SIGGRAPH ASIA 2017 BANGKOK

Computational Design and Fabrication of Soft Pneumatic Objects with Desired Deformations

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CONFERENCE 27 – 30 November 2017 EXHIBITION 28 – 30 November 2017 BITEC, Bangkok, Thailand

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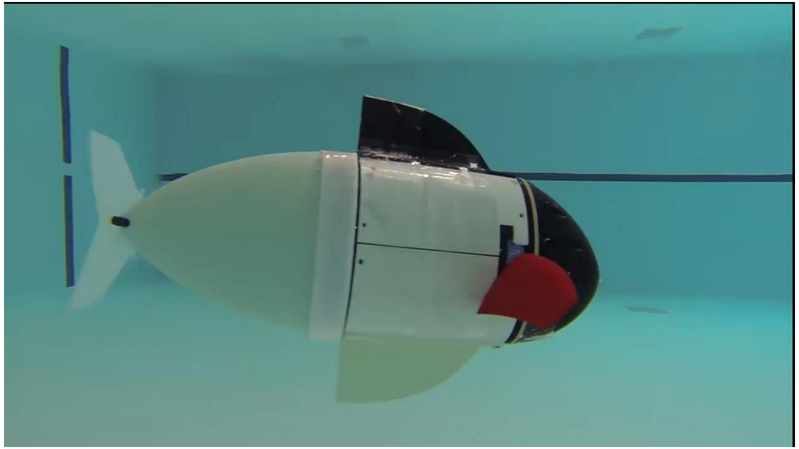
Pneumatic Soft Robotics

Industry Pneumatic Gripper

[Soft Robotics Inc]

Soft Robots



[Marchese et al. 2014, Ariel et al. 2016]

Our Goal

The digital deformable model

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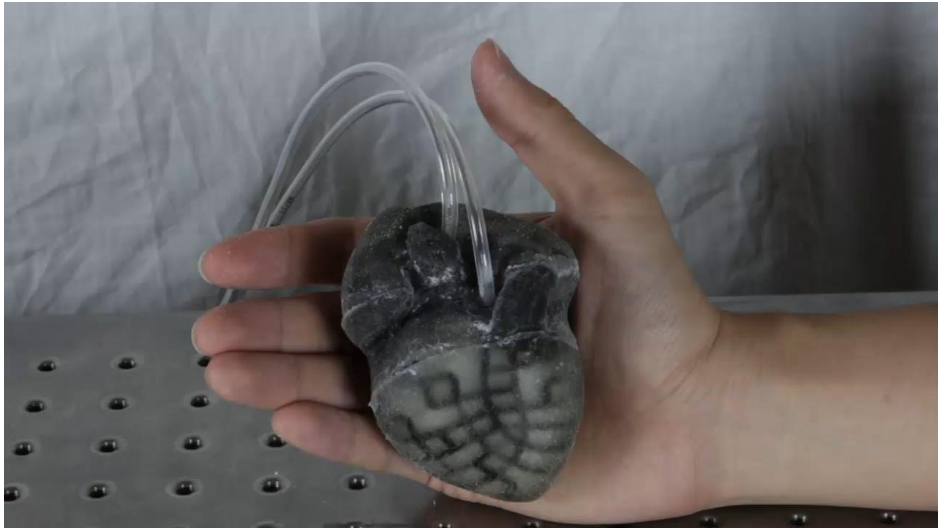
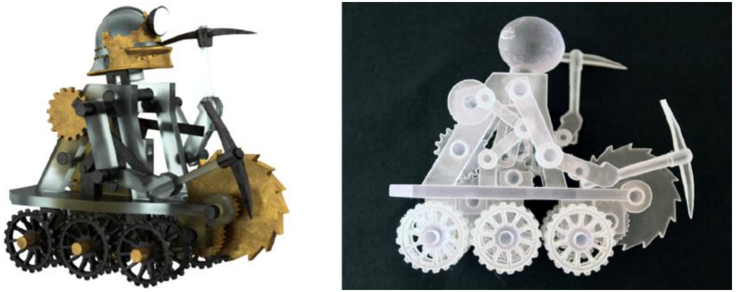
The digital deformable model



The fabricated deformable object

Related Works: Computational Fabrication

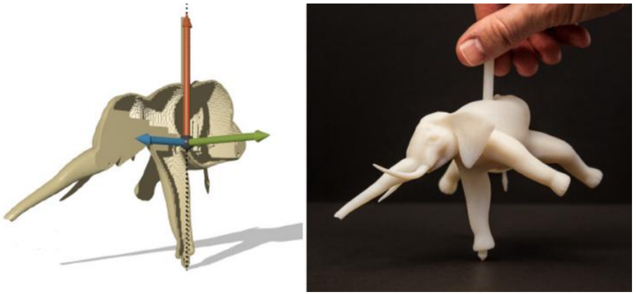
[Hasan et al. 2010]



[Coros et al. 2013]

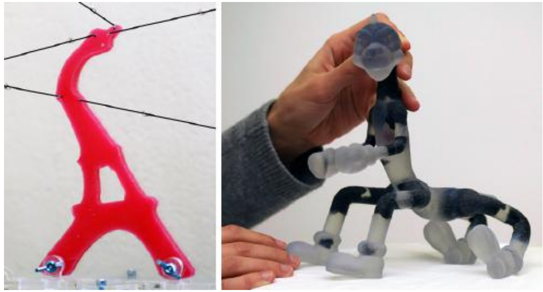
[Megaro et al. 2017]

[Prévost et al. 2013]

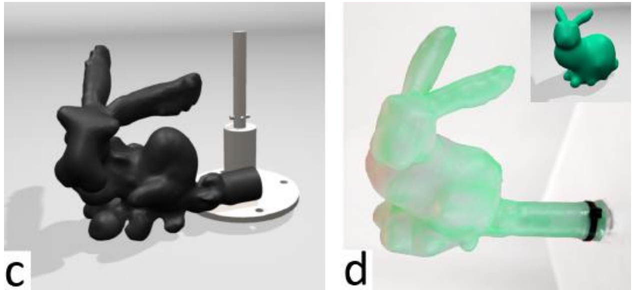


[Bächer et al. 2014]

Related Works: Flexible Object Fabrication



[Mélina et al. 2013]

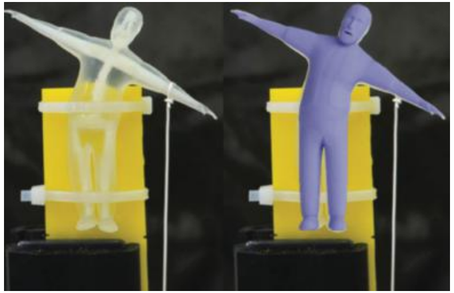


[Mélina et al. 2012]

[Schumacher et al. 2015]

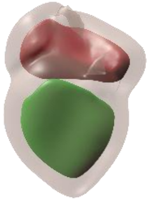
[Chen et al. 2014]

[Bickel et al. 2012]

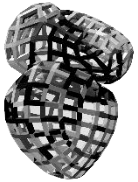


[Chen et al. 2015]

Key Challenges



Chambers



Material distribution

[howtoairbrush.com]

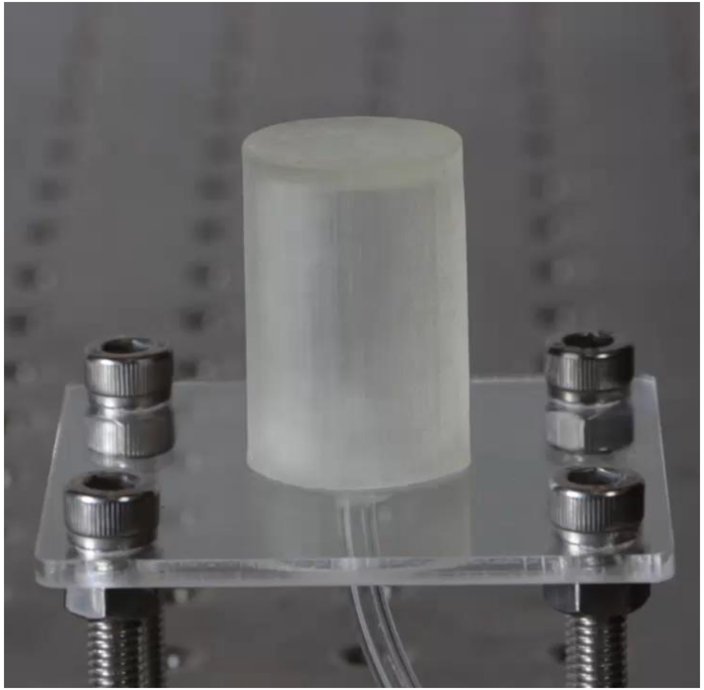
Air pressure

Deformation

Key idea: Chambers
(empty space inside the model)

Inflation result in volume increase.

If deformation has volume increase,
we can set a chamber there.

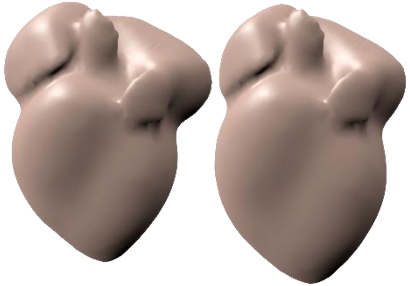


Key idea: Wireframes

Material distribution affects physical property

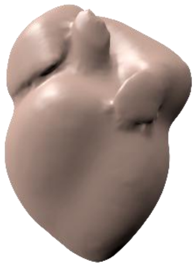
Pipeline

Rest shape

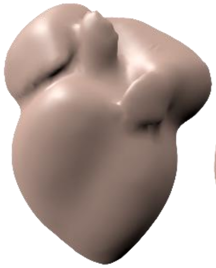


Target 1 Target 2

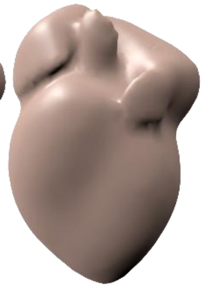
Pipeline



Rest shape

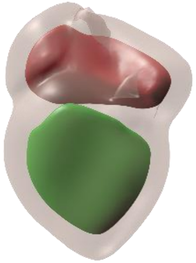


Target 1



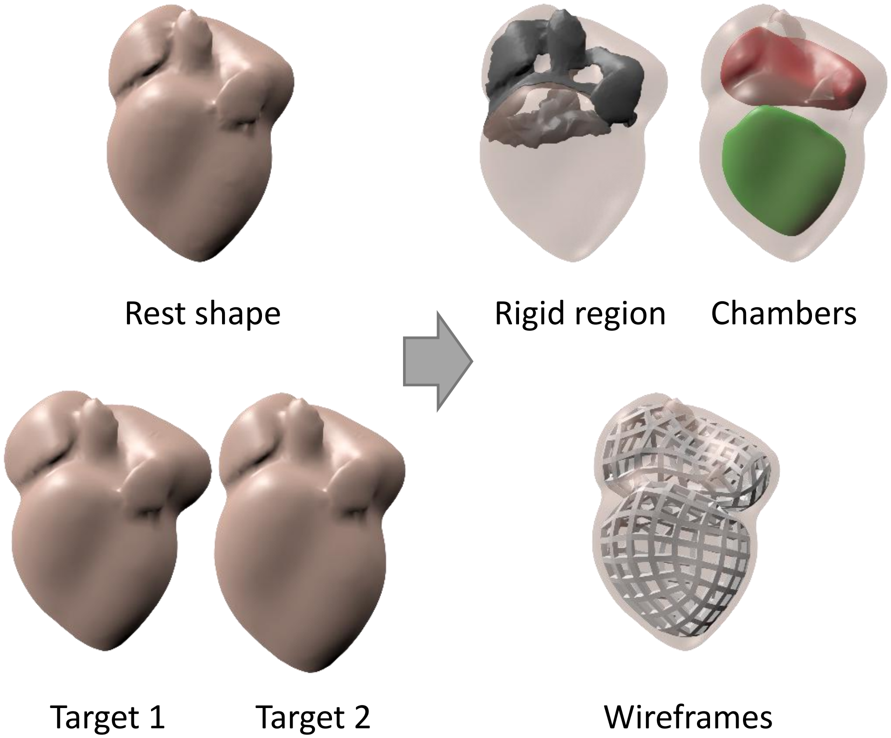
Target 2

Rigid region

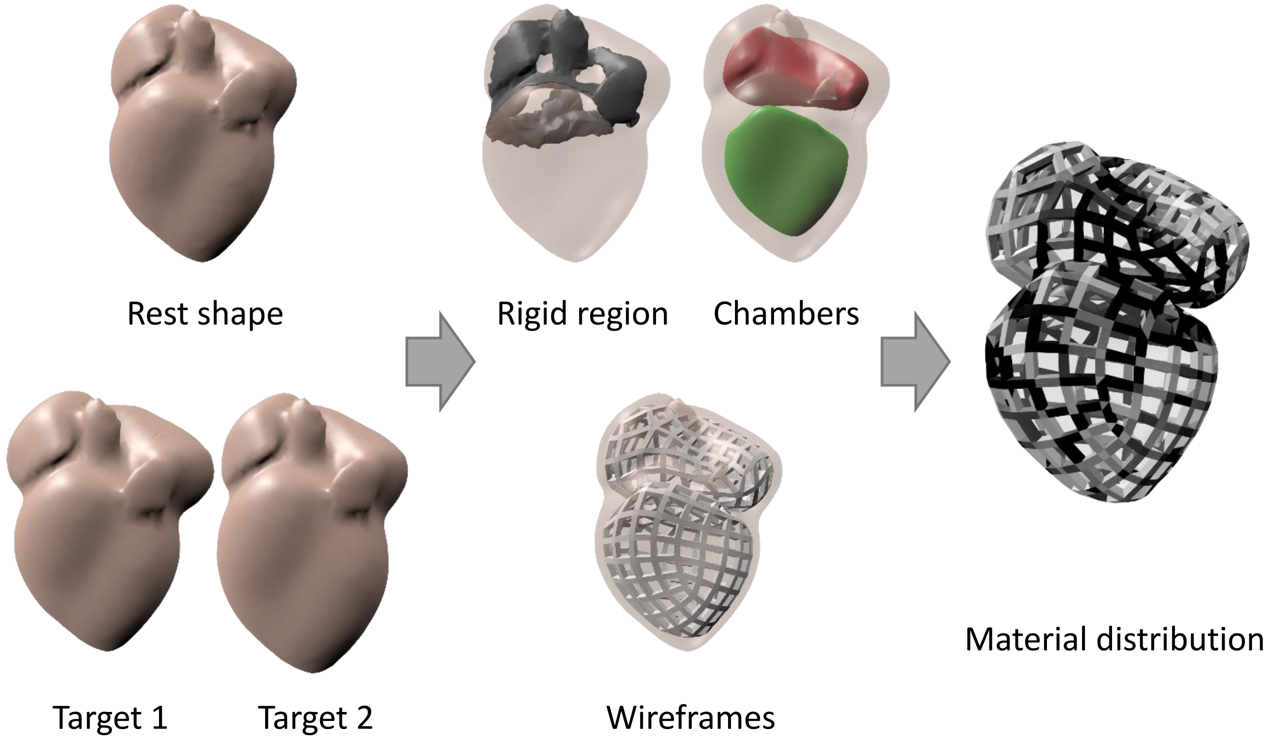


Chambers

Pipeline

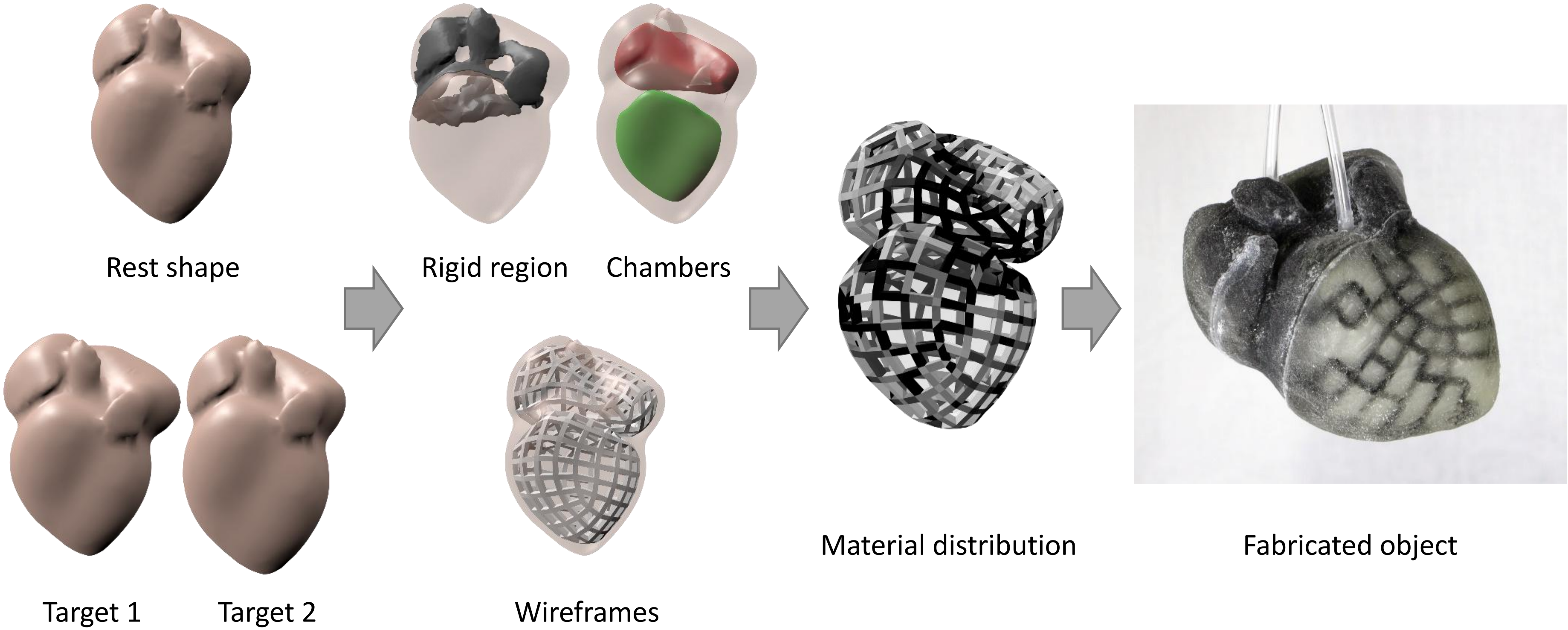

Rest shape
Rigid region
Chambers
Target 1
Target 2
Wireframes

Pipeline



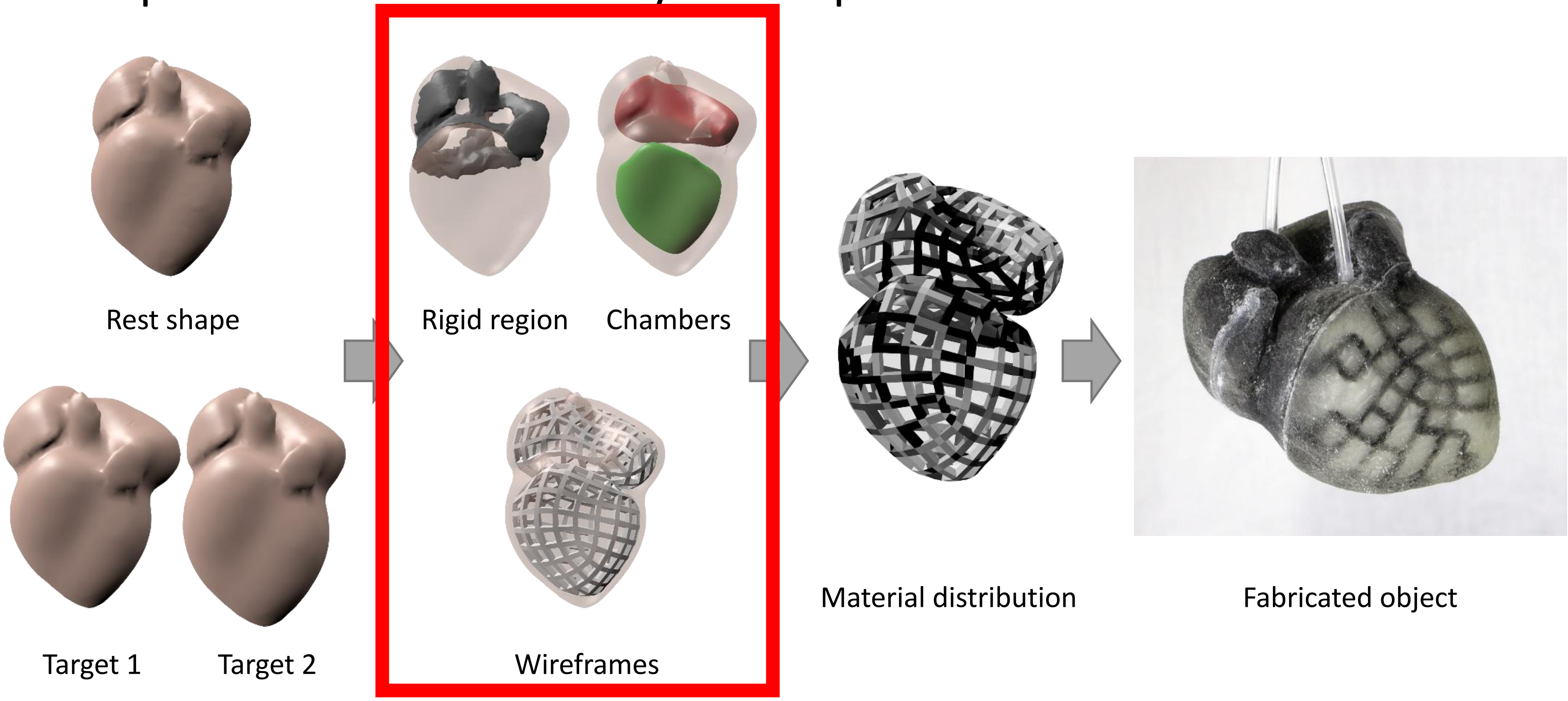
Rest shape
Target 1
Target 2
Rigid region
Chambers
Wireframes
Material distribution

Pipeline



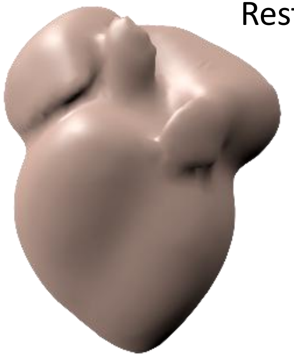
Rest shape
Target 1
Target 2
Rigid region
Chambers
Wireframes
Material distribution
Fabricated object

Pipeline : Geometry Setup



Geometry Setup

Rest shape



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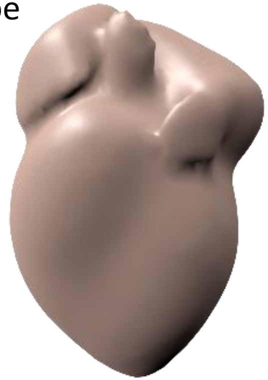
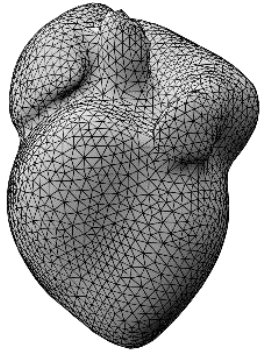
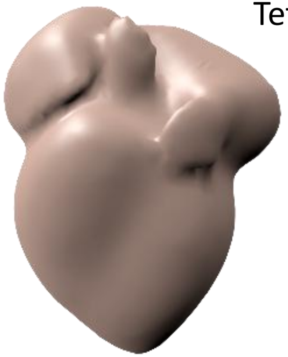


Target 2

Geometry Setup



Tet mesh



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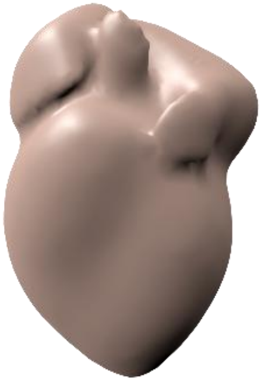

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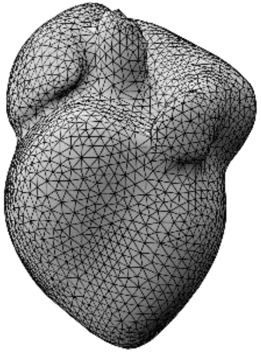
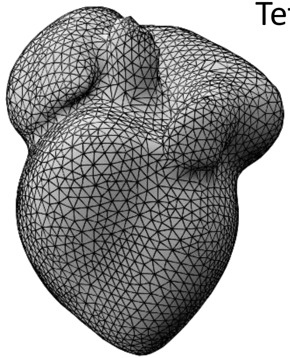
Geometry Setup



Tet mesh



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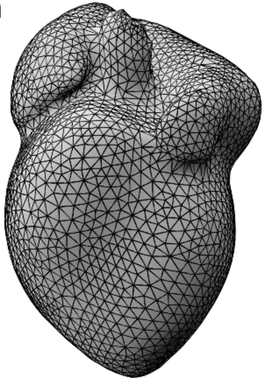

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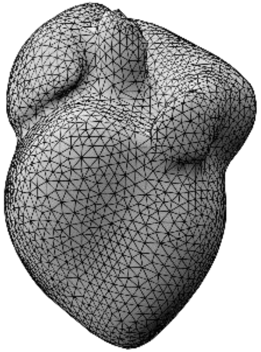
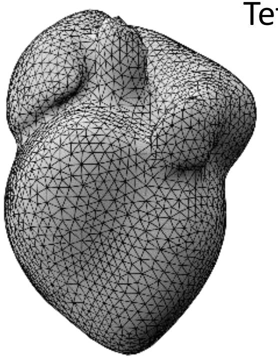
Geometry Setup



Tet mesh



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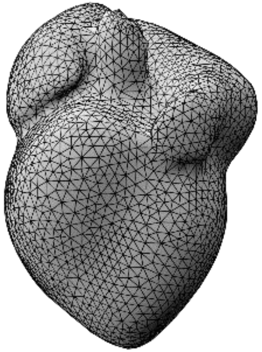

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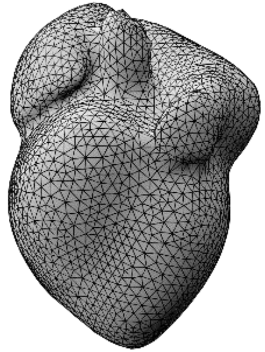
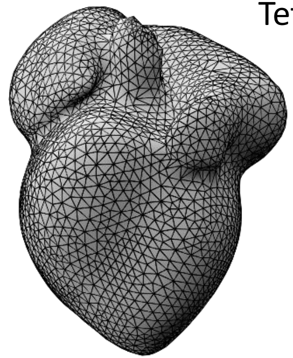
Geometry Setup



Tet mesh



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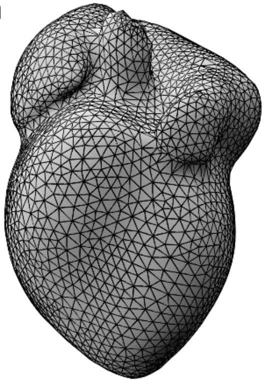

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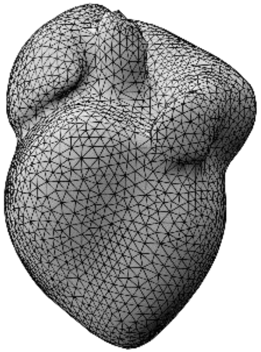
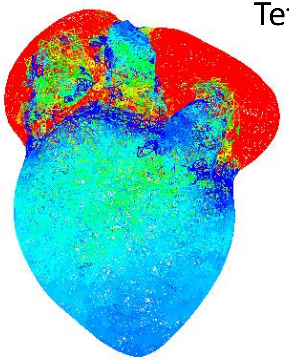
Geometry Setup



Tet mesh



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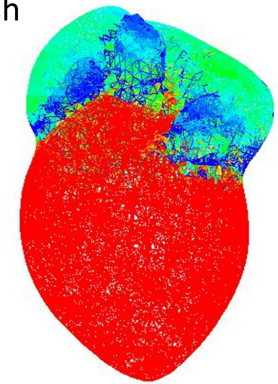
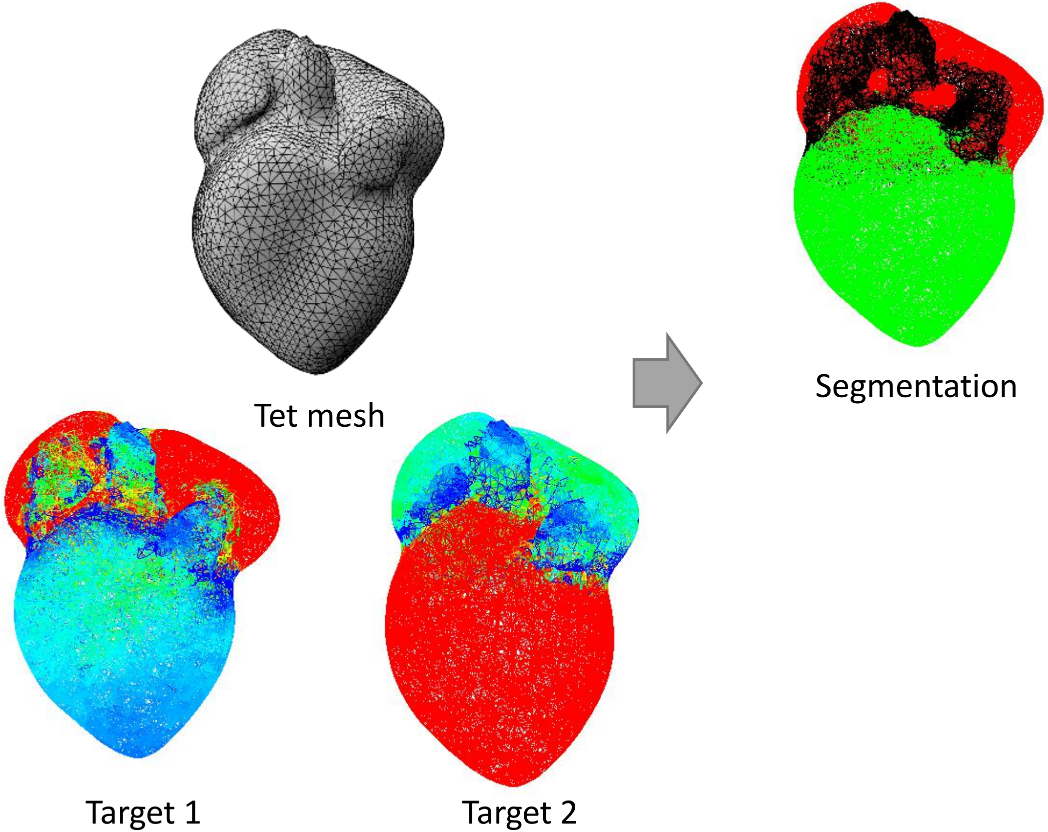
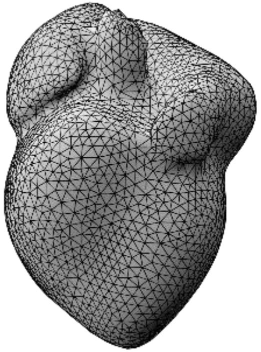


Target 2

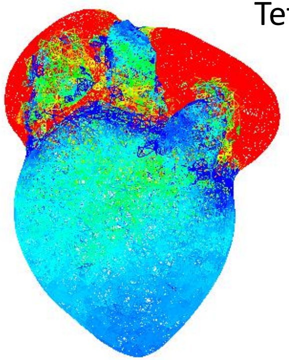
Geometry Setup



Geometry Setup



Tet mesh



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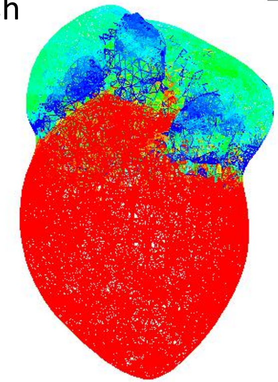
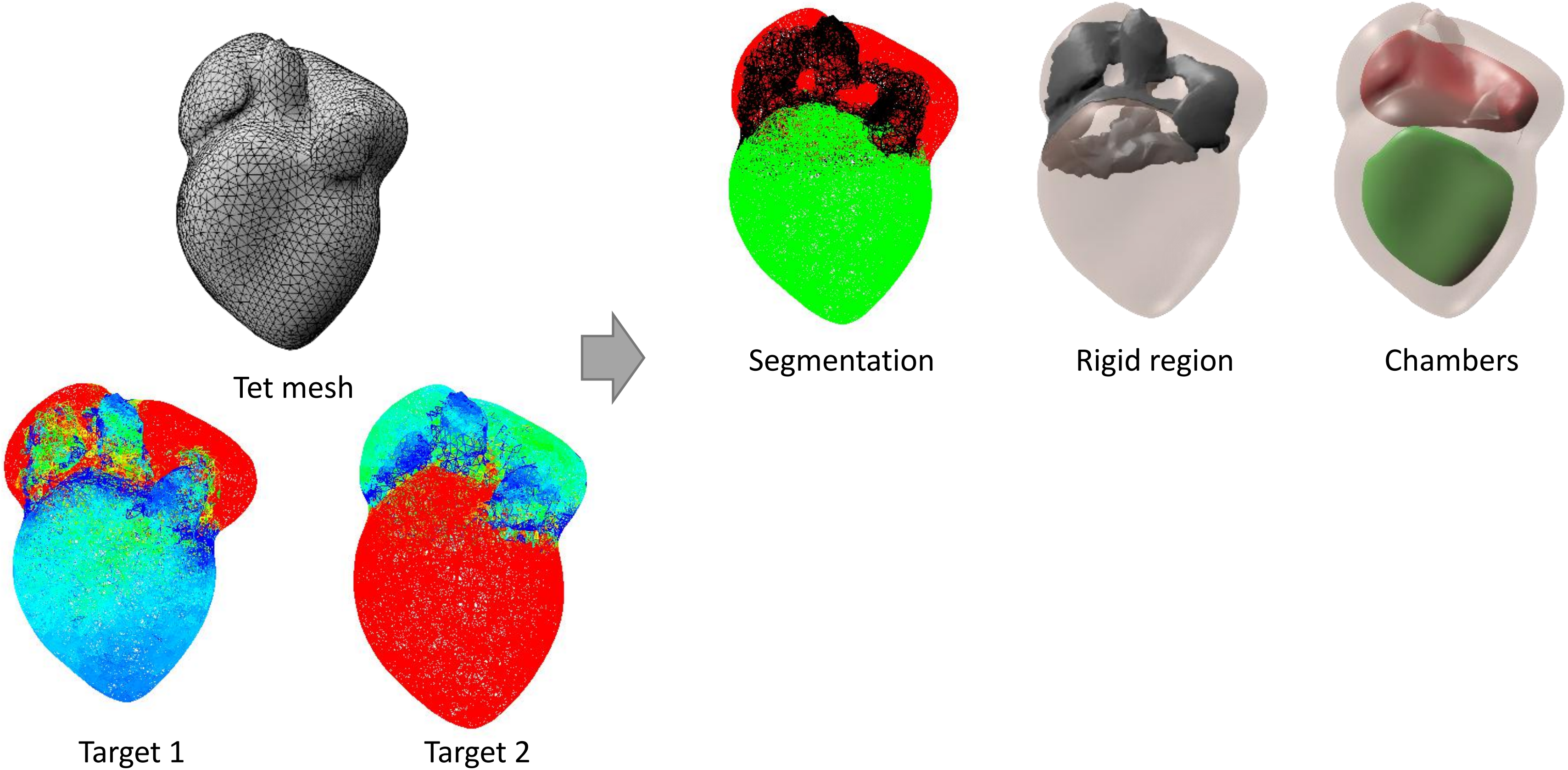


Target 2

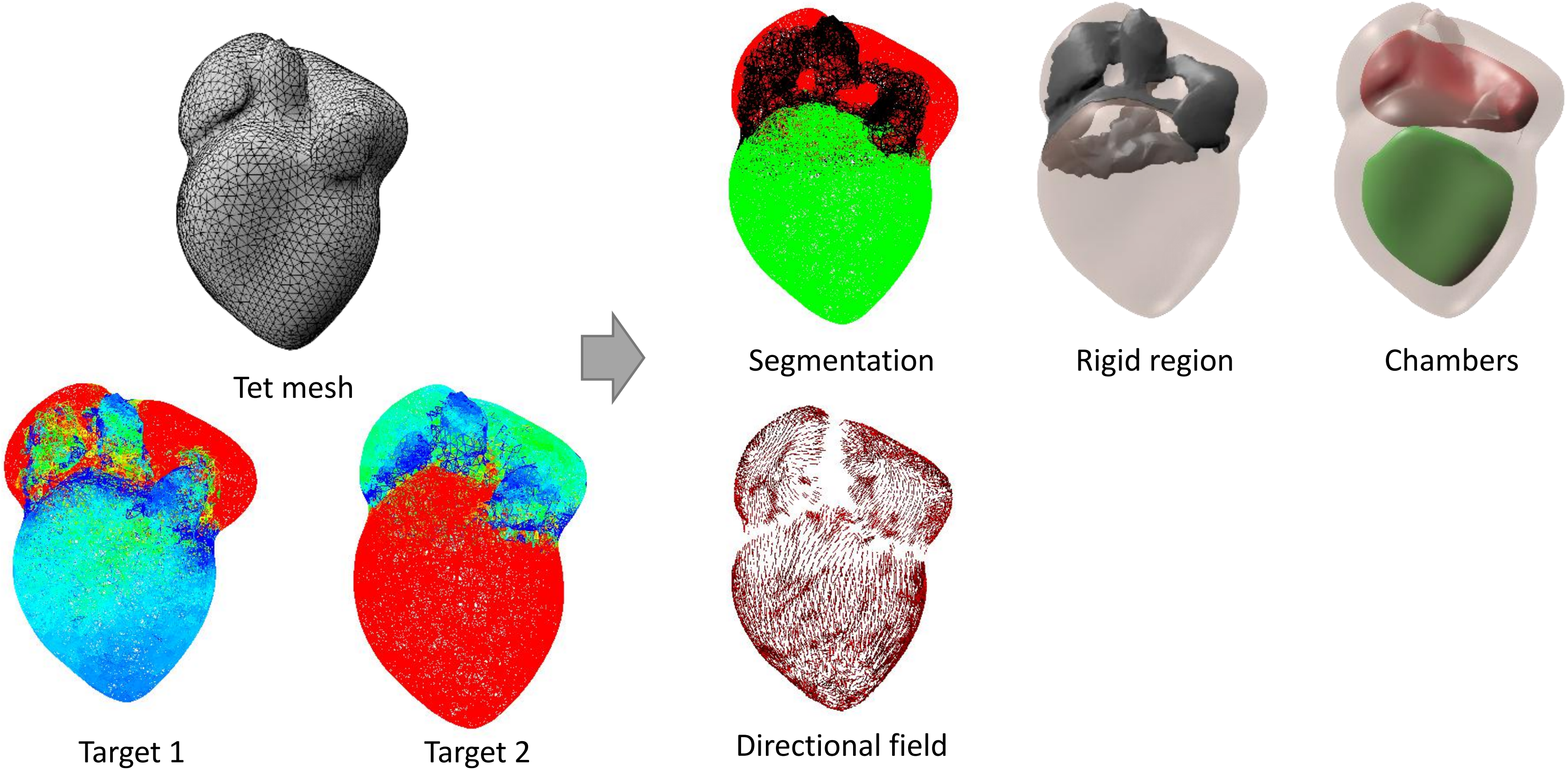
Segmentation

Rigid region

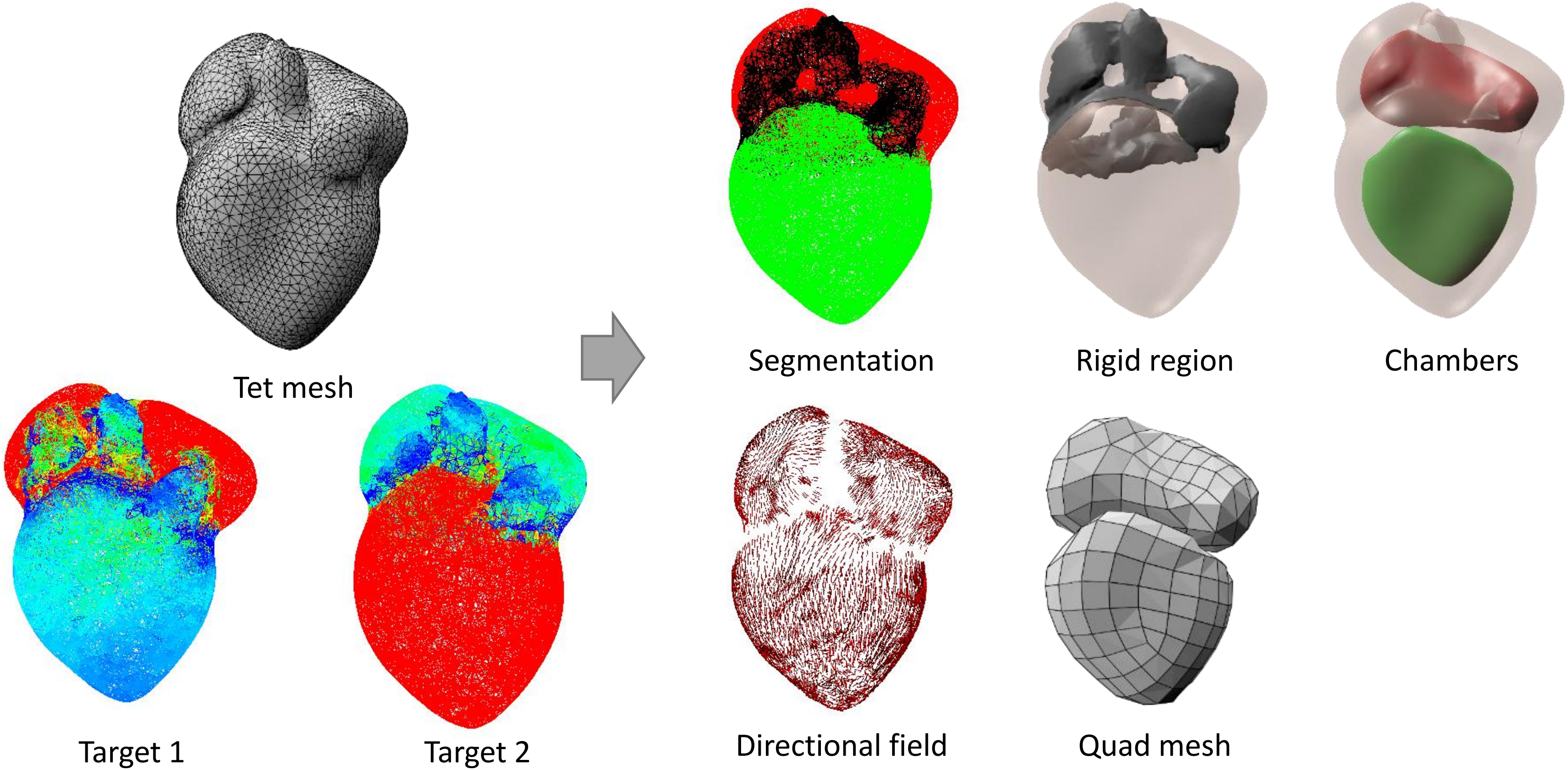
Geometry Setup



Geometry Setup



Geometry Setup



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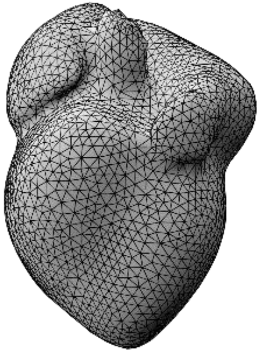
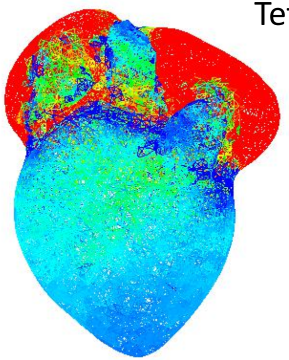


Tet mesh



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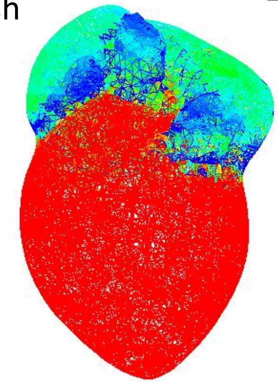
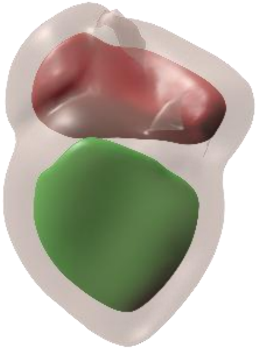


Target 2

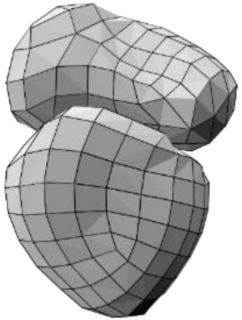
Segmentation

Rigid region

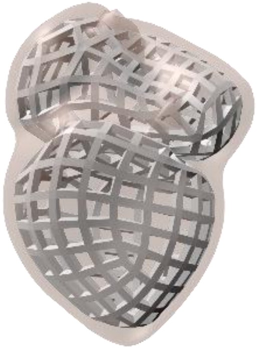


Chambers

Directional field

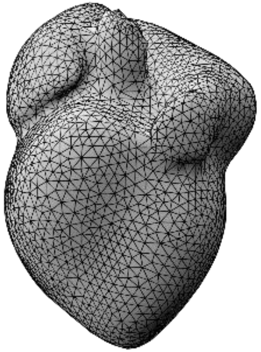


Quad mesh

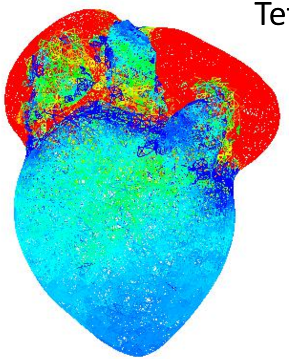


Wireframes

Geometry Setup



Tet mesh



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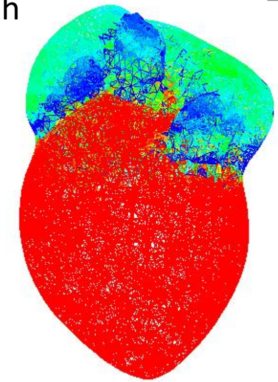

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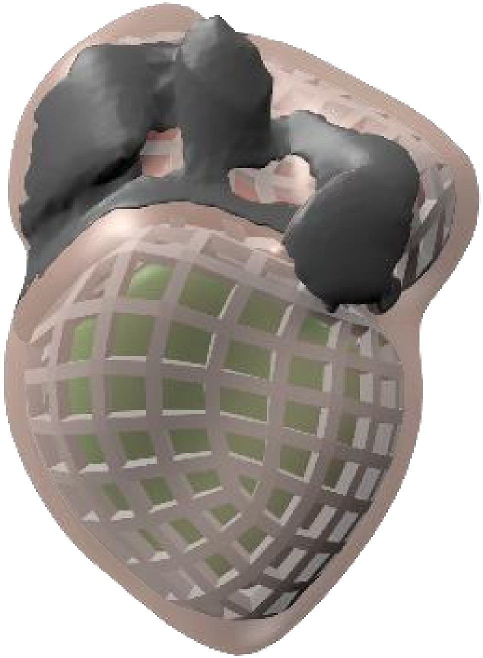
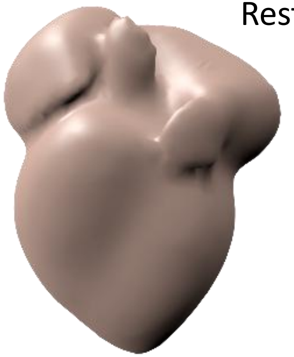


The geometry

Geometry Setup

Rest shape



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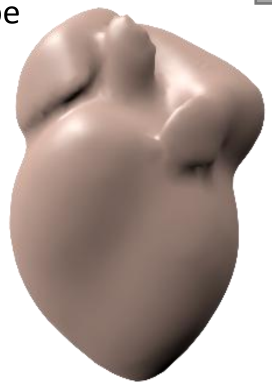

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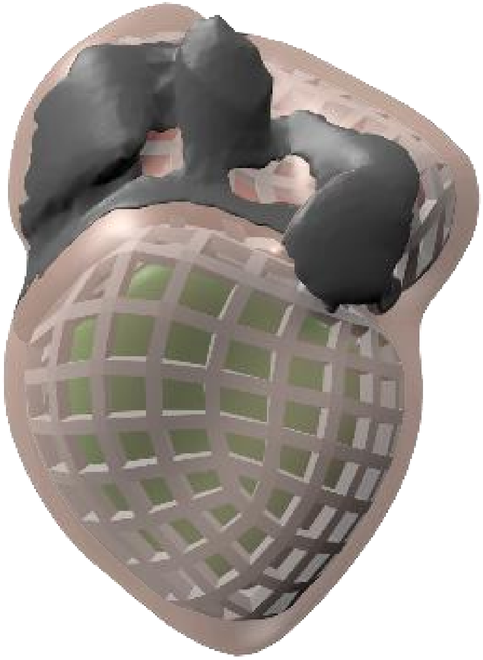
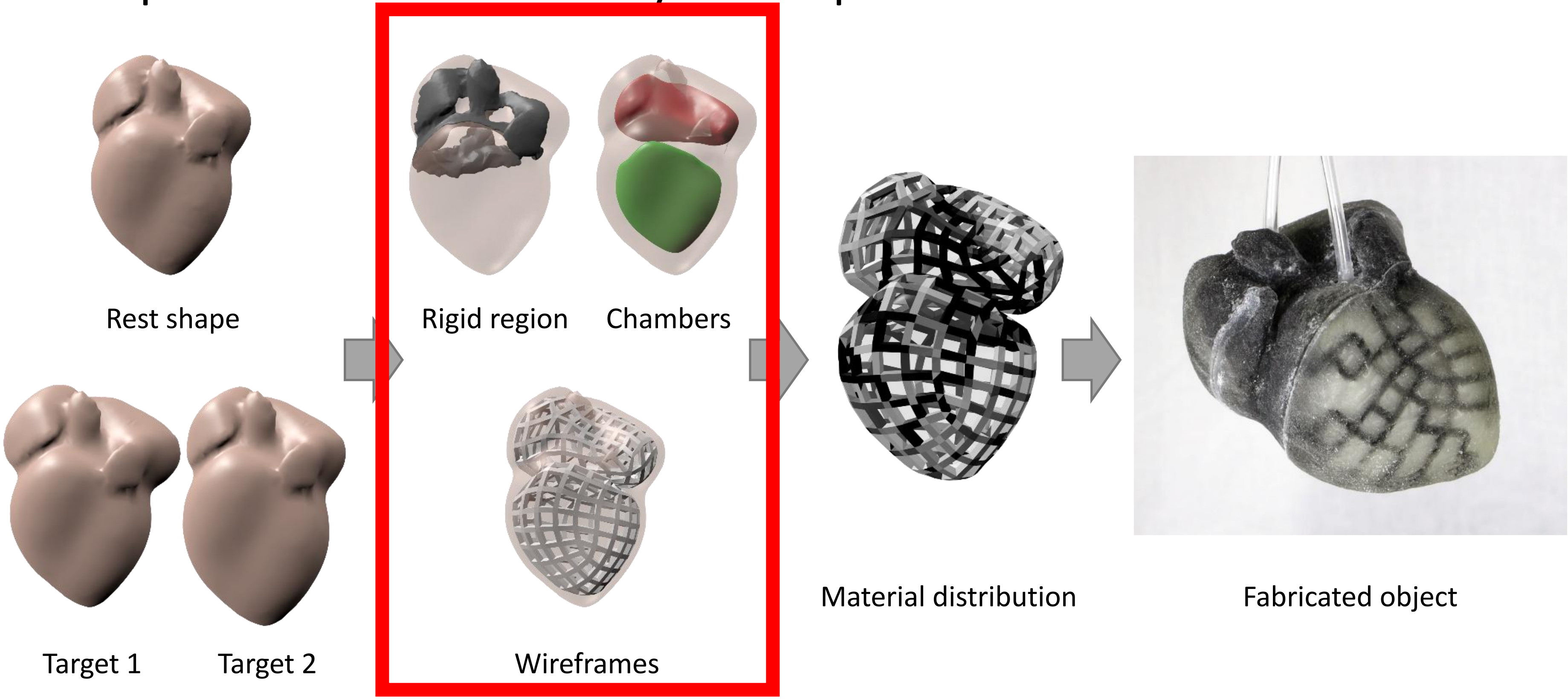
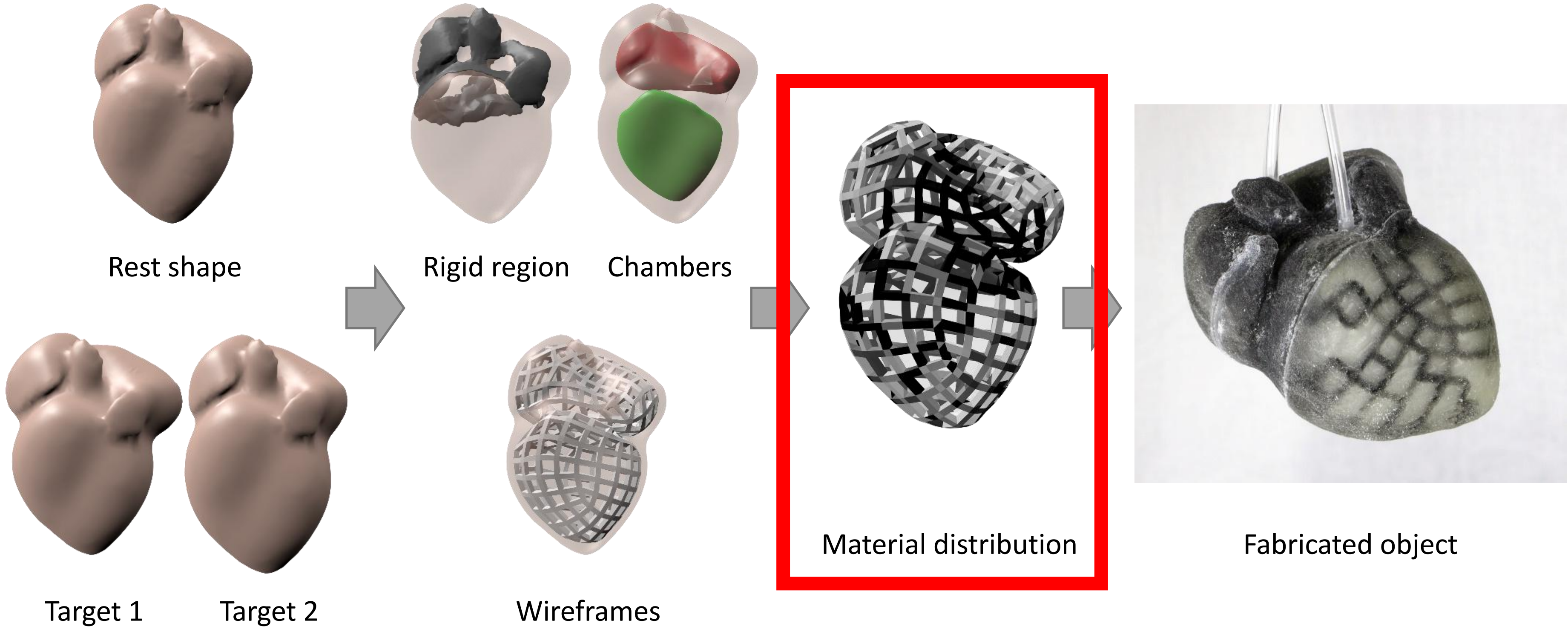


The geometry

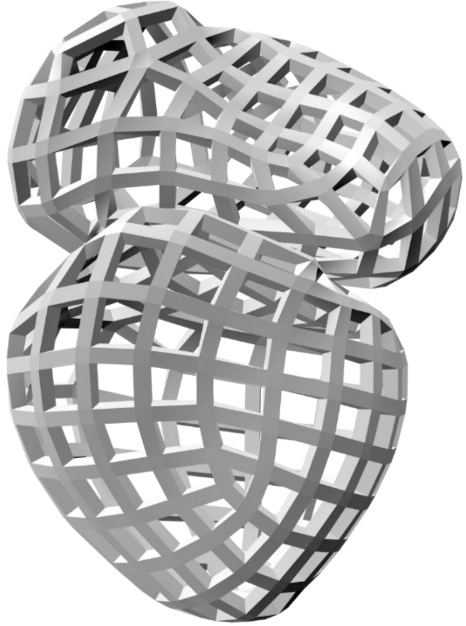
Pipeline : Geometry Setup



Pipeline : Material Optimization

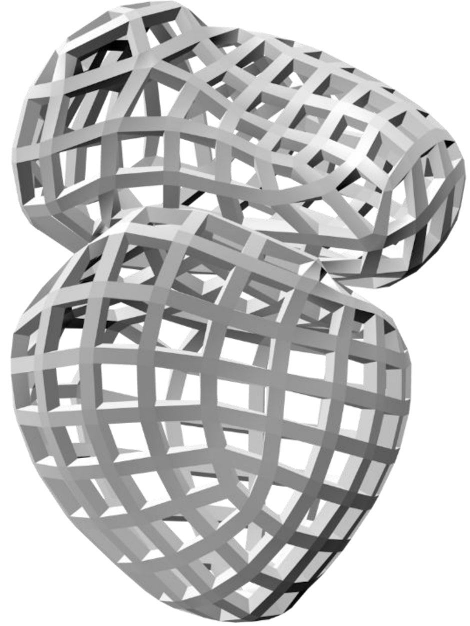


Material Optimization

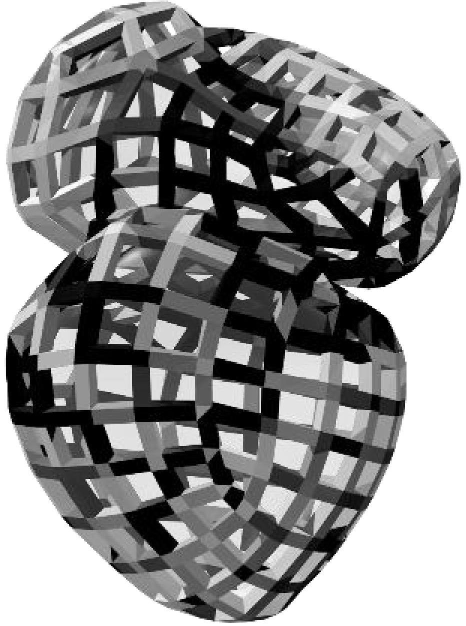


wireframe

Material Optimization

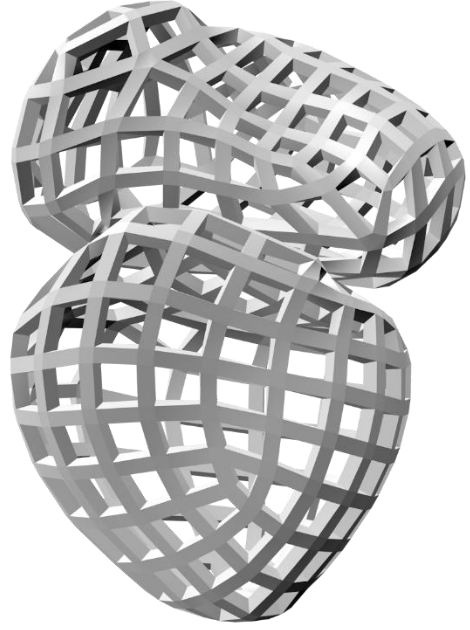


wireframe

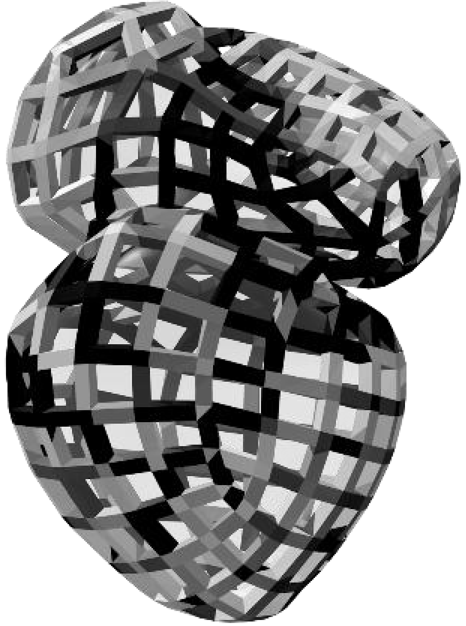


material distribution

Material Optimization



wireframe



material distribution

the model

Material Optimization

Anisotropic

Isotropic

Material Optimization

Neo-Hookean model

$$\Psi_{\mathrm{i}} = \frac{\mu_i}{2}\{\mathrm{tr}(F_i^T F_i) - \log[\det(F_i^T F_i) - 3]\} + \frac{\lambda_i}{8}\log^2[\det(F_i^T F_i)]$$

$$\mu_i = \frac{E_i}{2(1+\nu_i)} \qquad \lambda_i = \frac{E_i}{3(1-2\nu_i)}$$

Material blend

$$E_{blend} = (1-\beta)E_{soft} + \beta E_{stiff}$$

$$E_{elas}(x,\beta) := \sum_{t_i} \Phi[F_i(x);\beta]\mathrm{vol}(t_i)$$

Equilibrium

$$\left(-\frac{\partial E_{elas}}{\partial \boldsymbol{x}} + \boldsymbol{p}^T \frac{\partial V}{\partial \boldsymbol{x}} - p_0 \frac{\partial V_0}{\partial \boldsymbol{x}}\right)\Big|_{x=x_{eq}(p,\beta)} = 0$$

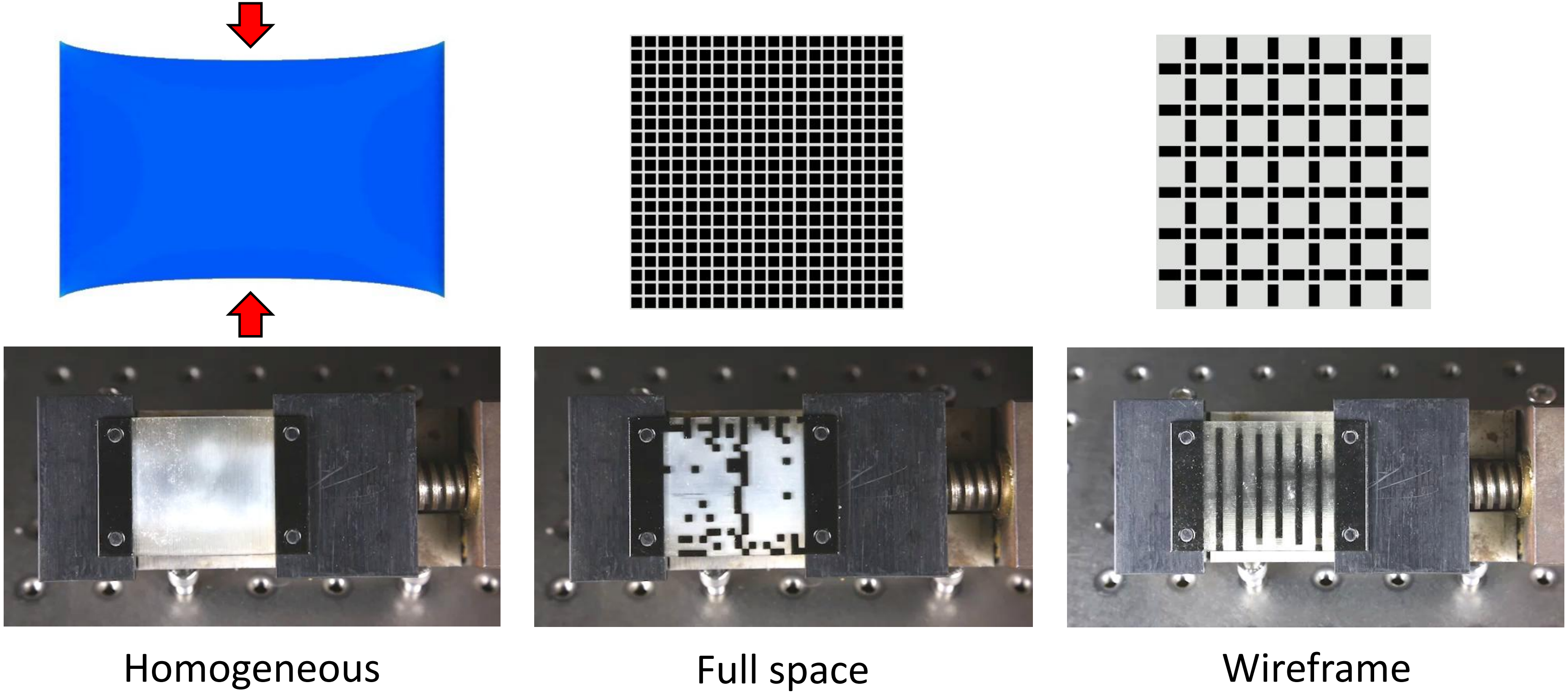
Energy

$$W_{match}^{(j)}(x) := \left\|\boldsymbol{x} - \boldsymbol{X}^{(j)}\right\|^2$$

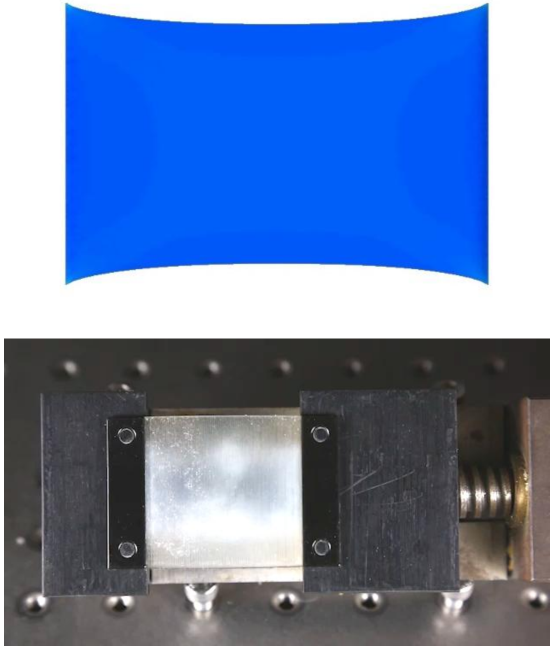
Optimization

$$\min_{\beta, p^{(1)},\ldots,p^{(K)}} \sum_{j=1}^{K} W_{match}^{(j)}[x_{eq}(p^{(j)},\beta)] + \alpha \sum_{j=1}^{K} E_{elas}[x_{eq}(p^{(j)},\beta),\beta]$$

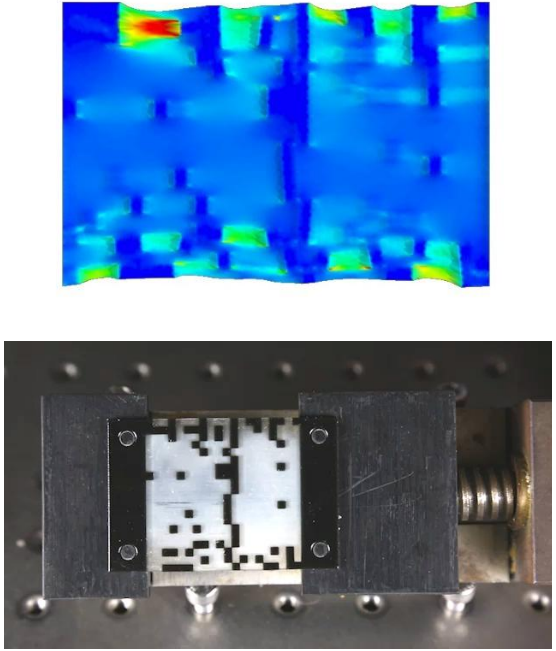
Wireframe vs. Full Space



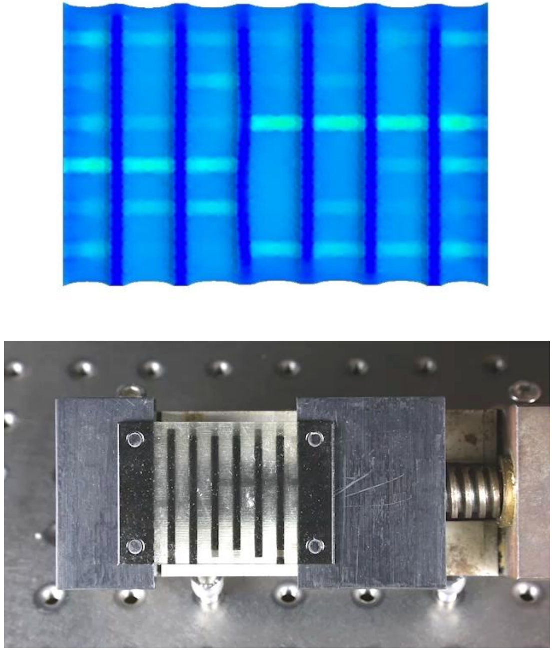
Wireframe vs. Full Space



Homogeneous

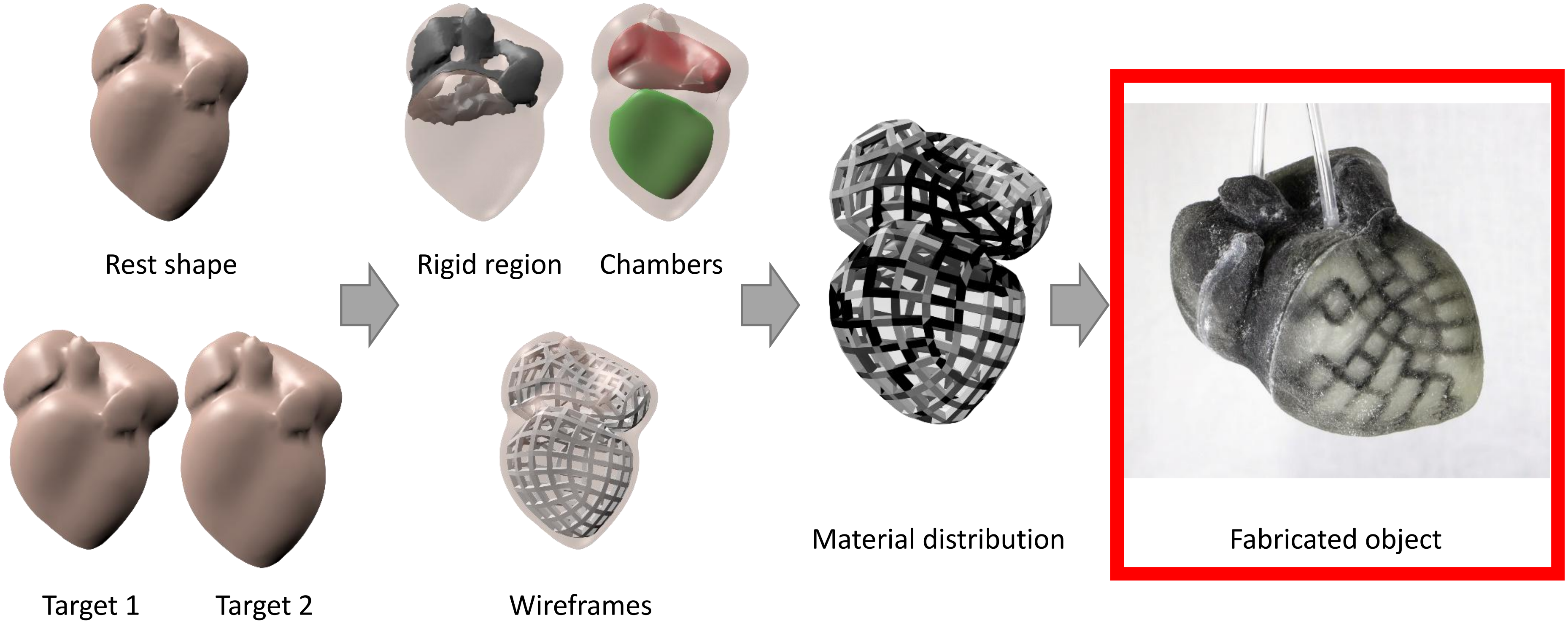


Full space



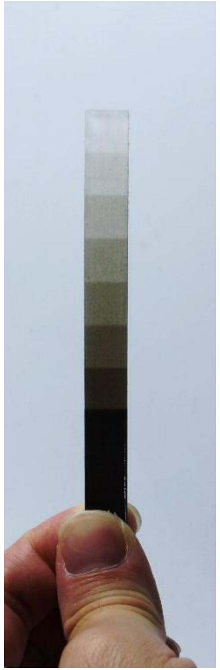
Wireframe

Pipeline

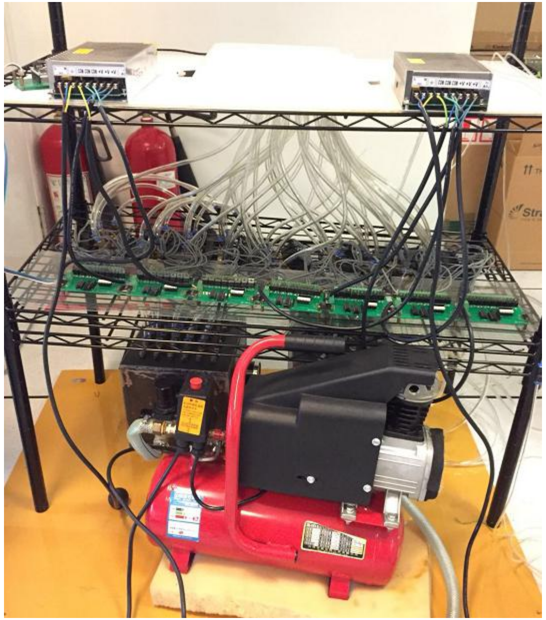


Rest shape
Target 1
Target 2
Rigid region
Chambers
Wireframes
Material distribution
Fabricated object

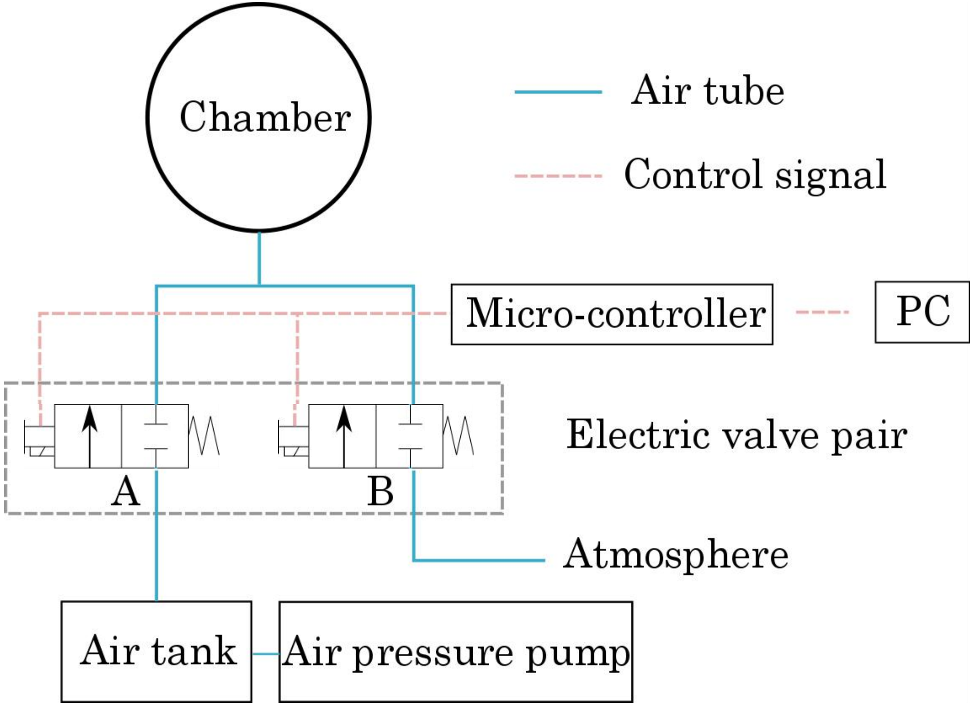
Physical Realization



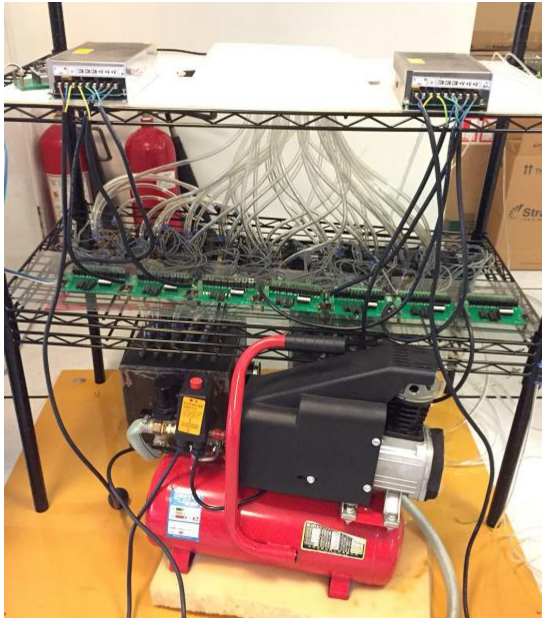
Pneumatic Control System



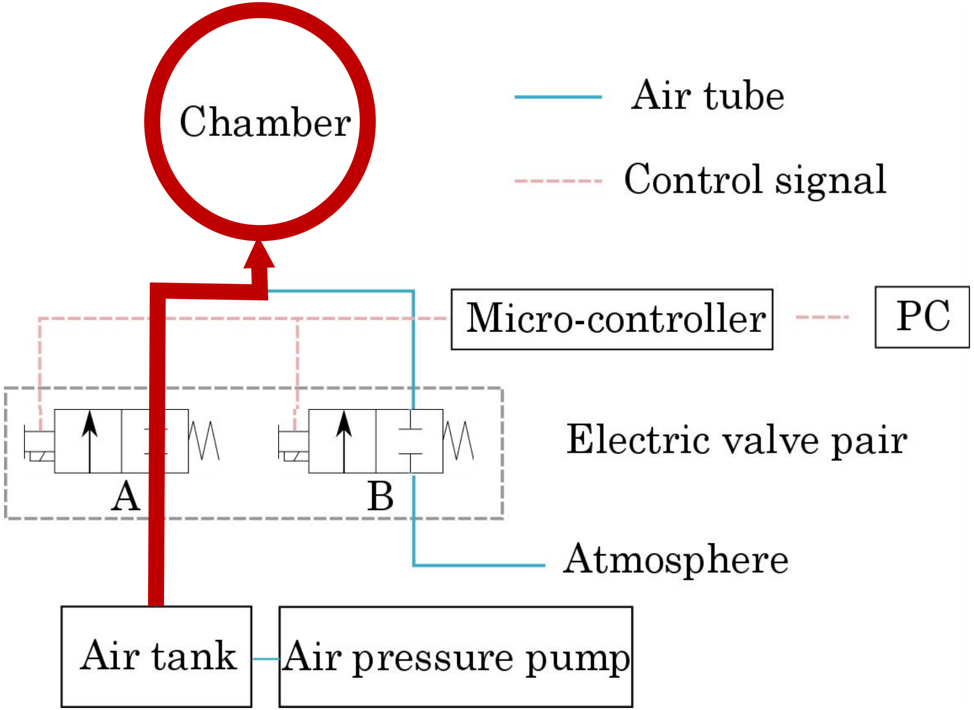
[Hachisu et al. 2014]



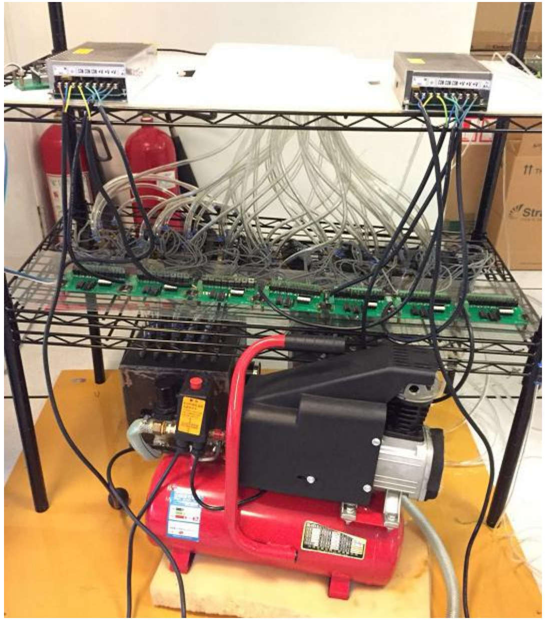
Pneumatic Control System



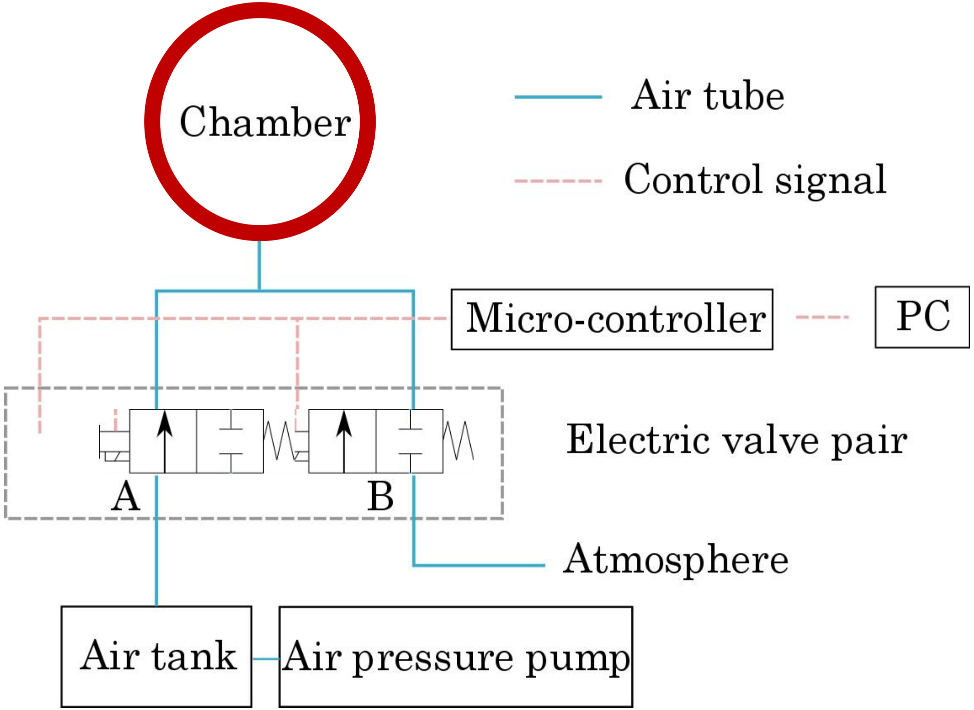
[Hachisu et al. 2014]



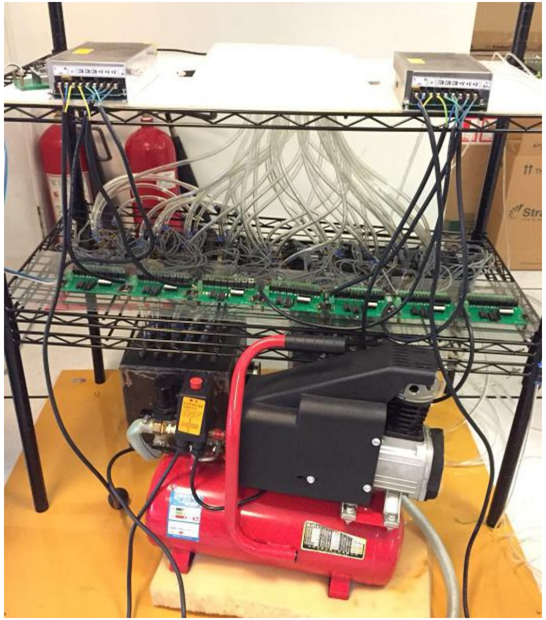
Pneumatic Control System



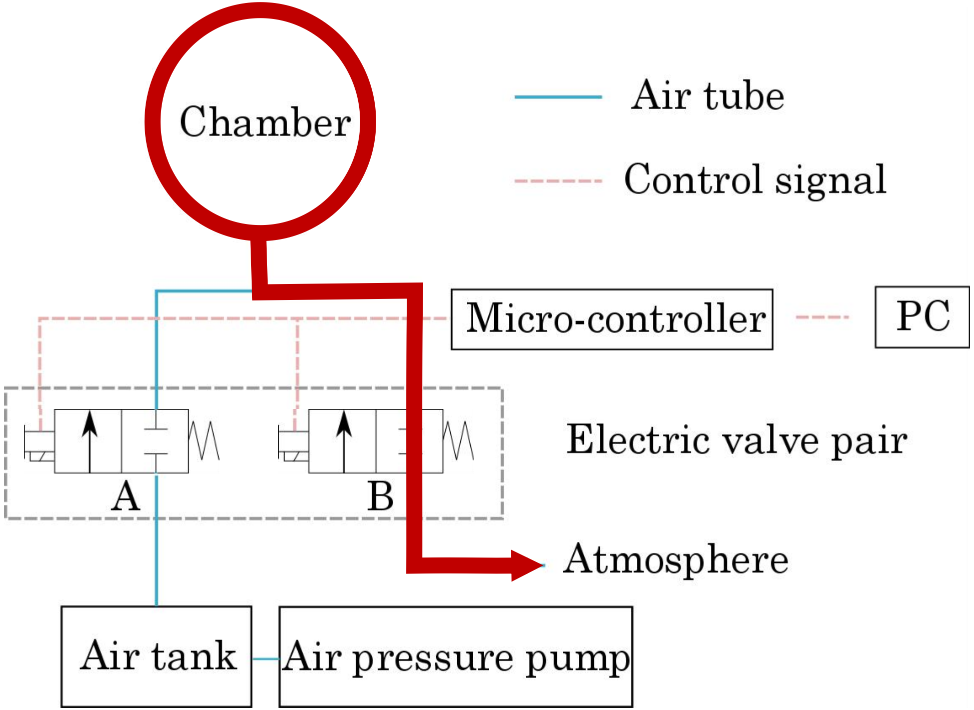
[Hachisu et al. 2014]



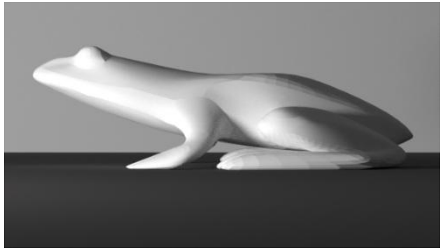
Pneumatic Control System



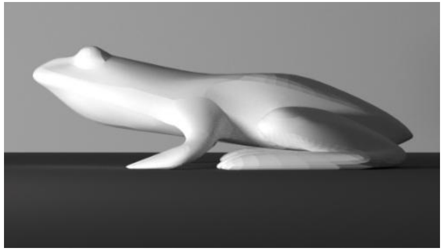
[Hachisu et al. 2014]



Physical Realization



Rest pose



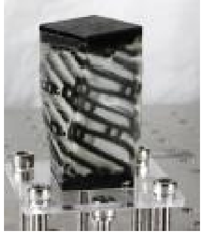
Target pose

Results : optimization timing

9 min

8 min

9 min



29 min

3 min

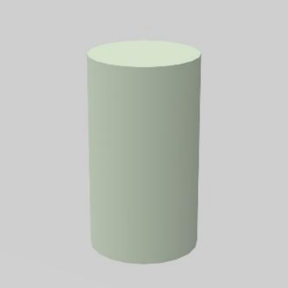
1 min

34 min

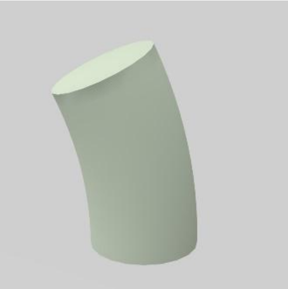
3.5 h

1 h

extrude

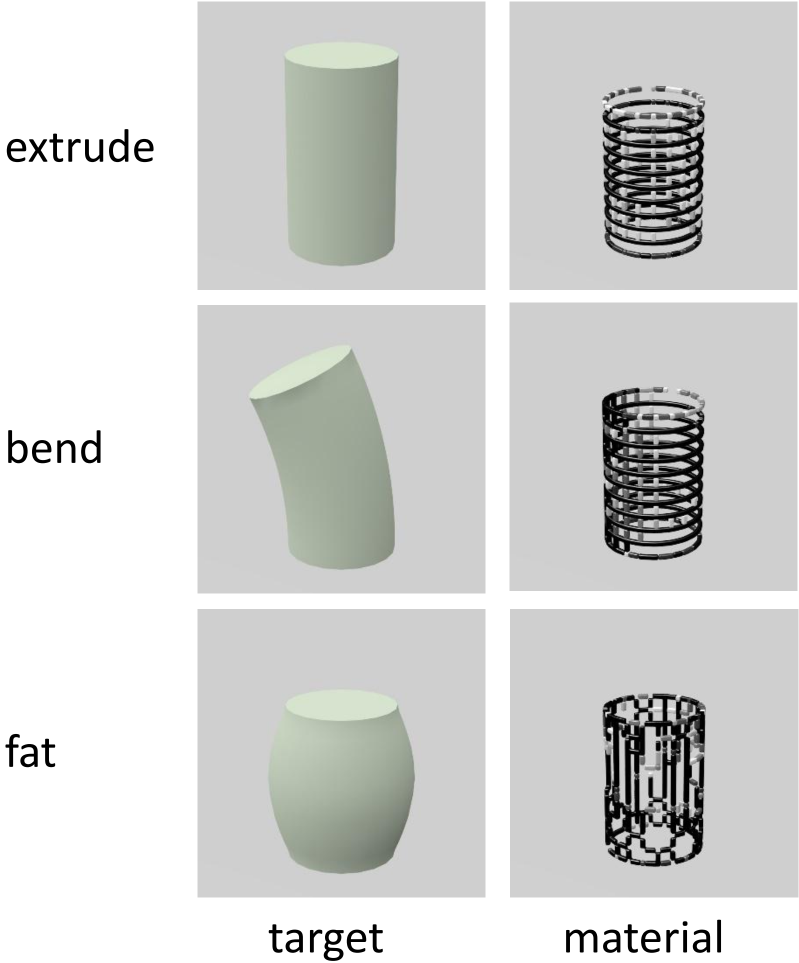


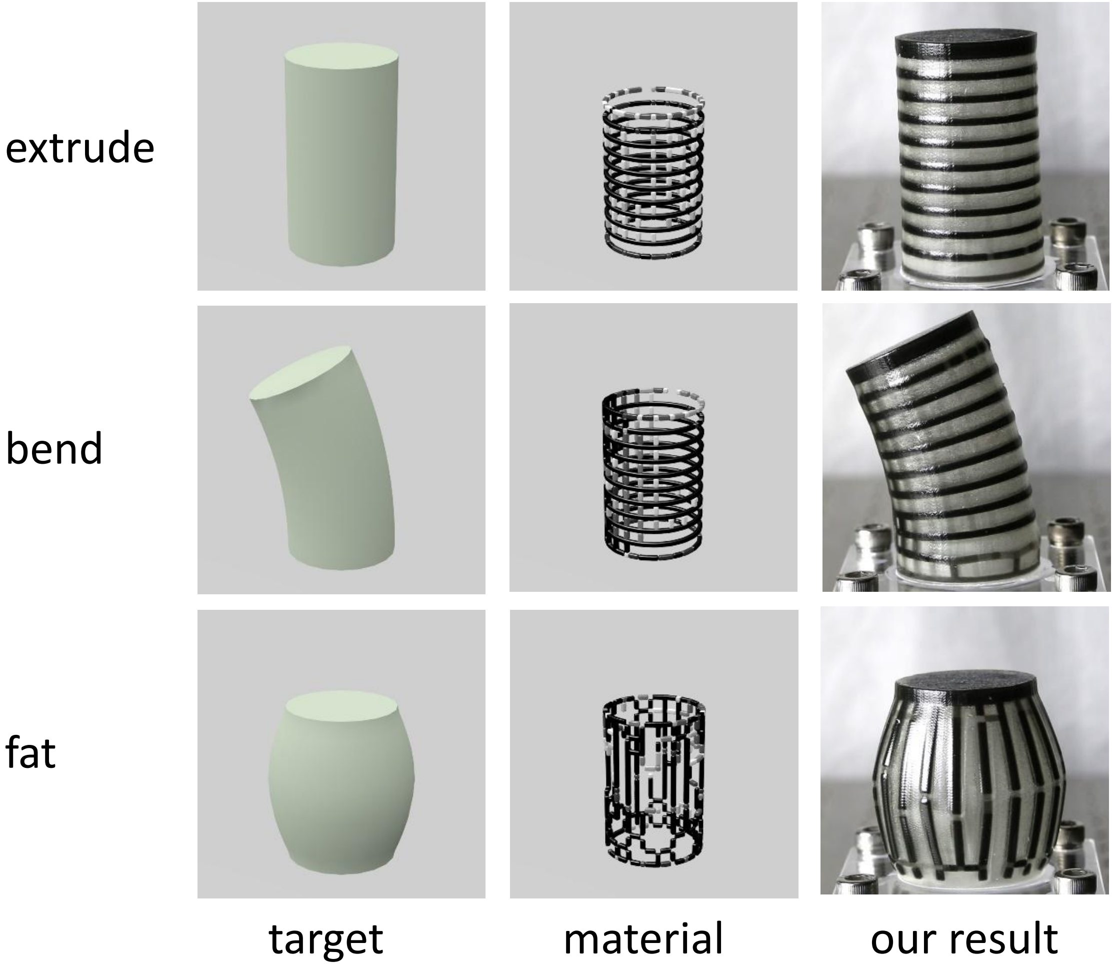
bend

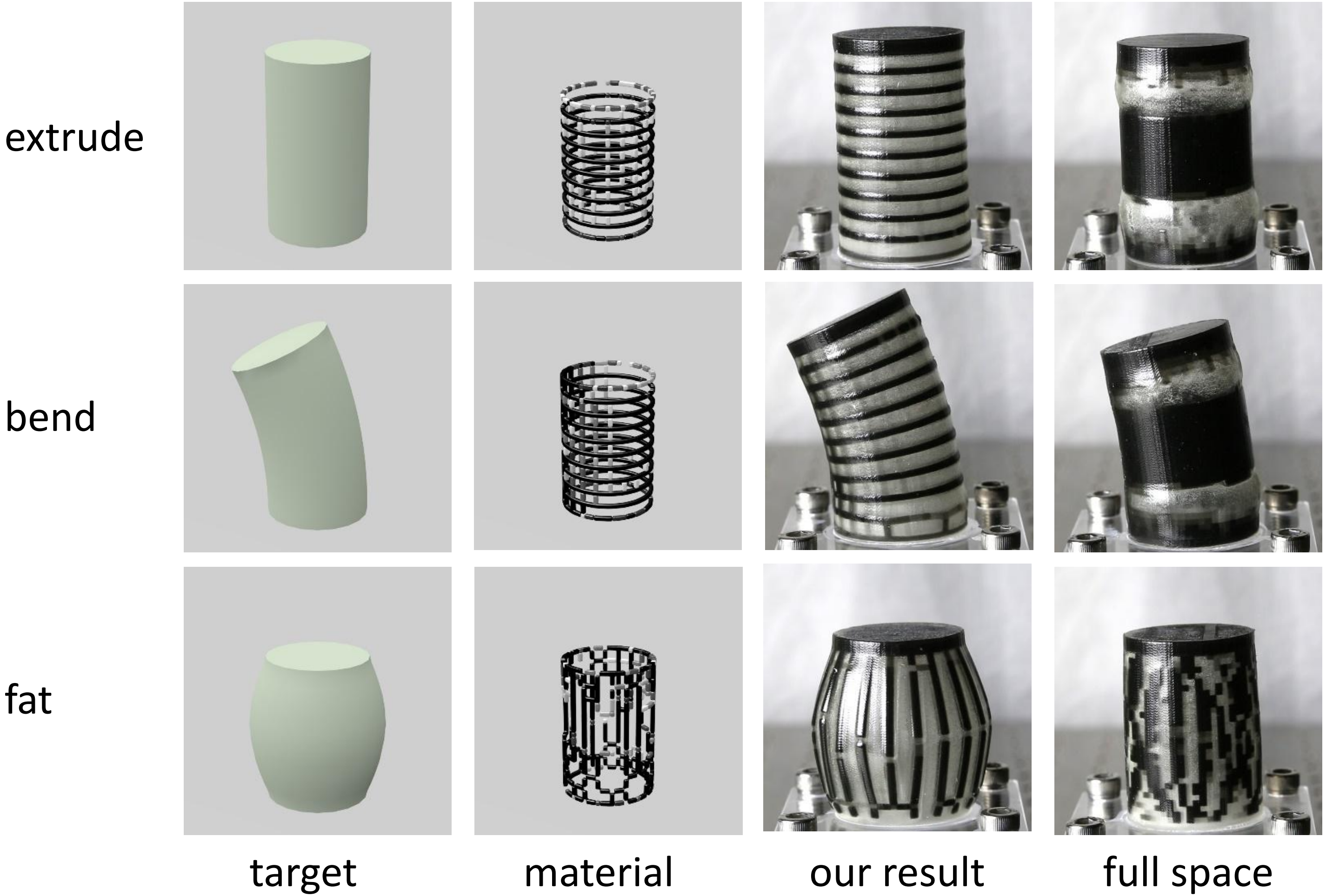


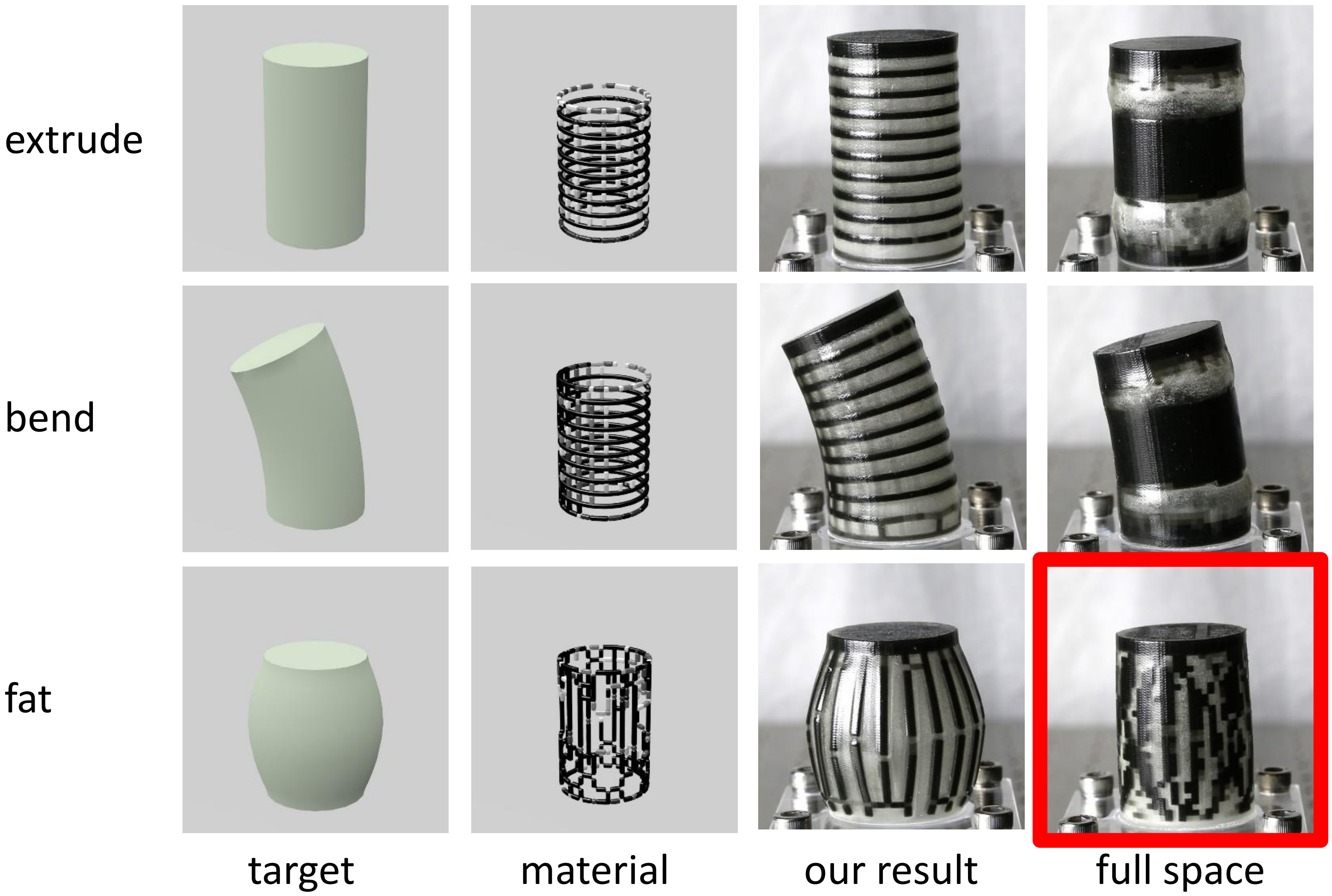
fat

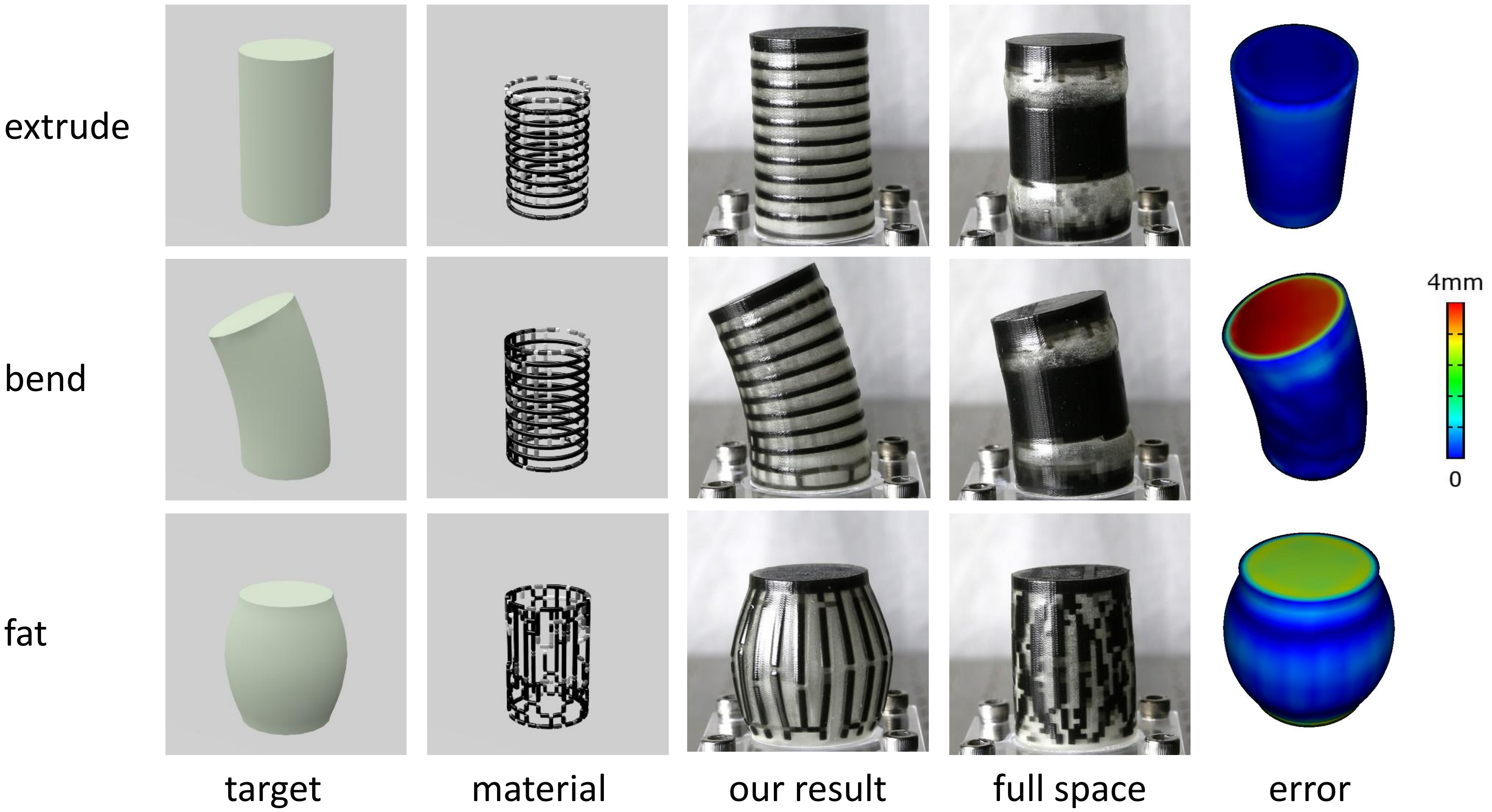
target


extrude
bend
fat
target
material

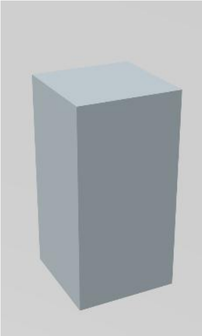

extrude
bend
fat
target
material
our result


extrude
bend
fat
target
material
our result
full space

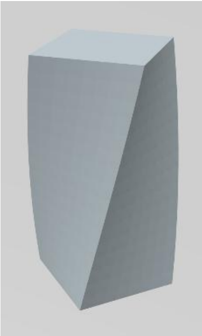

extrude
bend
fat
target
material
our result
full space


extrude
bend
fat
target
material
our result
full space
error
4mm
0

Single Chamber Result: Twisted Bar

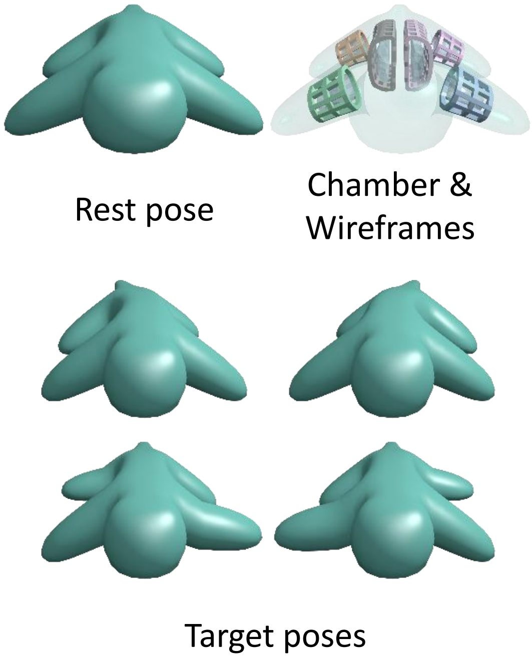


Rest pose



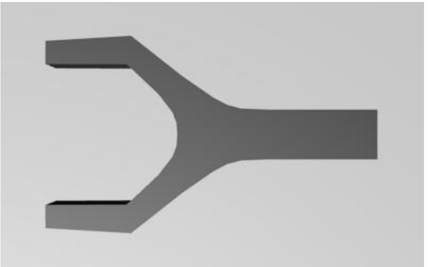
Target pose

Multi-Chamber Results: Crawling Creature

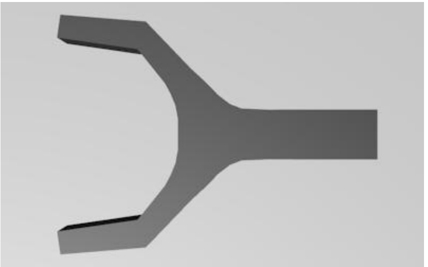


Multi-Chamber Results: Crawling Creature

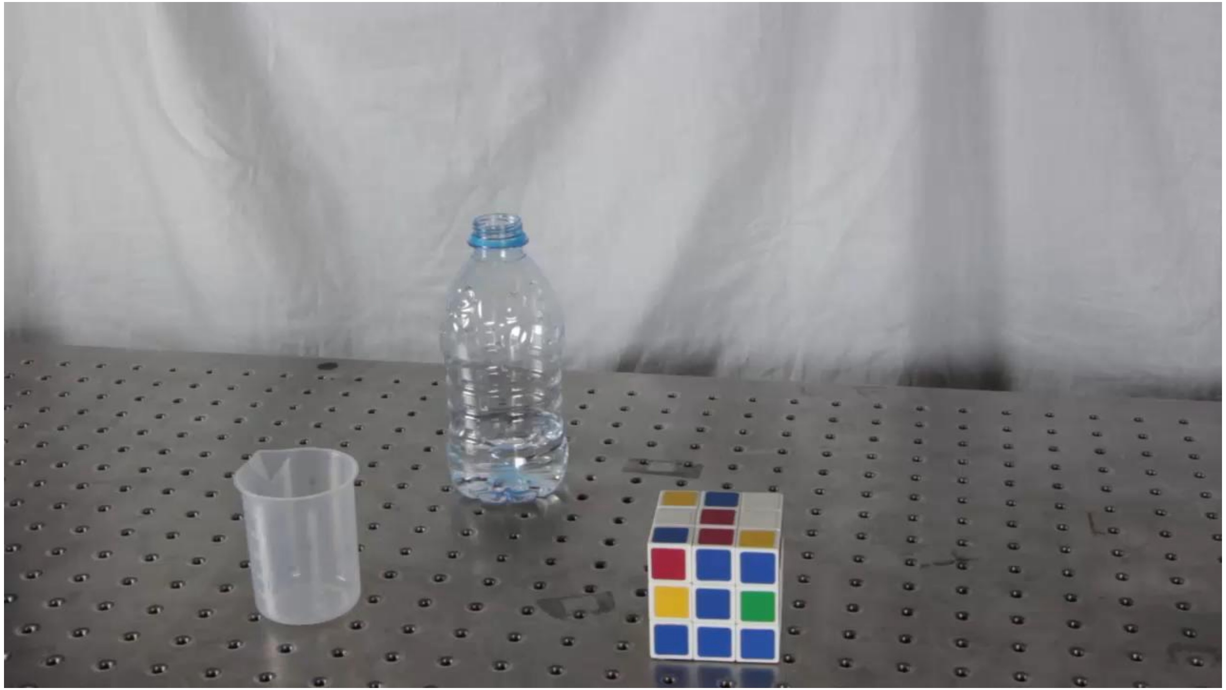
Application: Pneumatic Gripper



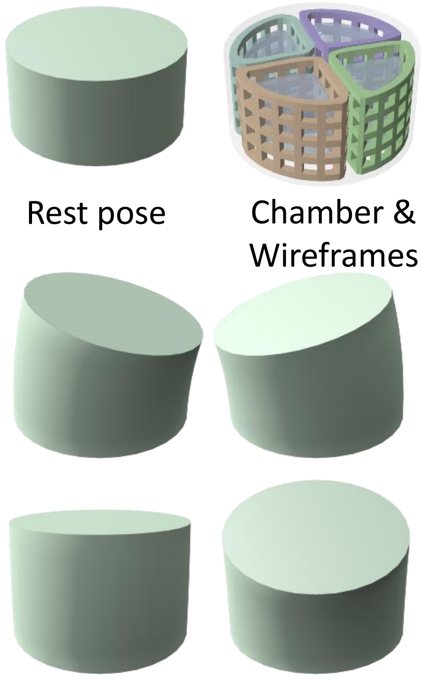
Rest pose



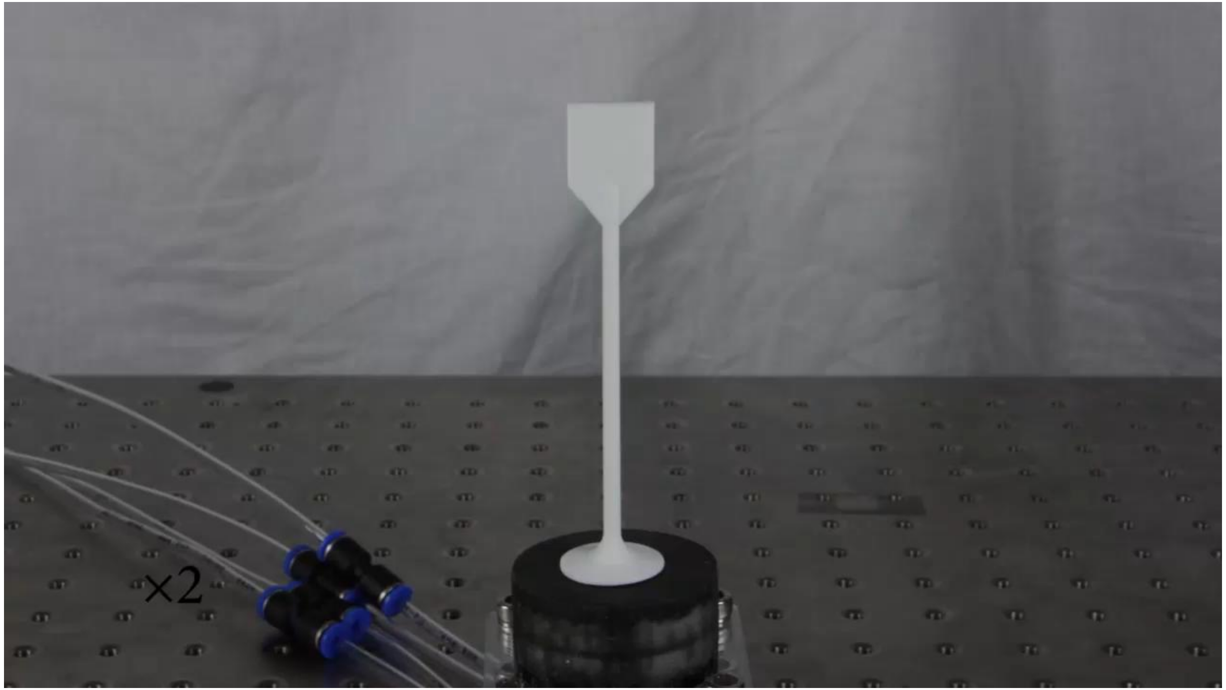
Target pose



Application: Multi-directional Pneumatic Module



Target poses



Conclusion

- A Ⓢ□//⌰⌰ Ⓟ∅○—Ⓜ∠⌰⌰⌯▱ □⊥⌖○▱⌰⌰Ⓢ ◠○Ⓢ⌯⌀⌀ ∠∅◠ //∠⊥◎⌯▱∠⌰⌰⌯□∅ //◎∠Ⓜ○√□◎⌒
- F∠⊥◎⌯▱∠⌰⌰○ —Ⓢ⌯∅⌀ 3D Ⓟ◎⌯∅⌰⌰⌯∅⌀
- C□∅⌰⌰◎□○○○○

Limitations

- M∠⇗⇗○◎≟∠Ⓛ
- D○//□◎Ⓜ∠⇗⇗≟□∅ ⓈⓅ∠▱○

Future Work

- M□◎○ ∠▱ ⇗⇗— ∠⇗⇗≟□∅ Ⓜ○⇗⇗ ↗□◠Ⓢ, Ⓢ—▱↗ ∠Ⓢ Ⓜ□⇗⇗□◎, ⊔∠▱——Ⓜ Ⓟ—ⓂⓅ, ○⇗⇗▱.

Acknowledgements

- [illegible]
- [illegible]
- [illegible]

Computational Design and Fabrication of Soft Pneumatic Objects with Desired Deformations

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