Topology optimization procedure TOPOPTIM V2.1

History, improvements and new features in comparison to the first version

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Outline

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1. **Principle**

2. Basic Examples

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Topology optimization principle

- Optimal distribution of a material in a specified 2D or 3D design domain Ω
- Considering a given volume V occupied by the material
- Constraints and equilibrium have to be satisfied

$\rightarrow$ Iterative process minimizing/maximizing a physical quantity
(*e.g.* compliance/stiffness)

- Often based on the Finite Element Method
- Topology can be parametrized by a scalar element field $\phi(x)$
  - $\phi = 0$ void
  - $\phi = 1$ material

$\rightarrow$ For minimum compliance design with an isotropic material:
$E(x) = \phi(x) E_0$; $\int_{\Omega} \phi(x) \, d\Omega \leqslant V$; $0 \leqslant \phi \leqslant 1$; $x \in \Omega$

Reference codes and TOPOPTIM

- O. Sigmund's "88 lines code"
  - Penalty factor $p > 1$ to steer the solution to solid-void (or black and white): $E(x) = \phi(x)^p E_0$
  - Lower bound $\phi_{\min}$ instead of 0 to prevent any possible singularity of the equilibrium problem
  - Optional fixed solid region and fixed void regions in sub-area of the reference domain

- W. Hunter's TOPY code
  - Gray Scale Filtering to yield predominantly, or even purely, solid-void designs

- TOPOPTIM V1.0 (presented at Club Cast3M 2014)
  - Elements reaching the lower bound $\phi_{\min}$ are automatically (and temporarily) removed for better efficiency
  - The mesh is not necessary structured
  - The optimal shape mesh is given as output
  - Fully interpreted code (Gibiane language) easy to modify to combine TOPOPTIM with all other possibilities offered by Cast3M

- TOPOPTIM V2.1
  - Same as TOPOPTIM V1.0 with various additional features...

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Examples of optimized topology
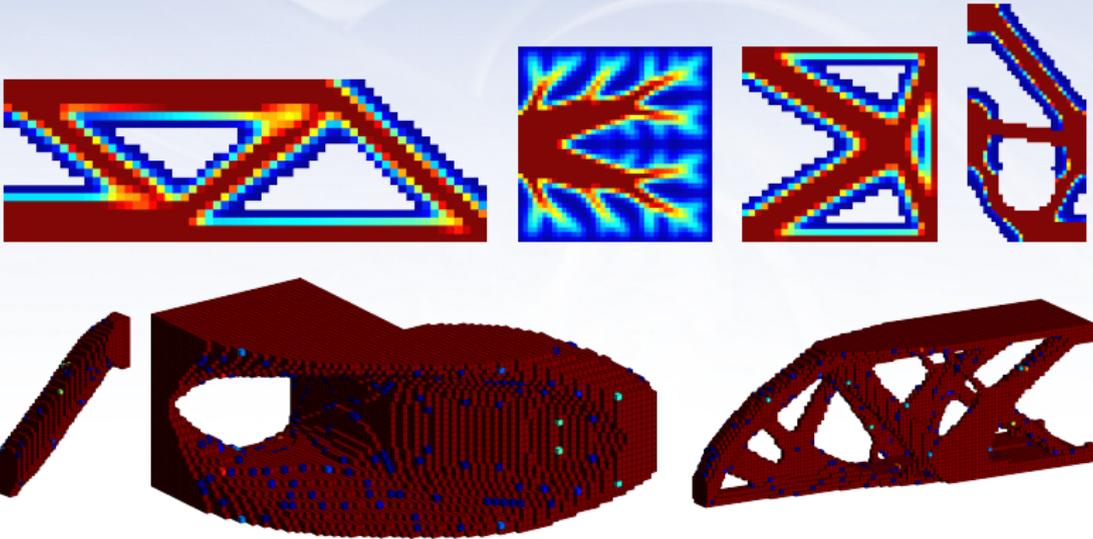
These examples were initially developed with TOPOPTIM V1
and presented at Club Cast3M 2014

They have been updated to make them compatible with TOPOPTIM V2
(the output topology is not affected)

Example of script: 2D MBB beam problem

```
01 * General options
02 OPTI 'DIME' 2 'MODE' 'PLAN' 'CONT' 'ELEM' QUA4 ;
03
04 * Mesh
05 nelx0 = 60 ;
06 nely0 = 20.0 ;
07 p0 = 0.0 0.0 ;
08 p1 = 0.0 (FLOT nely0) ;
09 p2 = (FLOT nelx0) 0.0 ;
10 lgn0 = DROI nely0 p1 p0 ;
11 msh0 = TRAN lgn0 60 p2 ;
12 p2 = msh0 POIN 'PROC' p2 ;
13
14 * Model and material
15 mod0 = MODE msh0 'MECANIQUE' 'ELASTIQUE' ;
16 mat0 = MATE mod0 'YOUN' 210.0e9 'NU' 0.3 ;
17
18 * Boundary conditions and loading
19 bc0 = (BLOQ 'UX' lgn0) ET (BLOQ 'UY' p2) ;
20 load0 = FORC (0.0 -1.0) p1 ;
```

```
21 * Finite element model table
22 mdl0 = TABL ;
23 mdl0.'MODELE' = mod0 ;
24 mdl0.'CARACTERISTIQUES' = mat0 ;
25 mdl0.'BLOCAGES_MECANIQUES' = bc0 ;
26 mdl0.'CHARGEMENT' = load0 ;
27
28 * Optimization table
29 tab0 = TABL ;
30 tab0.'RESOLUTION_LINEAIRE' = mdl0 ;
31 tab0.'FRACTION_VOLUME' = 0.5 ;
32
33 * Optimization
34 TOPOPTIM tab0 ;
35
36 * Plot to screen
37 topo0 = tab0.'TOPOLOGIE'.(tab0.'CYCLE') ;
38 topomsh0 = tab0.'MAILLAGE'.(tab0.'CYCLE') ;
39 TRAC (REDU topo0 topomsh0) (REDU mod0 topomsh0)
40     (PROG 0.0 'PAS' (1.0 / 56.0) 1.0) ;
```
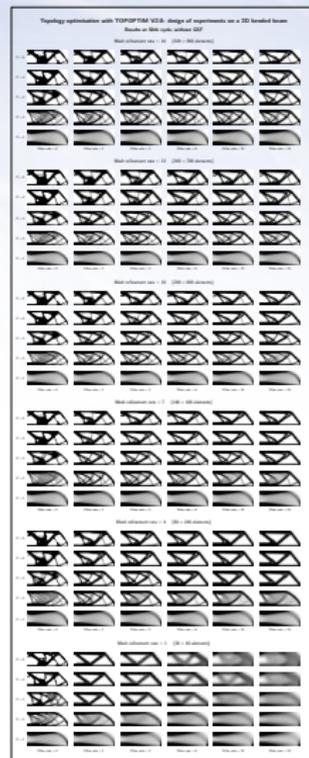
Influence of the optimization parameters

Design of experiments on 2D MBB beam problem without GSF:

- 6 mesh refinement rates (from 20×60 to 320×960 elements)

- 5 values of P factor (1 to 5)

- 6 values of Filter rate (1 to 15)

See files Topoptim_DoE.pdf and Topoptim_DoE_BnW.pdf

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Improvement of the performances

- In TOPOPTIM 1.0, on larger meshes, low performances were observed using ELEM 'SUPE' for removing the elements whose density decreased below a given threshold value.

- In TOPOPTIM 2.1, the performances are improved by using POSI 'DANS' in combination with MASQ 'SUPE'.

Restarts or non-homogeneous initial state

- It is now easier to continue a suspended topology optimization by giving the same table and

  - Changing the maximum number of cycles if the previous value was reached
  - Changing the convergence criterion if convergence was reached
  - Other data can also be specified/modified such as the P factors, the GSF and also the mesh in case of remeshing

- An input topology can be specified and

  - It does not longer need to be supporter by the mesh of the model to be optimized.
  - Only the occupied domains of the topology mesh and the model mesh should be identical.

Remeshing

The input topology does not need to fit the elements of the input mesh
making remeshing during optimization easier

Nonlinear behaviors and multiphysics

Compatibility with `PASAPAS` procedure allowing:

- Plasticity / Anisotropy
- Dynamic
- Contact
- Large strains
- Large displacements
- Large rotations
- ...

Example of non-linearity: Contact

Contact between a rigid sphere (on top, not represented)
and a purely elastic support to be optimized to minimize its compliance

Geometric restrictions

- Geometric restrictions (constraints) can be applied on the topology

  - Central symmetry
  - Axial symmetry
  - Planar symmetry
  - Axial periodicity
  - Circular periodicity

- All geometric restrictions can be combined together

- All geometric restrictions can be applied on the total domain
  or a sub-domain

Geometric restrictions

Symmetry along a horizontal axis

Geometric restrictions

Circular periodicity

Geometric restrictions

Linear periodicity on a sub-domain

Compliant Mechanism: 2D Inverter

Compliant Mechanism: 3D Griper

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Compliant Mechanism: 3D Griper

External procedures

- `TOPOMATE` update the material properties to take into account the new density at each cycle just before the resolution
- `TOPORSTR` adds the geometric restrictions
- `TOPOFILT` filters the sensitivity field
- `TOPOCRIT` update the optimal criterion
- `TOPOSAUV` saves some results during the optimization

All these procedures can be easily redefined by the user.

In addition, a user defined procedure `TOPOPERS` can be called at each optimization cycle, just after the resolution.

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Topology smoothing procedure: TOPOSURF

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STL Import/Export function

- Topology results (`possibly smoothed from TOPOSURF`) were previously exported in STL using `SURF2STL`.

- `SURF2STL` was latter translated in Fortran (Thanks Clément Berthinier).

- `SORT 'STL'` is now called to generate STL files and can be used to 3D print the topologies.

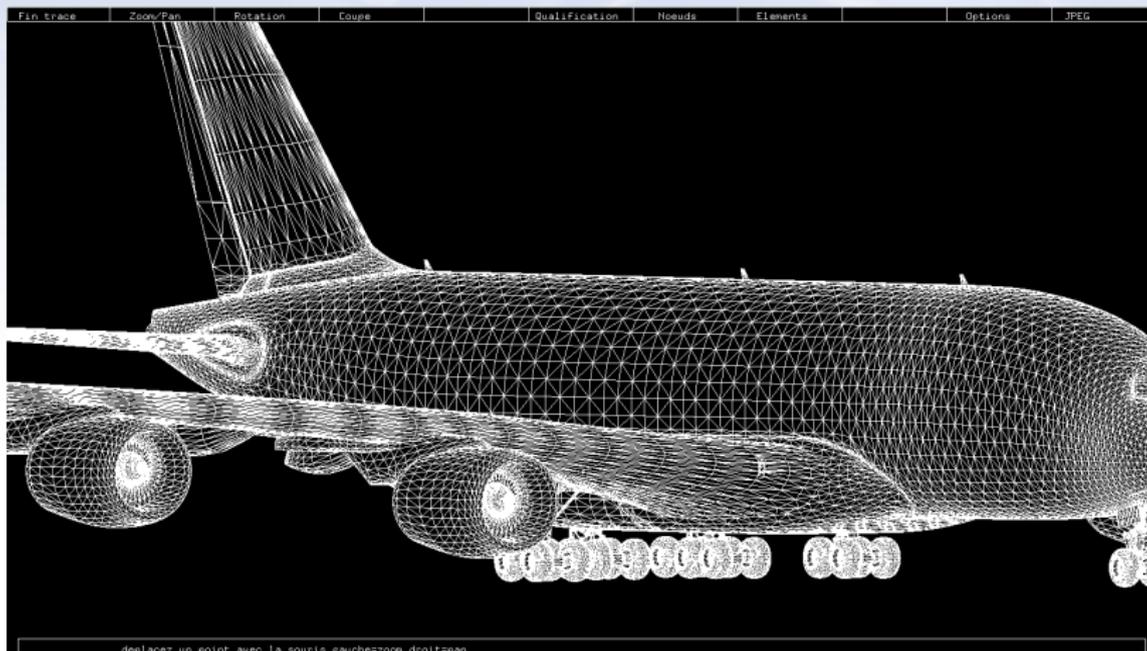- If needed STL files can also be imported in Cast3M (Thanks Clément Berthinier again) using `LIRE 'STL'`.

Example of STL Export
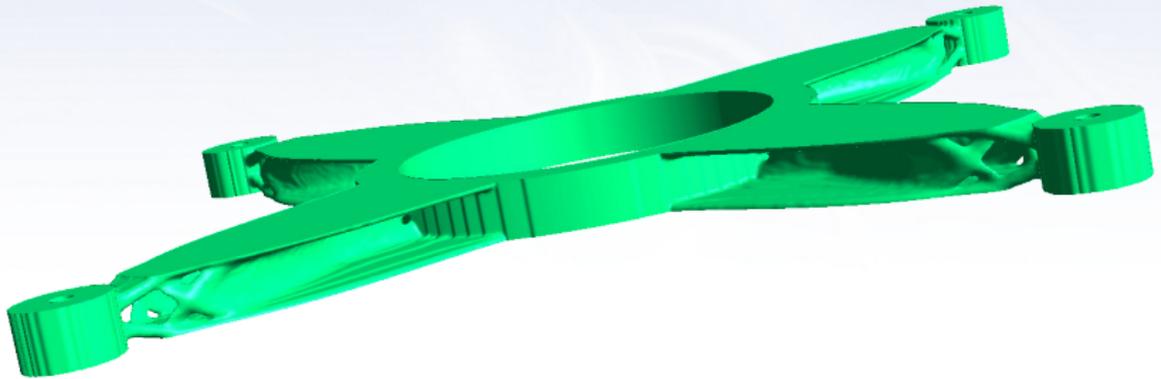
Mini drone frame sent to 3D printing.

This work was made by engineering students Romain Cleurennec and Marc Perruchaud in 2016

under the supervision of Éloi Dion.

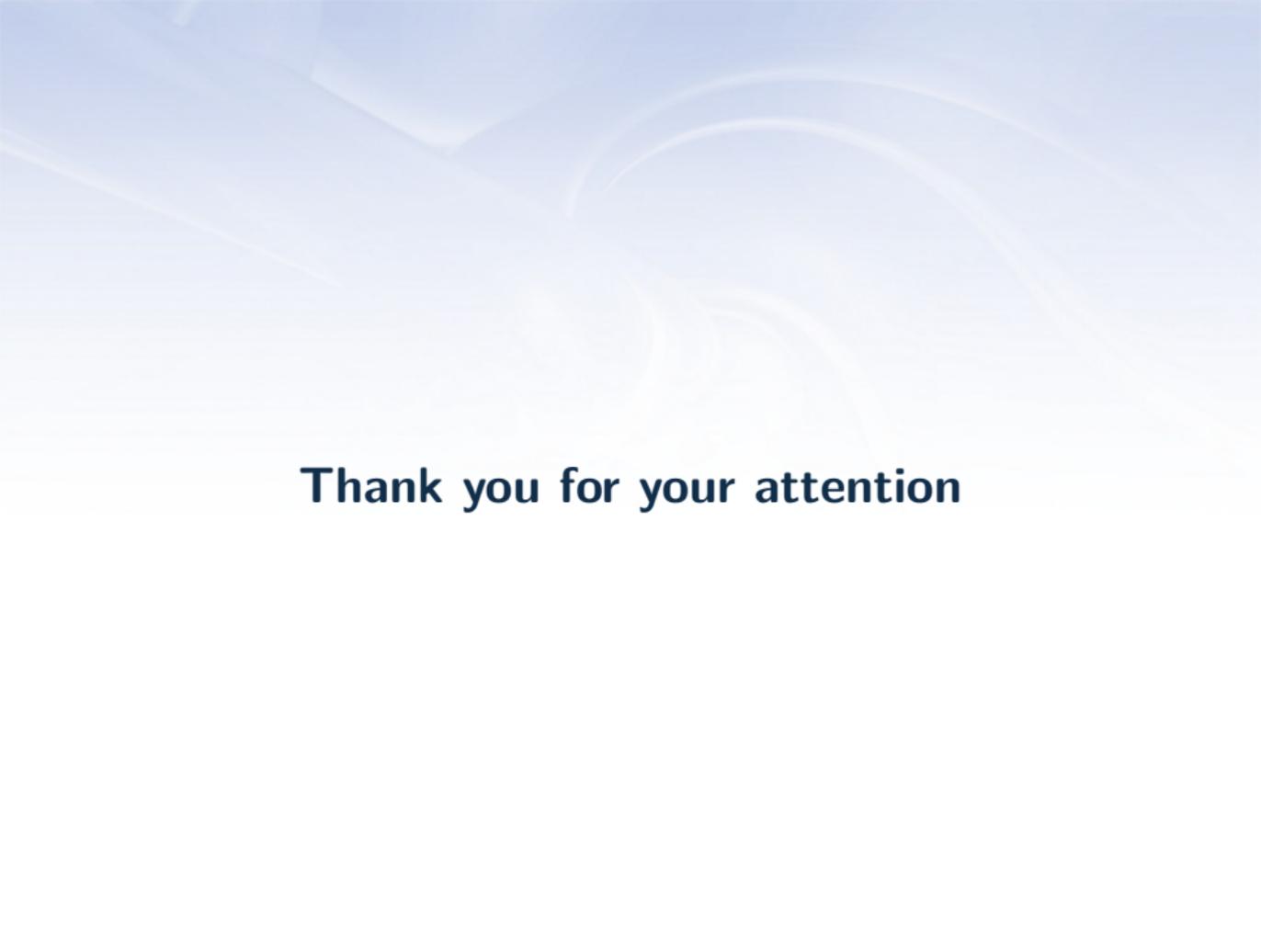# Example of STL Import

Just for fun...

Section

Conclusions and Perspectives

- Mean features of TOPOPTIM V2.1
  - **Multiphysics**, **multiobjective**, **nonlinear**, **anisotropic** materials
  - **Remeshing**, **input topology** (different mesh allowed), easy **restarts**
  - **Geometric restrictions** (can be combined; total or sub-domain)
  - Easy to **develop** (100% Gibiane) and easy to **customize** procedures
    (`TOPOPERS`, `TOPOMATE`, `TOPORSTR`, `TOPOFILT`, `TOPOCRIT`, `TOPOSAUV`)
  - And keep the same features as TOPOPTIM V1.0
    (optimal mesh given as output, not structured mesh,
    low stiffness element removing)
  - Better **performances** on larger meshes
  - The topology can be **smoothed** (`TOPOSURF`)
    and **exported** in STL format (`SORT 'STL'`) for 3D printing...

- Some perspectives
  - Adaptive mesh refinement
  - Parallelization with MPI
  - Better combination of the optimal criteria
    for multiobjective optimization

G. Le Quilliec, Topology optimization procedure TOPOPTIM V2.1, Club Cast3M 2017

Thank you for your attention