Monitoring and advanced diagnostics to enable AM fundamental understanding

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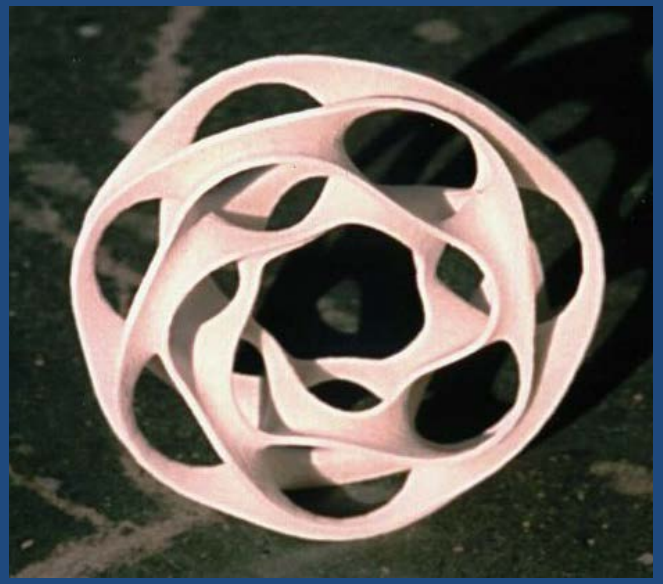
Context/Goal of AM

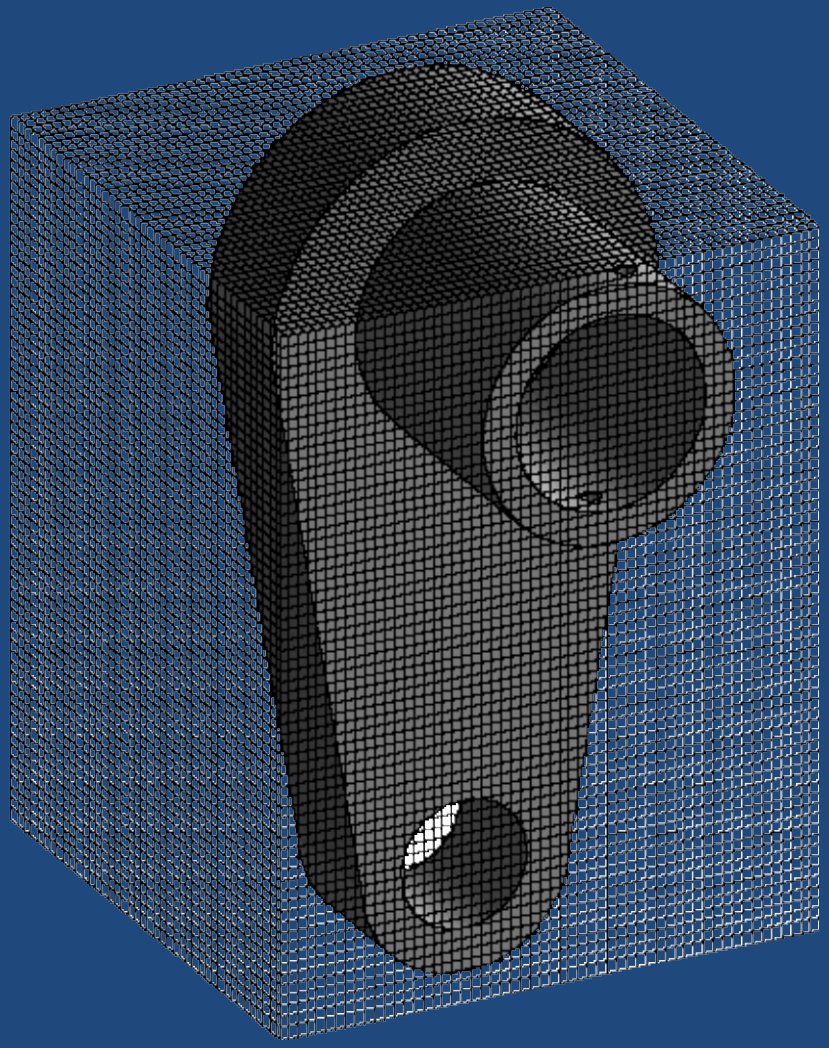
Solid Freeform Fabrication - SFF

Fabrication of complex freeform solid objects directly from a computer model of an object without part-specific tooling or human intervention.

Art to Part



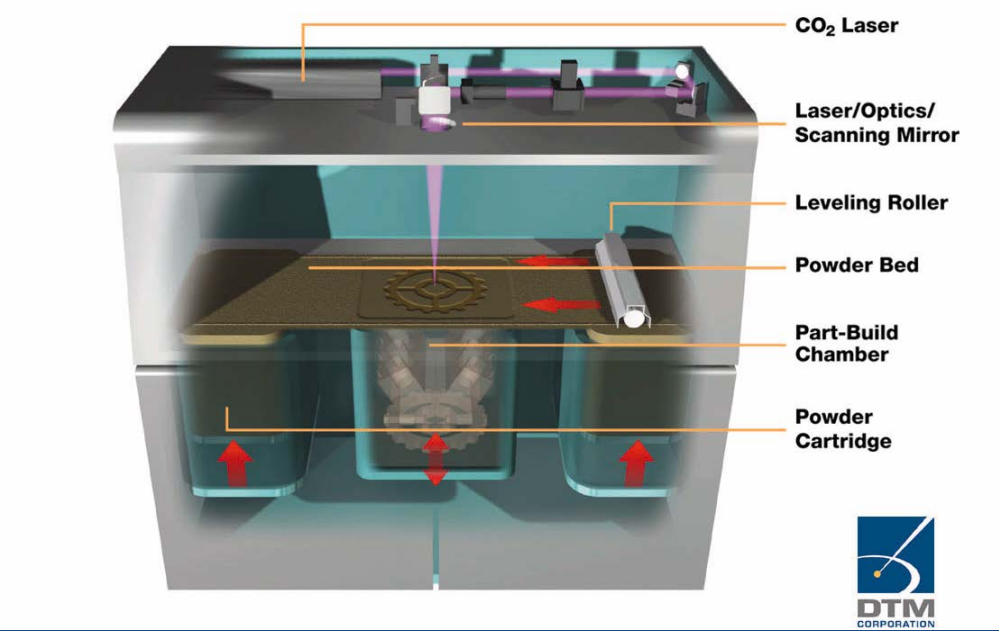
Voxel Manufacturing



Problem: How to make the first one of something quickly.

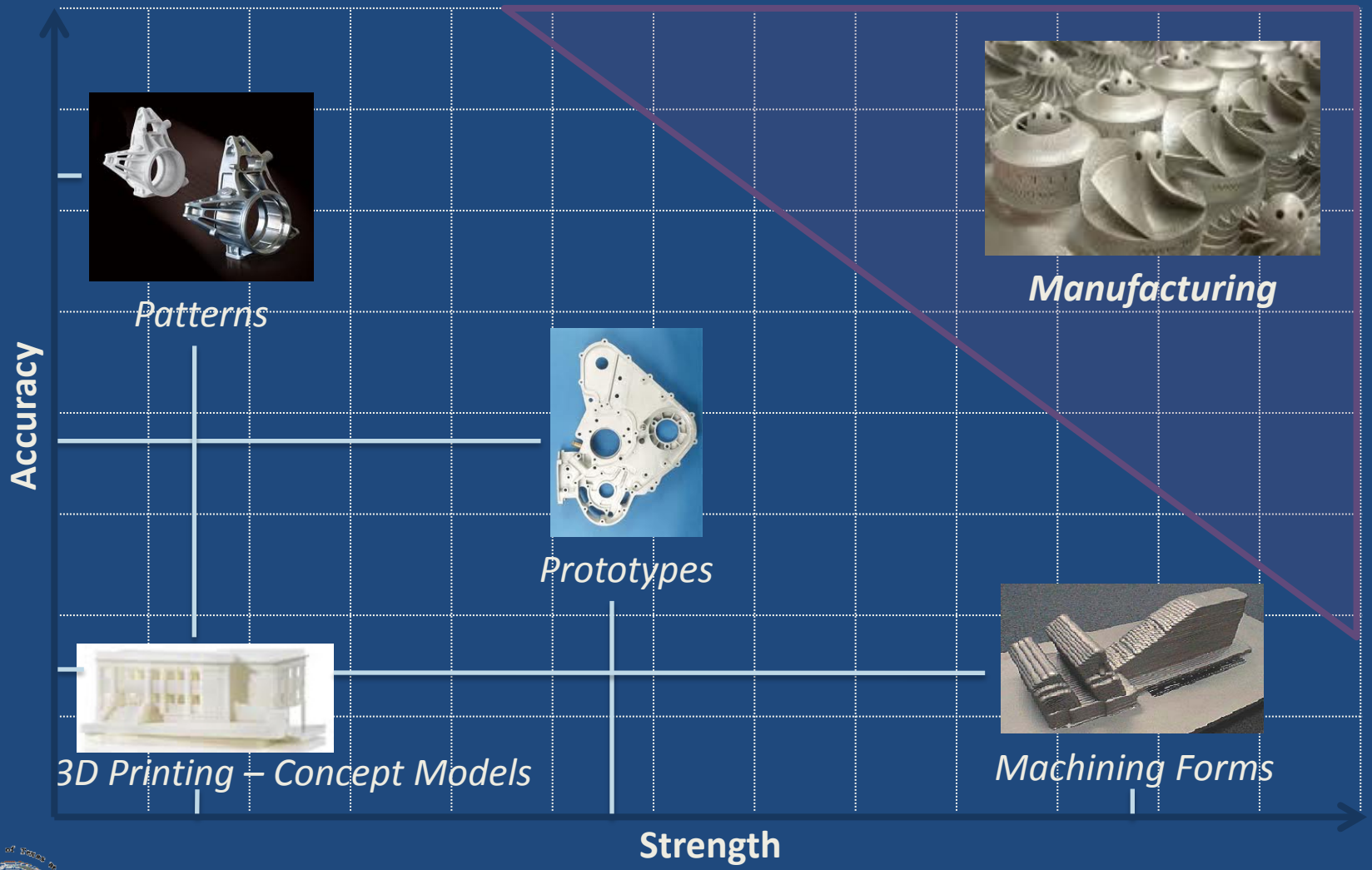
Solution: Voxel manufacturing or layered manufacturing with no fixtures (no supports)

SLS – A Thermal Process



- Part Bed Heater
- Feed Heater
- Laser Scanning

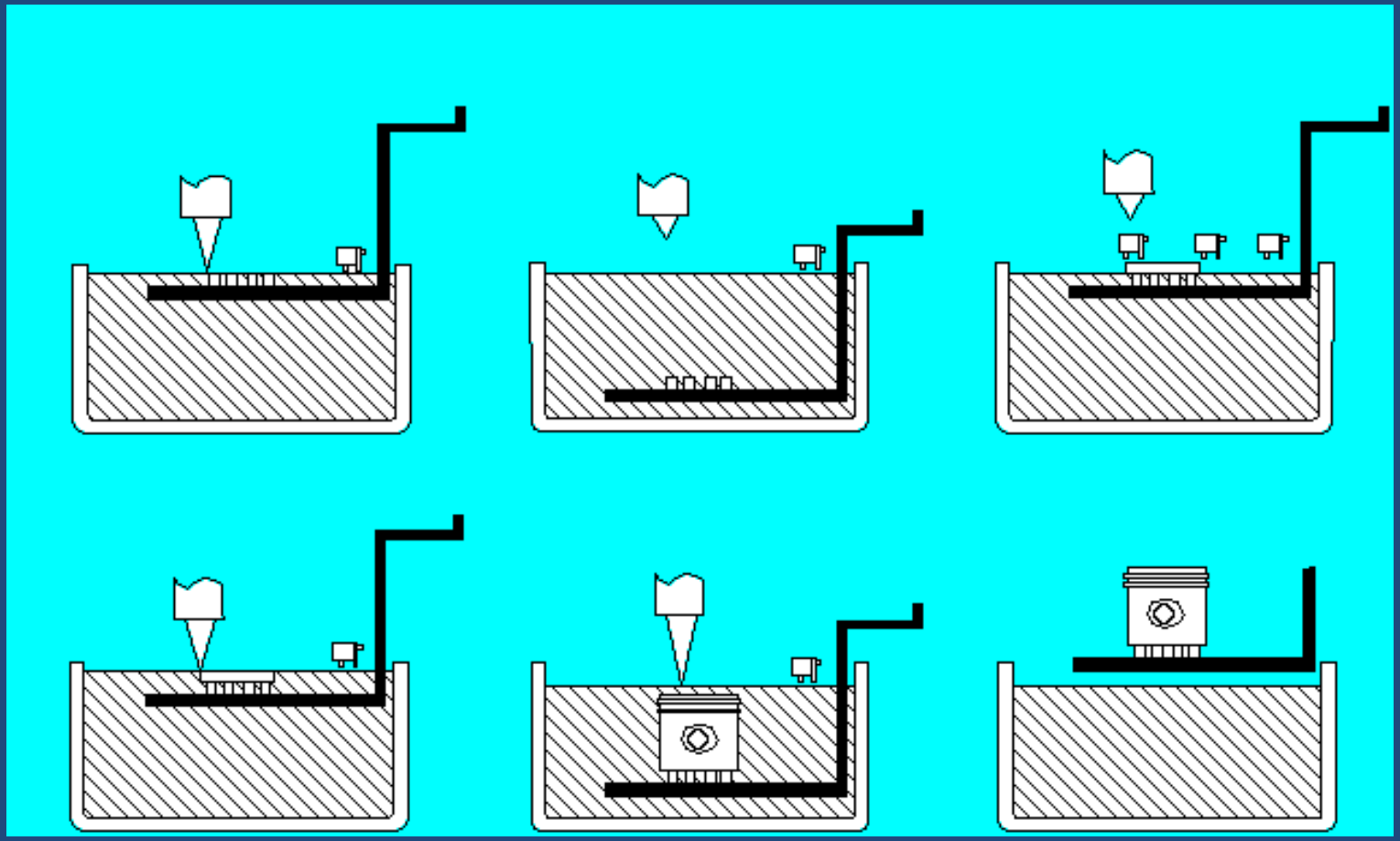
Understanding Markets (only ~ $3 Billion)



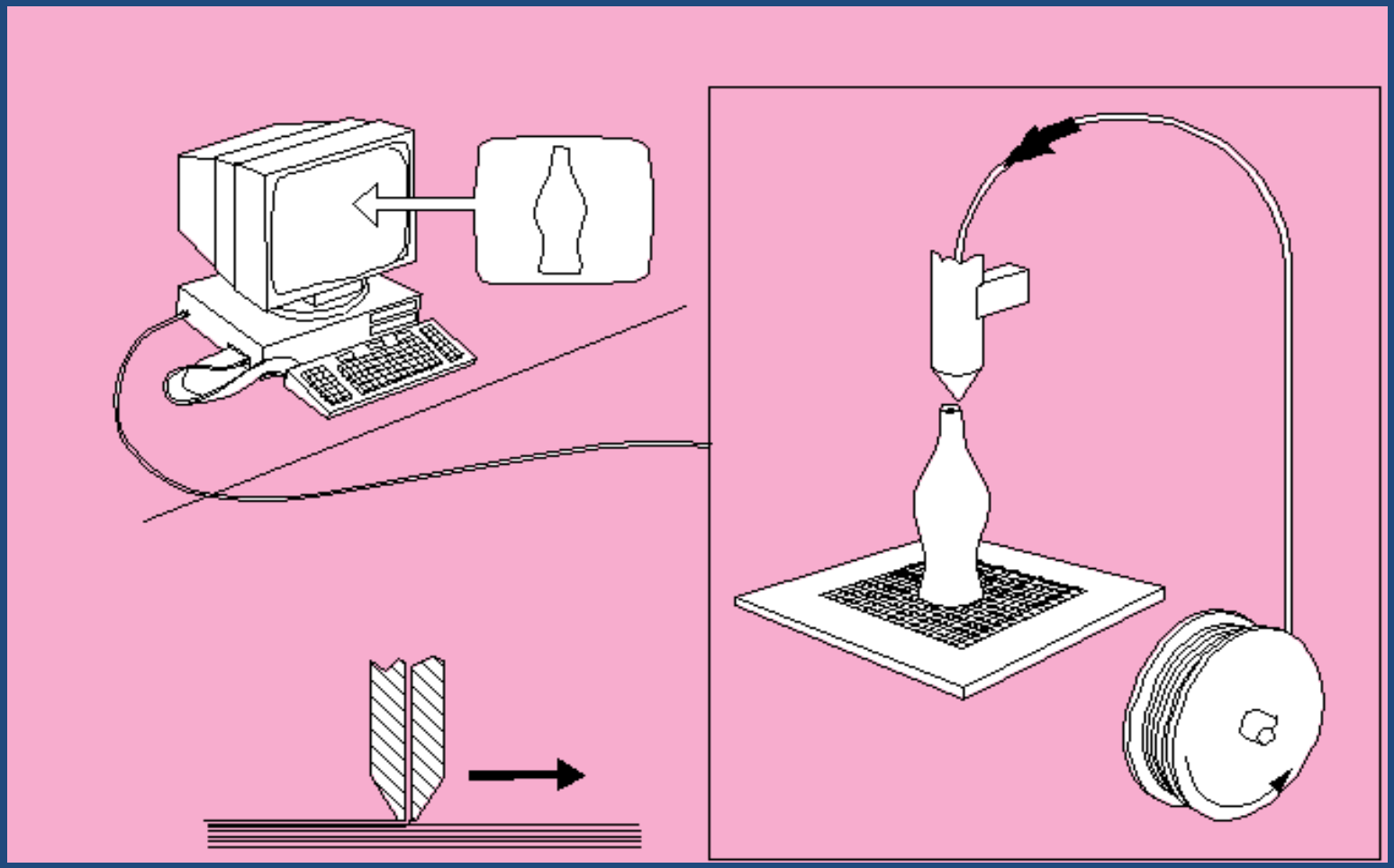
Barriers to Additive Manufacturing

- Surface finish
- Production speed
- Cost
  - Machines
  - Materials
- **Variation from part to part**
  - **Inadequate process control**
- Materials availability

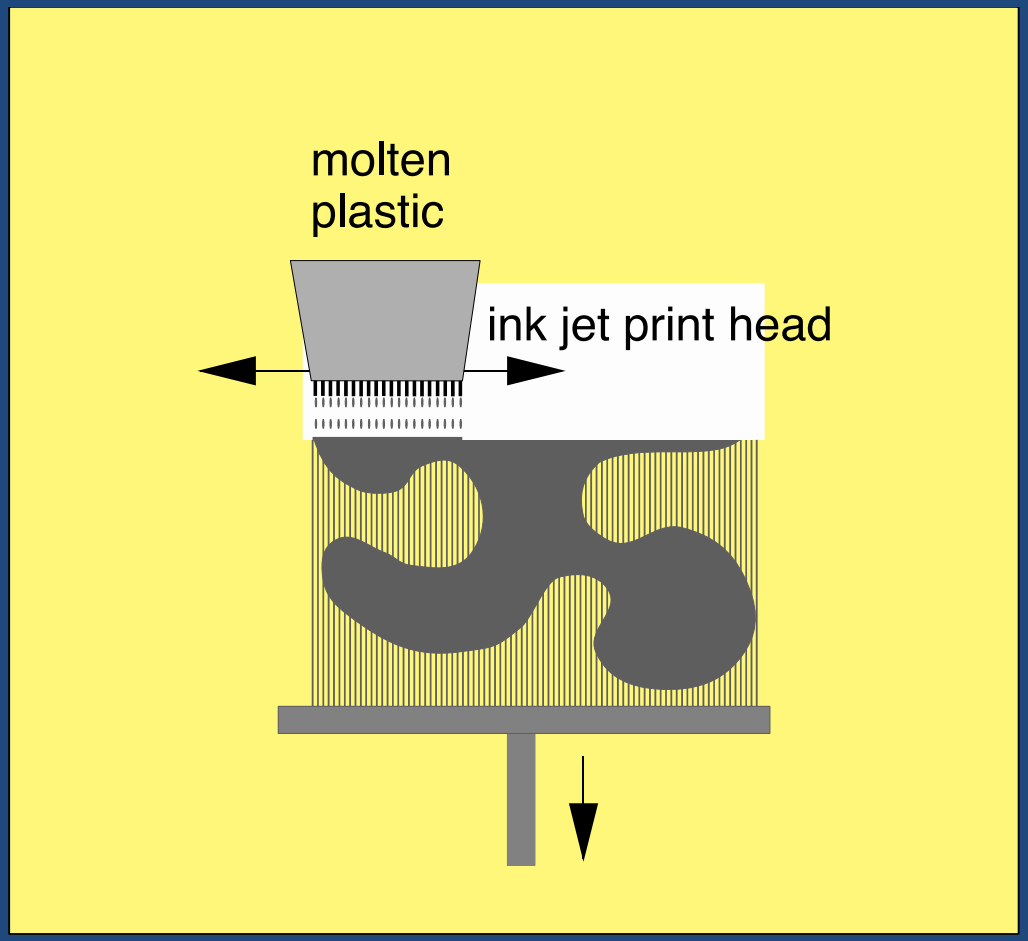
Stereolithography



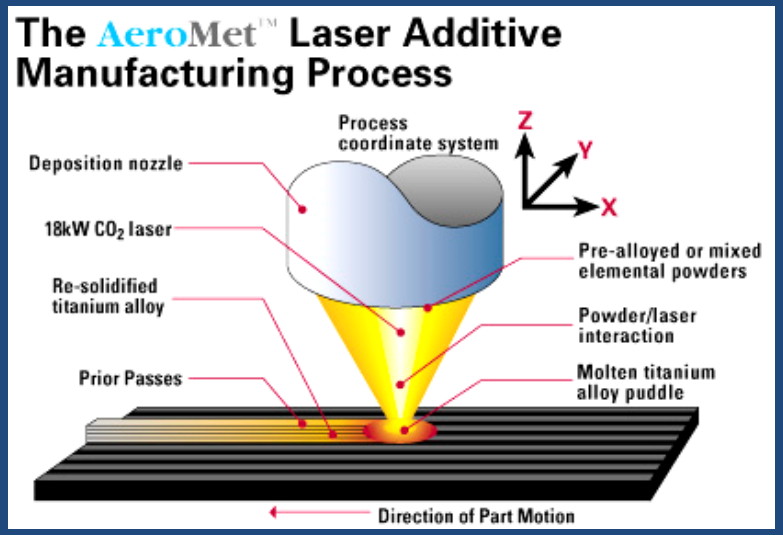
Fused Deposition Modeling

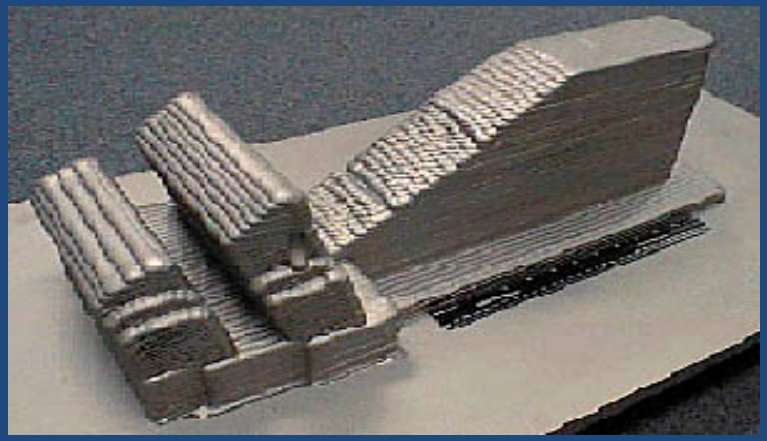


Ink Jet Systems

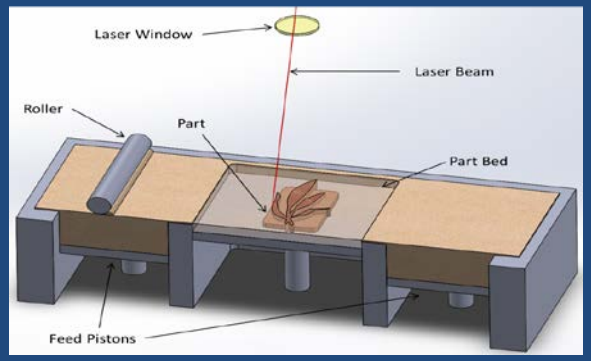


Laser Deposition

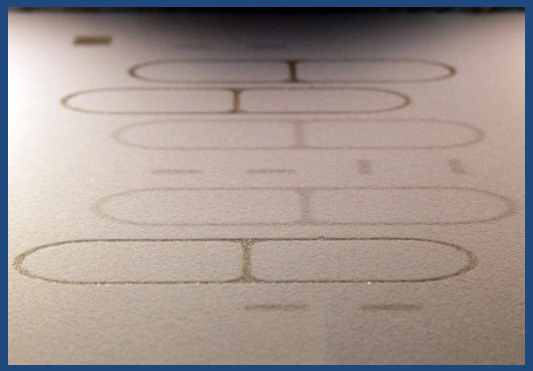




Direct Polymer SLS Process Control

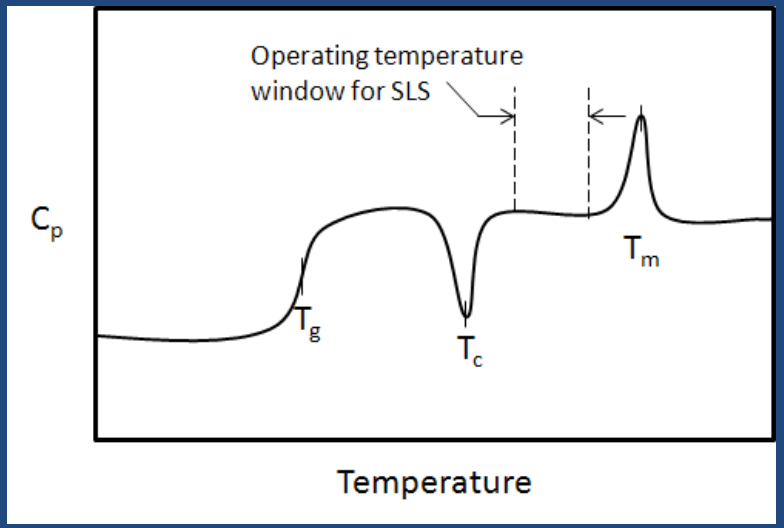


SLS Process



Laser Scanning

Polymer parts are processed without support structures.

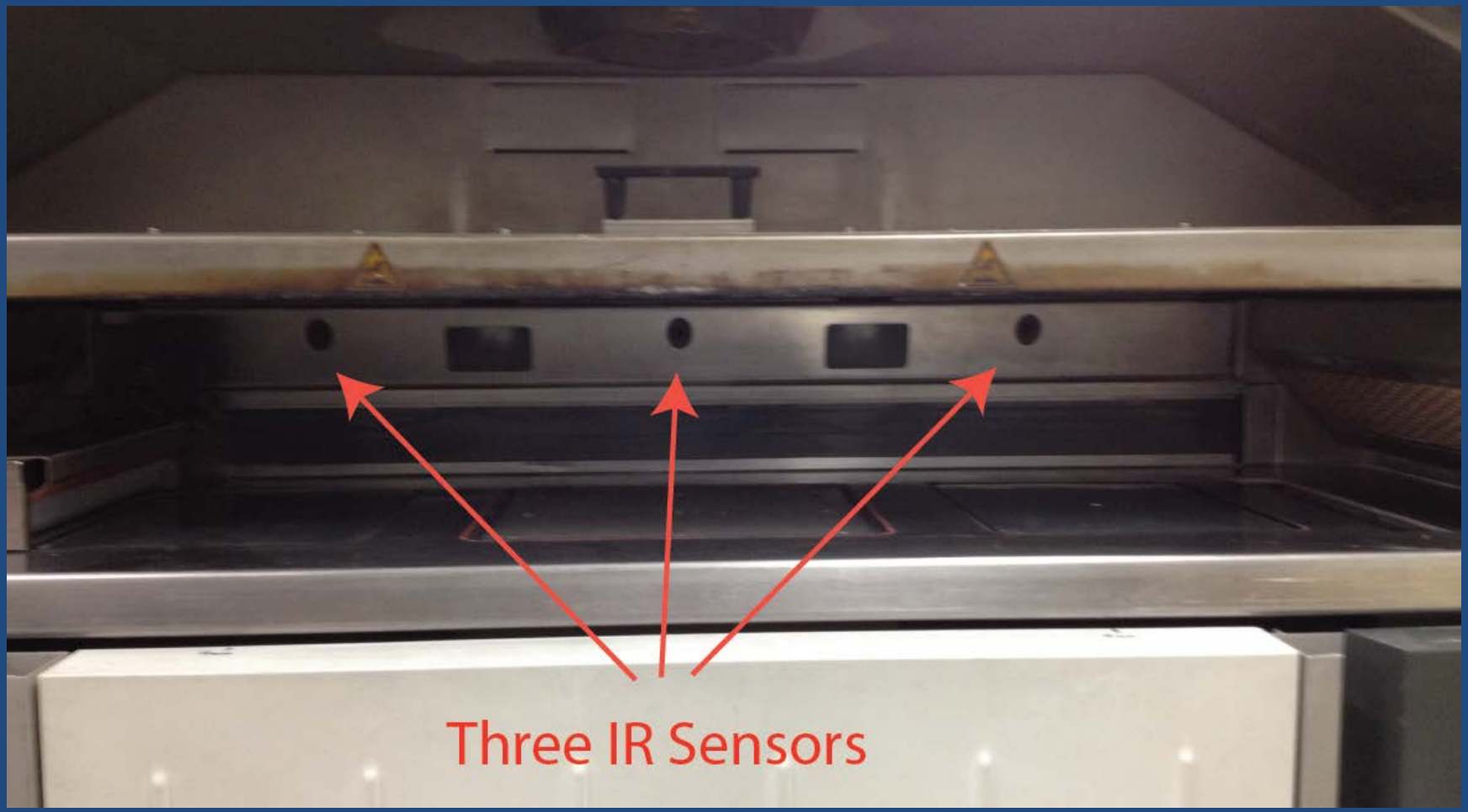


Differential Scanning Calorimetry

History of SLS Thermal Process Control for Direct Polymer Laser Sintering-DPLS

- 1990
  - Thermocouple in part bed
  - Part bed heater
  - Feed heater
- 1992
  - IR sensor on part bed
- 1994
  - 3 IR sensors – 2 feed cylinders & 1 part bed
  - Warm up profile
  - Cool down profile
- 2001
  - IR sensor drift correction
  - Physical flapper to control convective currents
  - Heater spatial variation correction
- 2004
  - Multi-zone heaters
  - Door sealing

Three IR Sensors

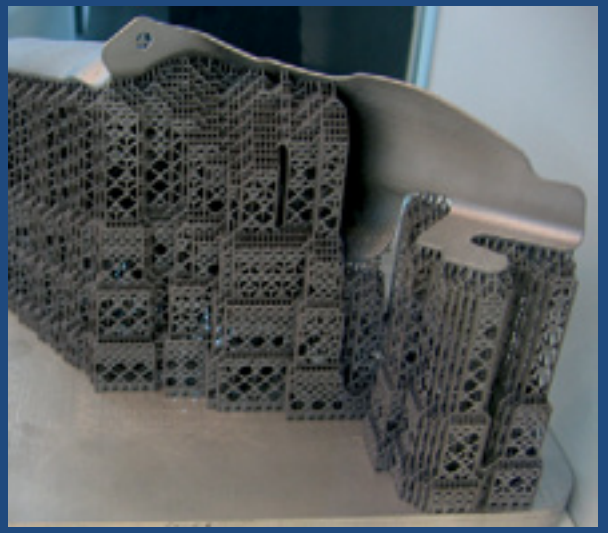


Commercial SLS Thermal Process Control for "Direct" Metals

- No thermal Control – Instead
  - Build on a plate
  - Support Structures to help control thermal warping
  - Heat treat to anneal part with support structures
  - Machine off supports
  - Finish machine

Heat treat

Support structures



But can still make complex shapes that cannot be made any other way

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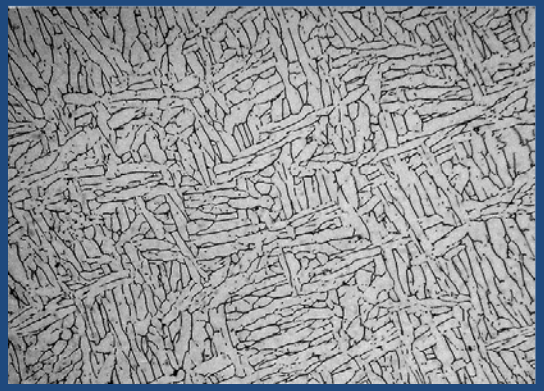
*Metal Components: SLS Titanium**

SLS processed AIM-9 Sidewinder missile guidance section housing (90% scale)

- 1998 – Mil Spec Titanium part built with experimental SLS system with thermal control
  - Feed heater
  - Part heater
  - Vacuum capability
  - Powder O_2 quality control
  - Biasing temperature ~ 700°C
  - Top surface mirror finish
  - 1KW CO_2 laser
  - No supports



*PhD work of Suman Das

Manufacturing Changes the Rules

- Certification of SLS as a manufacturing process
- Repeatability of Geometry and Properties

Short Runs are the New Marketplace

From: Anderson, C., Wired Magazine

Small Lot Process Control

- Small lots are often high value. How to make yield 100%?
- Large volume statistics are not available.

Improved Process Control for Additive Manufacturing

- Required for manufacturing market.
- Is by nature small lot.
- Maybe the single biggest roadblock to using SLS for Manufacturing
- It is not an easy problem – noisy and uncertain measurement environment with uncertain control actuation.
- The time-temperature window required to process desired materials can be very tight.

Three Enabling Technologies for Small Lot Process Control Today

1. Advances in high fidelity multi-physics computer models
2. Advances in modern, nonlinear estimation & prediction
3. Inexpensive parallel computing – GPU

Modern Bayesian Estimation Methods

Physics with states *x* & uncertainty leads to Markov system

$$dx = f(x)dt + d\beta \qquad \left\langle d\beta d\beta^T \right\rangle = Qdt$$

Discrete measurements *z* with structured uncertainty

$$z_i = h(x_i) + v_i \qquad \langle v_i v_i^T \rangle = R_i$$

Modern Bayesian Estimation Methods

Two Step Estimation Process

1. Propagate probability density function in real time from the physics based model starting at t_1
2. Take measurement at time t_2 and update probability

Difficult part is probability propagation

- Linear -> Kalman filter
- Manufacturing models are not typically linear (if they are trying to predict defects) -> monte carlo, which yields large numbers of parallel systems*

*Felipe Lopez

Cyber & Modeling Enablers

- Cyber – a parallel computer architecture is optimal for a parallel algorithm*

GE GTX TITAN has 12 streaming multiprocessors with 192 scalar processors each, allowing massive parallelization

- Models must have uncertainty quantification

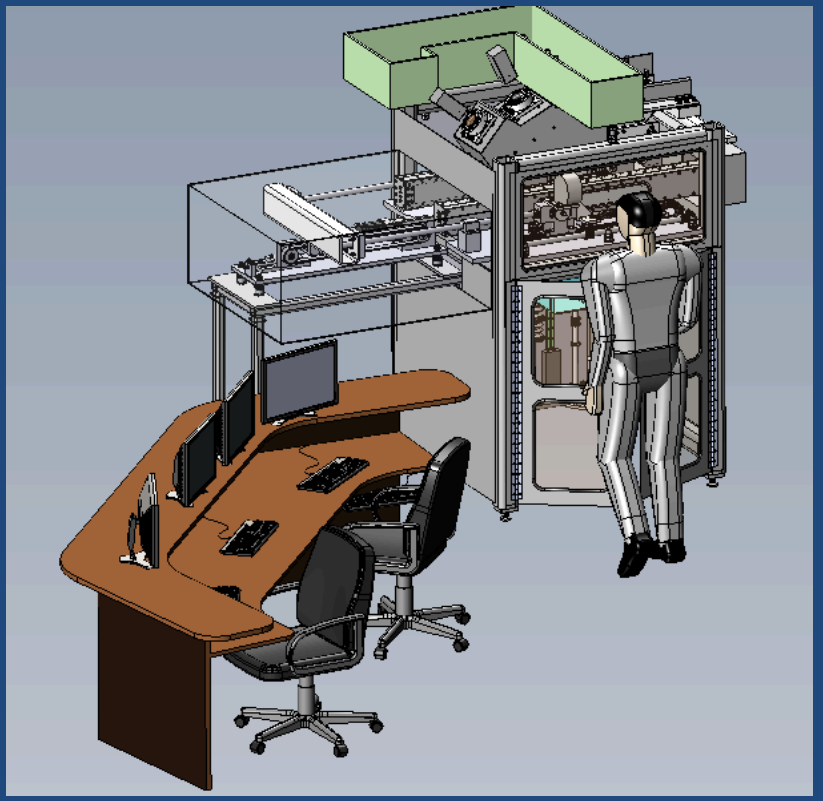
*Al Mok

Cyber Enabled Manufacturing Systems: CeMs

- The application of cyber systems technology and high fidelity physical models with characterized uncertainty to small-volume, high-cost manufacturing
  - Design “accurate” physics-based dynamics models for control and defect prediction
  - Combine with multiple measurements and sensor data
  - Use modern real time computer architecture.

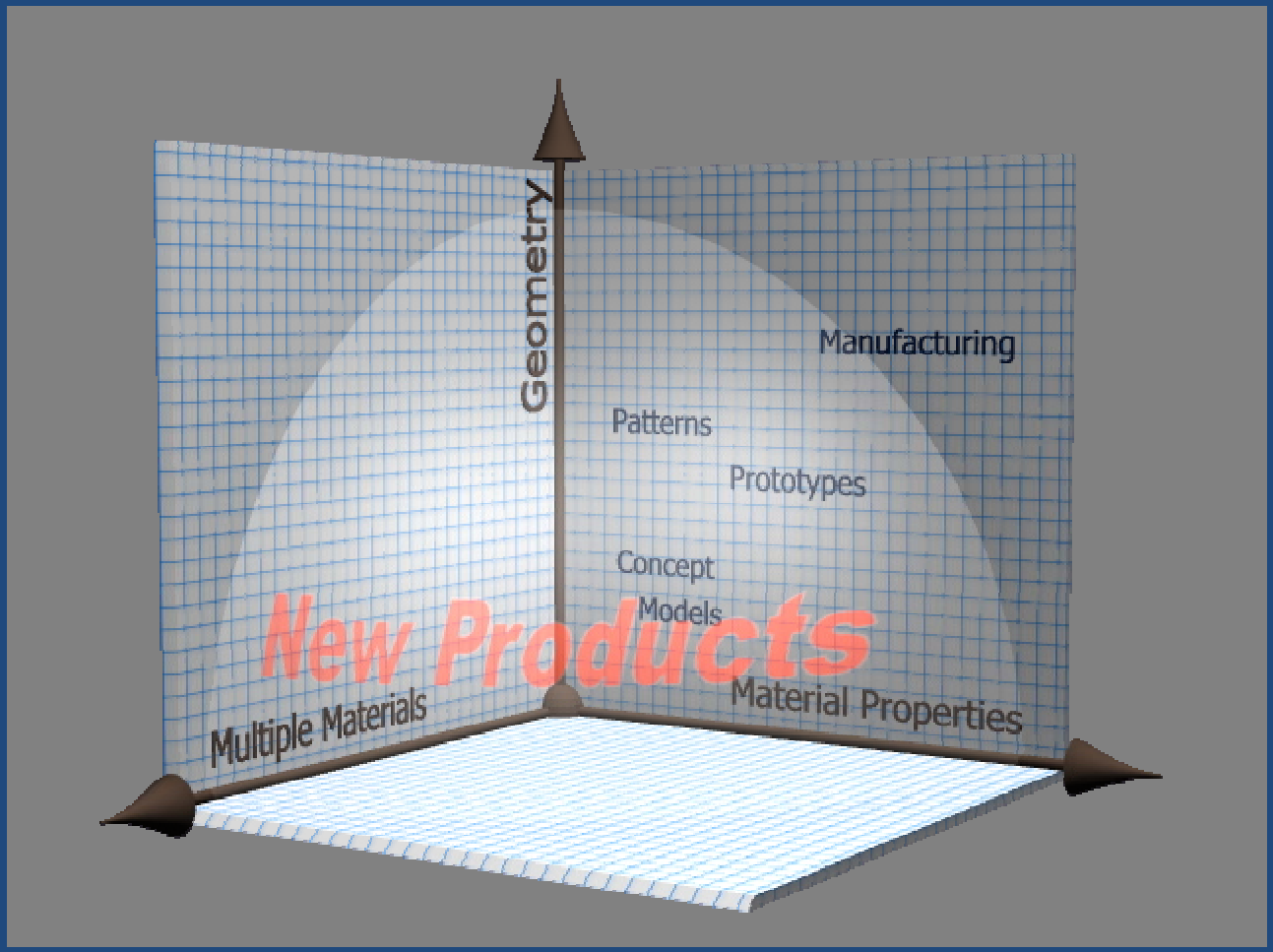
Process Control Test bed- LAMPS*

- Laboratory Scale System
- High Temperature System ~ 350°C
- In-Situ Measurement
- Open Architecture Software to research
- Multiple and new measurements and control inputs



*Patent pending

Multiple Materials



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Closing Thoughts

- Layer by layer process control (measurement and analysis in real time) is unique to AM
- Layer by layer also means there is more opportunity for defects
- Small lots requires new types of process control
  - Multiple measurements
  - Real time multiple physics
  - Fusion
- AM Systems will be changing and newer methods will emerge
- AM more complicated than most existing manufacturing processes – machining for example
- Cool down is important
- Special Thanks to NSF, ONR (Ralph Wachter)