76,937

Current AM Technology



- 3D CAD model
- STL file
- “slicing” of STL file
- Tool path generation

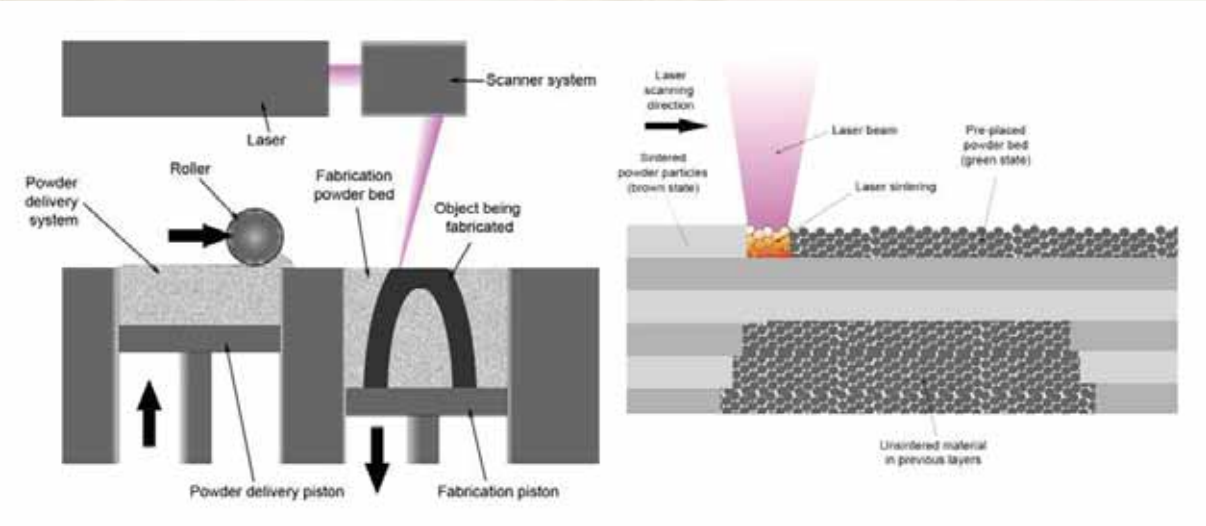
AM System

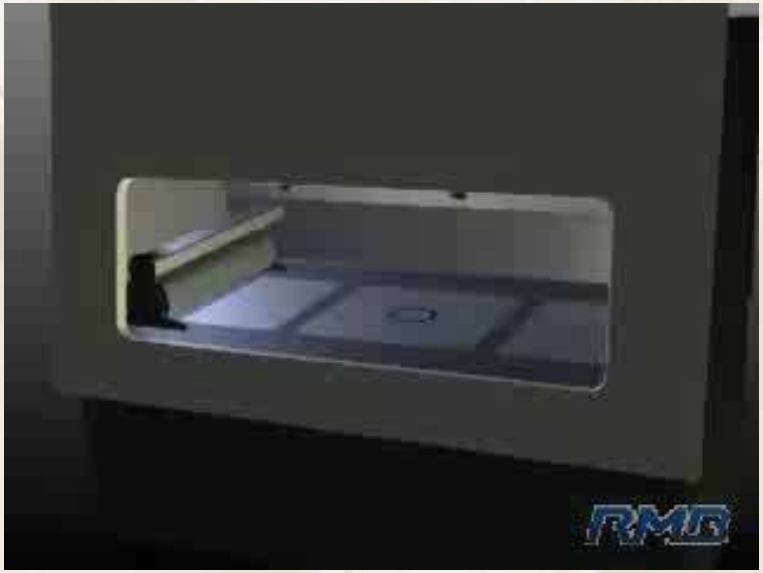
Powder

Comparison of DED and PBF

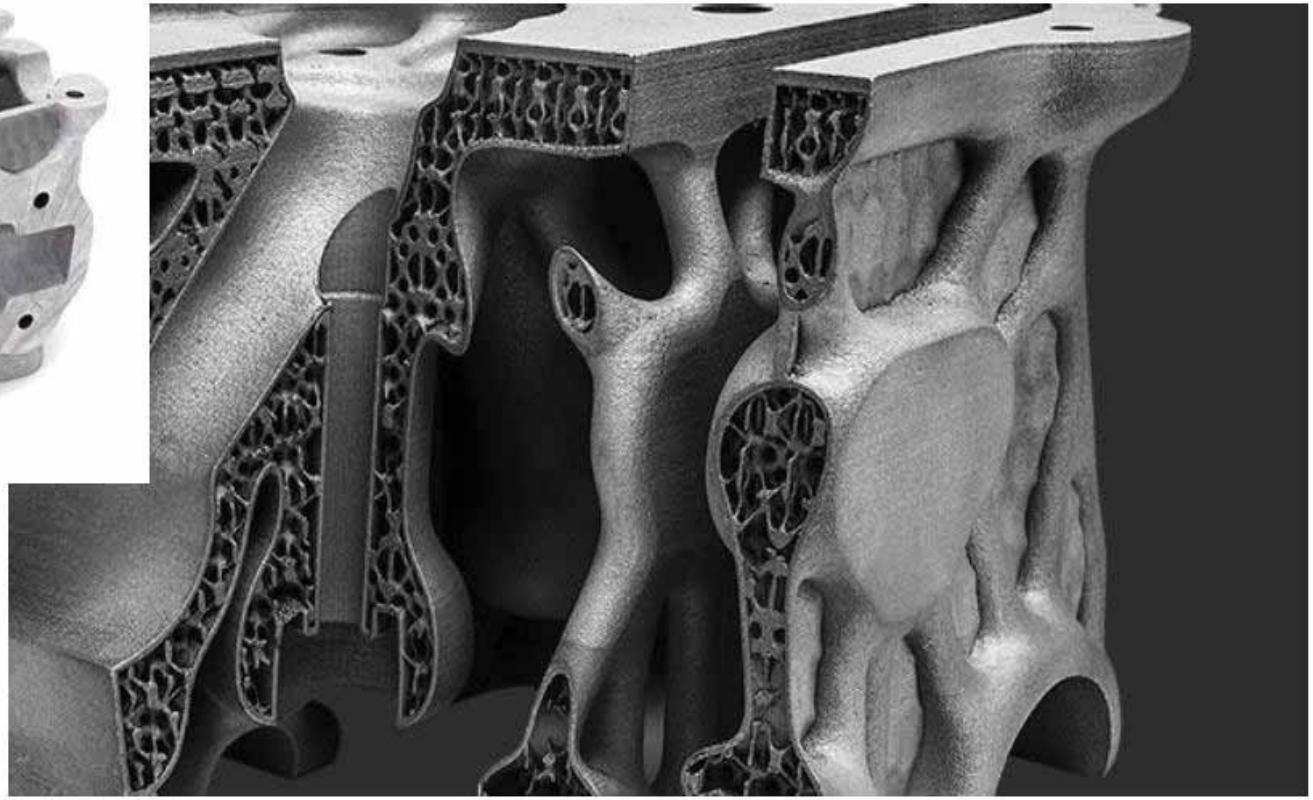
Criteria	Laser PBF	Laser DED
Materials	Limited and lower experience compared to DED (typically controlled by OEM)	Large diversity of materials/ also capabe of creating new materials (i.e. FGM)
Part Complexity	Nearly unlimited	Limited
Builds on	flat surfaces	3D surfaces & existing parts
Layer Thickness	>0.1-1mm	>0.03-0.1 mm
Build speed	5-20 cm^3/hr (~40-160 g/hr)	~ 70 cm^3/hr (up to 0.5 kg/hr)
Accuracy	(+/-) 0.02-0.05 mm per 25mm	(+/-) 0.125-0.25 mm per 25mm
Detail capability	0.04 - 0.2 mm	0.5 - 1.0 mm
Surface finish	Ra 4-10 μm	Ra 7-20 μm
Max. Part size	500 mm × 280 mm × 325 mm	2,000 mm × 1,500 mm × 750 mm
Avergae Price	$560,000-$750,000	$630,000-$950,000

Selective Laser Sintering/Melting (PBF)





- Thin powder layer is spread over build platform
- Laser beam scans over area corresponding to first STL cross section of part
- Powder layer in scanned area is fused onto build platform
- Thin powder layer is spread over first fused layer
- Laser beam scans over second STL cross section and fuses to first layer
- Process is repeated until all STL cross sections have been processed and the part is complete.



Images from FIT production GmbH

TRADITIONAL DESIGN

Source: SAVING project

- A conventional steel buckle weights 155 g[1)]
- Weight should be reduced on a like-for-like basis within the SAVING project
- Project partners are Plunkett Associates, Crucible Industrial Design, EOS, 3T PRD, Simpleware, Delcam, University of Exeter

AM OPTIMIZED DESIGN

Source: SAVING project

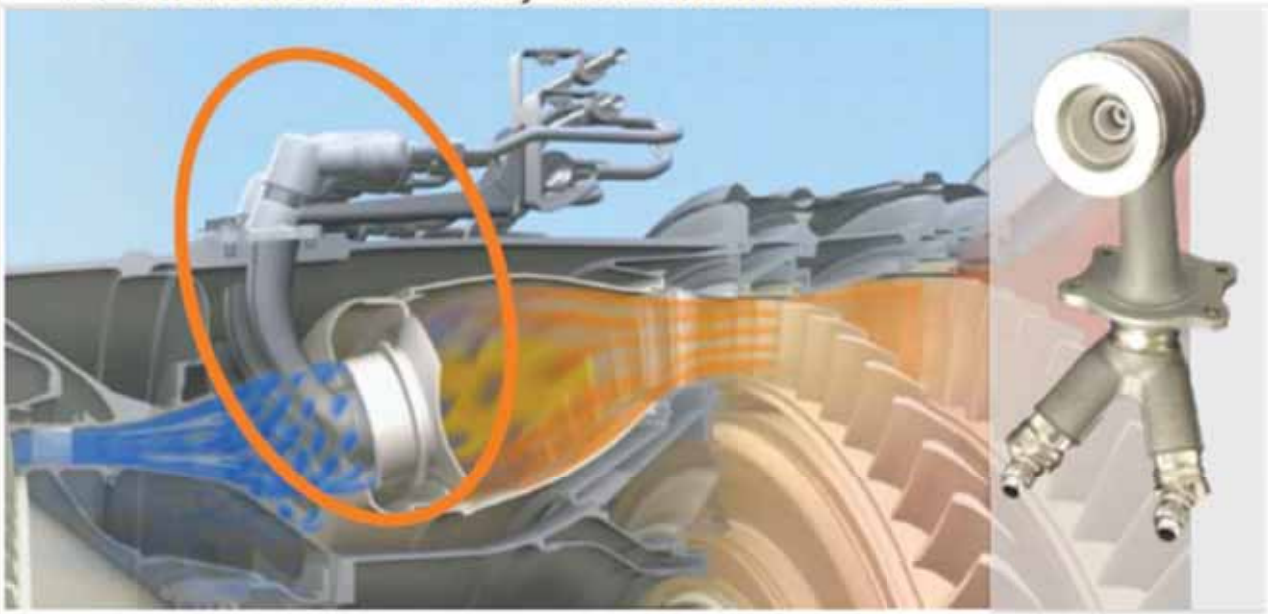
- Titanium buckle designed with AM weighs 70 g – reduction of 55%
- For an Airbus 380 with all economy seating (853 seats), this would mean a reduction of 72.5 kg
- Over the airplane's lifetime, 3.3 million liters of fuel or approx. EUR 2 m could be saved, assuming a saving of 45,000 liters per kg and airplane lifetime

1) 120 g when made of aluminum

Slide source: Roland Berger

GE Aviation .. First Production Parts

- LEAP/9X Fuel nozzle – from 25 braze joints to 5 joints
- 5X durability & 25% lower weight
- 50% reduction in NOx
- 19-20 parts/engine ... 100K+ parts by 2020
- New topology that was previously impossible
- Consolidation of assemblies into single parts: 20 to 1
- Frees constraints imposed by traditional processes
- Production facility in Auburn-AL

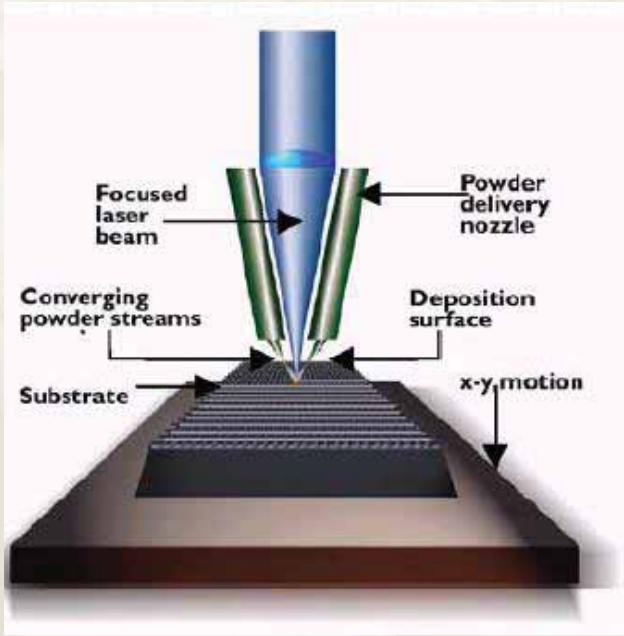


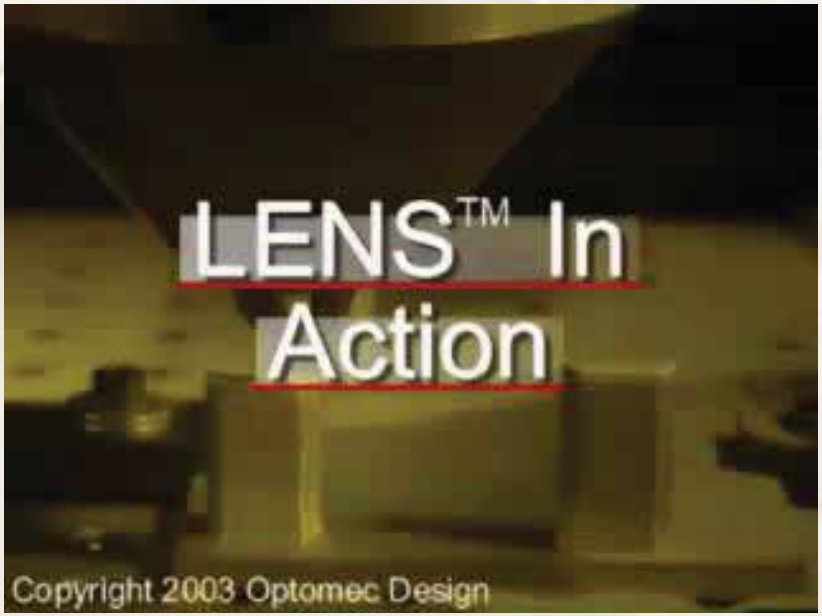
"I need very complex shapes. I need shapes that a machine tool cannot generate."

-Joshua Mook, Lead Engineer GE Aviation

https://www.asme.org/engineering-topics/media/aerospace-defense/video-printing-high-performance-fuel-nozzle. Photo credit: GE Aviation

Direct Energy Deposition





DED employs the same process fundamentals as laser cladding:

- Powder is fed with a nozzle into a laser generated melt pool.
- Melt pool is translated to follow a tool path covering the 2D area corresponding to the required cross section from the STL file.
- The molten powder re-solidifies as the melt pool follows the tool path.
- This process is repeated for each cross section of the STL file until the part is completed.

commercial technologies for maintenance activities – CTMA

ITEM #1
Third (3rd) Stage Turbine Rotor

ITEM #2
Fourth (4th) Stage Turbine Rotor

ITEM #3
Second (2nd) Stage Nozzle

ITEM #4
Compressor Stator 1st L.P.

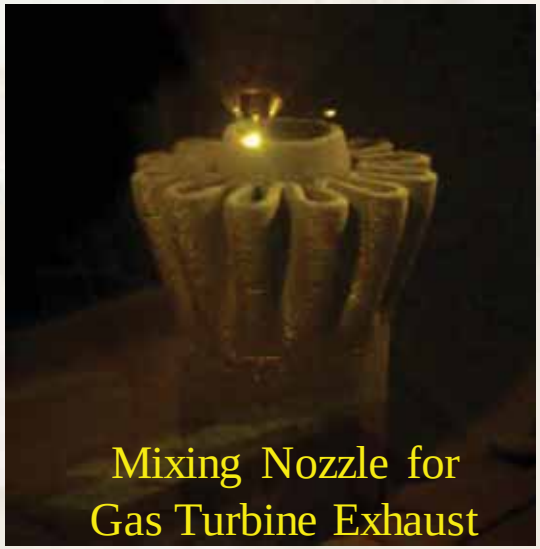
LASER ENGINEERED NET SHAPING (LENS) - PER YEAR COST SAVINGS

ITEM	PART	MATERIAL	PART NUMBER	NEW PART COST	ESTIMATED REPAIR COST	SAVINGS PER PART	PARTS REPAIRED PER YEAR	SAVINGS PER YEAR
1	Third (3rd) Stage Turbine Rotor	M3610C/Inconel 713LC	12271565	$ 8,297	$ 2,000	$ 6,297	230	$ 1,448,416
2	Fourth (4th) Stage Turbine Rotor	M3610C/Inconel 713LC	12281566	$ 5,485	$ 2,000	$ 3,485	230	$ 801,529
3	Second (2nd) Stage Nozzle	M3602/Inconel 713C	12286886	$ 6,032	$ 2,250	$ 3,782	600	$ 2,269,140
4	Compressor Stators (H.P. and L.P.)							
	1st L.P.	AMS 5510/321 Stainless	12302430	$ 910	$ 300	$ 610	175	$ 106,759
	2nd L.P.	AMS 5510/321 Stainless	12286149	$ 1,170	$ 300	$ 870	175	$ 152,264
	3rd L.P.	AMS 5510/321 Stainless	12302480	$ 610	$ 300	$ 310	175	$ 54,304
	4th L.P.	AMS 5510/321 Stainless	12286161	$ 611	$ 300	$ 311	175	$ 54,495
	5th L.P.	AMS 5510/321 Stainless	12302429	$ 701	$ 300	$ 401	175	$ 70,091
	1st H.P.	AMS 5504/410 Stainless	12286257	$ 604	$ 300	$ 304	175	$ 53,155
	2nd H.P.	AMS 5504/410 Stainless	12286261	$ 1,188	$ 300	$ 888	175	$ 155,377
	3rd H.P.	AMS 5504/410 Stainless	12286266	$ 575	$ 300	$ 275	175	$ 48,038
	4th H.P.	AMS 5504/410 Stainless	12286568	$ 1,893	$ 300	$ 1,593	175	$ 278,782
5	Fourth (4th) Stage Seal Runner	AMS 5662/Inconel 718	122[illegible]	$ 319	$ 200	$ 119	600	$ 71,268
				$ 28,395	**$ 9,150**	**$ 19,245**	**3,235**	**$ 5,563,617**

Bell Helicopter Engine Test

Unmanned Combat Armed Rotorcraft

CAD FILE



LENS FAB

LENS PART

Time required for producing a casting: 9 weeks.
LENS part delivered in 3 weeks (Build time 8 hours)

- 1/6th scale **Ti6Al4V** mixing nozzle for gas turbine exhaust.
- Used in a small turbine engine for a benchtop demo of the new PATS anti-torque system.
- Survived extremely high temperatures in airflow demo.

Primary Success Driver for Above Application

Faster - Better Material Properties - Lower Cost

Aeroswift
1st generation HSLA – PBF system

AEROSUD INNOVATION & TRAINING CENTRE

CSIR our future through science

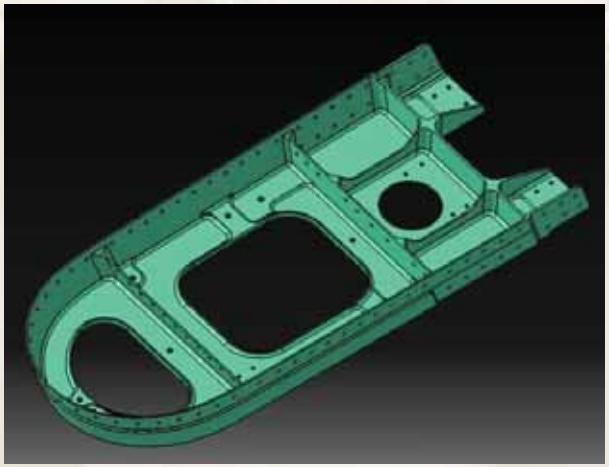
science & technology
Department: Science and Technology
REPUBLIC OF SOUTH AFRICA

The aim is to create the first ever large scale additive manufacturing systems that are locally produced to create full scale components for the aerospace industry.

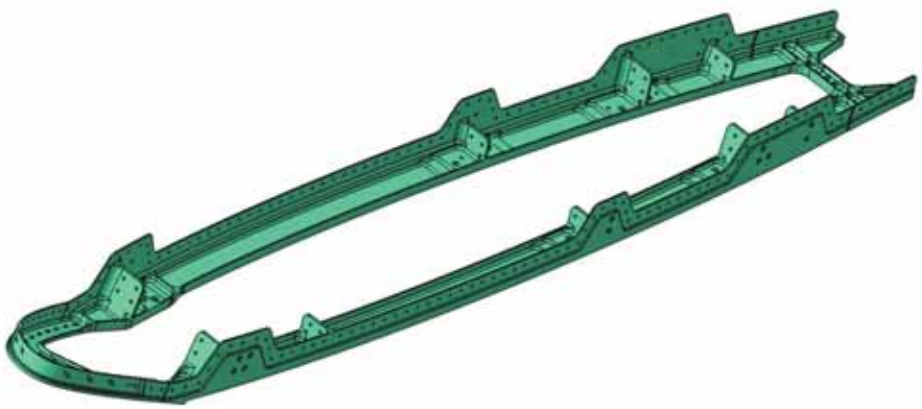
NIU

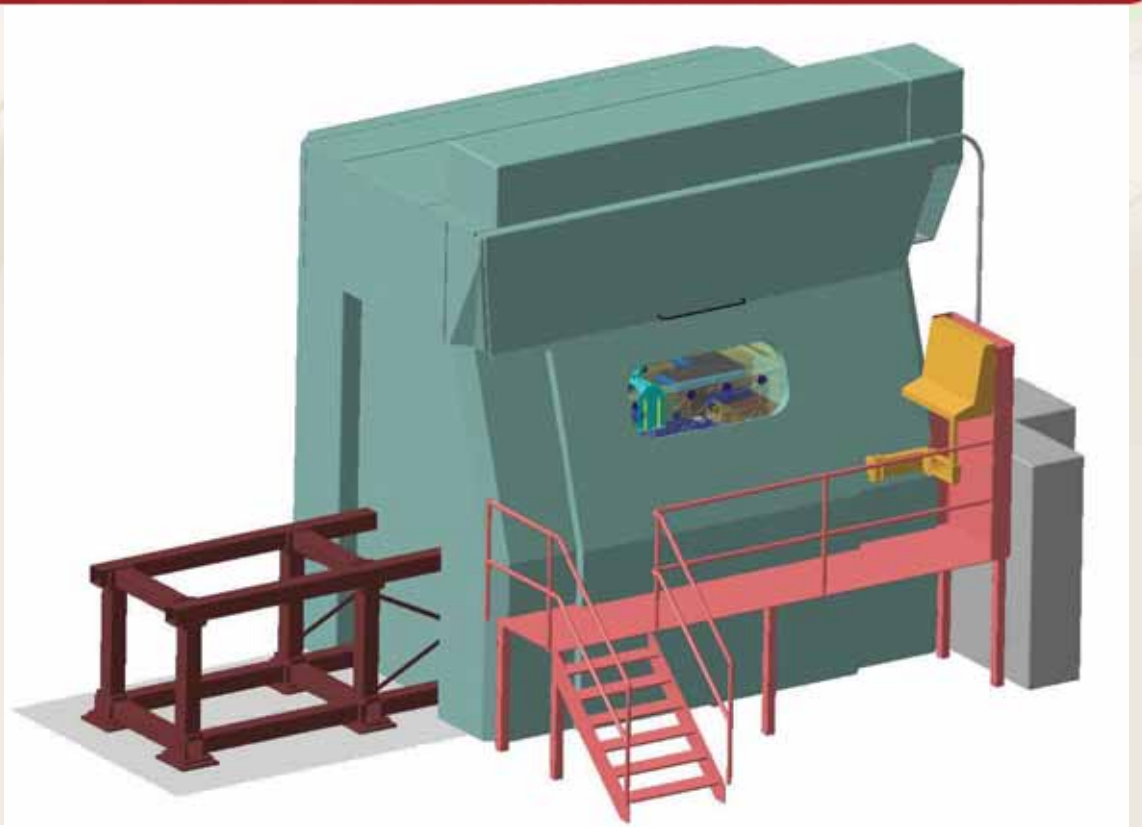
AEROSWIFT IMPACT

A400M – wingtip
610 × 220 × 70 mm



A400M – wingtip
1860 × 340 × 107 mm





AeroSwift status

- Phase 1: **Machine design and construction** completed
  - Commissioning in progress

- Phase 2: Process development and optimization started.
  - Machine testing, evaluation and optimization
  - Parameter testing and optimization
  - Milestone: Flight ready demonstrator part end 2017

- Process development achievements
  - Consolidation rates up to 60mm^3 /sec demonstrated
  - Low sample porosity (0.5% and lower)

AEROSWIFT IMPACT – First parts created



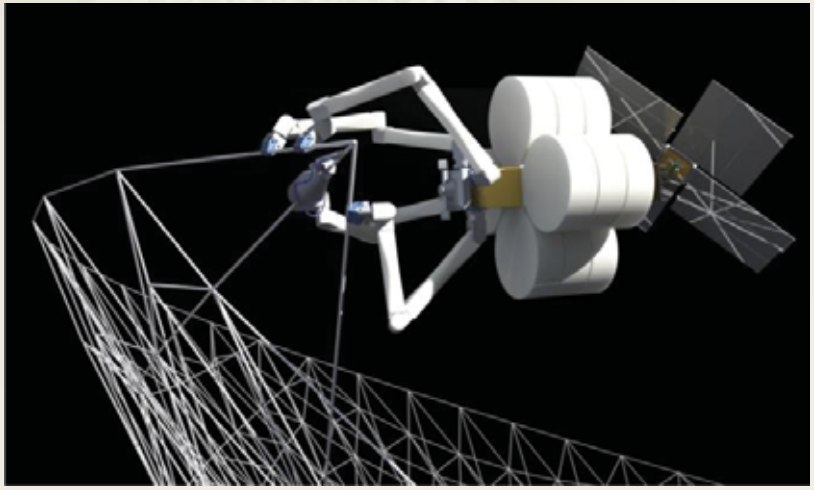


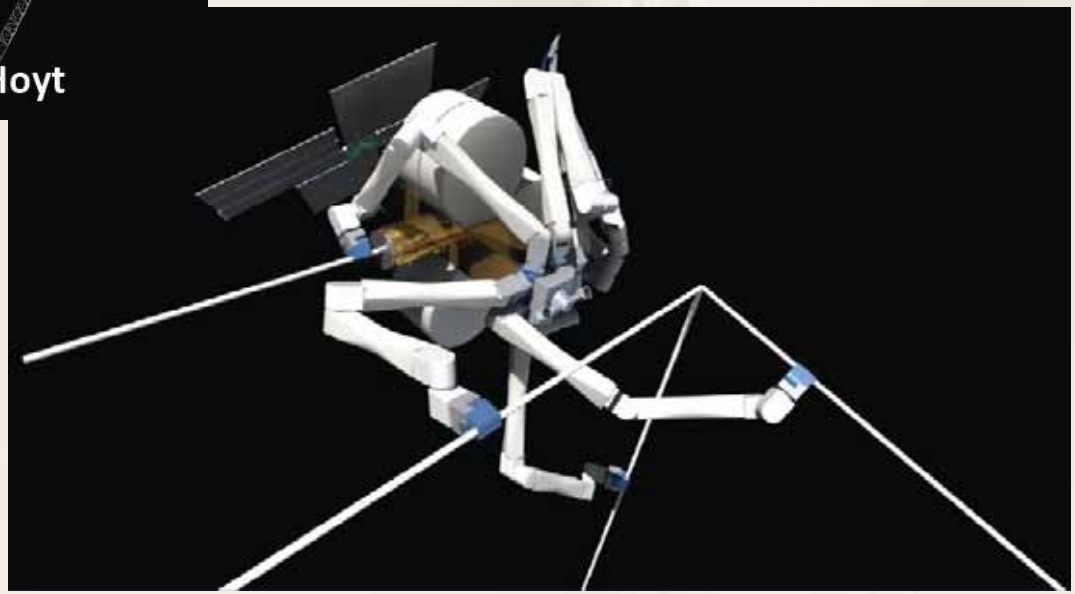

Above: Test part for Aerospace customer

Below: Part for Advanced High Performance Reconnaissance Light Aircraft

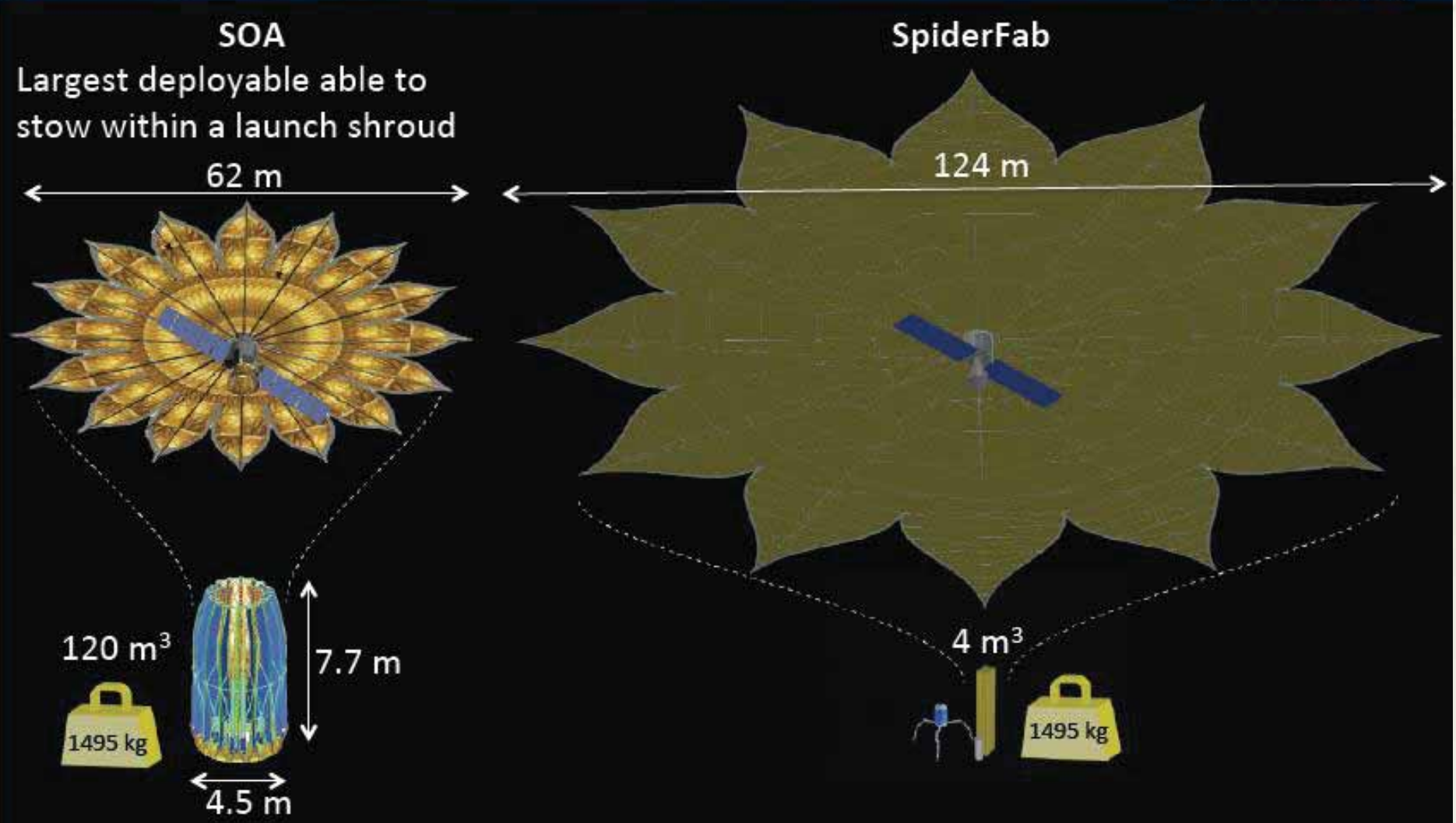
On orbit printing!

www.tethers.com





Make it BIGGER



- **On-orbit fabrication enables 2X larger starshade with 1/30 stowed volume and same mass**

DMDII Project Vision for Rapid Process Certification and Verification for High-Value-Added and Low-Volume Production

Establishing a foundation for rapidly certifying manufacturing processes using physics-based simulation tools and real-time sensors integrated by the efficient Bayesian update framework

Three missing capabilities in this regard:

- A unified material data structure and process data structure
  - Providing a seamless link between material and process modules
- An adaptive Bayesian inference algorithm
  - Considering uncertainties in physics-based computational models
- A direct integrated framework
  - Developing an efficient computational method in order to update material microstructural and mechanical properties real-time

Methodology

This project can be divided into five technical tasks:

- **Task 1**: Digital material structure
- **Task 2:** Digital process structure
- **Task 3:** Low-volume certification methodology
- **Task 4:** Simulation software integration
- **Task 5:** Verification and validation

Figure 1: Foundation of the Verification Framework

Task 1: Digital Material Structure

(QuesTek 60%, Northwestern 25%, NIU 10%, PDA 5%)

Developing a digital thread for materials based on microstructure and thermo-mechanical properties for improved predictive capability, including heat transfer, thermo-dynamics and particle movements.

Data structure should be dynamic and flexible, and links with common inputs such as forms of material (powder or bulk) and implicit time-, temperature- and rate-dependent behaviors.

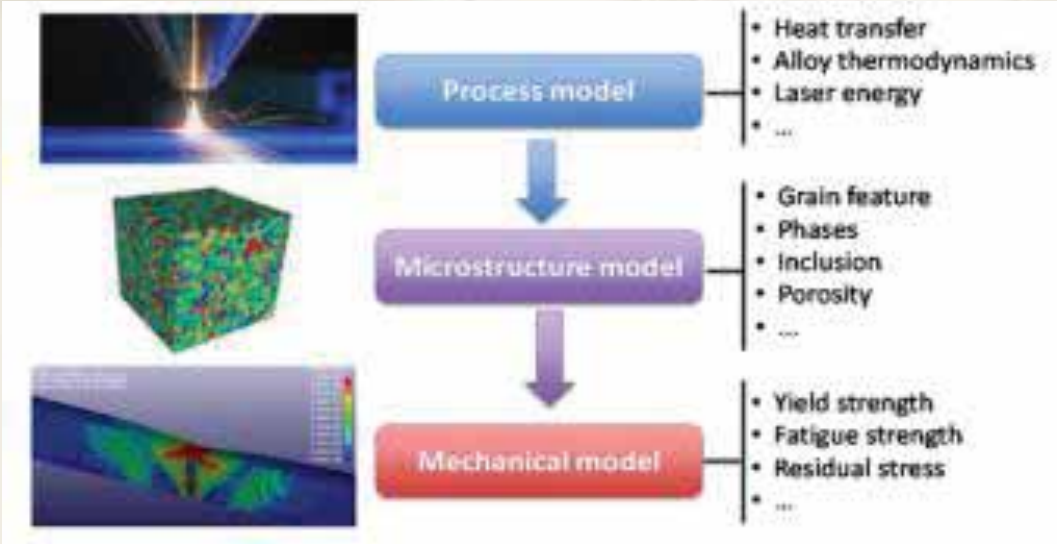


Figure 3: Relationship among different models in the virtual manufacturing framework

Task 2: Process Data Structure

(Northwestern 60%, NIU 20%, Siemens 10%, PDA 10%)

Provides a volumetric-based model powered by a process data structure capable of:

I. Dynamically generate analysis information
II. Store experimental information
III. Encode microstructural information of the product obtained from the digital material structure and in-situ sensors

Octree voxels is being used in order to selectively refine the voxel size, and thus to reduce the memory usage by the data structure.

GPUs are being used to dynamically generate the data structure required for the thermal analysis and mechanical-behavior prediction with reduced computation time for real-time control in the proposed verification framework.

Task 3: Certification Methodology

(Northwestern 80%, PDA 10%, Siemens 10%)

In this task, we apply an adaptive Bayesian inference technique for efficient and cost-effective identification of key unknown parameters in the material model.

The spatial random process models will be constructed as surrogates for the expensive simulation models.

Markov Chain Monte Carlo and Gaussian process approaches is being proposed for this purpose.

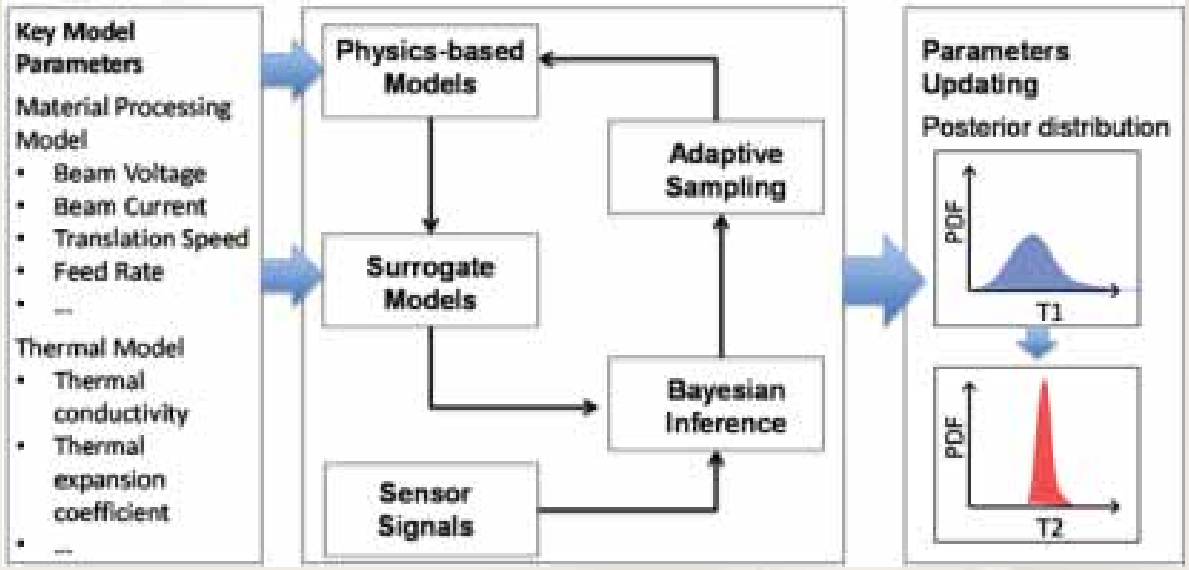


Figure 4: Adaptive Bayesian inference framework

Task 4: Simulation Software Integration

(Siemens 60%, Northwestern 20%, PDA 10%, QuesTek 10%)

This task creates a software framework to integrate together the different components needed to perform virtual validation of manufacturing processes and to facilitate the flow of information from overall input parameters to resulting properties of the manufactured part.

It will be kept generic with respect to manufacturing processes.

An interface with NX software will be developed.

Compatibility with simulators for other processes, such as casting (PDA) and forming (NU), will be considered.

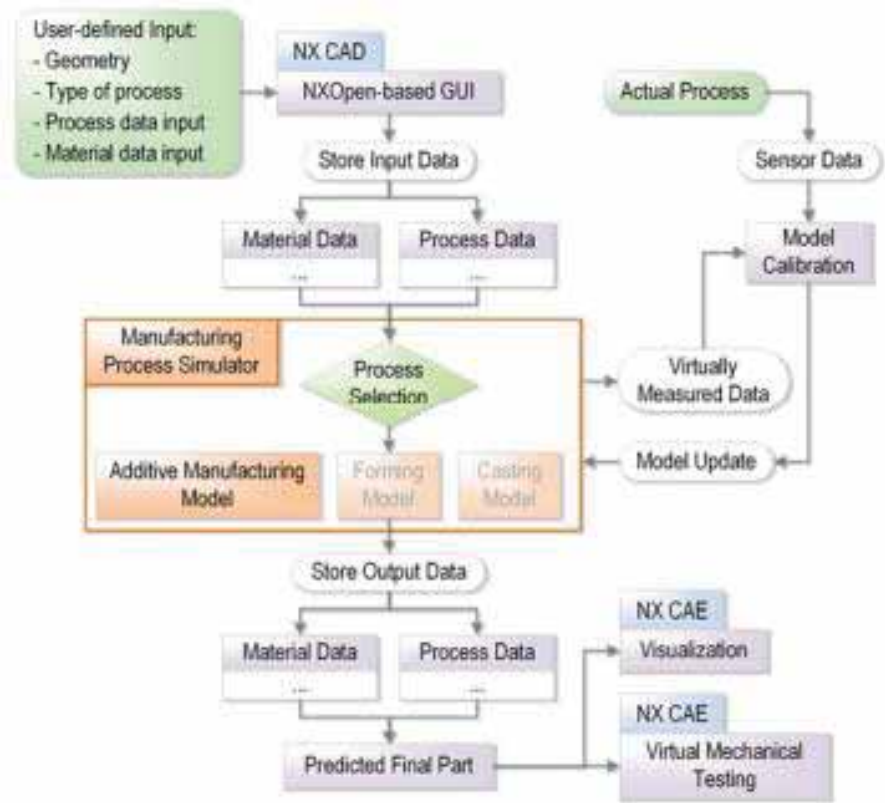


Figure 5: Structure of the proposed software framework

Task 5: Verification and Validation

(NIU 45%, NU 25%, Siemens 15%, PDA 10%, QuesTek 5%)

Validation samples with be fabricated in NIU AM laboratory using LENS. NIU will use a specified tool path history on a calibration test sample geometry designed for extraction of mechanical test coupons (by EDM) to calibration of the process model. This task include three subtasks:

- Design AM Property QA Witness
- Build Tool Path Design for AM QA Witness
- Validation and Certification

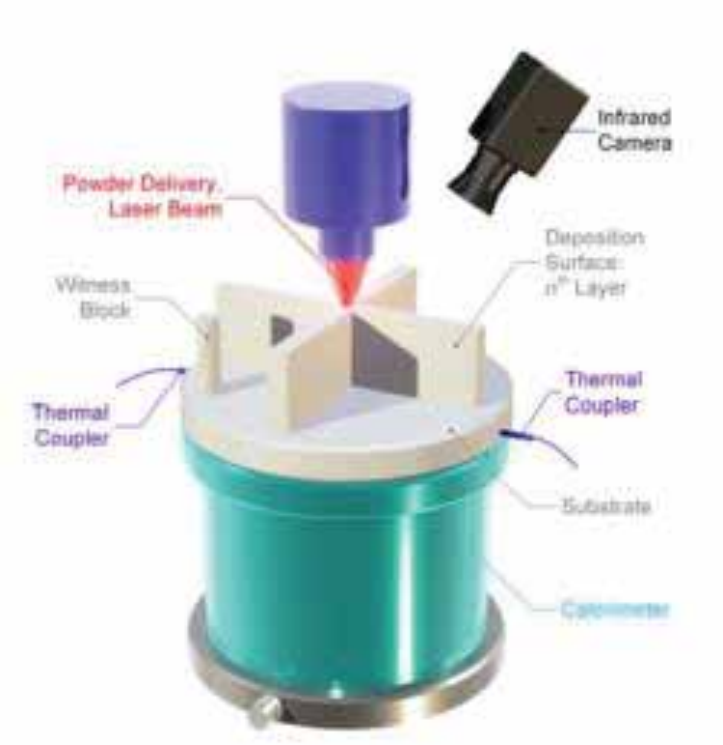


Figure 6: AM with in-situ sensing systems and sample parts