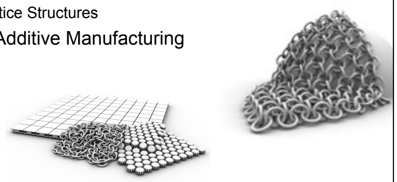
Exploiting the Design Freedoms of Additive Manufacturing for Light-Weighting and Multi-functionality

Prof Richard Hague

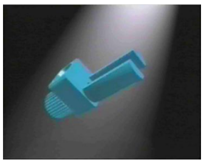
Contents

- Design for AM
  - New design opportunities
  - Limitations of existing approaches
- Design Tools
  - Customisation
  - Optimised / Lattice Structures
- Multifunctional Additive Manufacturing



Introduction

- Effectively "3D Printing"
  - Emerging from Rapid Prototyping type techniques (SL, LS, etc)
  - Conceptually simple – belies significance
  - AM is *very* different to RP – even if same systems are used
- Dedicated manufacturing systems beginning to emerge
  - Plastics
  - Metals (increasingly useful)
- Principal advantage?
  - No mould tooling
  - Un-paralleled Geometric freedom



Background

- Increasingly being used in demanding applications
- Ideal for Complex, High Value, medium-low volume, customised products

AMRG Research

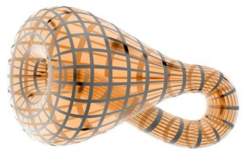
- Processes are just enablers
- The real potential of AM comes from the *Design* & *Implementation* areas
  - Design possibilities unlocked by AM capabilities
  - Need materials data to undertake design work
- Excellent potential to exploit design freedoms for radically different design potential
- Significant research still to be undertaken
  - Just "scraping the surface" at present

Geometry for "free"?

- Conventional manufacturing:
  - Costs directly linked to complexity
- Additive processes:
  - Costs linked to volume and build direction
  - Complexity (geometry) not important
  - Therefore costs independent of complexity
- Geometry / complexity for "free"
- AM will be "Manufacture for Design" (MFD)
- Without tooling, CAD becomes the new bottleneck

Problem with CAD

- CAD is seen as a great enabler, but……
  - Current CAD developed to suit traditional manufacturing techniques
  - AM able to produce virtually any complexity of parts
  - CAD not suitable for geometrical freedoms of AM
  - *New design tools required*



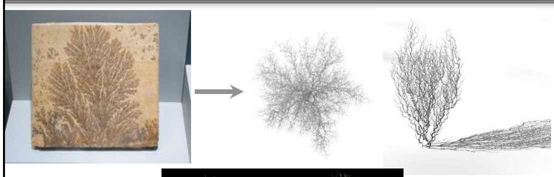
Areas of interest (to me…..)

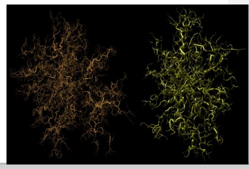
- Biomemetics
  - Optimisation, Biological structures
- Customisation
- Micro level design
  - Textures, textiles & foams
- Design possibilities / restrictions
  - polymers and metals
- All of these require new Design Tools to maximise potential

Biomemetics: Copying nature – but how??

Images from: mark.technolope.org/photo/2003/2003-07-06/list.html

Fractals



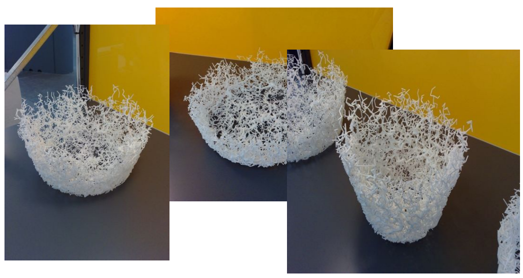


Images from: http://mark.technolope.or g/dla3d/

What practical application does this have?

http://local.wasp.uwa.edu.au/~pbourke/fractals/dla3d/

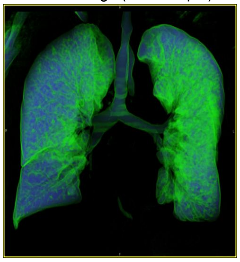
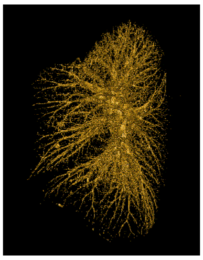
Fruit bowls by Constrained 3D DLA



Images from RCA Summer Show 2007; Student – David Sutton

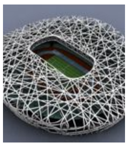
Constrained 3D DLA

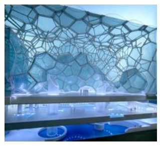
- Biomedical AM will require new design tools
  - Are lungs (for example) so different from the 3D DLA structures?

Design Optimisation / Lattices

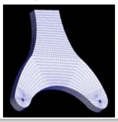
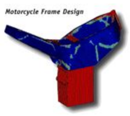
- Use of Optimisation / lattices to minimise material usage
- Potential for skeletal designs (minimisation of materials)
  - Common in construction industry due to fabrication
  - Not generally used in product manufacturing



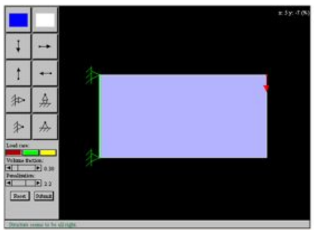


Design Optimisation

- Very likely that optimised parts would be un-manufacturable by conventional techniques
  - AM the enabling technology
  - Real opportunity for product design
    - Will require different skills
- Need to research new methods of generating optimised 3D designs – new design tools based on:
  - Genetic algorithms, Knowledge based engineering, Biomimetics - Multi Disciplinary / Objective Optimisation (MDO / MOO)

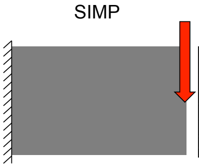
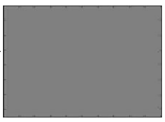
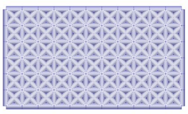



Topology Optimisation example – Uniform Stress Distribution,

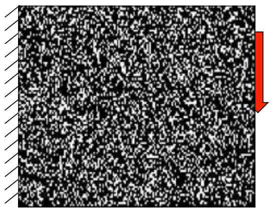
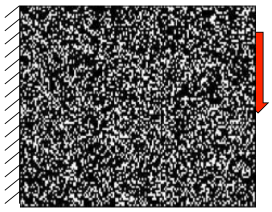



Available Mechanisms of Topology Optimisation

- Research into optimisation fundamentals and method improvement, targeted at design for additive manufacturing

SIMP	BESO	Lattices
		
Varying density between 0 and 1	Varying between 0 and 1 discretely	Sizing optimisation of predetermined lattice

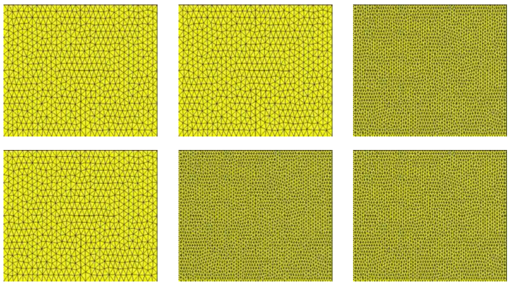
Incorporation of stochastic methods: Random starting point

Both solutions have same compliance of 1.87mm/N and volume fraction of 0.5

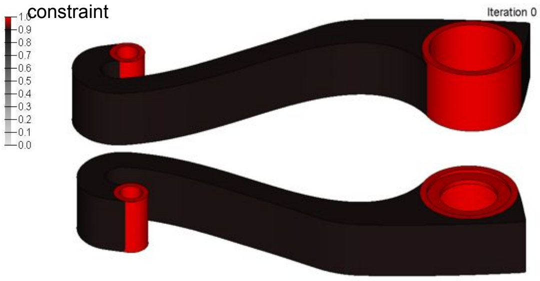
Intelligent iterative mesh refinement

- Improves efficiency and reduces sensitivity to starting mesh



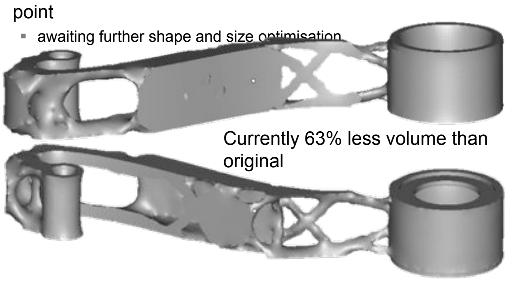
Practicalities of applied optimisation methods

- Minimise mass subject to stress constraint



Practicalities of applied optimisation methods: Smoothed

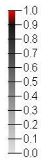
- Not the final design: topology optimisation is only the starting point
  - awaiting further shape and size optimisation



Currently 63% less volume than original

Another example

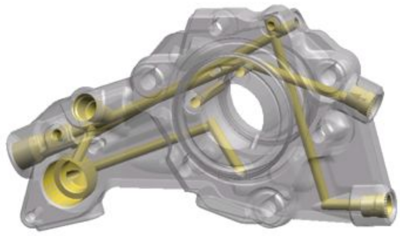
- Minimise mass subject to stress constraint



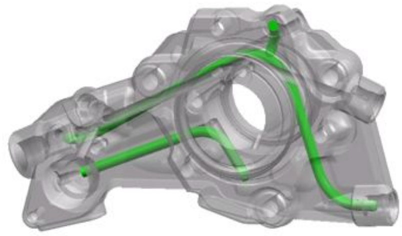
Optimisation of flow

Optimisation of flow

Optimisation of flow



Optimisation of flow



Design for Low Carbon

40% weight saving over original component design

Enabling Low Carbon Manufacturing

[redacted]

- Atkins project funded by Technology Strategy Board
  - Developing a low carbon manufacturing system based on AM for transport applications
  - £1.4M Grant, £1.4M Industry
- ATKINS exemplifies joined up research approach
  - Enabled by initial work undertaken on EPSRC projects

Project Partners

DELPHI

alcon

MTT TECHNOLOGIES GROUP

BOEING

Virgin atlantic

BENTLEY

econolyst taking a closer look

AMRG Additive Manufacturing Research Group

[redacted]

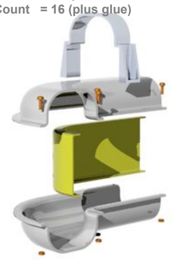
Objectives of ATKINS

[redacted]

1. Investigation of waste minimisation during production: (material recycling, optimised & repeatable)
2. Exploration of process efficiency gains wrt conventional manufacturing (AM vs casting, machining, etc)
3. Reducing transportation (digital supply chains)
4. Product design for whole life cycle impact (minimising weight)
5. Product design for optimised performance: (maximise performance)

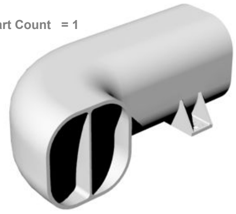
Parts Consolidation

(A) Conventional Duct fabricated from Vac Formed plastic
Part Count = 16 (plus glue)



(B) Component modified and consolidated for fabrication via Additive Manufacture

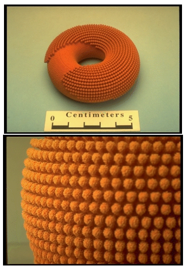
Part Count = 1



Parts Consolidation

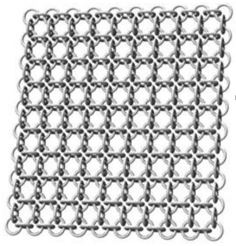
Micro-level design: Textures

- Real textures virtually impossible with conventional CAD or manufacturing
- Normally a function of the tool or manufacturing process
- Potential with AM for enhanced textures
  - Implants
  - Micro heat exchangers, etc



3D Conformal Textiles

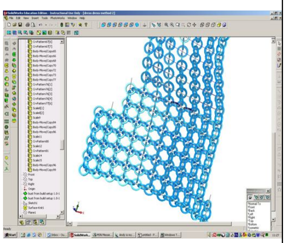
- Currently relatively easy to produced flat sheets



Courtesy of FOC

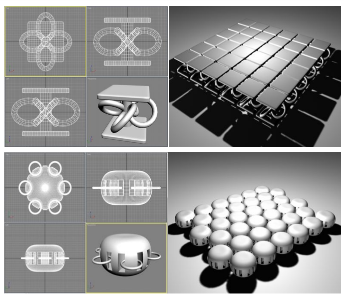
3D Conformal Textiles

- Entirely different matter when moving to fitted apparel



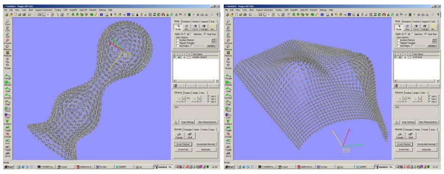
Loughborough Textile work

- Maximise geometrical freedoms
  - Move away from 'simple' links
  - Design AM textile 'linkable' structures for specific properties or applications



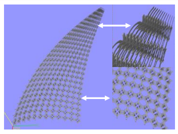
3D Conformal Textiles

- Methodology established for lofting simple links over complex shapes
  - Conformal to the shape
  - Blended links

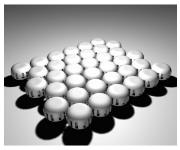


3D Conformal Textiles

- Current Limitations
  - Distortion of links resulting in deformation of resultant structure

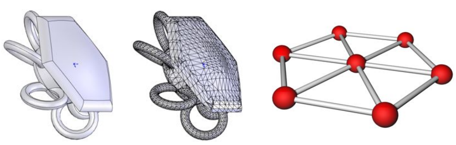


  - Inability to use complex link designs



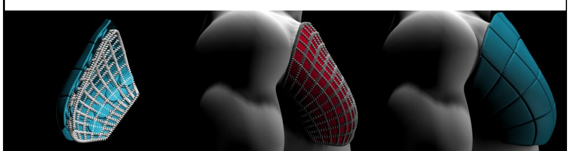
Direct Import of CAD AM textile structures

- New software developed to allow direct import of CAD data
  - AM textile single 'link' structures exported from CAD via STL format
  - STL link structure can then be mapped to the individual Nodes or Element midpoints of the mesh



Customised Personal Protective Equipment (PPE)

- Research undertaken to exploit design freedoms of AM for design & manufacture of custom-fitting PPE
  - High performance / impact resistant apparel
  - Custom-fitting, flexible & tailored to individual / sport

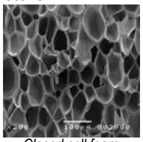


End Goal

- Customised Personal Protective Equipment, incorporating intelligent design, novel materials and integrated sensors

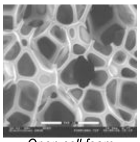
Structure of Polymeric Foam

- Characteristic compressive behaviour due to cellular structure



Closed cell foam

- Cell walls form between struts
- Isolated cells of gas
- Walls, struts and gas contribute to compressive behaviour



Open cell foam

- Cell walls receded into struts
- Gas moves freely through structure
- Struts alone contribute to compressive behaviour

Images from: Mills, N.J., Fitzgerald, C., Gilchrist, A., Verdejo, R. Polymer foams for personal protection: cushions, shoes and helmets. Composites Science and Technology. 2003;63:2389-400

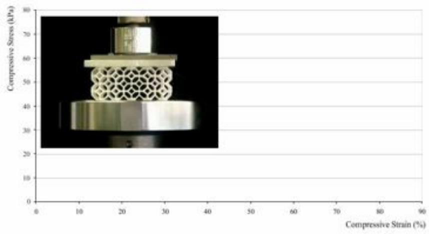
IARMS – Straight Strut Design

- An open-cell arrangement of struts forming a Kelvin structure
- File size a genuine limitation in the generation of lattice structures

IARMS – Helical Strut Design

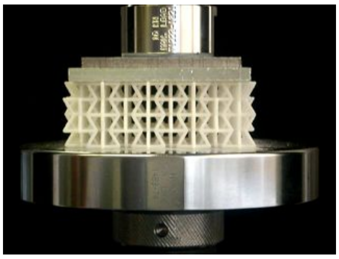
- Same underlying structure with a helical strut applied to it
- Very large file sizes
- Helix utilised to increase the length of the strut, making the structure more flexible

Straight Strut Compression



Further Work

- Auxetic IARMS



Lattice generation: Computational difficulties

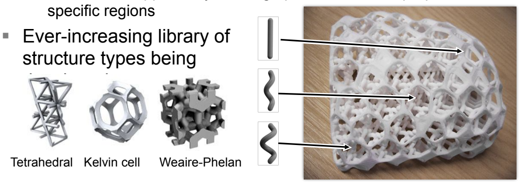
- Conventional modelling techniques (e.g. CAD) are inefficient at generating lattice structures
- Software is being developed that generates lattice structures that conform to a volume

Input volume

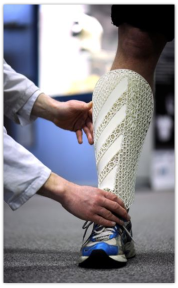
Conformal structure

Lattice generation: Structure Complexity

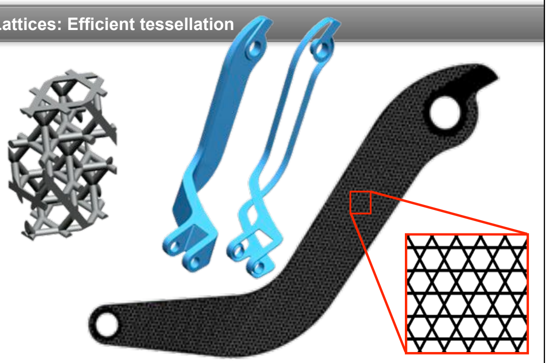
- Speed of software is largely independent of structure complexity
- Software is capable of smoothly blending between different structure types across the part – 'functional grading'
  - Presents an opportunity to design parts with varied properties in specific regions
- Ever-increasing library of structure types being



Lattice generation: Example of conformal structure

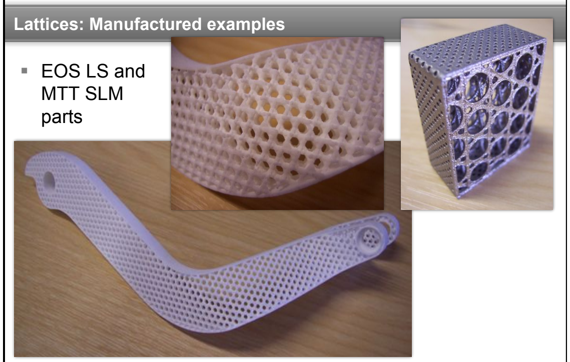


Lattices: Efficient tessellation



Lattices: Manufactured examples

- EOS LS and MTT SLM parts



Lattices: Research into efficient generation and optimisation

Functionally Graded Materials

- Technically possible to achieve FGM's
  - Not possible to achieve with current CAD systems
  - Not possible to represent graded structures
  - Probable move to voxel modelling
- Great idea in theory – very difficult to achieve in practice
- Highly problematic for recycling
  - Both at the materials processing stage
  - End of lifecycle

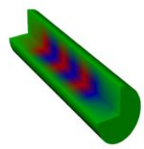


Image courtesy of TNO

Do we want multiple materials?

- Example: over-moulding
  - Over-moulding is a classic example of how a manufacturing technique can influence design:
    - allows the combination of two or more materials in one component
    - It enables extra functionality and enhanced design
  - Two or more materials to give:
    - Better design
    - More functionality
    - Better products
- What will multiple materials do for design?

Current multi-material system

RM Metals

- Great interest in metals
  - Re-engaging people with the concept of AM
    - Real materials
- Much less design freedom for metals than with plastics
  - Key difference from plastics is the need for support structures
    - Similar design restrictions to Stereolithography
  - Requires some extra thought in the design process

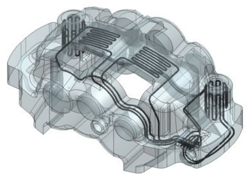
But all is not lost for metals…….

Image courtesy of MCP

Design Summary

- AM enabled by design – no AM without a 3D model (of some kind)
  - Current CAD not suitable for the complexity of parts achievable
  - New design tools required to exploit the freedoms of design
- True customisation becomes affordable
- Designers limited by materials
- Greatest challenge – cultural changes
- AM - a new industrial revolution?
- Significant opportunity for multi-material, multi-functional design systems
  - Fundamental to the new EPSRC Centre

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing



Who are EPSRC?

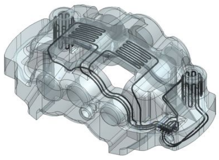
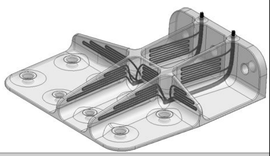
- EPSRC are the main “Science” funder for Universities in UK
  - Similar to NSF in US
- Core-business for Engineering and Physical Science disciplines / academics
  - More biased towards fundamental (low TRL) activities
- Highly Competitive / Prestigious
- Loughborough one of 12 EPSRC “Framework” Universities
- EPSRC increasingly moving to:
  - Longer-larger grants
  - Concentrating on particular subjects / people

Funded Centres

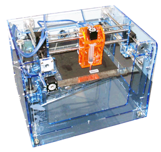
Liquid Metal Engineering	-	Brunel (Birmingham, Oxford)
Industrial Sustainability	-	Cranfield (Cambridge, Loughborough, Imperial)
Ultra Precision	-	Cranfield (Cambridge, NPL)
Through-life Engineering Services	-	Cranfield (Durham)
Regenerative Medicine	-	Loughborough (Nottingham, Keele)
Intelligent Automation	-	Loughborough (Cranfield)
Additive Manufacturing	-	Loughborough
Emergent Macromolecular Therapies	-	UCL (Imperial, LS Pharmacy)
Advanced Metrology	-	Huddersfield
Composites	-	Nottingham (Bristol, Cranfield, Manchester)
Photonics	-	Southampton
Continuous Manufacturing & Crystallisation	-	Strathclyde (Bath, Glasgow, Herriot Watt Loughborough, Edinburgh, Cambridge)

EPSRC AM Centre

- EPSRC - £5.2M grant, 5 years, start Oct 2011
- Centre Vision:
  - *The creation of multi-material, multifunctional products and components enabled by Additive Manufacturing to amalgamate electrical, optical and structural properties within a single manufacturing process*

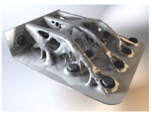
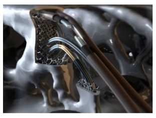



Multifunctional AM today



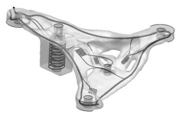
Challenges

- Move from single materials, passive AM to multifunctional “active” AM
- Based on exploiting the design freedoms of AM to print systems in one go
- Based on existing AM philosophy, but not on existing equipment
  - Much process and material development
  - Underpinning design systems

Location

- Nucleus of the Centre is located at Loughborough
- Investigators
  - Richard Hague (Director), Phil Dickens, Neil Hopkinson, Russ Harris, Chris Tuck, Paul Conway, Ricky Wildman, Ian Ashcroft
  - Will pull in external expertise where required (eg optics)
- Has a remit to also act as a National Centre
  - Outreach, coordination, dissemination



Our Partners

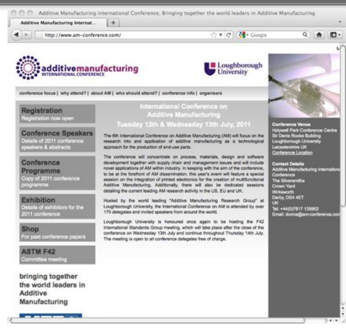
Flagship Themes

- Multi-functional AM Processes, Materials and Design Systems
  - Design Systems
  - New processes based on Jetting, Powder, Solid State
    - Not embedding, but printing
- Scaling down
  - meso / micro scale multifunctional AM

EPSRC Centre Summary

- Excellent opportunity to move research area forwards
  - Won't mean the end of existing work (single material), but this will not be EPSRC funded
  - Current set-up used increasingly for EU Framework / TSB-type activity / Knowledge Transfer / Contract research
- New research area very challenging
  - important to hit the ground running

Shameless advertising……



Questions?

r.hague@lboro.ac.uk

www.lboro.ac.uk/amrg

www.am-conference.com