# The Latest Advances and Opportunities in Additive Manufacturing for Aerospace

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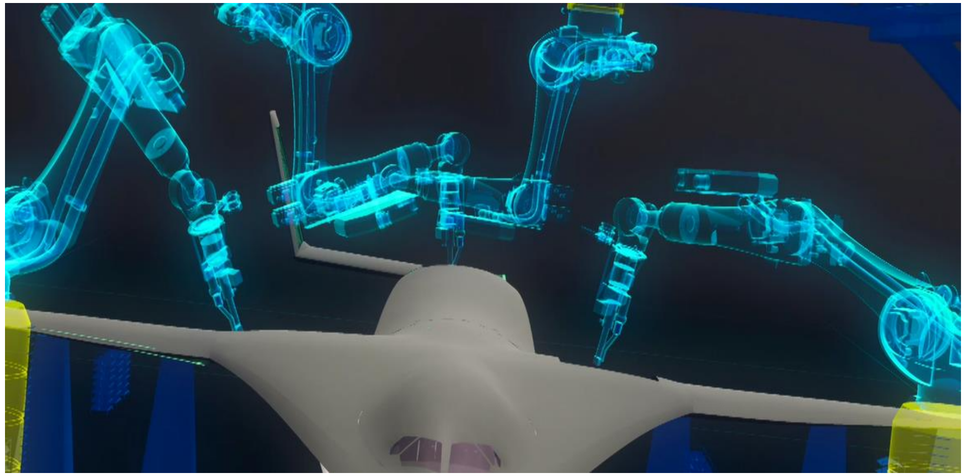
# Introduction

- **Product Launch**
  - Research and Development
  - Engineering Development
  - Manufacturing Demonstration
  - Product Case Studies
  - Transition and Adoption
- **Manufacturing Technology Transitions**
  - Titanium Propellant Tanks
  - Multi-Robotic Additive Clusters
  - Large Polymer Additive Manufacturing
  - APEX Thermoplastic Nanocomposite
  - Orion Composite Fairing Tooling
  - Carbon Nanotube Structural Treatments
  - Other

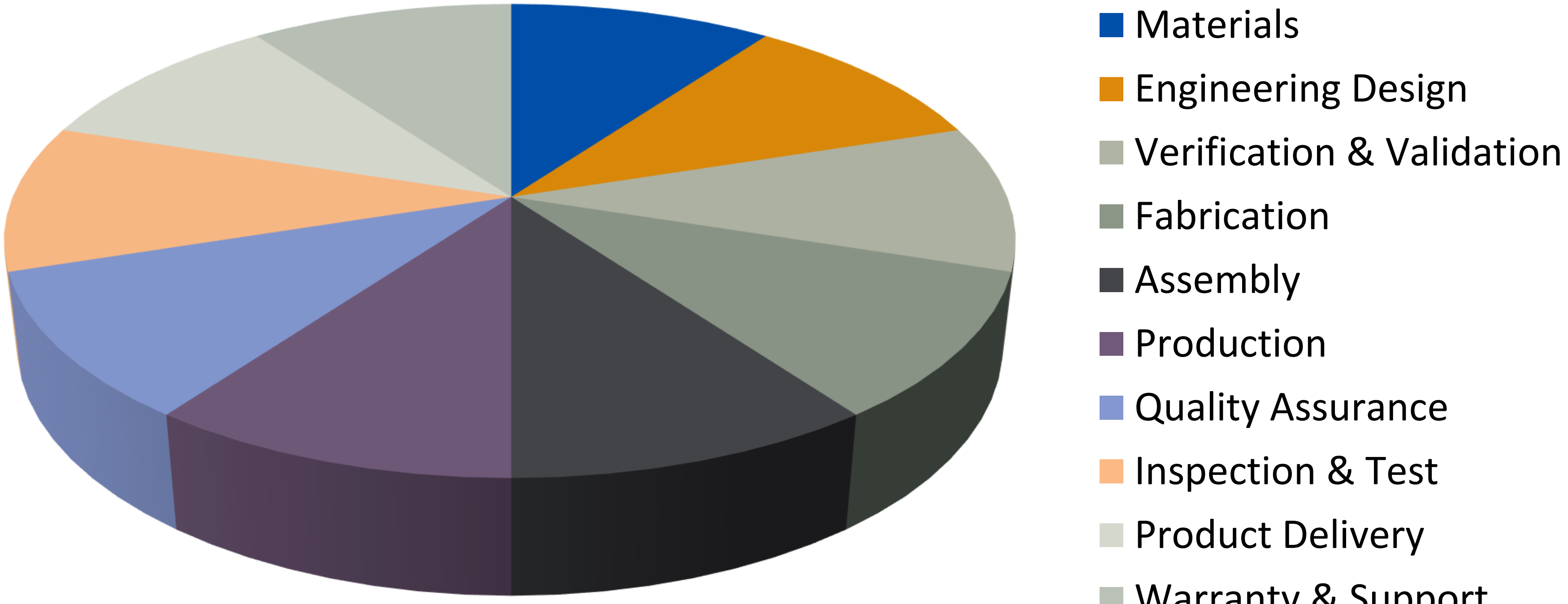

http://www.additivemanufacturing.media/articles/the-possibilities-of-electron-beam-additive-manufacturing



https://youtu.be/KyWuHcvyqD0

# Manufacturing Defined

- **Responsibilities and Requirements**
  - Cost, Schedule, Rate, Quality, Performance
  - Operations, Personnel, Equipment, Facilities
  - Commitments, Accountability, Relationships



# Juno Spacecraft Titanium Brackets

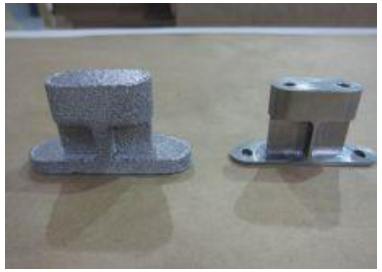
## NASA Juno Mission

- Science mission to Jupiter
- Launch Aug 5, 2011
- Arrive July 4, 2016
- 32 polar elliptical orbits
- Gravity map, magnetic fields and atmospheric composition

## Titanium Waveguide Brackets

- Powder bed additive manufacturing
- **50% cost savings (billet)**
- 50% schedule savings
- Confidence testing (equivalent)

http://www.additivemanufacturing.media/blog/post/additive-manufactured-components-reach-jupiter



http://www.techbriefs.com/component/content/article/ntb/tech-briefs/manufacturing-and-prototyping/18883

# Lockheed Martin Propellant Tanks

## Titanium Spacecraft Propellant Tanks

- High value product critical to satellite design
- Stores propellant for on board propulsion system
- 16 to 46 inch diameter

## Additive Manufacturing Impact

- **Lead time reduced to 2 weeks from 20 months**
- Cost reduced 50% from forging
- Design flexibility
- Capable of 59 inch diameter
- 50 test cycles at max expected pressure
- Failure above 200% design pressure

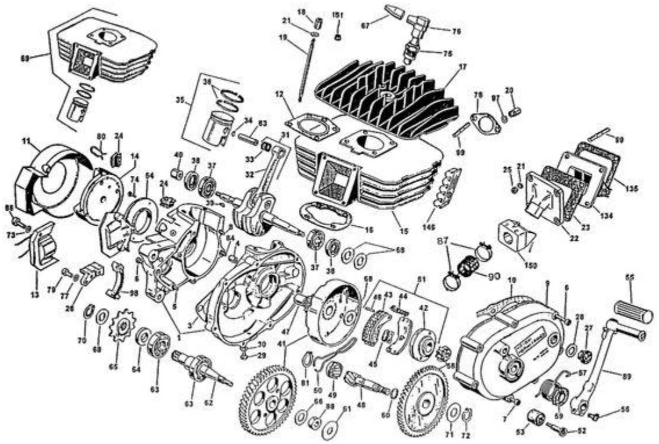

http://www.additivemanufacturing.media/articles/the-possibilities-of-electron-beam-additive-manufacturing

http://spacenews.com/lockheed-leaning-on-3-d-printing-to-bring-tank-work-in-house/
http://www.additivemanufacturing.media/articles/lockheed-martin-importance-of-closed-loop-control-in-am
https://3dprint.com/62099/lockheed-3d-print-fuel-tanks/
http://www.lockheedmartin.com/us/news/features/2015/by-the-numbers-3dprintingatlockheedmartin.html

# Traditional vs Disruptive Manufacturing

## Traditional = Sequential Operations

- Many Drawings
- Many Parts
- Many Fasteners
- Many Joints
- Intermediate Inspections
- Adjustments
- Dispositions



## Disruptive = Integrated & Unitized

- Solid Model of Complete Product
- Minimal Piece Parts
- Minimal Assembly Steps
- Digital Adjustment and Disposition

# GE LEAP Engine Fuel Nozzle

## Gas Turbine Engine Fuel Nozzle

- Flight critical, high thermal cyclic stress
- Cobalt chrome material
- Direct metal laser melting
- More than 40,000/year by 2018

## Benefits of the Leap Fuel Nozzle Design

- **Integration: Combining 20 piece parts into one**
- 5× life improvement of the fuel delivery system
- 25% weight reduction
- Further cost reductions as the design was optimized

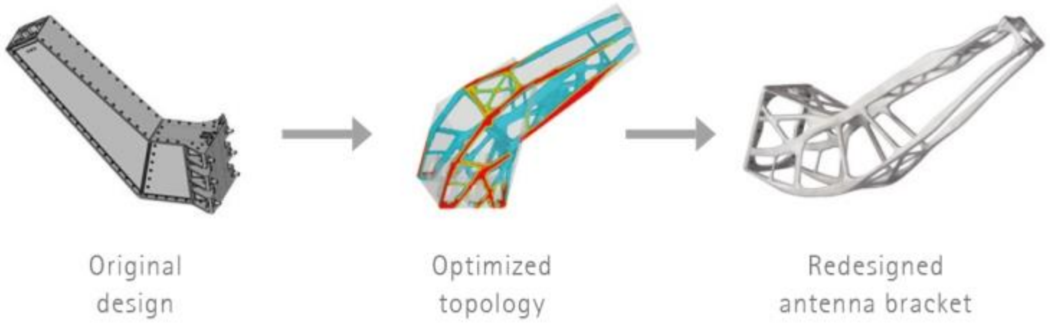
## High Volume Facility

- 300,000 sq ft, $125M in Auburn, AL
- Target 50 additive manufacturing machine capacity

http://www.industrial-lasers.com/articles/print/volume-28/issue-6/features/additive-manufacturing-at-ge-aviation.html

# RUAG Satellite Antenna Bracket

- **Antenna Bracket for RUAG's Sentinel Satellite**
  - € 20,000/kg cost of space payload
  - Lightweight design needed that addressed environment
    - Excessive vibration during launch
    - High G-forces
- **Optimized Design (video)**
  - Suitability and rigidity satisfied by aluminum alloy
  - **Weight reduction over 40%:** (940 g from 1.6 kg)
  - Minimum rigidity requirements exceeded by 30%
  - Uniform stress distribution




http://www.eos.info/case_studies/additive-manufacturing-of-antenna-bracket-for-satellite

# Aircraft Structural Brackets

## Airbus A320 Hinge Bracket

- **Design optimization**
- Streamlined lifecycle assessment
- Steel to titanium: 10kg savings per plane
- 40% $CO_2$ emissions reduction
- Improved manufacturing metrics
  - 25% reduction in material used
  - Reduced total energy consumption

## GE Bracket Design Contest

- Redesign jet engine loading brackets
- Global innovation challenge
- Reduce weight and fuel consumption
- Top 10 designs built and tested at GE

http://additivemanufacturing.com/2014/02/04/eos-and-airbus-team-on-aerospace-sustainability-study-for-industrial-3d-printing/

http://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/7095/DMLS-Leads-to-More-Sustainably-Manufactured-Metal-Parts.aspx

http://www.designfax.net/cms/dfx/opens/article-view-dfx.php?nid=4&bid=305&et=materials&pn=01

# Thermomechanical Components

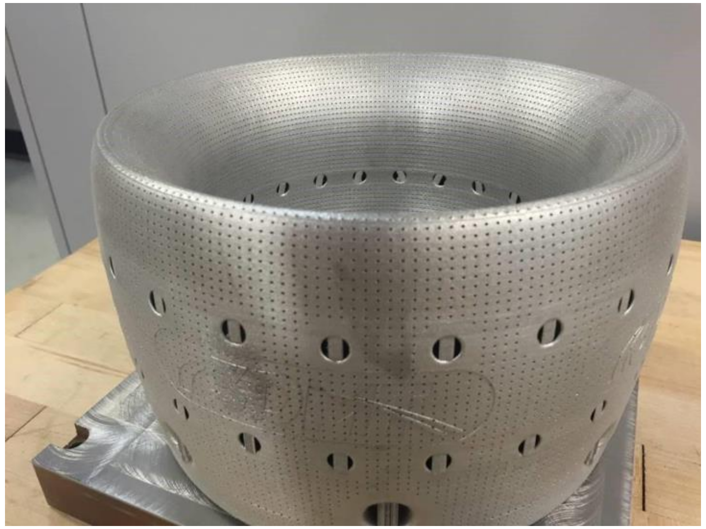
## Combustors and Nozzles

- Internal cooling flow passages
- Distributed thermal balance
- Optimizes mass and energy balance
- 3DMT Inconel 625 Combustor Liner
  - 102 Hour build
  - 1.5mm wall thickness
- EOS Nickel alloy jet engine combustor

## Tooling and Manifolds

- Improved cycle time for injection molds
- Reduced weight for cooling manifolds
- Improved energy efficiency and process

http://www.assemblymag.com/articles/93176-additive-manufacturing-takes-off-in-aerospace-industry



https://www.linkedin.com/company/3d-material-technologies-llc?trk=top_nav_home

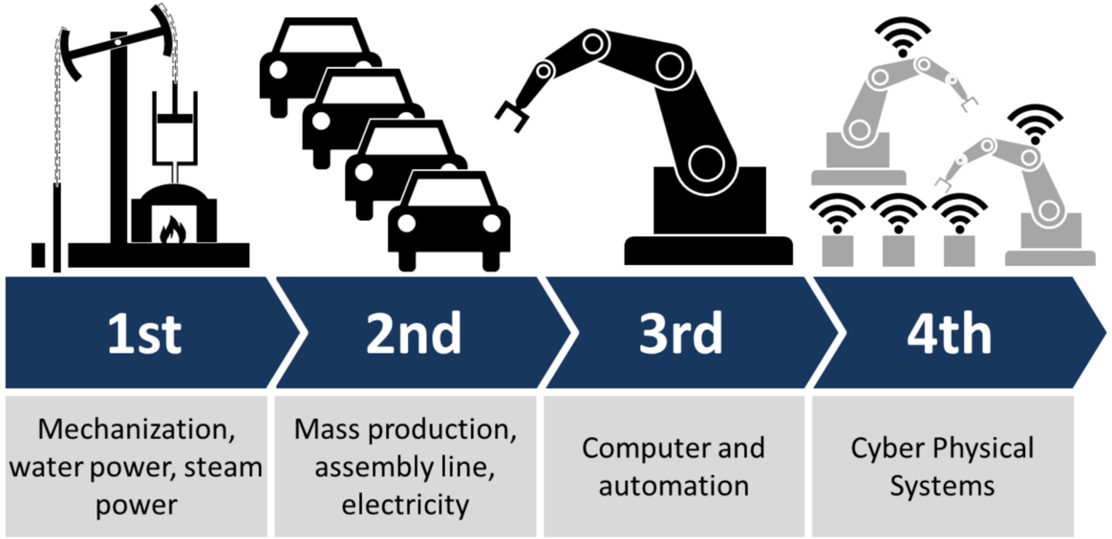
# Industry 4.0

## Trends and Expectations

- Automation and data exchange in manufacturing technologies
  - Cyber-physical systems & Industrial internet of things (IoT)
  - Cloud computing, big data and purposed networks
- Customization of products with highly flexible mass production
- Self-optimization, self-configuration, self-diagnosis, cognition and intelligent support of workers

## Principles of Implementation

- Interoperability (Industrial-IoT)
- Information transparency
  - Sensor ‘information’ from data
  - Augmented/Virtual Reality
- Technical assistance
- Decentralized decisions




Christoph Roser at AllAboutLean.com
https://commons.wikimedia.org/w/index.php?curid=47640595

# Digital Translations for Cyber-Physical Systems

## Visualization +

- 2D/3D Images
- Virtual and Augmented Reality
- Haptic Interaction Tools

## Physics Models

- Case Studies
- Operational Requirements
- Simulations
- Scenarios

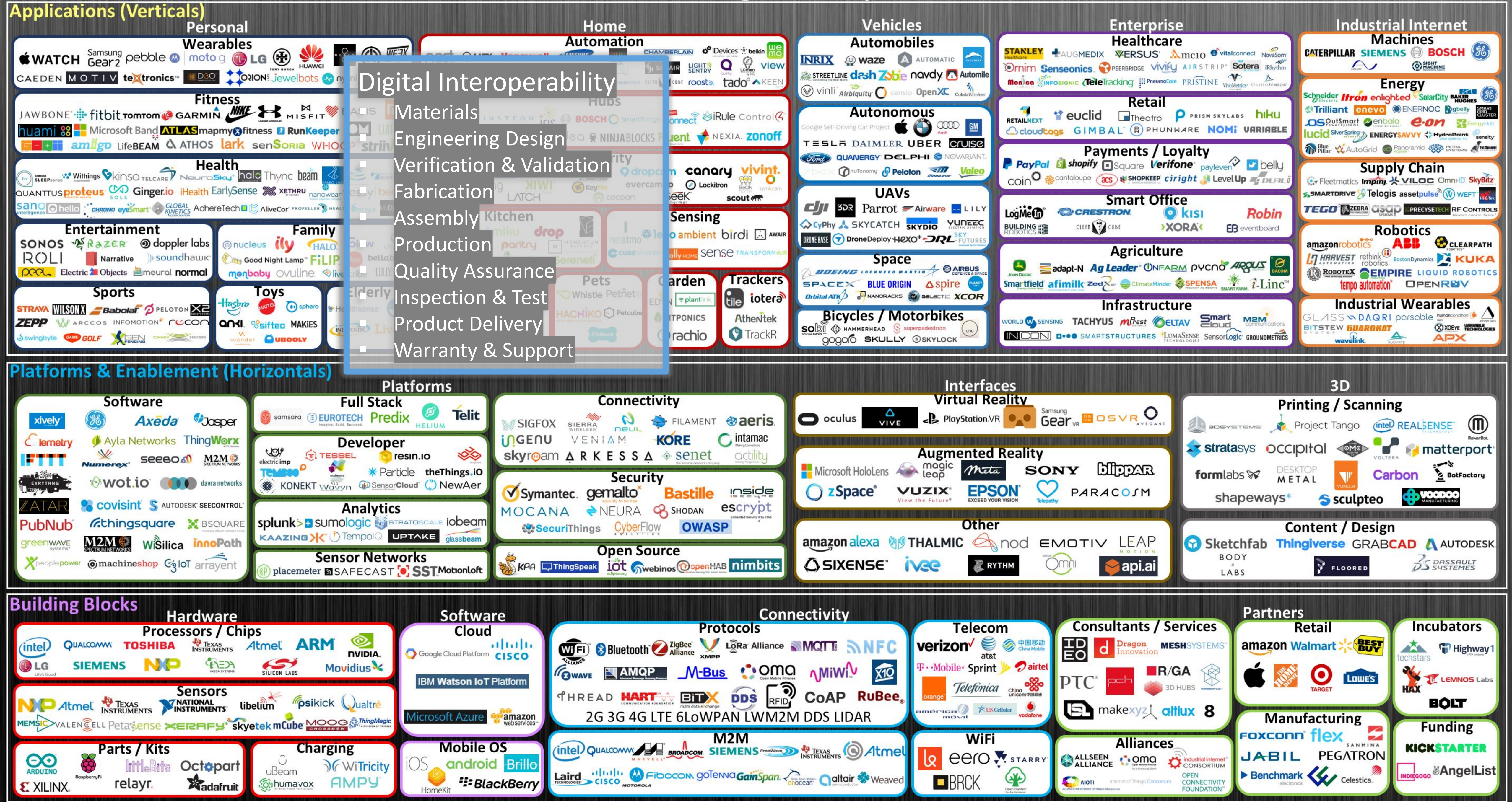
## Validation and Verification

- Model Results
- Measurements
- Comparisons

## Compatible Analytical Methods

- Contact Methods
  - Indentation
  - Abrasion
  - Scanning Probe
- Non-Contact Methods
  - Emission
  - Spectroscopy
  - Ultrasonic
- Material Augmentation for Analytical
  - Tracers/Markers
  - Indicators
- Impulse + Measurement
- Other

# Internet of Things Landscape 2016



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# Industry 4.0 AM Testbed

## Additive Manufacturing Design

- Enable next gen capabilities
  - Geometry, topography & integration
  - New analytical tools emerging
- New heuristics needed downstream

## Cyber-Physical Systems

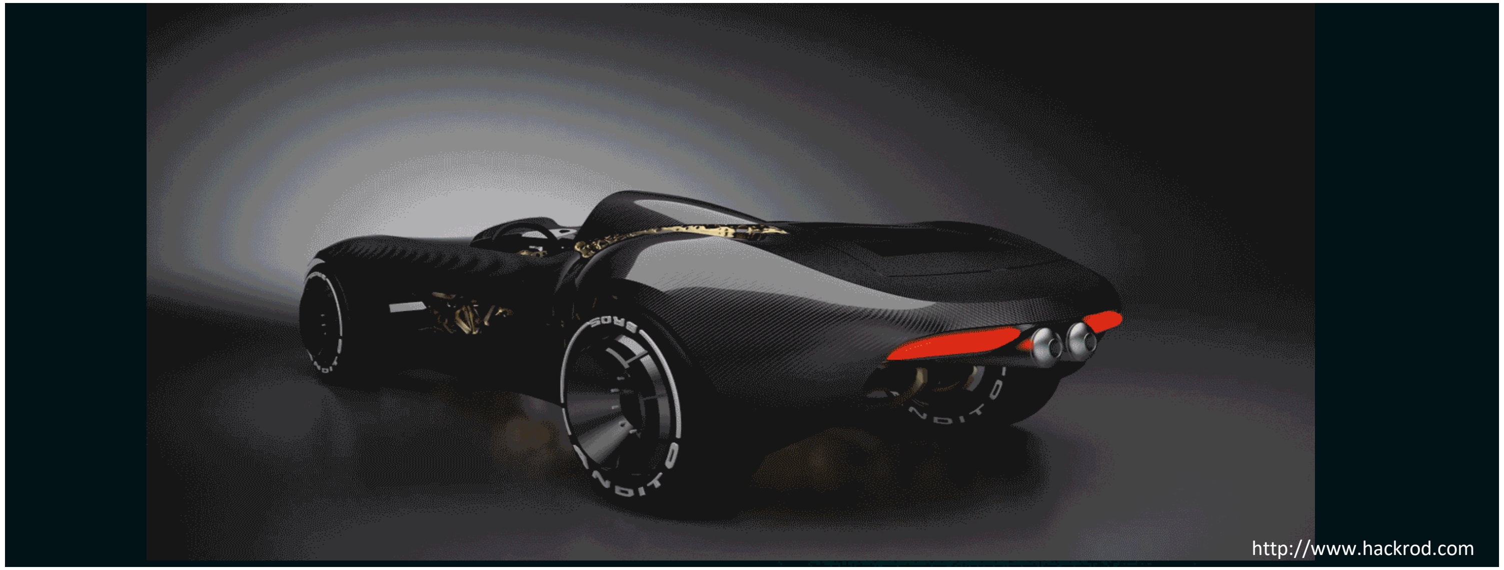
- Design networked with engineering
  - Augmented/Virtual reality
  - Artificial intelligence
  - Big data & cloud computing
- Engineering & manufacturing network
  - Sensor 'information' from data
  - High speed cloud computing
  - Intelligent multi-machine operations

http://www.engineering.com/AdvancedManufacturing/ArticleID/11039/VIDEO-Additive-Manufacturing-to-Revolutionize-Satellite-Aerospace-Design.aspx


https://twitter.com/LockheedMartin

# Hackrod

- **First Car Engineered with Artificial Intelligence**
  - Demonstrate cloud based software design solutions, distributed additive manufacturing and localized assembly (Industry 4.0)
  - Ripping reality, generative design, digital simulation
  - Bits to atoms – 3D print chassis and components
  - **Validate geometry prior to short production runs**



# Big Metal Additive

- **Addressing Gap in Manufacturing Capability**
  - **Rapid design verification of generative design**
  - Large scale wire fed metal additive manufacturing
  - Multi-robotic process for complex geometries
  - Current focus on aluminum structures
  - Flexible process minimizing operating economics
- **Scale and Complexity**
  - Auto chassis 5 x 18ft
  - Lattice configuration with many nodes
  - Optimize weight based on performance
  - Vision to incorporate Industry 4.0 philosophy
  - Long term target is aerospace

http://www.hackrod.com/

# Robotic Composite 3D Demonstrator

http://blog.stratasys.com/2016/08/24/infinite-build-robotic-composite-3d-demonstrator/


## Stratasys and Siemens shared vision

Siemens' Motion Control Hardware and PLM Software

Stratasys Advanced Extrusion Technologies

## Designed to revolutionize the 3D printing of composite parts

Delivers true 3D printing

8-axis motion system enables precise, directional material placement

reducing dramatically the need for speed-hindering support strategies

Redefines how future lightweight parts will be built

"We view the level of factory integration, automation and performance monitoring potentially offered by these new demonstrators as catalysts for the transformation to Industry 4.0." Ilan Levin, CEO, Stratasys.

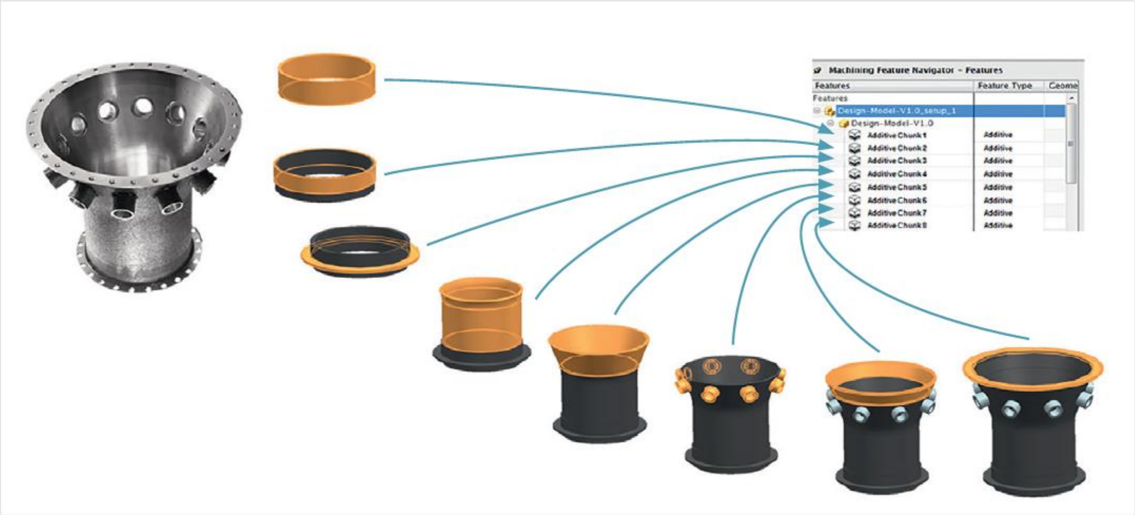
# Siemens NX
# Additive Manufacturing

**Benefits**

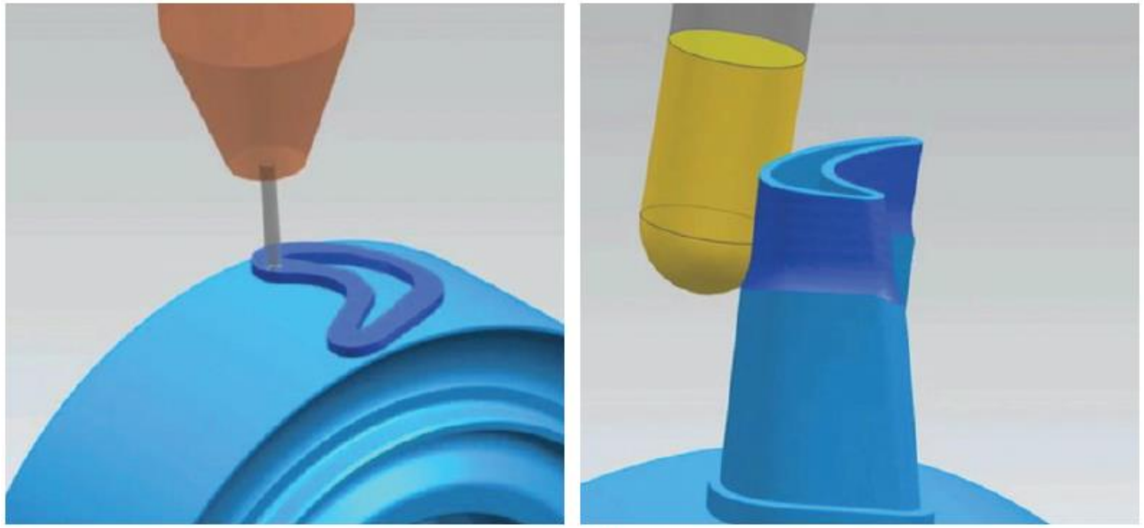
- Enable new designs
- Machine internal areas during build
- Repair parts easily
- Tightly control tolerance during build
- Produce finished parts on one machine

**Features**

- Feature decomposition for different build vectors
- New additive CAM operations
- Support for DMG MORI Lasertec Hybrid machines




*Automatic and semiautomatic decomposition of parts into features for additive/subtractive operations definition.*



*In-process workpiece and verification works for both additive and subtractive modes.*

http://www.plm.automation.siemens.com/en_us/products/nx/for-manufacturing/cam/hybrid-additive-manufacturing.shtml#lightview-close

# Big Picture Manufacturing Compatibility

Combine Multiple Materials

| | | |
|---|---|---|
| Metal | Polymer / Composite | Ceramics |
| Joints | Interfaces | Transitions |

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Provide for Many Manufacturing Operations

| | | | |
|---|---|---|---|
| Assembly | Joining | Bonding | Embedding |
| Wire | Cable | Plumbing | Fixtures |

Facilitate Process Monitoring and Inspection

| | |
|---|---|
| Sensing Data | Converted to Information |
| Digital Translations | Cyber-Physical |
| Industrial IoT | |

http://www.automateddynamics.com/wp-content/uploads/2013/11/Automation-1-300x199.jpg


https://www.robots.com/images/res-design/arcwelding/welding-app.jpg

# Impact on Future of Manufacturing

- **Revolutionary Designs**
  - Mass, thermal, electrical
  - Material use
- **Material Compatibilities**
  - Difficult combinations
  - Fabricated not assembled
- **Automation Extended**
  - Low volume / mixed part
  - Higher quality / assurance
- **Faster Product Launch**
  - Improvements quicker
  - Targeted needs
- **Product Efficiencies**
  - Mass, thermal, electrical
  - Material use and reuse
- **Customization**
  - Changes market dynamics
  - New tier of 'better' available
- **Quality of Life**
  - Mobility improvements
  - Medical enhancements
- **Workforce Elevated**
  - US competitive
  - Creative & innovative