Computer-Aided Design for Additive Manufacturing: Can We Exploit Shape and Material Complexity Capabilities?

David W. Rosen

George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405
david.rosen@me.gatech.edu 404-894-9668

Georgia Tech, Atlanta, GA

Georgia Tech

- 20,000 undergraduate and graduate students
- 800+ faculty
- >$300M in research funding
- Located in downtown Atlanta
- GT was the Olympic Village for 1996 Summer Games

Mechanical Engineering

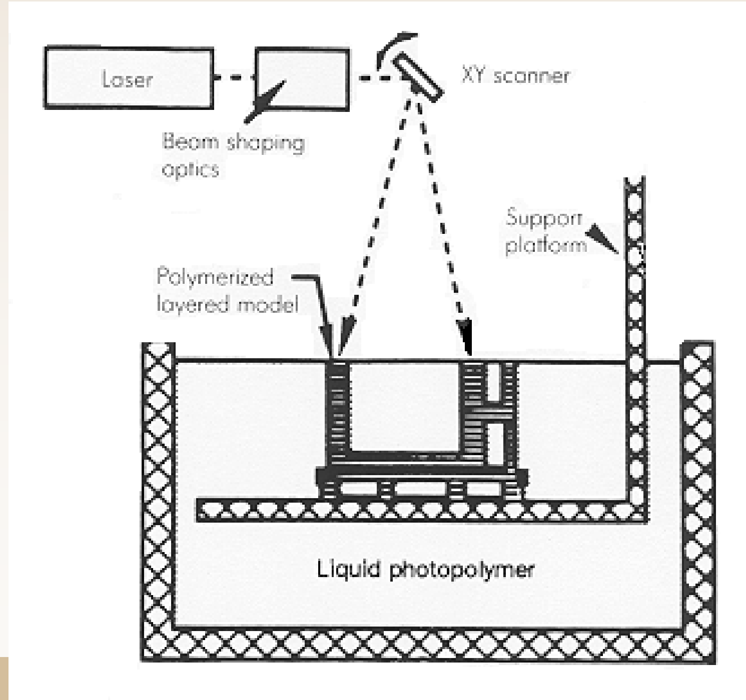
- Includes ME, Nuclear Engr., Health Physics
- 85 faculty
- 1850 undergraduate students
- 820 graduate students
- 11 Research Groups (CAEDesign, Mfg, Acoustics, MEMS, Bio, etc.)
- Top 5 program

Overview

- Additive Manufacturing
- Cellular Structures
  - Construction
  - Optimization
- Integrate Materials into Computer-Aided Design
  - Simultaneous product-material-process design
  - Process-structure-property relationships
- Exposure Controlled Projection Lithography

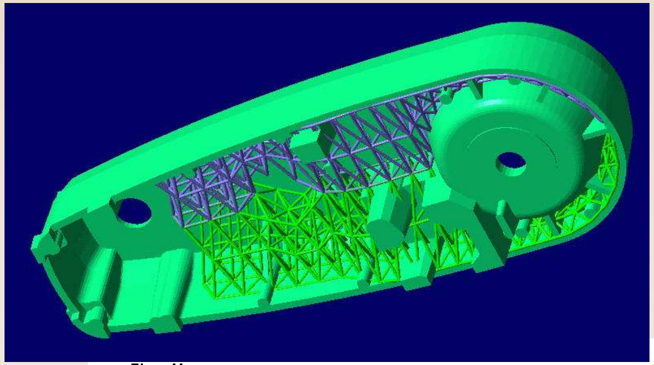
Additive Manufacturing

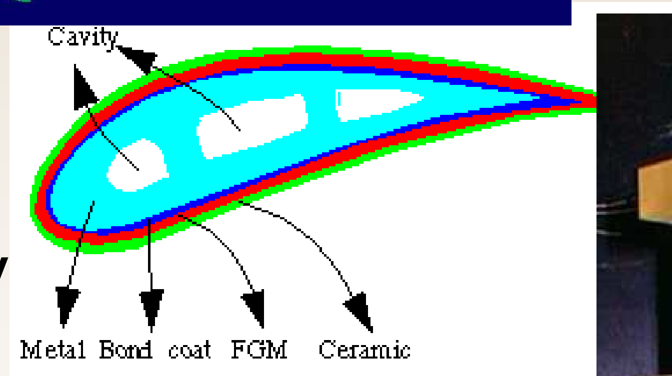
- Class of manufacturing processes that build parts one layer at a time.
- Stereolithography, Selective Laser Sintering, Fused Deposition Modeling, ...

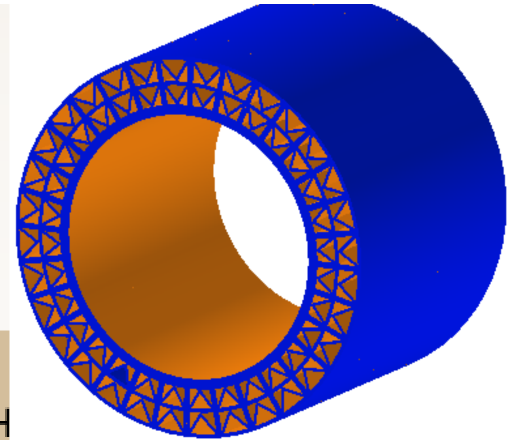


AM Unique Capabilities

- Shape Complexity
- Material Complexity
- Hierarchical Complexity
- Functional Complexity

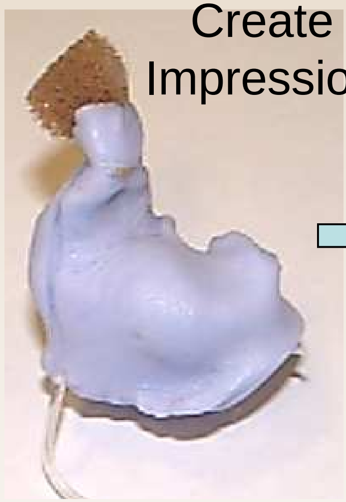




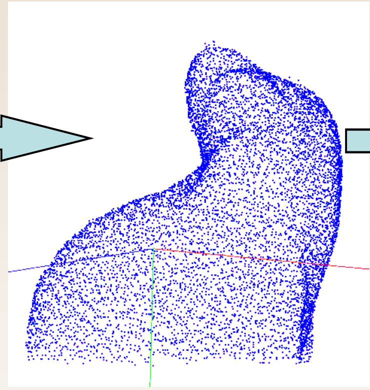


Hearing Aid Shells

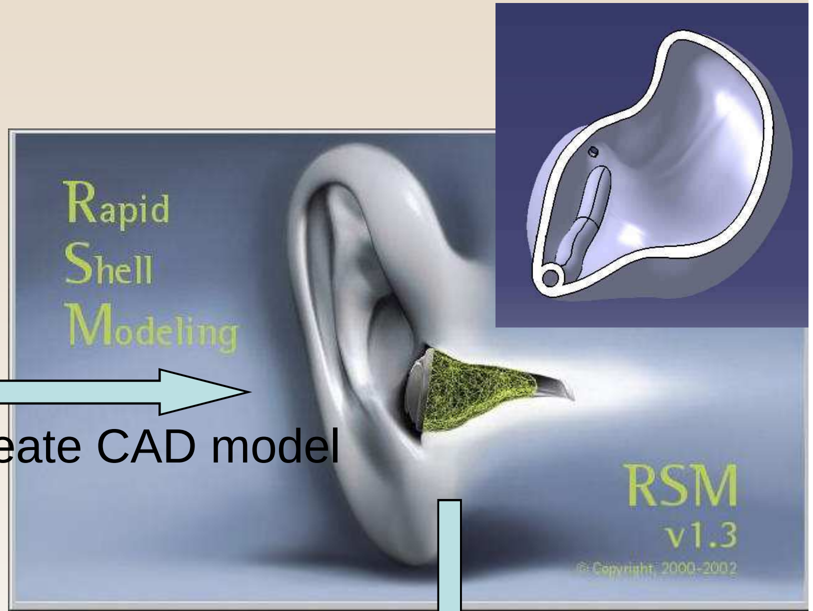
Create Impression



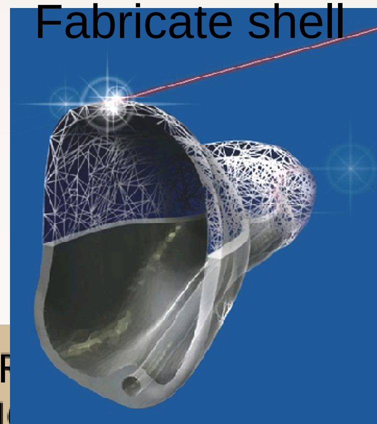
Scan Impression



Create CAD model



Fabricate shell



Assemble components

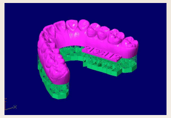
Invisalign Manufacturing Process

invisalign® Manufacturing Process

Timeline

Receiving & Order Entry → Dental Laboratory → Data Acquisition → Treat Operations → SLA Mold Fabrication → Aligner Fabrication

SLA Mold Fabrication



Prepare & Slice

- STL File Generation
- Packing (orient & place)
- Support Generation
- Slice Data

SLA Build

- Laser (Scanning)
- Re-coat (dip in resin)
- Sweep (remove excess resin)
- Part Removal & Post-cure

Quality Control

- Verify test parts
- Conduct individual mold inspection

Ship to Mexico

- Kit in transportation box

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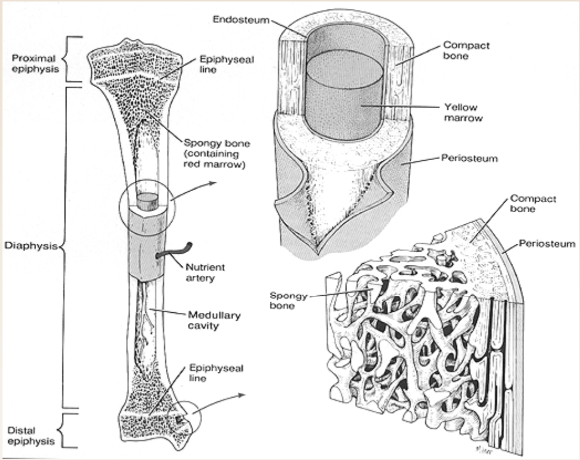
Cellular Structures

When modern man builds large load-bearing structures, he uses dense solids; steel, concrete, glass.

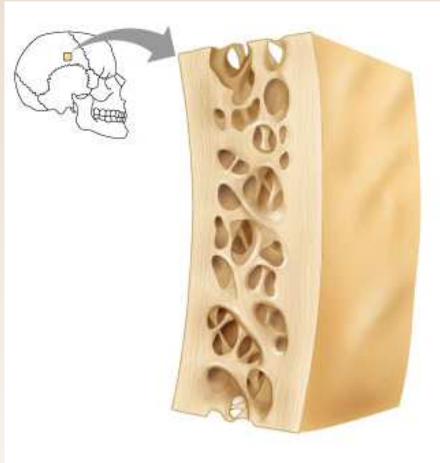
*When nature does the same, she generally uses **cellular materials**; wood, bone, coral.*

There must be a reason for it.

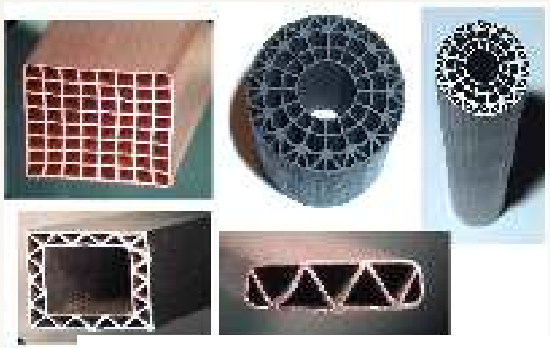
- Michael F. Ashby, Anthony Evans, et al.; Metal Foams: A Design Guide

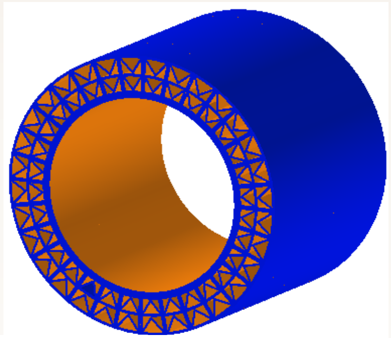


Bone Structure

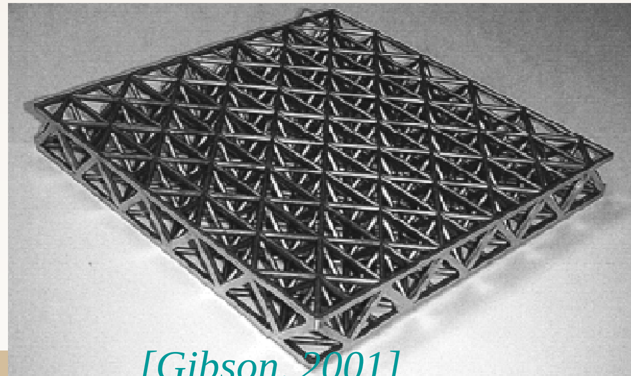


Human Skull





Linear cellular alloy parts [McDowell, 2004]



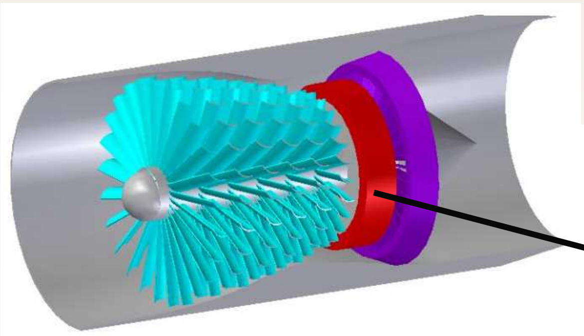
[Gibson, 2001]

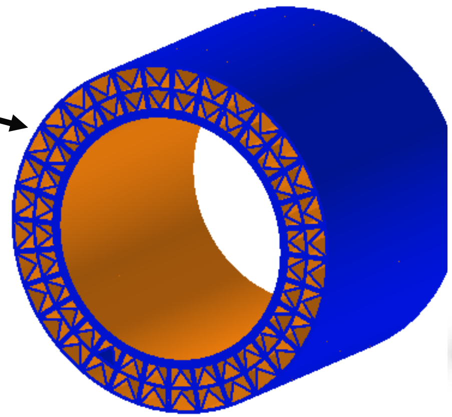
Design For Additive Manufacturing

Low volume ratio structure
(Adaptive Material Distribution)

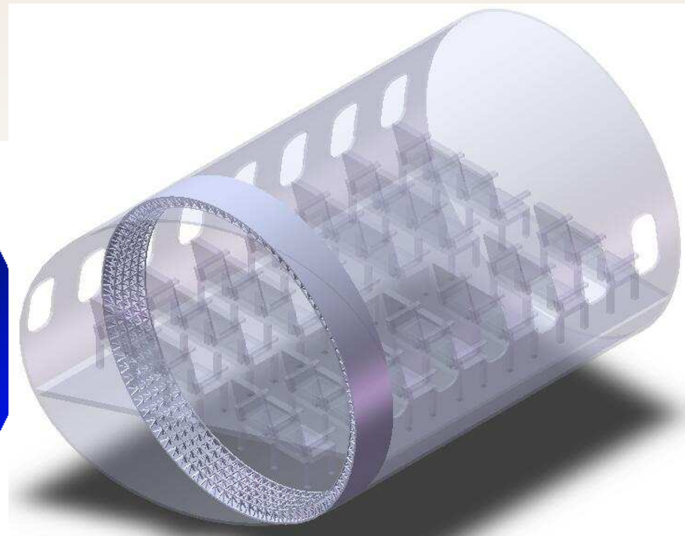
Multi-functionality:
Structure + Heat Transfer

Multi-functionality:
Structure + Acoustics

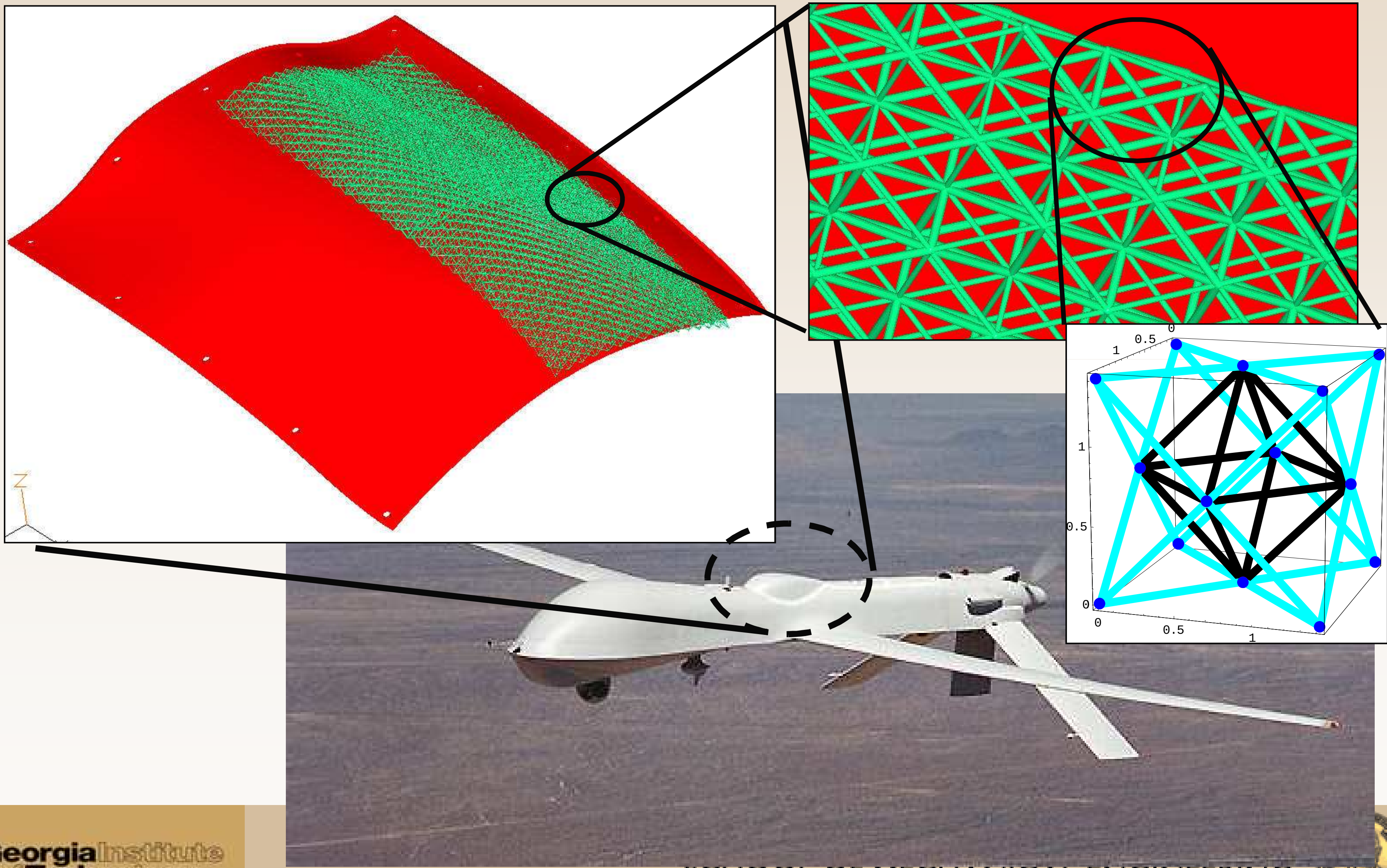




Combustor liner

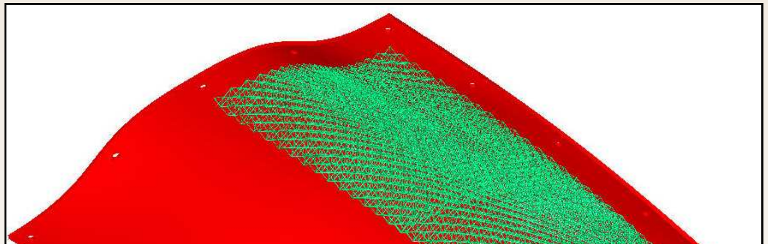


Design and CAD Methods

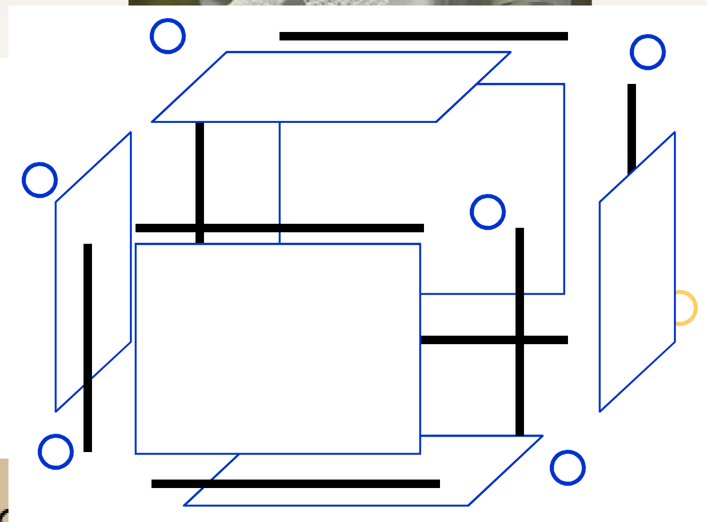


CAD Representations

- Purely geometry in CAD systems
- Boundary Representation solid modeling
  - all geometric details are always represented
  - 1-2000 geometric entities is limit

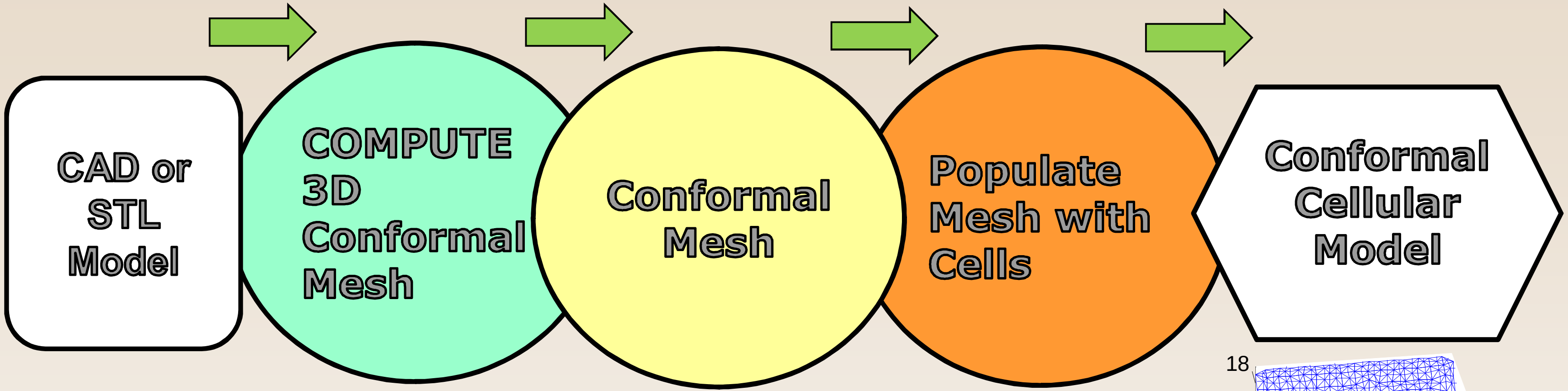


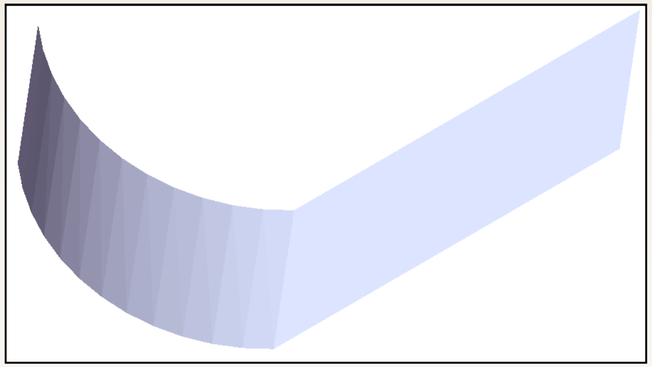
- Parametric dimensions
  - adjustable geometry
- Complicated topology

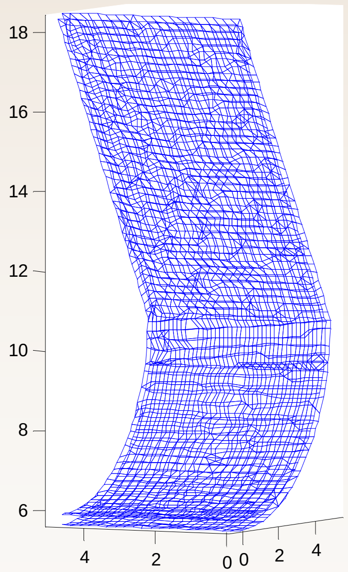


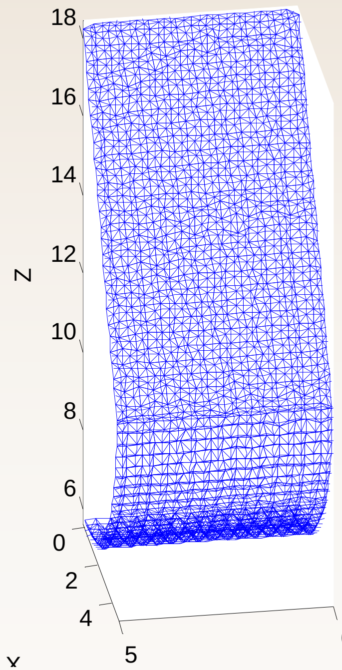
Loughborough Univ.

Conformal Lattice Structures

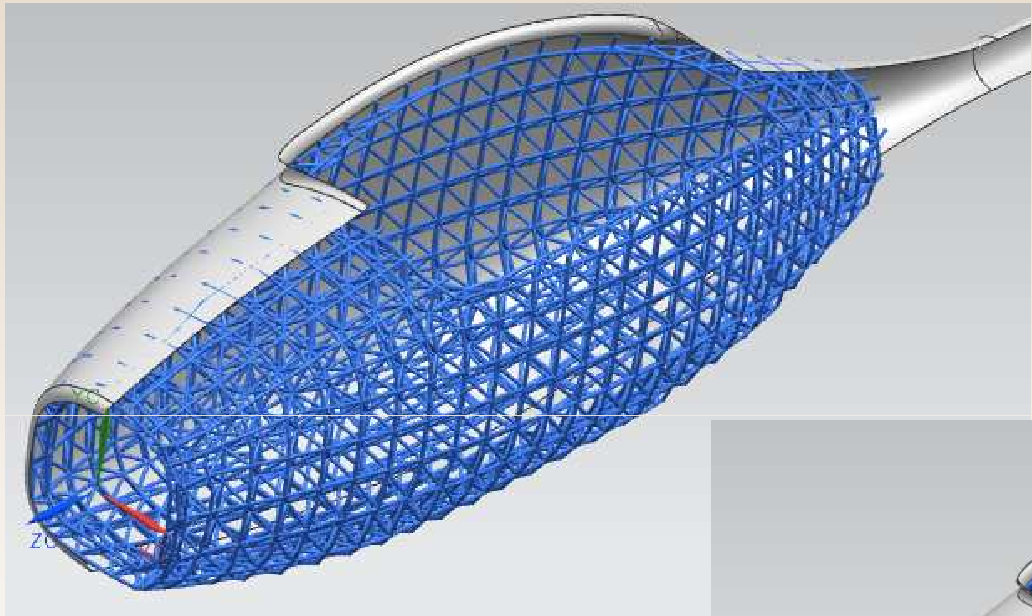


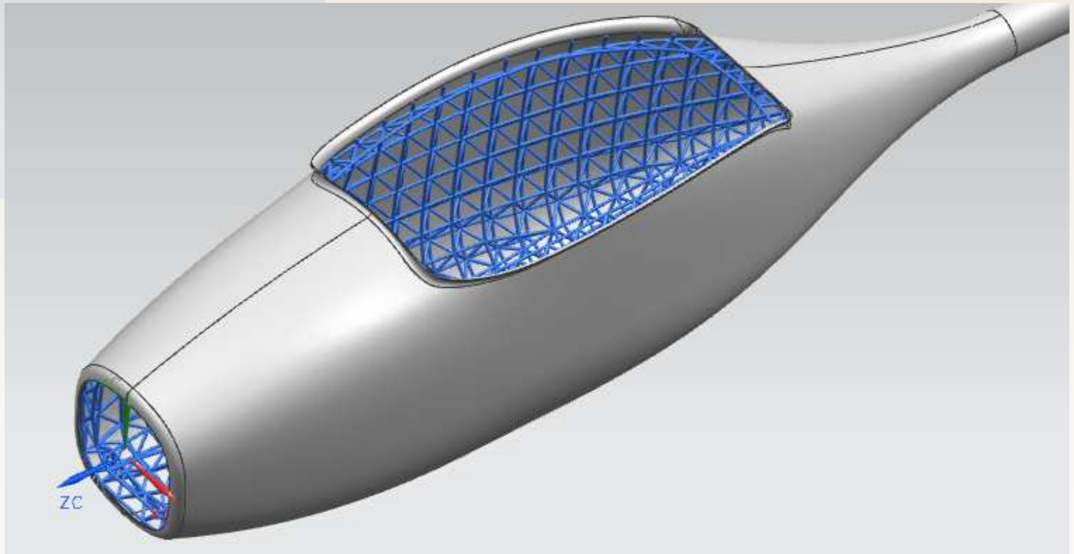




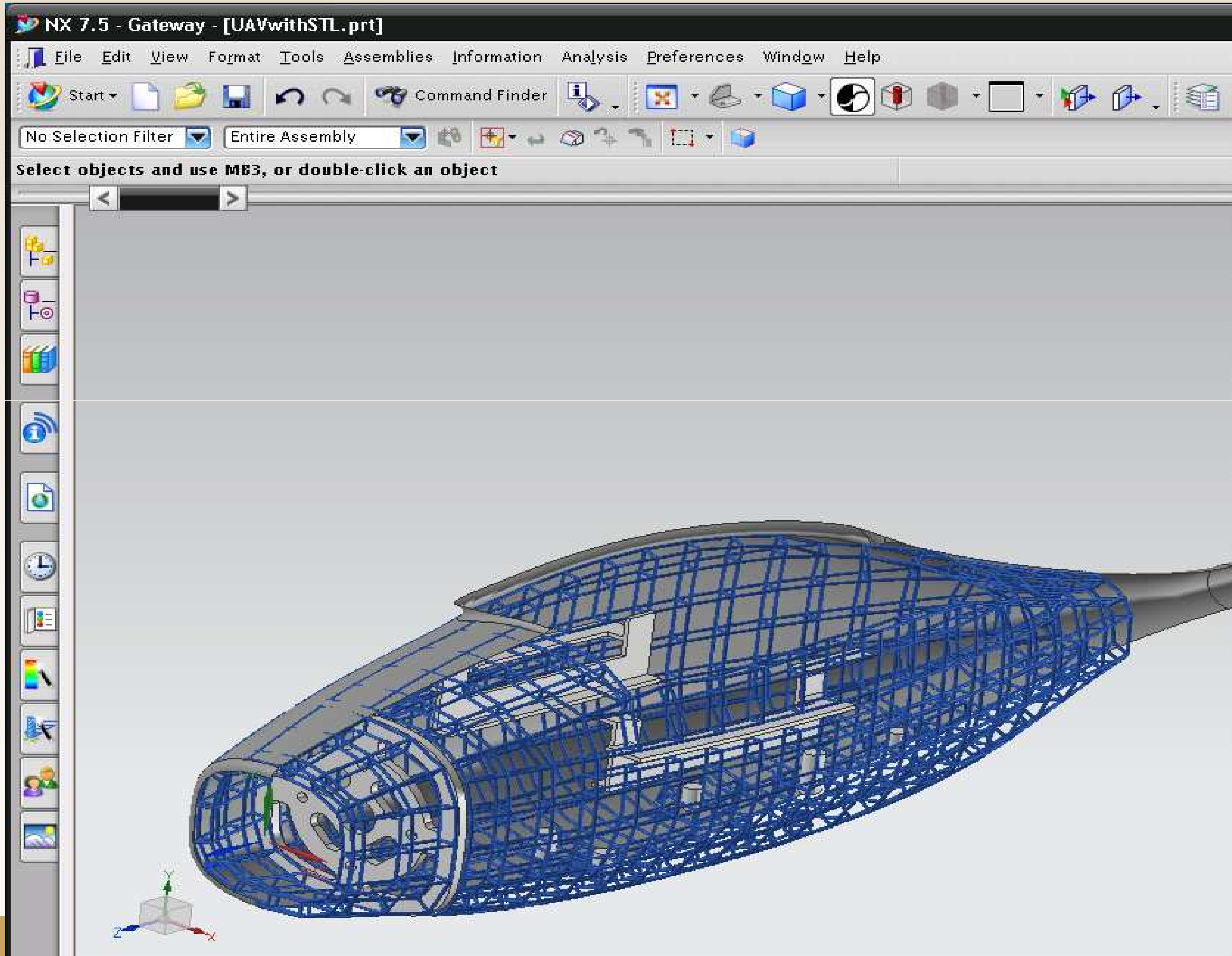


UAV & Micro-UAV Examples

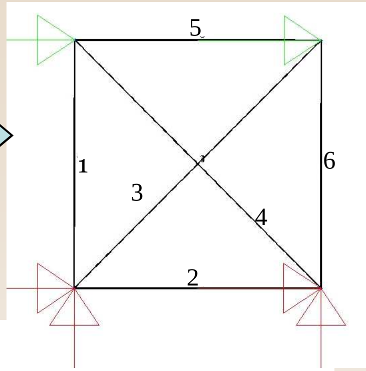


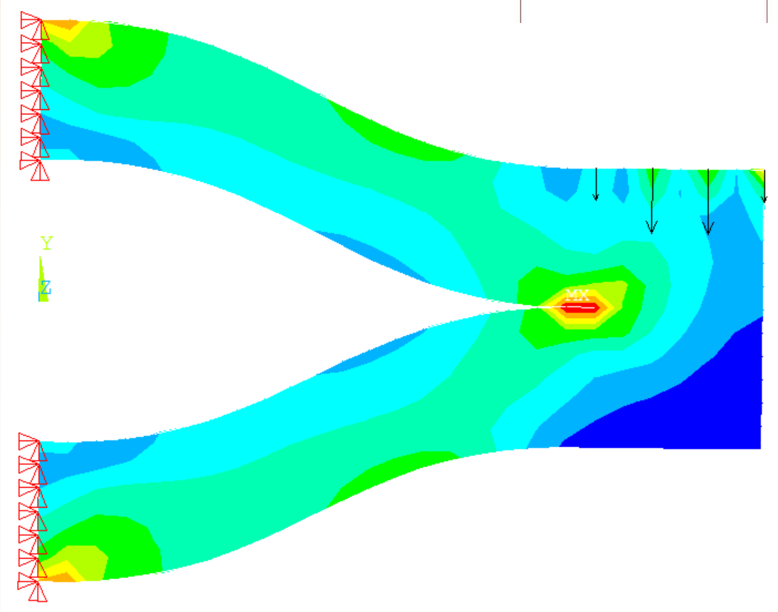


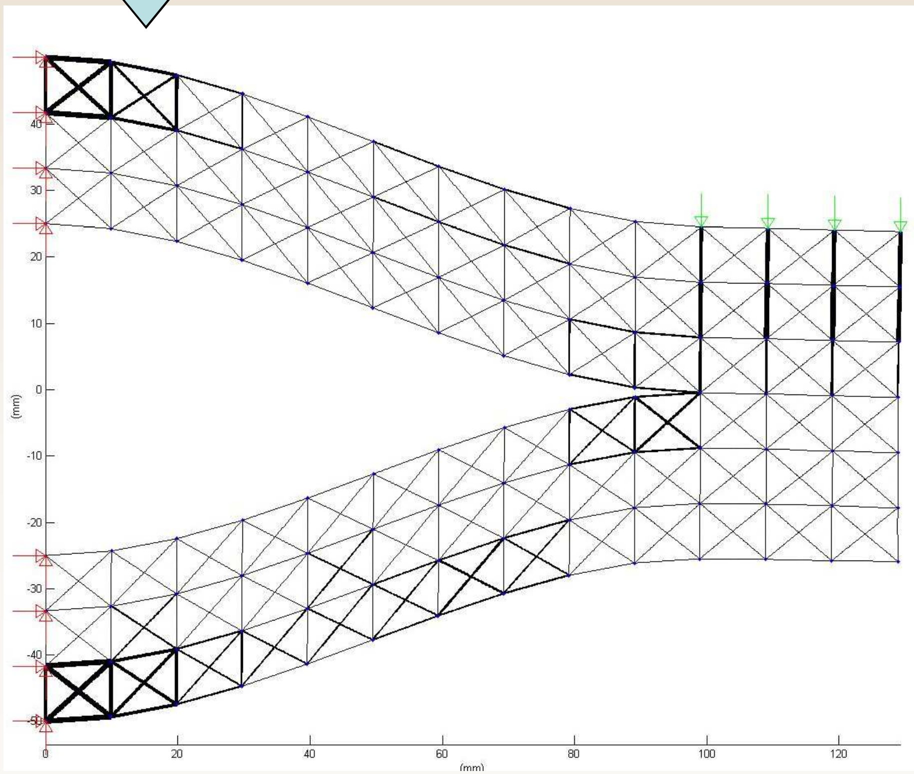
Application to UAV Fuselage



Size Matching & Scaling (SMS)

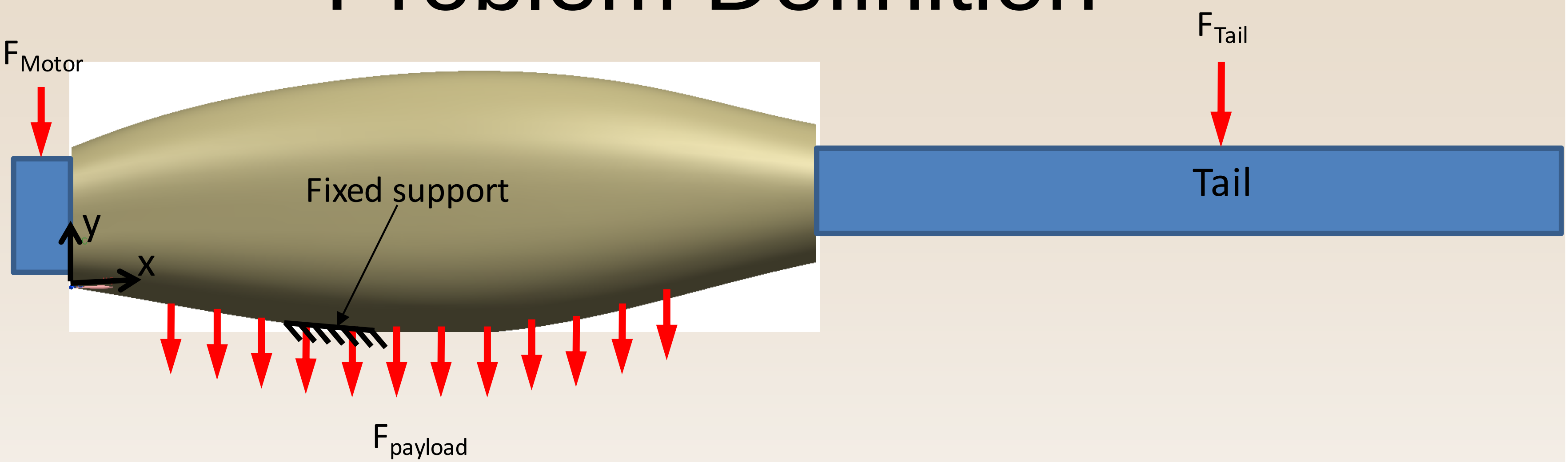






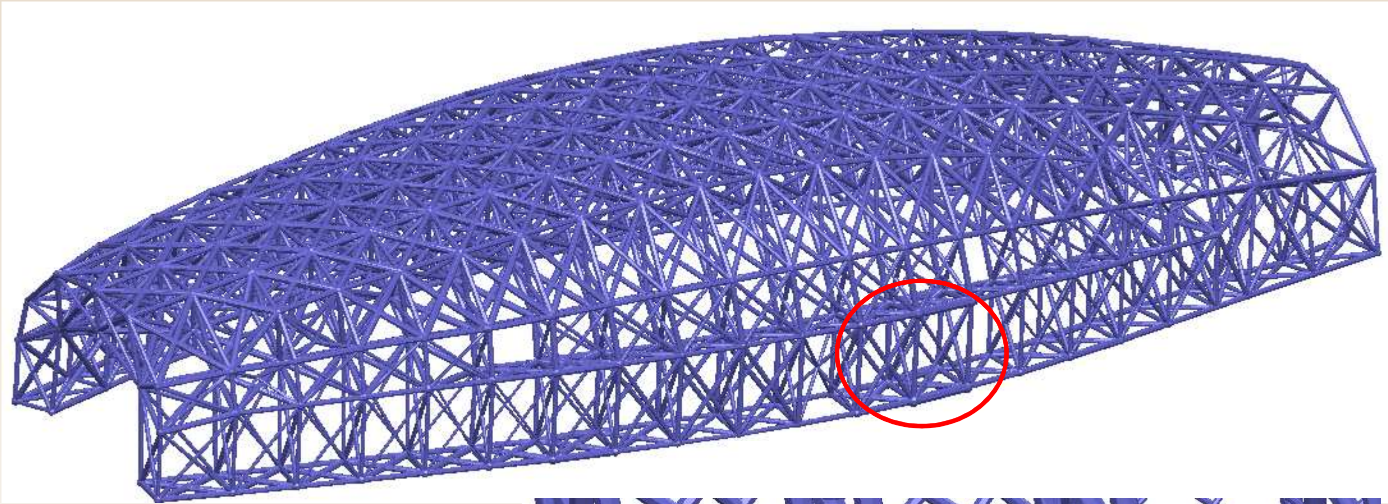
Greg Graf's MS Thesis (April 2009)

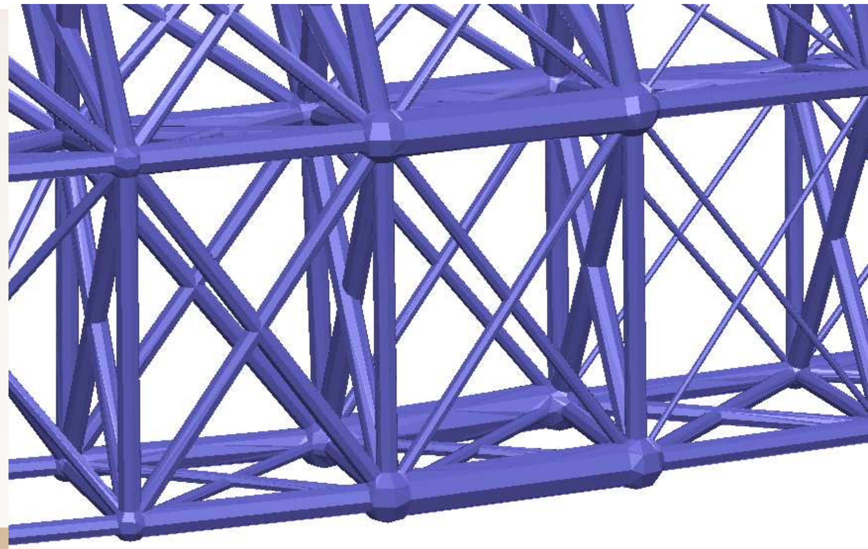
Micro Air Vehicle: Problem Definition



F_{Motor} (N)	5.9
F_{Tail} (N)	2.7
$F_{Payload}$ (N/mm^2)	0.1
Target Volume (mm^3)	100,000
Total Unit-Cell Count	214

Optimized MAV Fuselage





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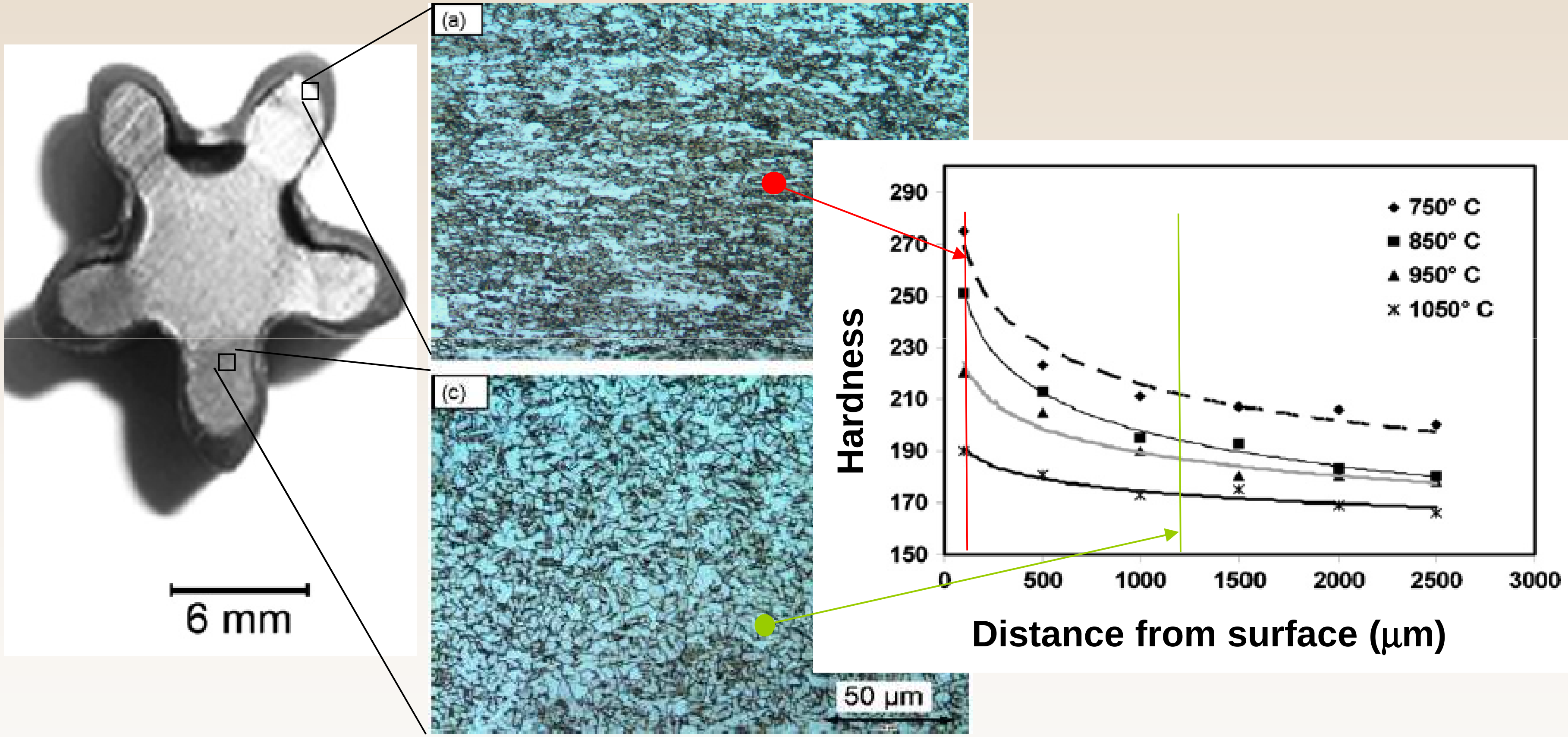
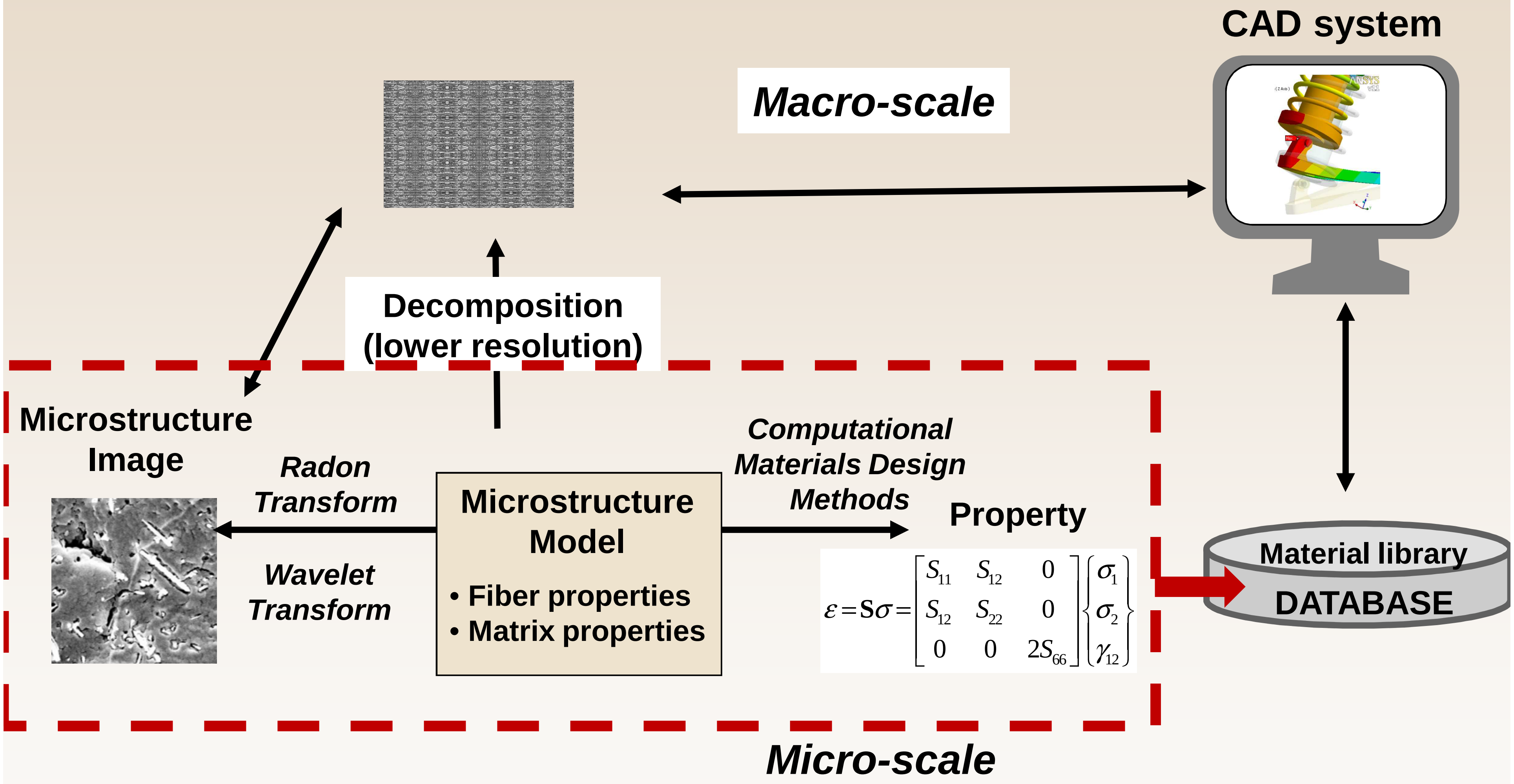
Structure-Property Relationship



Low carbon steel

Materials Chemistry and Physics, 112:1099-1105, 2008.

Motivation


CAD system
Macro-scale
Decomposition
(lower resolution)
Microstructure
Image
Radon
Transform
Wavelet
Transform
Microstructure
Model
• Fiber properties
• Matrix properties
Computational
Materials Design
Methods
Property
$\varepsilon = S\sigma = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & 2S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \gamma_{12} \end{Bmatrix}$
Material library
DATABASE
Micro-scale

Simultaneous Product / Material / Process Design Methods

Design Problem Formulation

Multi-Objective Optimization Methods

Process Design

Find: process variables

Satisfy: process constraints

Minimize: time, cost

↔

Materials Design

Find: volume fractions, grain size, shape

Satisfy: compatibility constraints

Maximize: energy absorption, mech properties

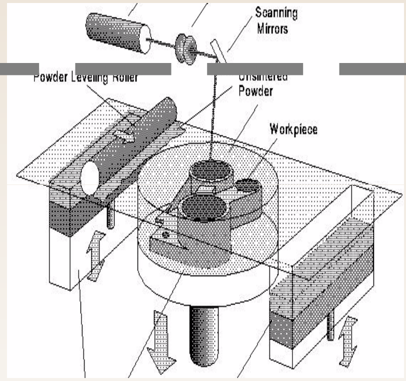
↔

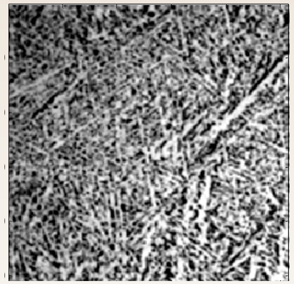
Part/Product Design

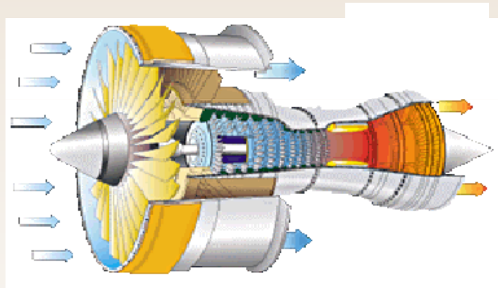
Find: dimension values

Satisfy: stress, strain

Maximize: energy absorption

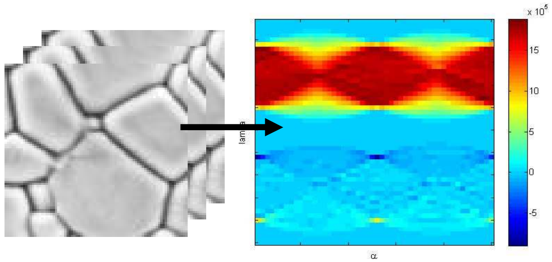




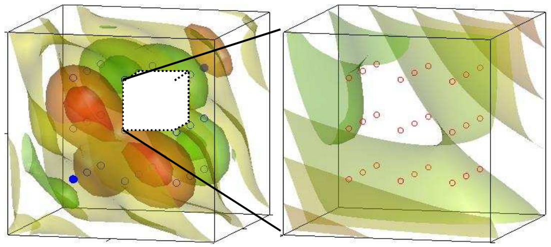


Process ↔ Structure ↔ Property ↔ Performance

Common Computer-Aided Design Models for Parts and Microstructure



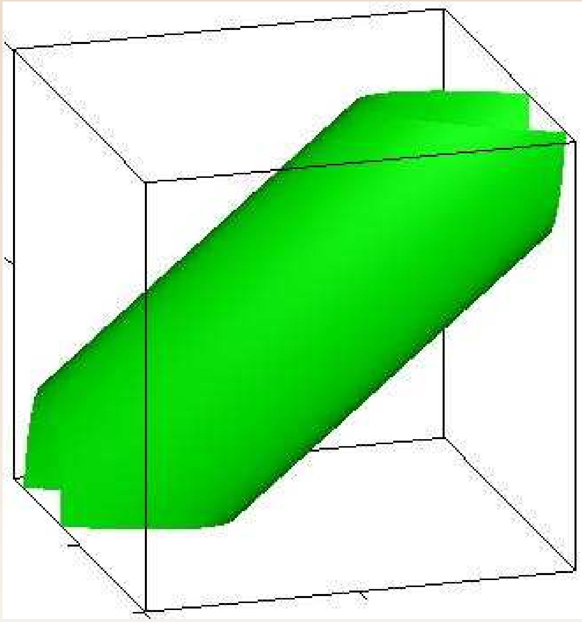
Encoding of microstructure using Surfacelet coefficients



“Zoom-in” and “Zoom-out” operations enabled by Surfacelet model

CAD methods enabled by geometric model based on wavelets and new surfacelets

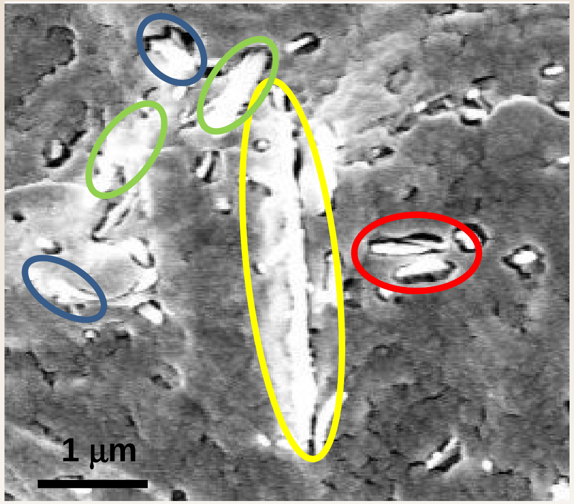
Dual-Rep Approach

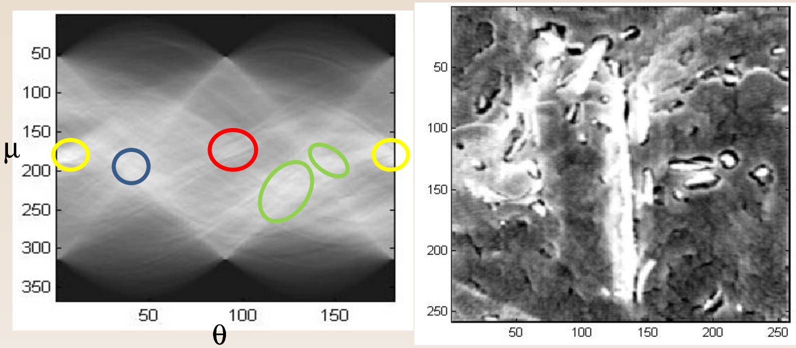


- Common geometric model for macro geometry and microstructure.
- Wavelets support multi-resolution modeling.
  - Extend to multi-scale.
  - Represent distributions of material, properties
  - inefficient in representing curve and surface *singularities*.
- Surfacelet: proposed complement to wavelets for representing boundaries.

$$y_{a,b,a,b,r_1,r_2}\left(\mathbf{r}\right) = a^{-1/2} y \left(a^{-1} \begin{bmatrix} r_1 \left(\cos b \cos a \cdot x + \cos b \sin a \cdot y + \sin b \cdot z - b\right)^2 \\ + r_2 \left(-\sin a \cdot x + \cos a \cdot y\right)^2 \end{bmatrix} \right)$$

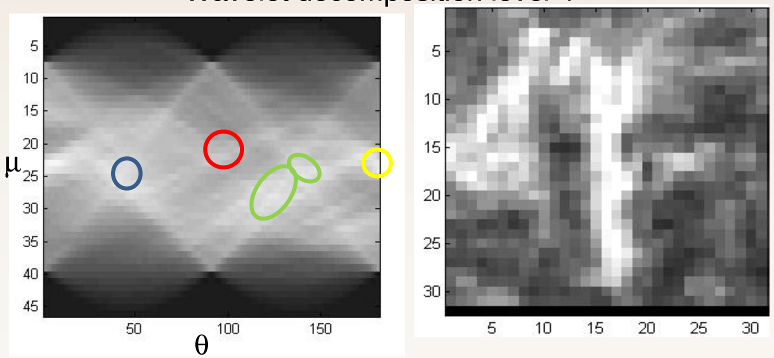
Physical CaP-PHB





a) Radon transform b) inverse Radon transform

Wavelet decomposition level 4



c) inverse wavelet transform d) inverse Radon transform

0~3° & 179~180° | 45~50° | 80~95° | 120~125° 135~140°

Three-CaP PHB fiber

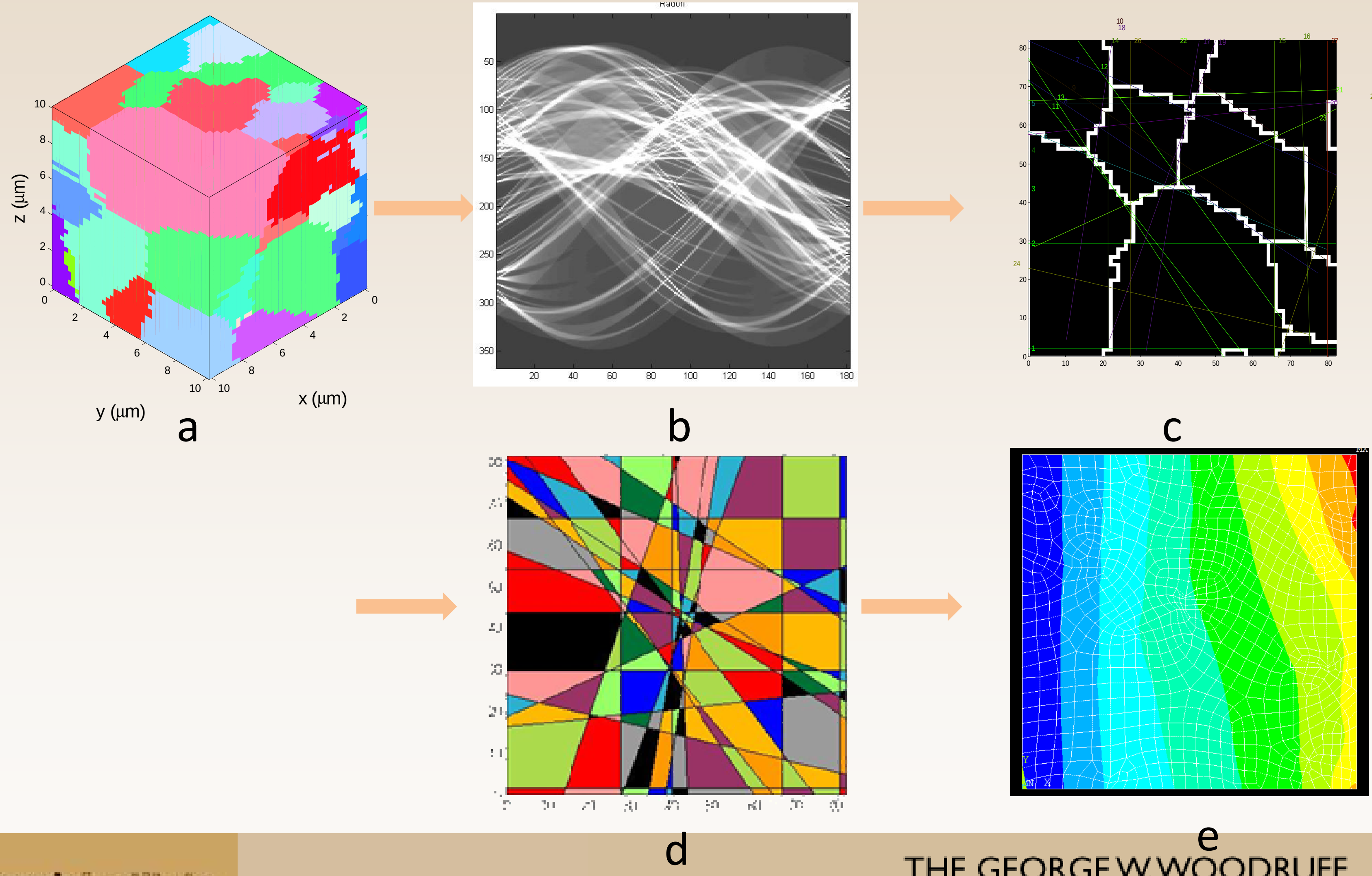
- Compute Mechanical Property From microstructure
  - Resultant elastic modulus matrix*

$$\mathbf{E} = 1e9 \begin{bmatrix} 3.93 & 0.793 & 0 \\ 0.793 & 3.26 & 0 \\ 0 & 0 & 1.59 \end{bmatrix}$$

  - Rule-of mixture : E_{eff}=3.45 GPa
  - Inverse rule-of mixture: E_{eff}=1.14 Gpa

*Kalidindi, S.R. and J.R. Houskamp 2007

IN100 Example



Computational Materials Design

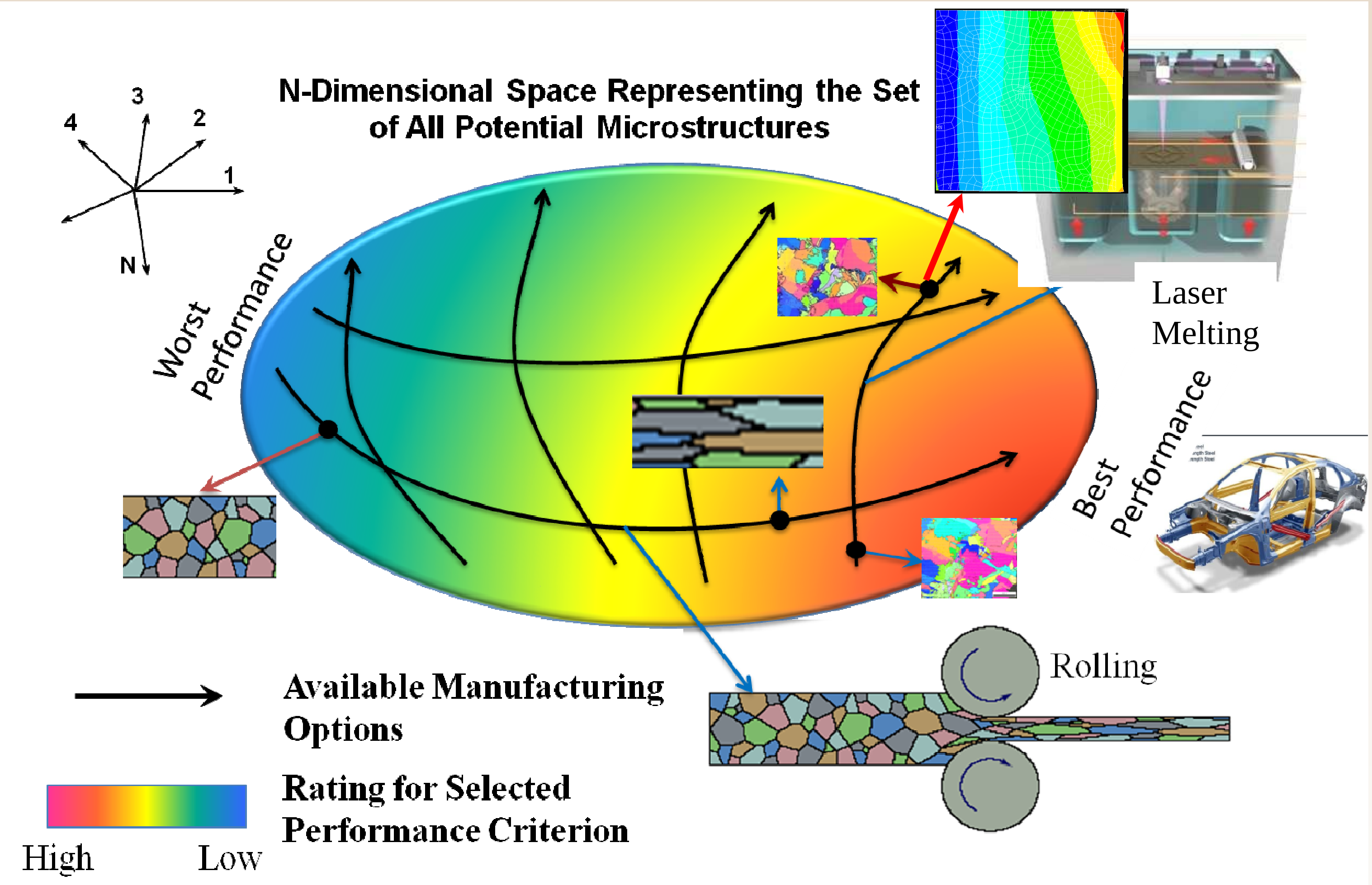


Figure courtesy Dr. Surya Kalidindi, Drexel University

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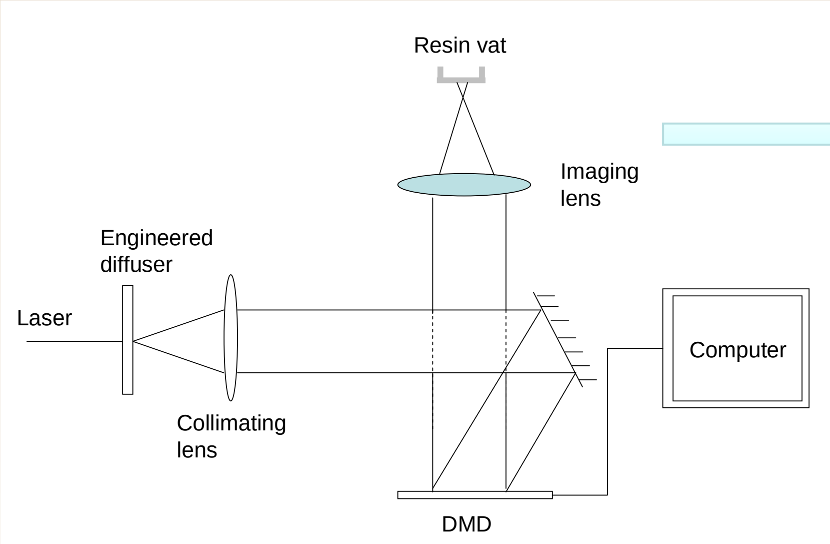
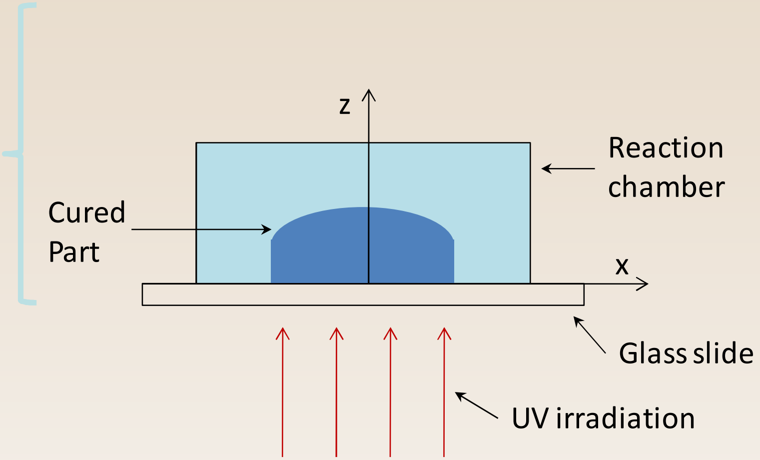
Exposure Controlled Projection Lithography



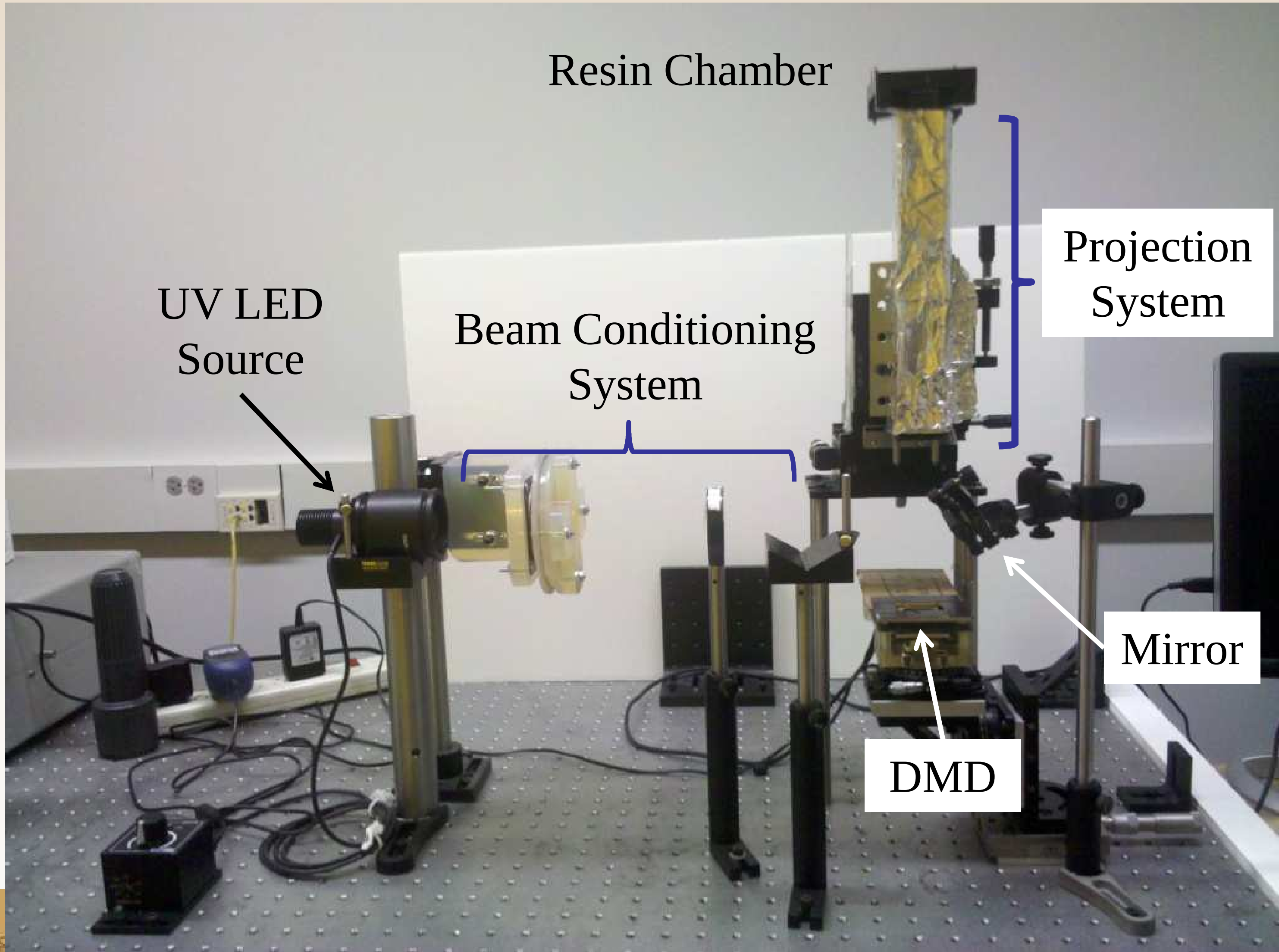


A more realistic model to predict the cured shape for a given exposure profile is required

?

Exposure (E) ←→ Cured height (z)

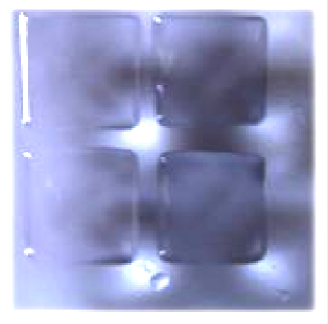
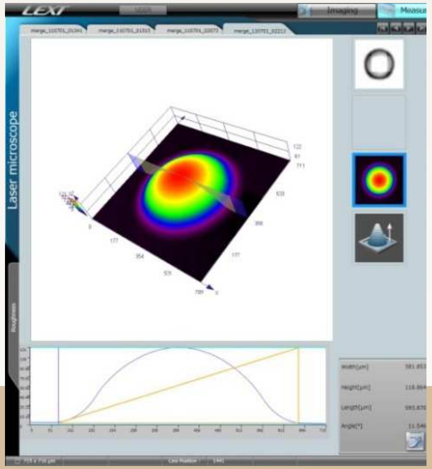
ECPL Process Overview

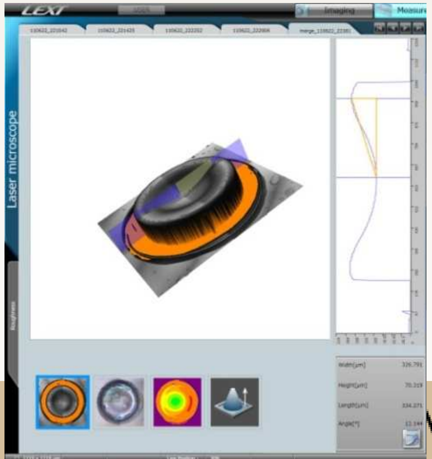


Samples Fabricated with ECPL

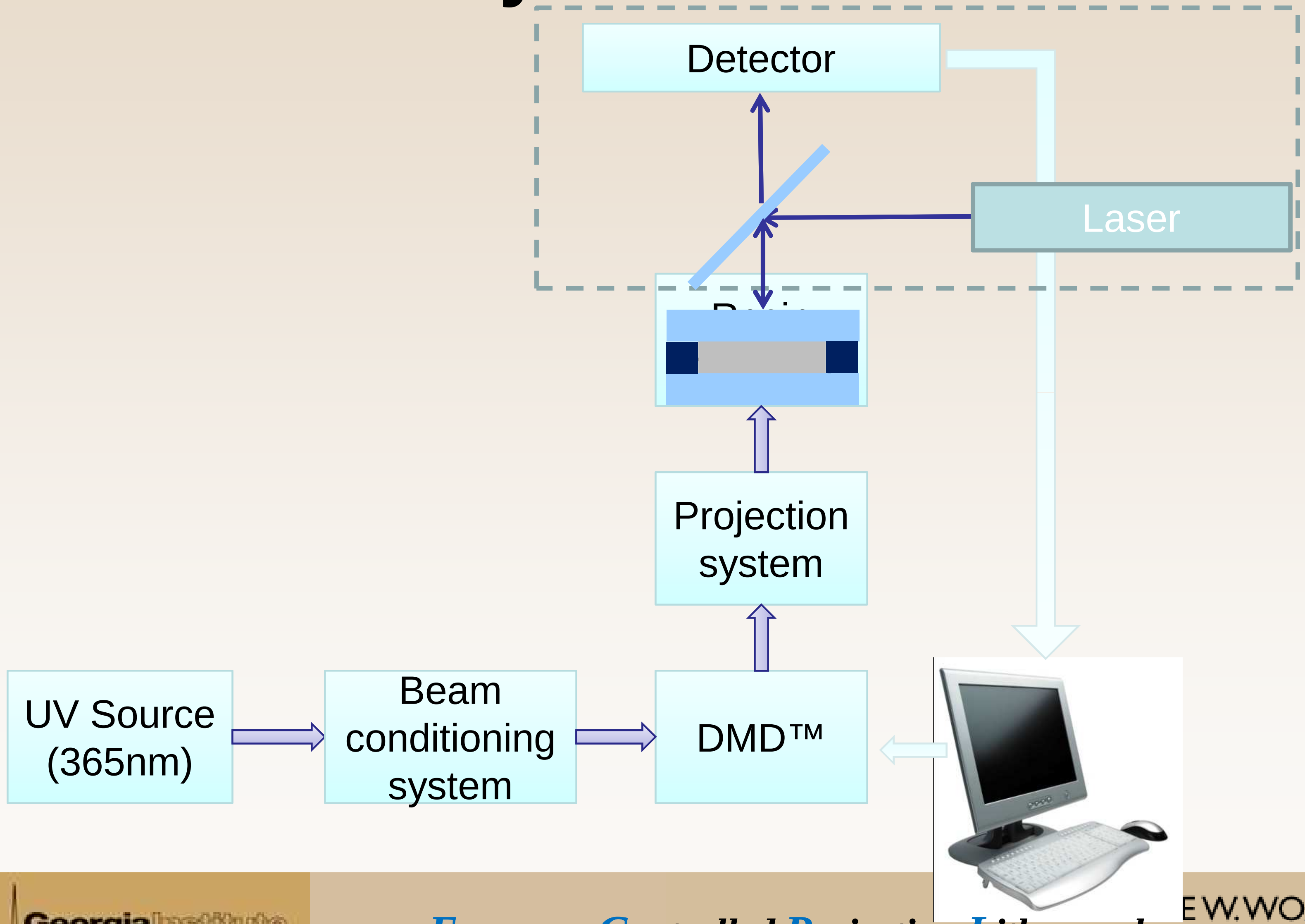
- Lenses ranging from 100µm to 10mm in a variety of shapes, with sag heights ranging from 80µm to 300µm



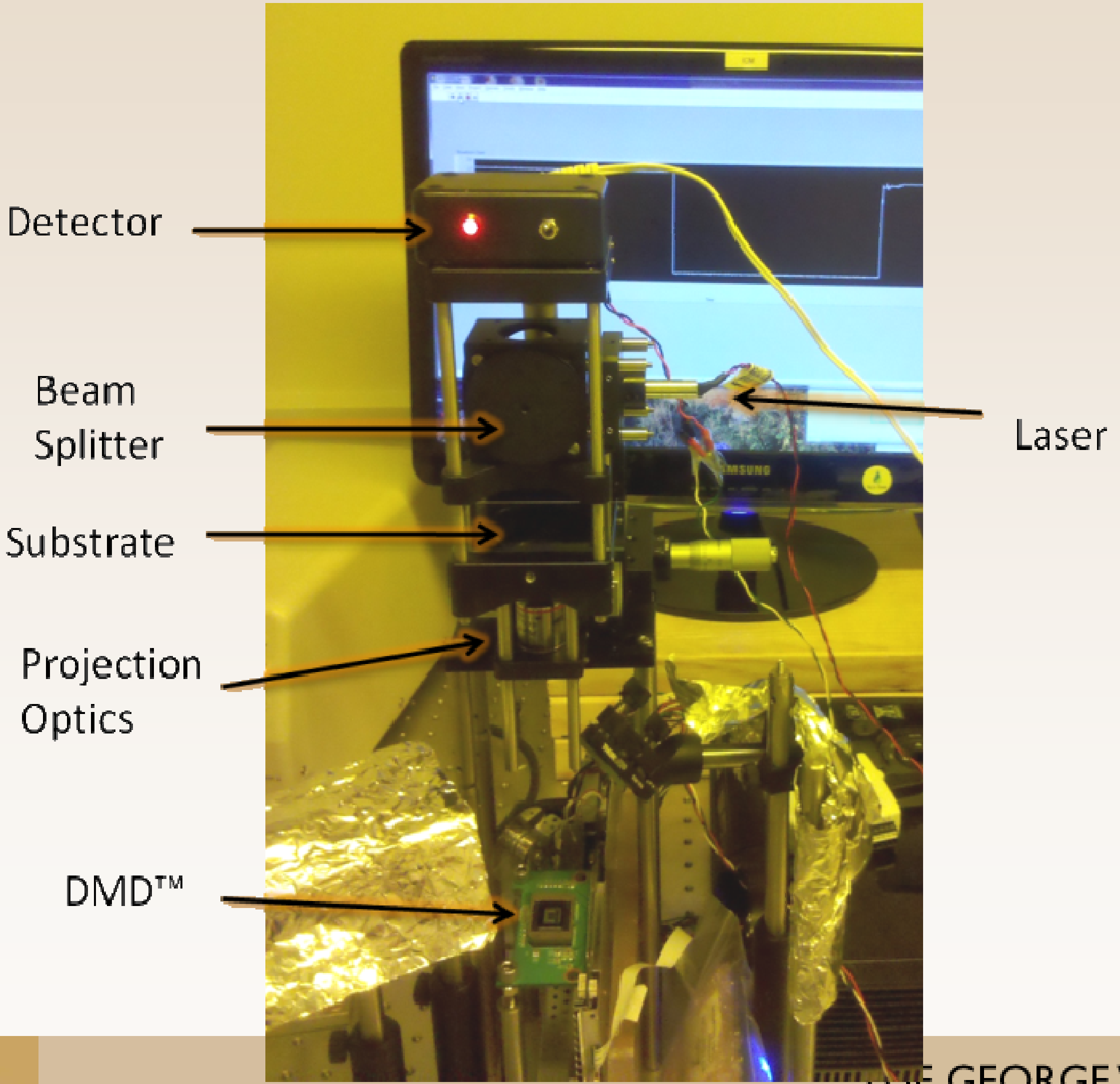





Real Time Monitoring System – System Overview



Real Time Monitoring System (Discrete point)

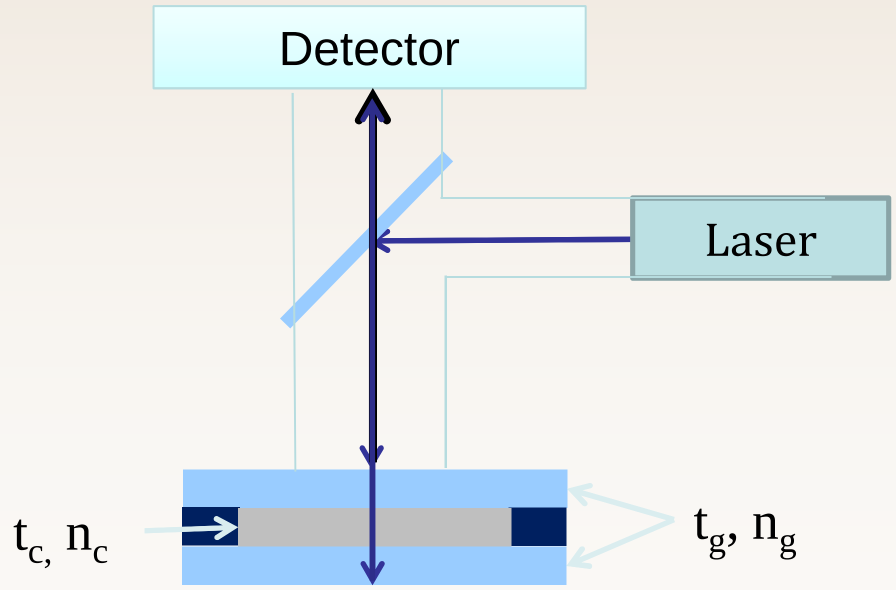


Working Principle

- Optical Path length, L = nt
- Round trip optical path length:$(4n_g t_g + 2n_c t_c)$
- Change in optical thickness by photocuring, $\Delta L = 2\Delta n_c t_c$
- Phase shift

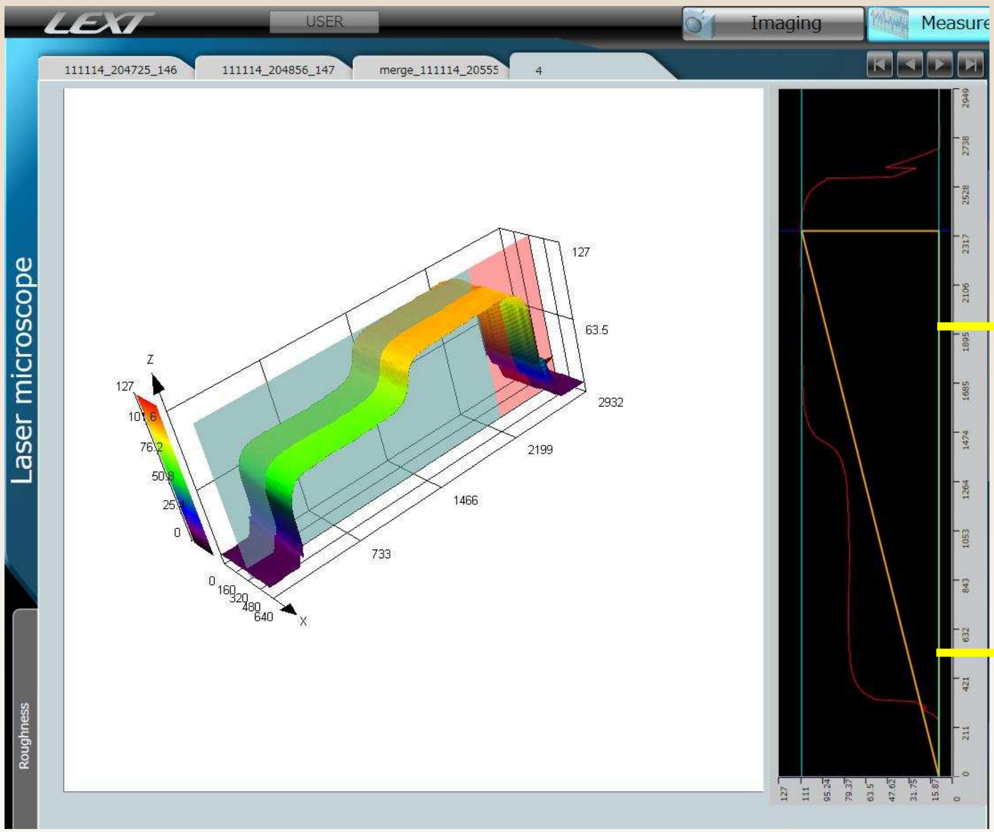
  $Ø = 2\pi \Delta L / \lambda$

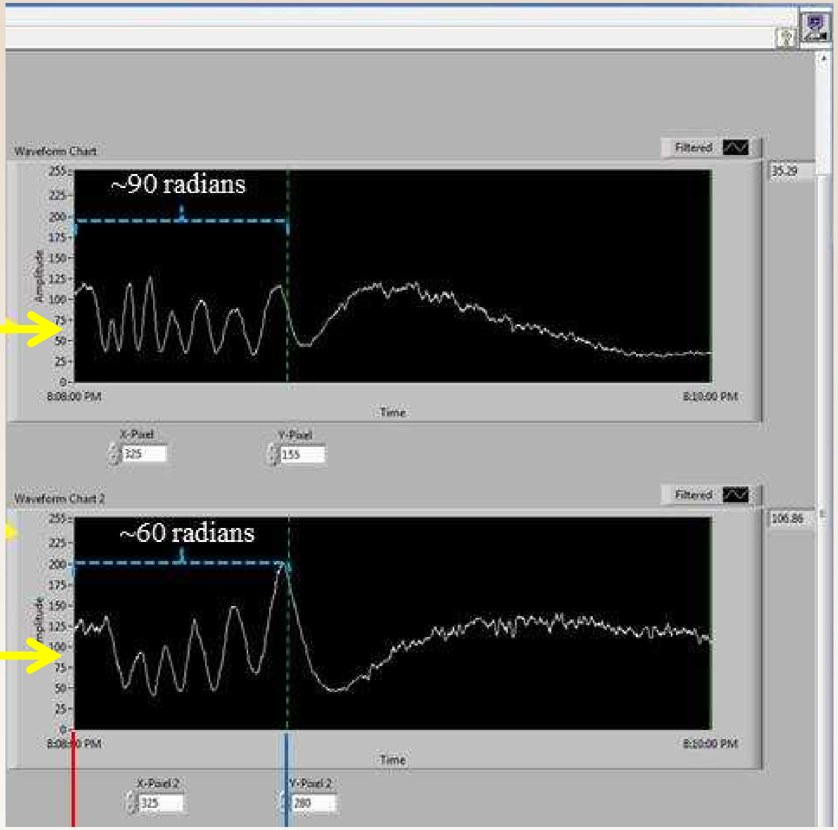
  $Ø = 4\pi \Delta n_c t_c / \lambda$



- n : refractive index
- t : thickness

Experimental Results





Snapshot of measuring the cured part from confocal microscope

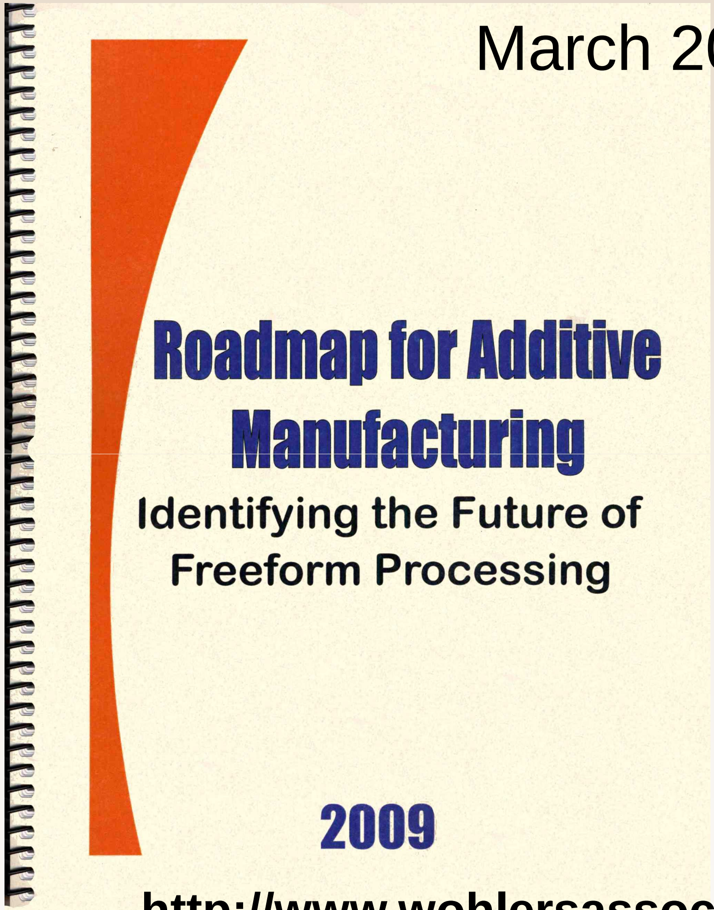
Estimated Height	Measured Height
105 µm	100 µm
64 µm	66 µm

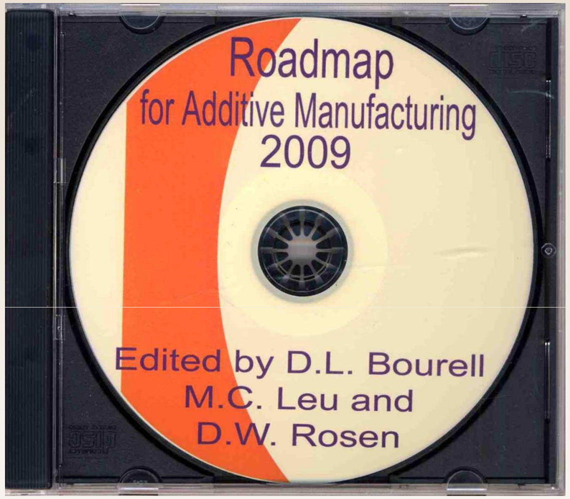
Conclusions

- Cellular materials are basis for lightweight structure design: repeated units arrayed along surfaces or fill volumes.
- TrussCreator NX: plug-in for commercial CAD that enables design, FEA, optimization of lattice structure.
- Take Advantage of AM geometric freedom.
- Size Matching & Scaling optimization method is efficient (2 variables) and effective.
- Progress toward material (process-structure-property relationships) integrated into Computer-Aided Design systems.

Roadmap for Additive Manufacturing Workshop

March 2009, US NSF, ONR funded





http://www.wohlersassociates.com/roadmap2009.html

Gibson
Rosen
Stucker

Additive Manufacturing Technologies
Rapid Prototyping to Direct Digital Manufacturing

Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing deals with various aspects of joining materials to form parts. Additive Manufacturing (AM) is an automated technique for direct conversion of 3D CAD data into physical objects using a variety of approaches. Manufacturers have been using these technologies in order to reduce development cycle times and get their products to the market quicker, more cost effectively, and with added value due to the incorporation of customizable features. Realizing the potential of AM applications, a large number of processes have been developed allowing the use of various materials ranging from plastics to metals for product development. Authors Ian Gibson, David W. Rosen and Brent Stucker explain these issues, as well as:

- Providing a comprehensive overview of AM technologies plus descriptions of support technologies like software systems and post-processing approaches
- Discussing the wide variety of new and emerging applications like micro-scale AM, medical applications, direct write electronics and Direct Digital Manufacturing of end-use components
- Introducing systematic solutions for process selection and design for AM

Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing is the perfect book for researchers, students, practicing engineers, entrepreneurs, and manufacturing industry professionals interested in additive manufacturing.

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404-894-9668 david.rosen@me.gatech.edu