Topology optimization for additive manufacturing: accounting for overhang limitations using a virtual skeleton

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Context – AATiD consortium

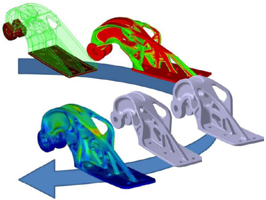
Develop advanced technologies for design and 3-D printing of optimized complex aero-structures made of Titanium alloys, Ti-6Al-4V

Detailed goals:

- Identify cost-effective parts, material qualification, optimize process, simulate process, welding of printed parts, ...
- Use **topology optimization** to achieve superior aero-structures design compared with traditional design, in terms of weight, cost and performance;
- **Embed printing technologies' limitations in the structural design process**.

Coupling TopOpt and Titanium AM

Airbus A320 nacelle hinge bracket [Tomlin and Meyer, 2011]:



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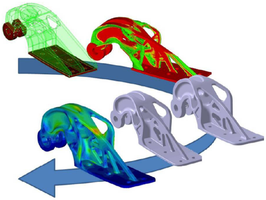
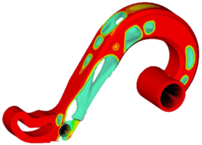
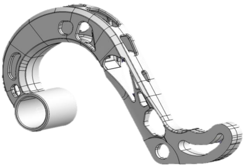


IAI Gulfstream G250 gooseneck hinge [Muir, 2013]:





Challenges in AM

Additive manufacturing typically requires **extensive support material** to prevent curling and distortion:

- Support overhang / inclination angle;
- Support horizontal bridging distances;
- Improve heat transfer.

Support material **counter-balances achievements of optimal design**:

- Longer build time, more material usage;
- Extensive rework required for removing supports;
- Difficulties in clearing supports in internal holes;
- Compromise on stiffness-to-weight.

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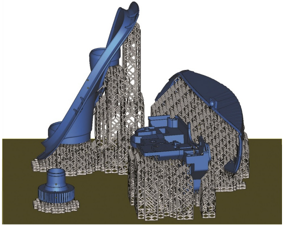

Support structure (Materialise)

Dealing with overhang limitations

Necessary to embed the support requirement into the optimization

- Post-process an optimized design?
- Optimize for no-support?
- Optimize for minimum support?
- Optimize the build direction?

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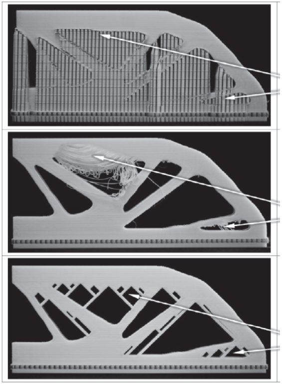
Post-process via geometry
[Leary et al., 2014] →



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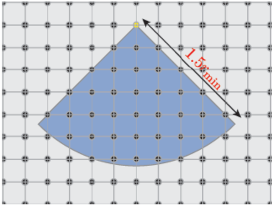
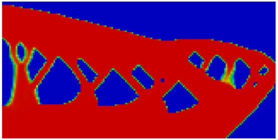


Use projection method to require support in specified angle [Gaynor, 2015] →



Current research

Goal: Derive a procedure that can account for a given overhang limitation

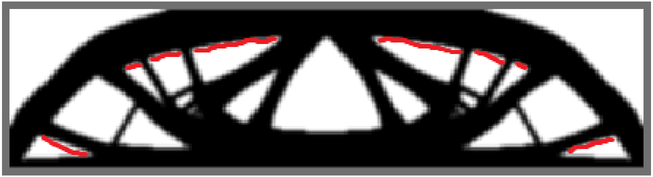
Desired features:

- Can generate designs with no support;
- Can generate designs with limited support;
- To be investigated in 2-D but extendable to 3-D;
- Minimal compromise on performance $\equiv$ stiffness-to-weight trade-off.

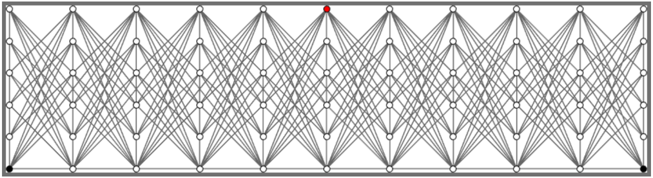
Virtual skeleton approach

Main idea: allowable directions defined on a discrete line model (truss...) $\rightarrow$ virtual scaffold for continuum topology optimization

Standard TopOpt



AM-oriented truss

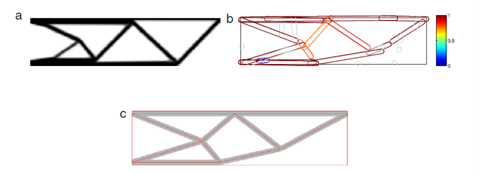


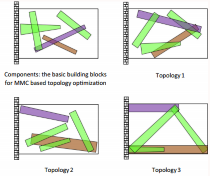
Mapping truss-continuum

The work is inspired by several recent ideas:

[Norato et al., 2015], [Zhang et al., 2016]

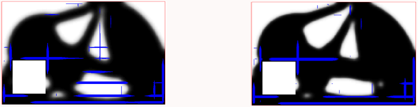
Optimize size & location of bars, project to continuum





OA, 2013

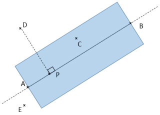
Truss-continuum filter to enforce bars to be covered

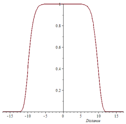


Mapping truss-continuum

Initial trials:

- Define compatible truss ground structure with allowable bars only
- Truss bar areas **a** are the design variables, mapped to continuum domain by super-gaussian function, $\rho_j = \sum_i e^{-\left(\frac{2\cdot d_{ij}}{a_i}\right)^N}$





- Response evaluated on continuum with density $\boldsymbol{\rho}(\mathbf{a})$

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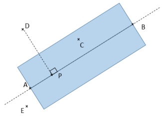

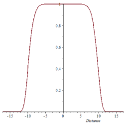

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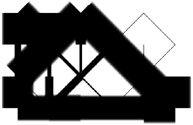
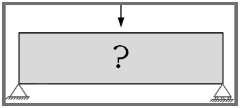
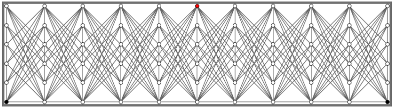
Results not encouraging...
basically a truss-looking design



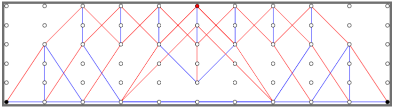
Suggested procedure (1)

1. Define continuum design domain, generate standard ground structure
2. Define AM-compatible ground structure: suppress excessive overhang bars and horizontal bars





3. Optimize truss using well-established procedures: min. c s.t. V

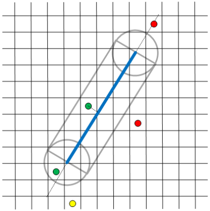


$\rightarrow$ obtain bar areas $\{\mathbf{a}\}$

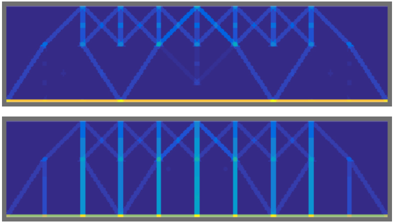
Suggested procedure (2)

4. Map optimized truss bars to prioritized continuum → matrix [**T**]

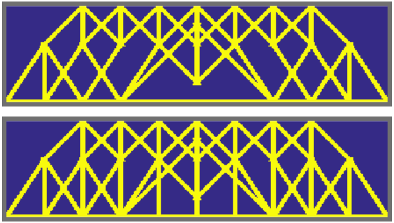
- Distance between element and truss bar $\leq d_{max}$
- Distance between element and truss bar $> d_{max}$
- Element can anchor the bar to the printing bed



[**T**] depends on sizes of {**a**}



[**T**] depends on topology of {**a**}



Suggested procedure (3)

5. Run standard topology optimization: min. c s.t. V:
   - Use $[\mathbf{T}]$ as an initial guess
   - Define priority to material points coinciding with the mapped truss:

$$E_e = (E_{min} + \widetilde{\rho}_e^p (E_{max} - E_{min}))(1 + T_e(\alpha^+ - 1))$$

   - Optionally, penalize void regions that coincide with the mapped truss:

$$E_e = (E_{min} + \widetilde{\rho}_e^p (E_{max} - E_{min}))(1 + T_e(\alpha^+ - 1)) - (1 - \widetilde{\rho}_e^p)(E_{max} - E_{min}) T_e \alpha^-$$

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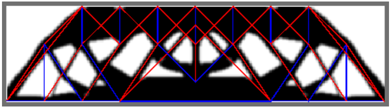

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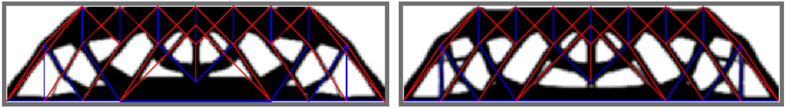
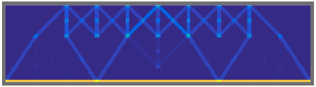
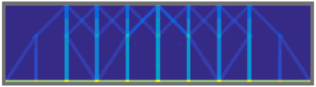
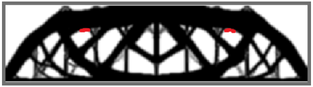


Preliminary results

Simply supported beam, printing -Y

$d_{max} = 2,\ \alpha^{+} = 10,\ \alpha^{-} = 10,\ 45^{\circ}$ overhang

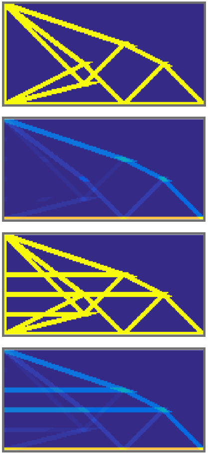
$[\mathbf{T}]$	$\widetilde{\boldsymbol{\rho}}$	compliance $\Uparrow$
		15%
		24%
		19%
		21%

Preliminary results

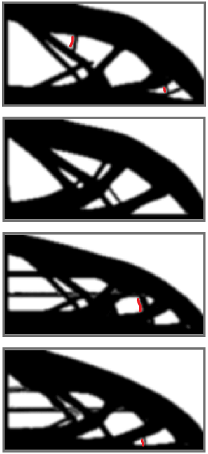
Simply supported beam, symmetric half, printing -X

$d_{max} = 2$, $\alpha^{+} = 10$, $\alpha^{-} = 10$, 45° overhang

[T]



$\widetilde{\rho}$



compliance ⇑

6%

7%

12%

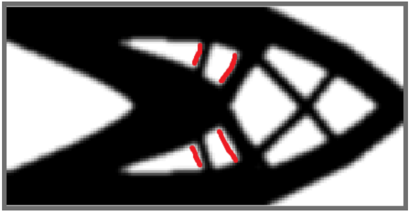
15%

Preliminary results

Cantilever beam, baseline design

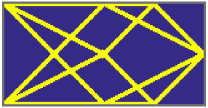
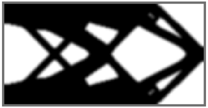
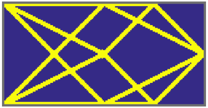
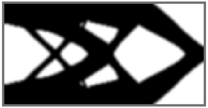
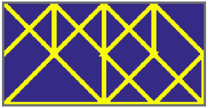
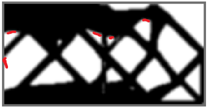
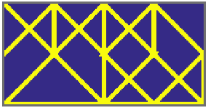
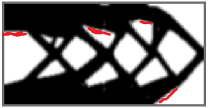
printing -Y

printing -X



Preliminary results

Cantilever beam, various options

options	[T]	$\widetilde{\boldsymbol{\rho}}$	compliance $\Uparrow$
-X, $\alpha^{+} = 10$, $\alpha^{-} = 10$			5%
-X, $\alpha^{+} = 5$, $\alpha^{-} = 0$			3%
-Y, $\alpha^{+} = 10$, $\alpha^{-} = 10$			19%
-Y, $\alpha^{+} = 5$, $\alpha^{-} = 0$			7%

Conclusions

- Simple approach, based on two standard procedures
- Possibility for control: truss ground structure, d_{max}, penalties α^+, α^-, overhang angle, ...
- Easy to define and compare printing directions
- Buildability not 100% guaranteed, some post-processing may be required
- Compromise on optimized performance
- 3-D needs some thought...

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Thank you for listening

Sliced approach

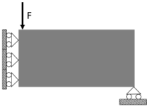

Figure 10: MBB beam model

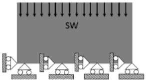

Figure 11: Vertical self-weight model

Figure 12: Horizontal self-weight model

Figure 13: One slice, $\theta = 1.3e^{-5}$, $f = 257$

Figure 14: One slice, $\theta = 2e^{-5}$, $f = 228$

Figure 15: Five slices, $\theta = 1.3e^{-5}$, $f = 268$

Figure 16: Five slice, $\theta = 2e^{-5}$, $f = 227$

Figure 17: Ten slices, $\theta = 1.3e^{-5}$, $f = 331$

Figure 18: Ten slice, $\theta = 2e^{-5}$, $f = 231$

Figure 19: $\theta = 0$, $f = 214$

Figure 20: Example of design produced with 'horizontal' printing

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