femto-st SCIENCES & TECHNOLOGIES

Realizing Programmable Matter with Modular Robots

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ANR (ANR-2011-BS03-005),
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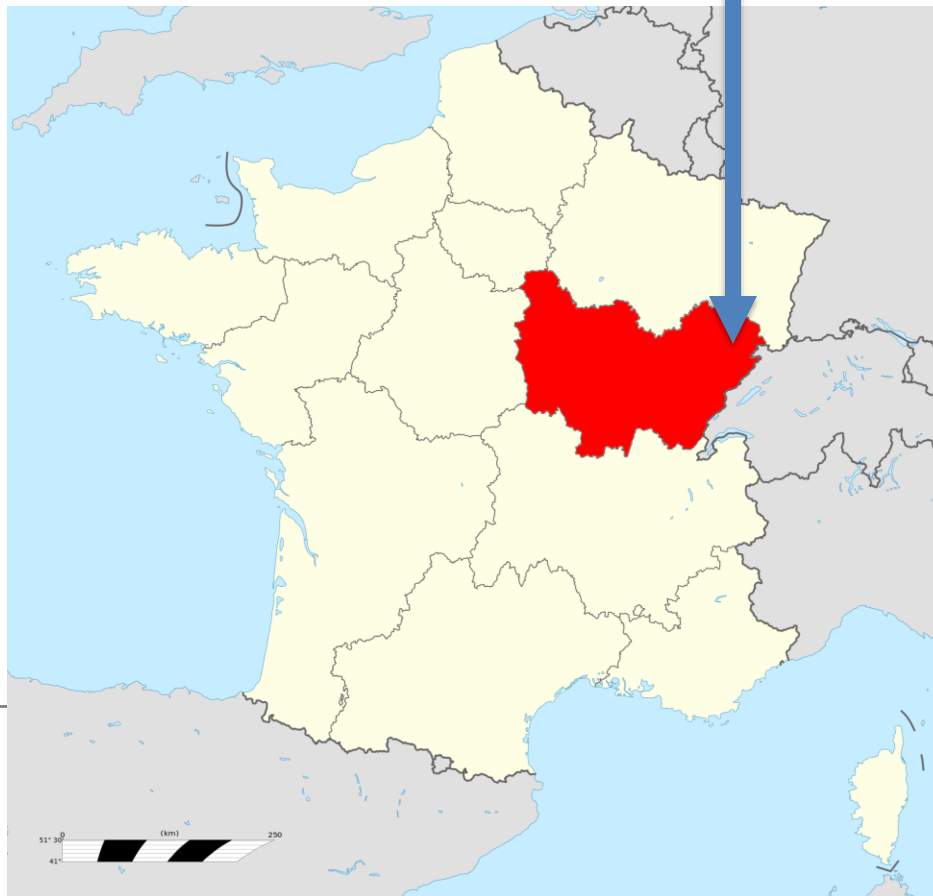
Intel Corporation
Microsoft

Where do I come from?

- University Bourgogne Franche-Comté (UBFC)
- University of Franche-Comté (UFC)
- FEMTO-ST Institute/CNRS, 700 researchers and staff
  - Collegium Smyle with EPFL
- CNRS ranked #1 (article count) in

Nature Research Index, 2018

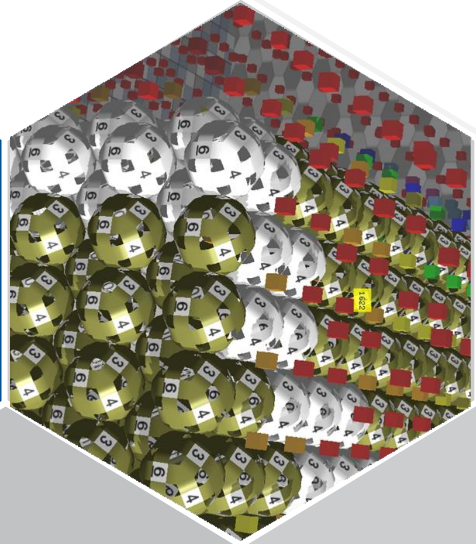
Montbéliard
(Peugeot Citroën
car home city)



cnrs dépasser les frontières

Outline

Our Vision



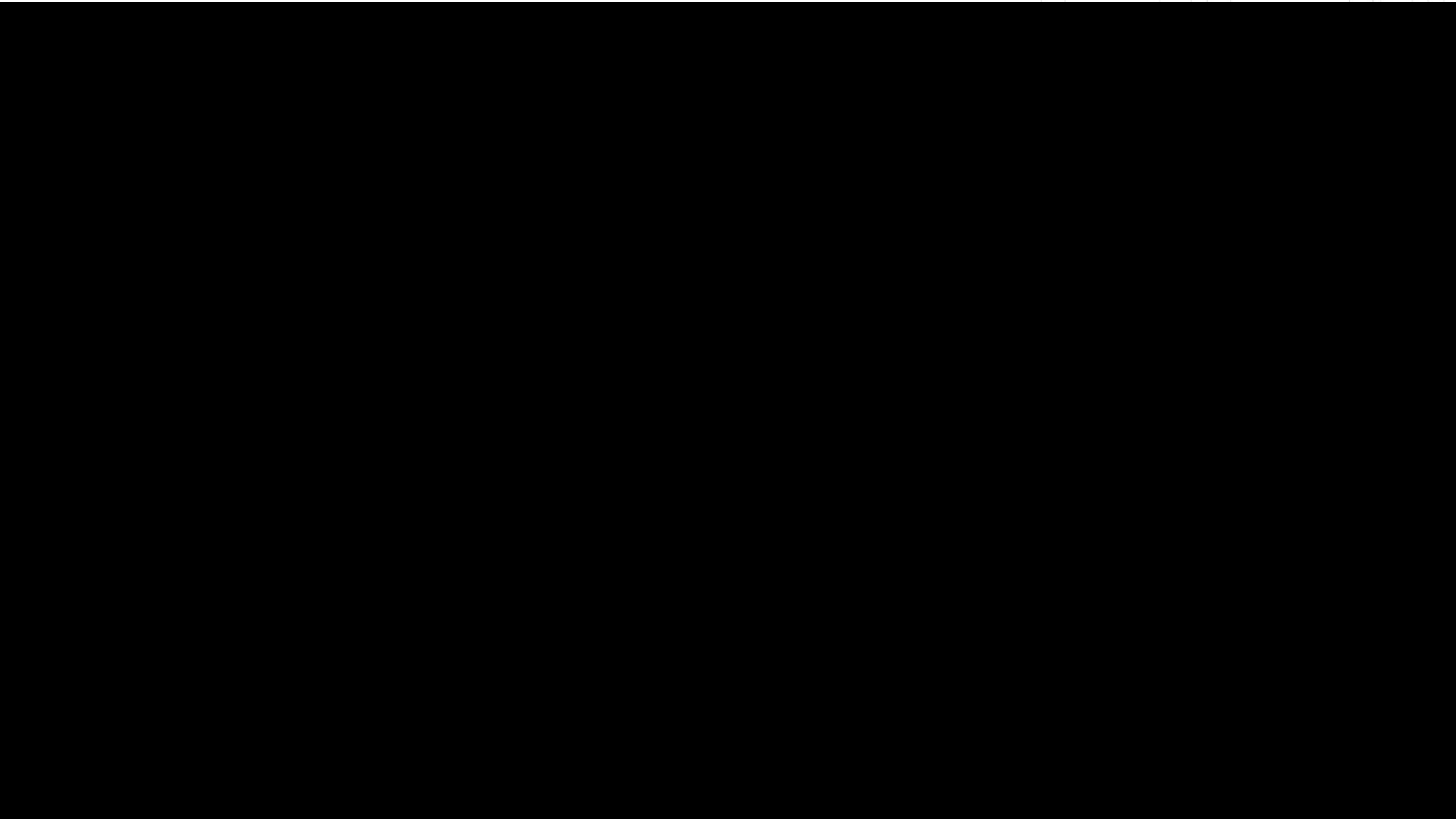
What's Next?

Hardware design

Software

Art

Programmable matter examples



Programmable matter

- Nice video but we cannot do magic!
  - Reconfiguration speed
    - Moving is slow, moving millions of modules is VERY VERY slow
    - 12 hours for reconfiguring 800 sliding-cubes!!
    - (or 11.66 hours for moving 1024 Kilobots)
  - Reliability
    - Having millions of modules, you WILL have failures
  - Sturdiness
    - Very few studies about mechanical resistance of such a complex system

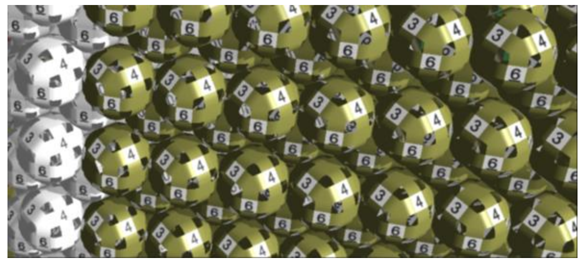
Programmable matter applications

Complex surgery

Take an MRI

MRI imaging

3D model

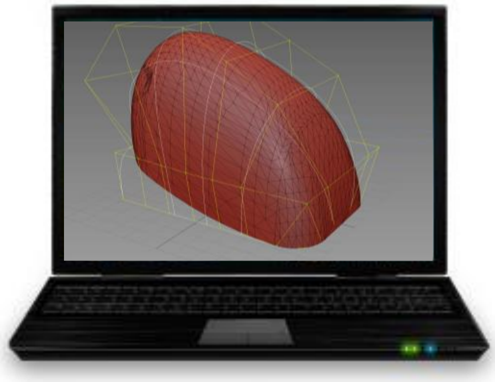


Programmable matter representation

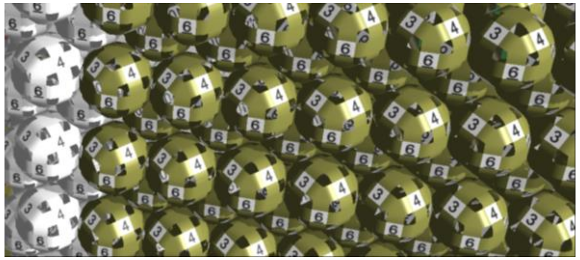
Interactive training

Programmable matter applications

Complex part design



CAD model

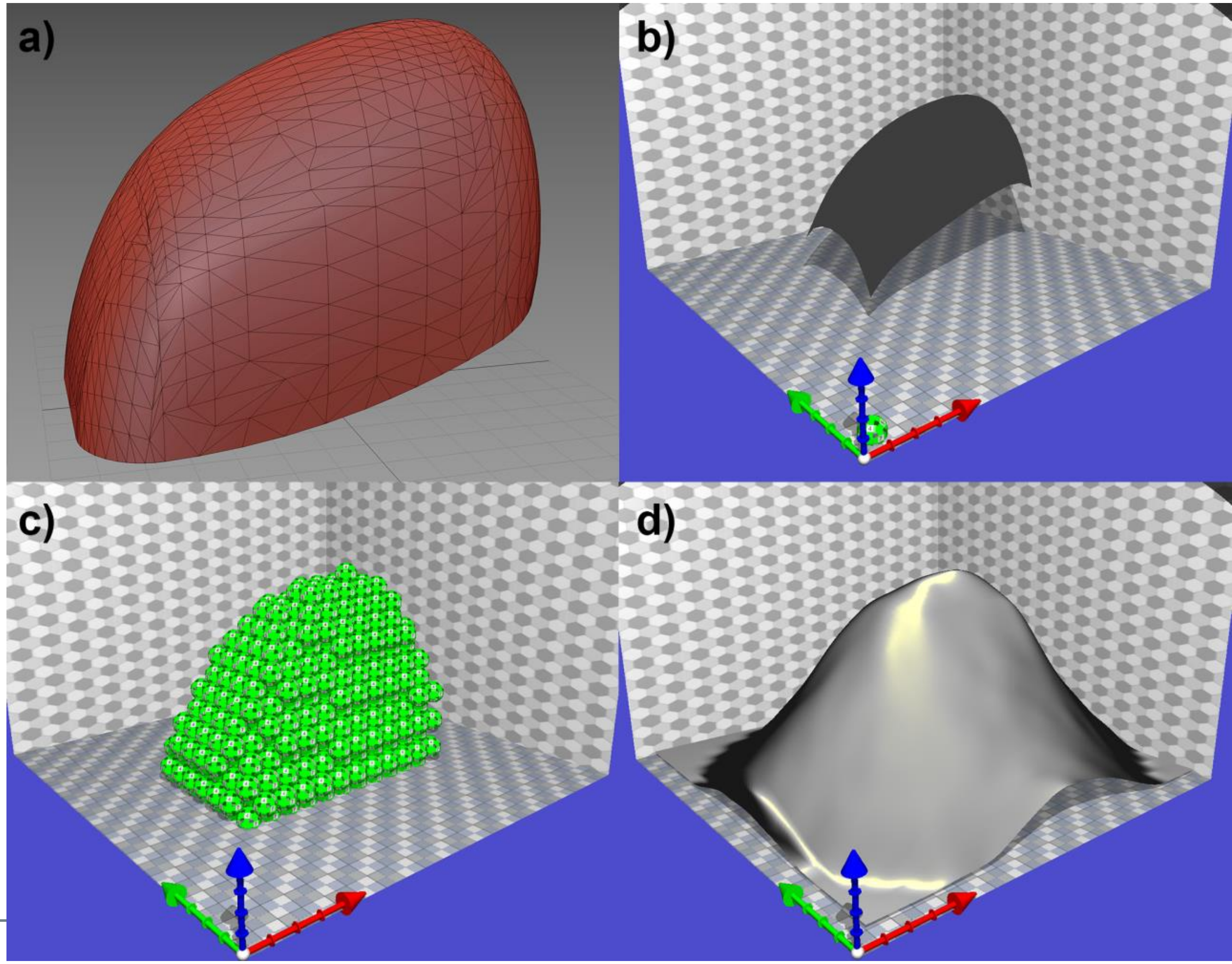


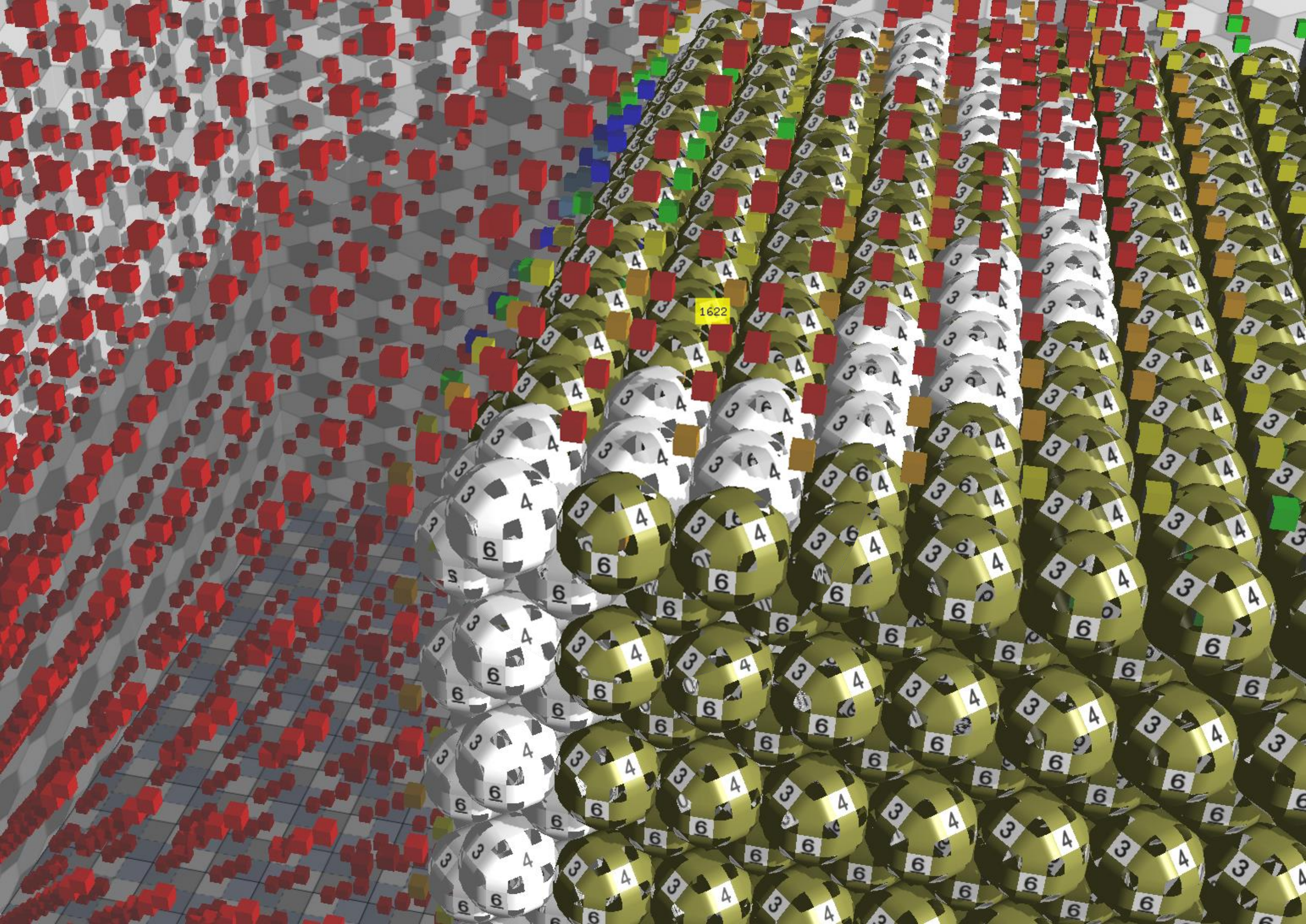
Programmable matter representation

User modifications

Programmable matter applications

Sculpting a shape-memory polymer sheet

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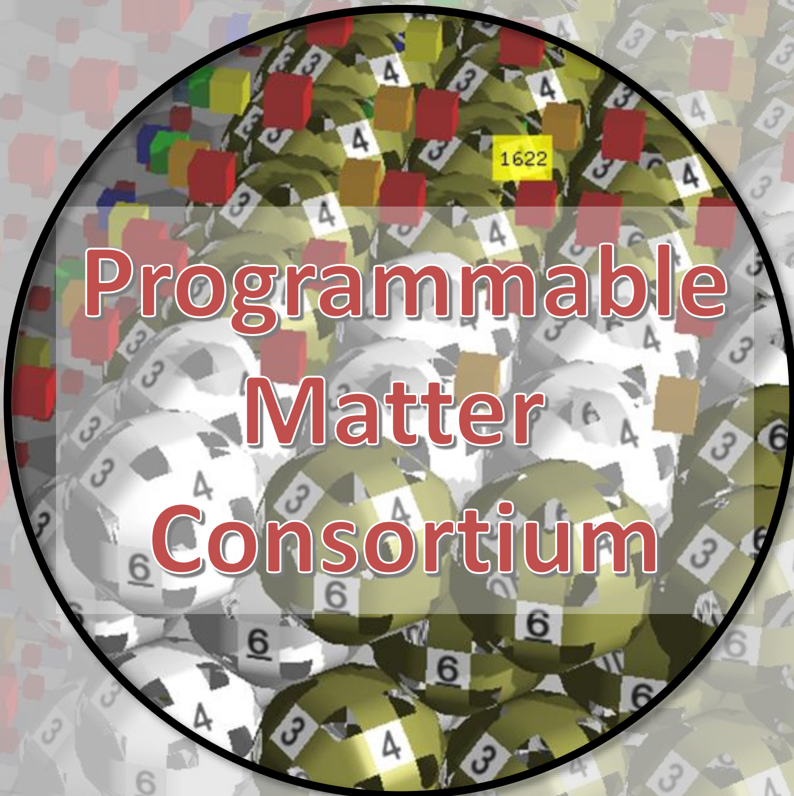
Programmable Matter Consortium



Computer Science

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UBFC

cnrs

L2i

Carnegie Mellon University

Micro- and Nano-Electro-Mechanical Systems

LIMMS Laboratory for Integrated Micro-Mechatronic Systems LIMMS/CNRS-IIS UMI 2820

The University of Tokyo

Electrical Engineering

University of Michigan

Mechanical Engineering

IPPT PAN

Industrial partners

PSA Groupe

Peugeot, Citroën, DS Automobiles, Vauxhall, Opel

CubeWorks

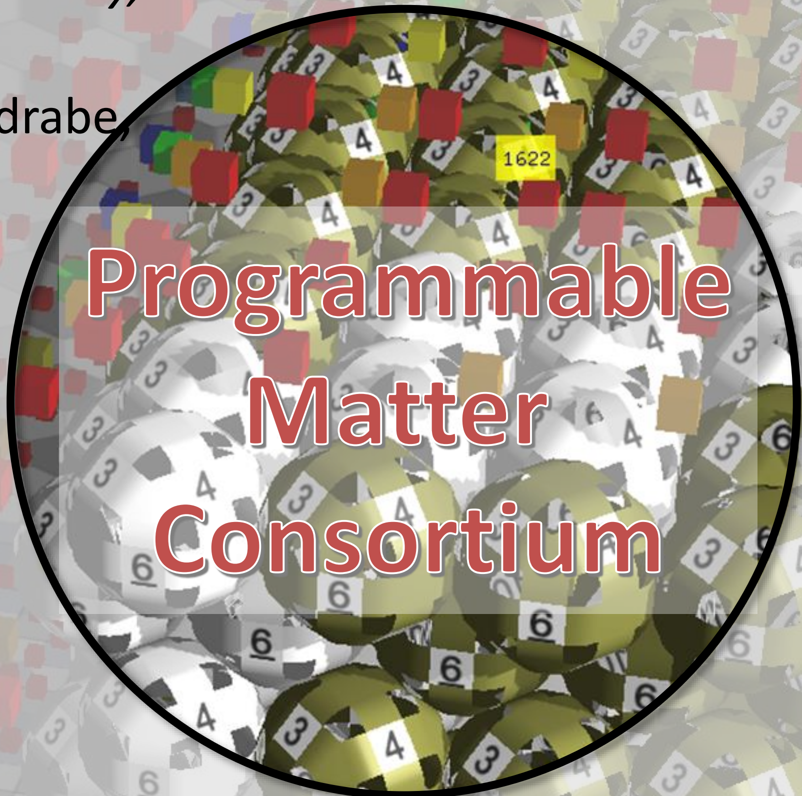
Tech Power Electronics Group

Art

scenocosme

I-SITE BFC

ANR — Projet financé par l'ANR — Project funded by the ANR



Programmable Matter Consortium

Computer Science

Seth Copen Goldstein

Benoit Piranda, Eugen Dedu, Hakim Mabed, Dominique Dhoutaut, *André Naz, Thadeu Tucci, Pierre Thalamy, Florian Pescher*

Philippe Lutz, Micky Rakotondrabe, Abdenbi Mohand Ousaid, Dominique Gendreau, *Romain Catry*

Wahabou Abdou, Olivier Togni, Nader Mbarek, *Nicolas Gastineau*

Micro- and Nano-Electro-Mechanical Systems

Yoshio Mita, Eric Lebrasseur, Gwenn Ulliac, *Naoto Usami*

Electrical Engineering

David Blaauw, Dennis Sylvester, David Wentzlof, HunSeok Kim, Jamie Philip

Mechanical Engineering

Jakub Lengiewicz, Pawel Holobut, *Pawel Chodkiewicz*, Anna Górzyńska-Lengiewicz

Industrial partners

Stéphane Delalande

Salvatore Gora

Art

Grégory Lasserre

Anaïs met den Ancxt

I-SITE BFC

PROJET FINANCÉ PAR L'ANR · PROJECT FUNDED BY THE ANR

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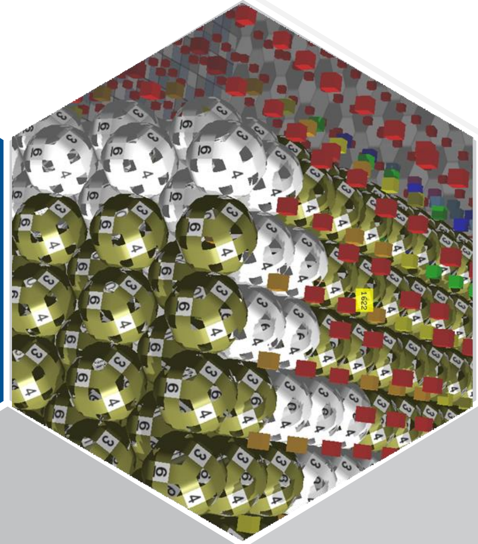

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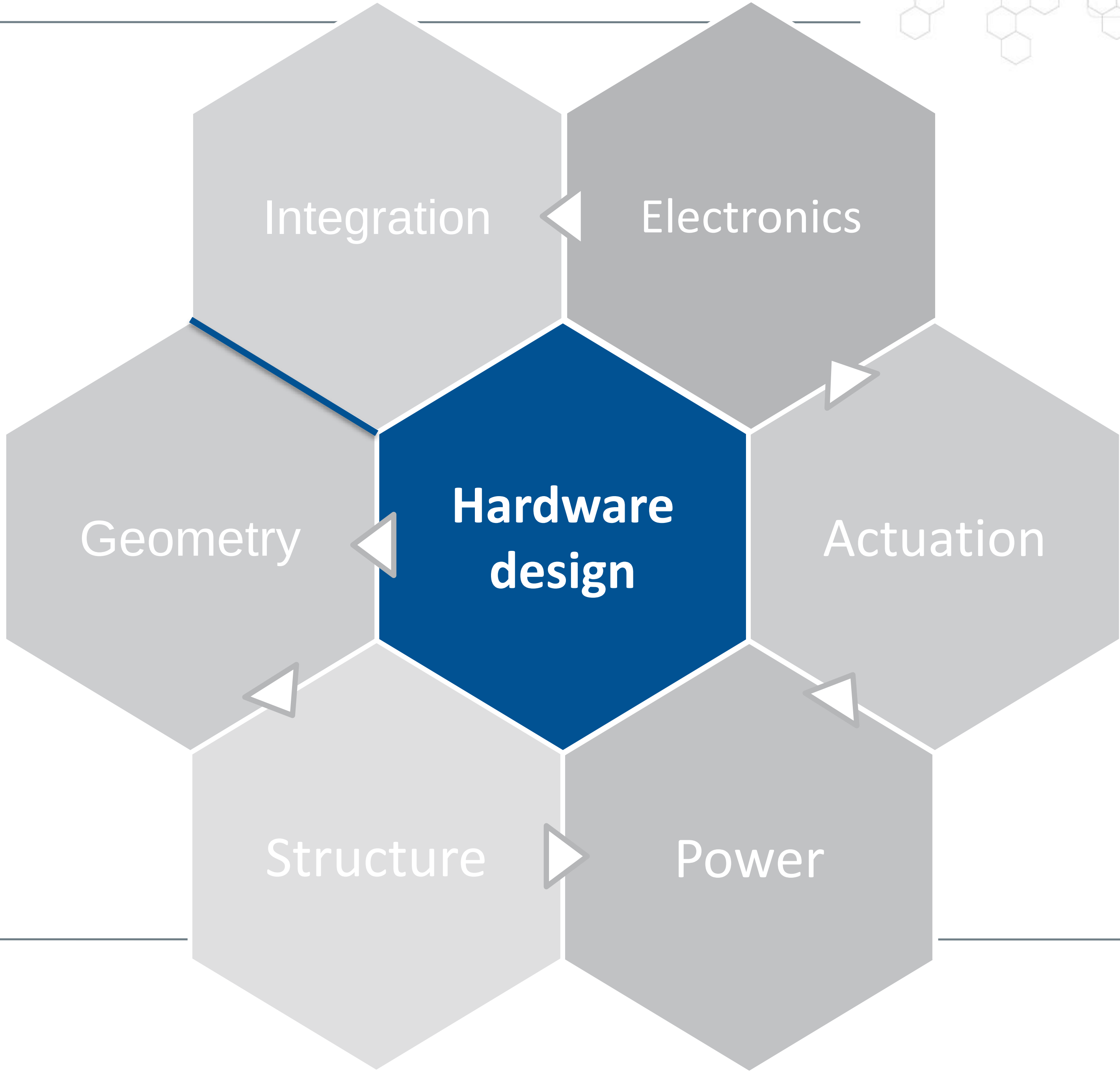
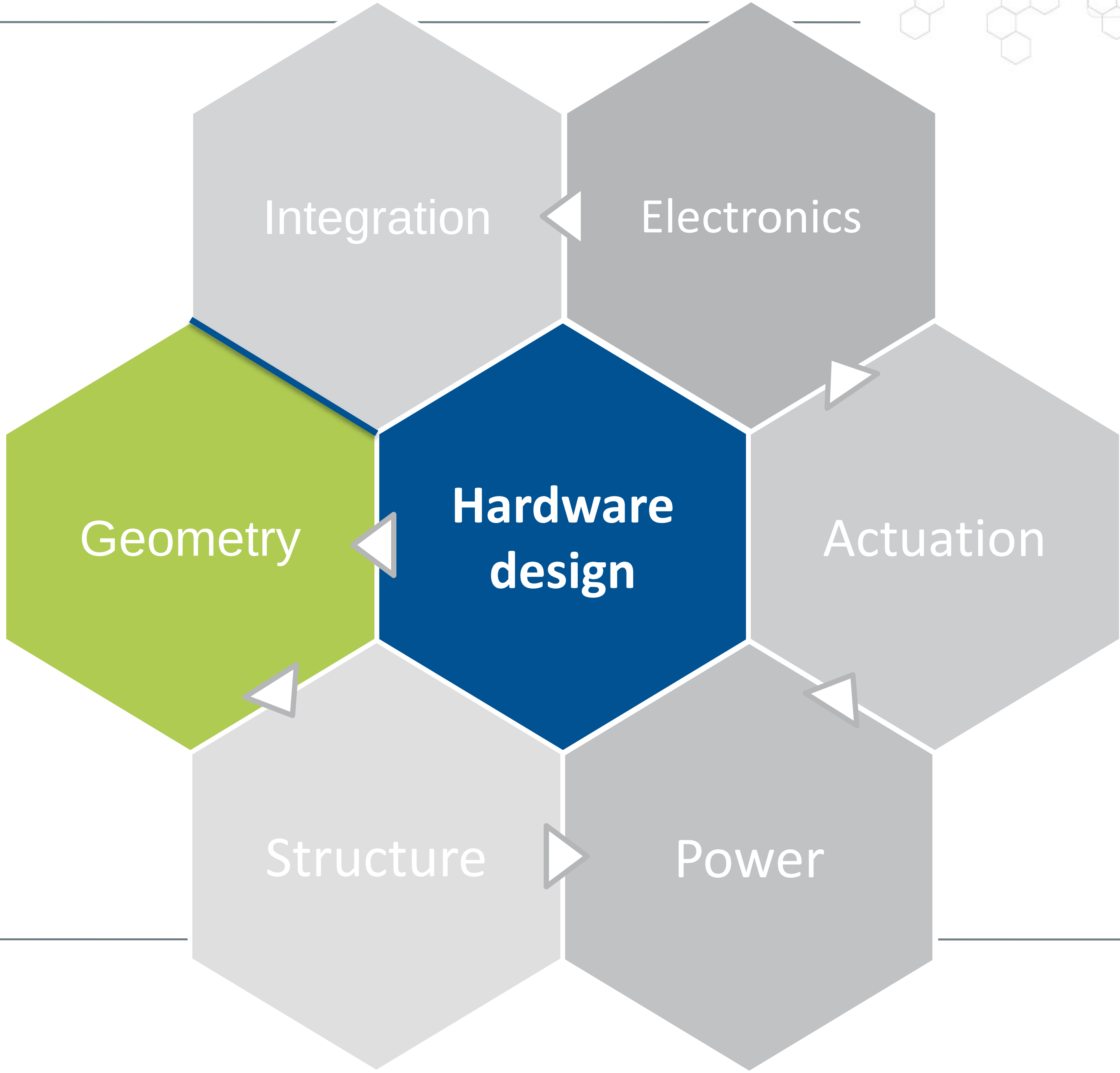

Integration
Electronics
Hardware design
Geometry
Actuation
Structure
Power

Outline



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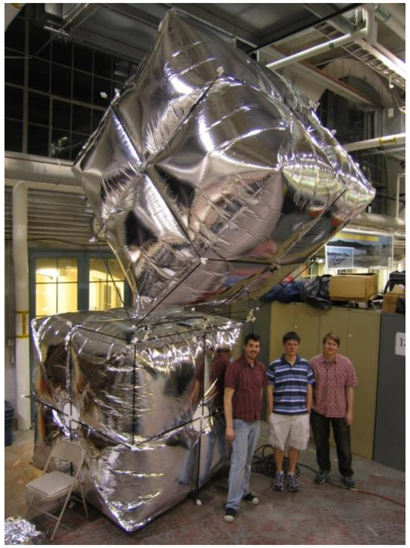
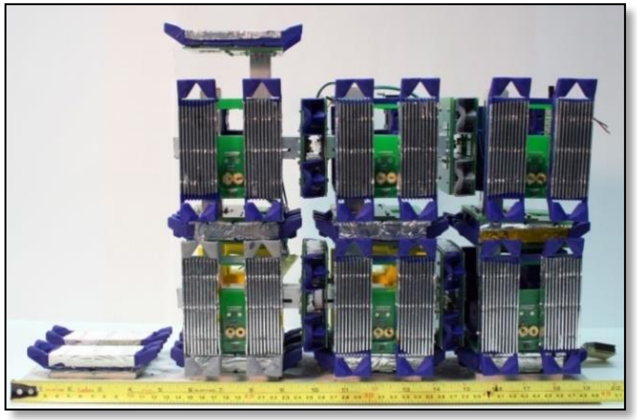
Claytronics Atoms: Catom

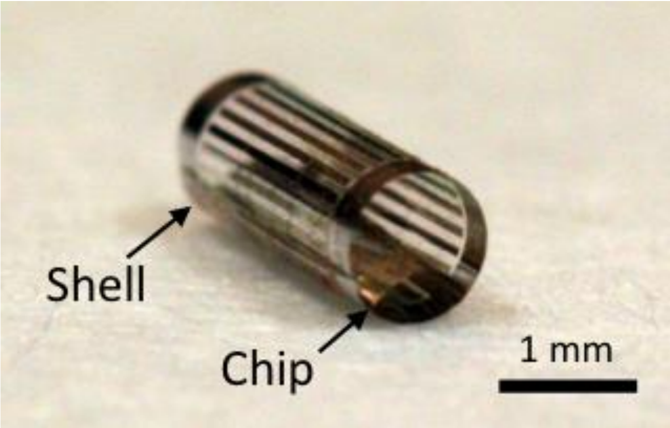
~meters (2006)



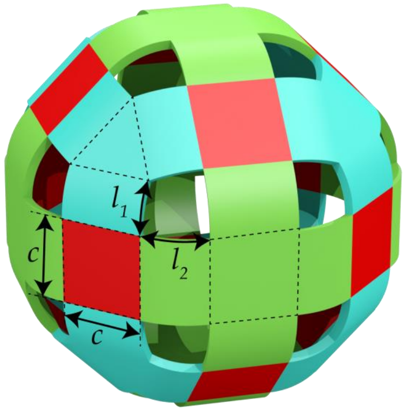
~decimeters (2007)



~centimeters (2007)



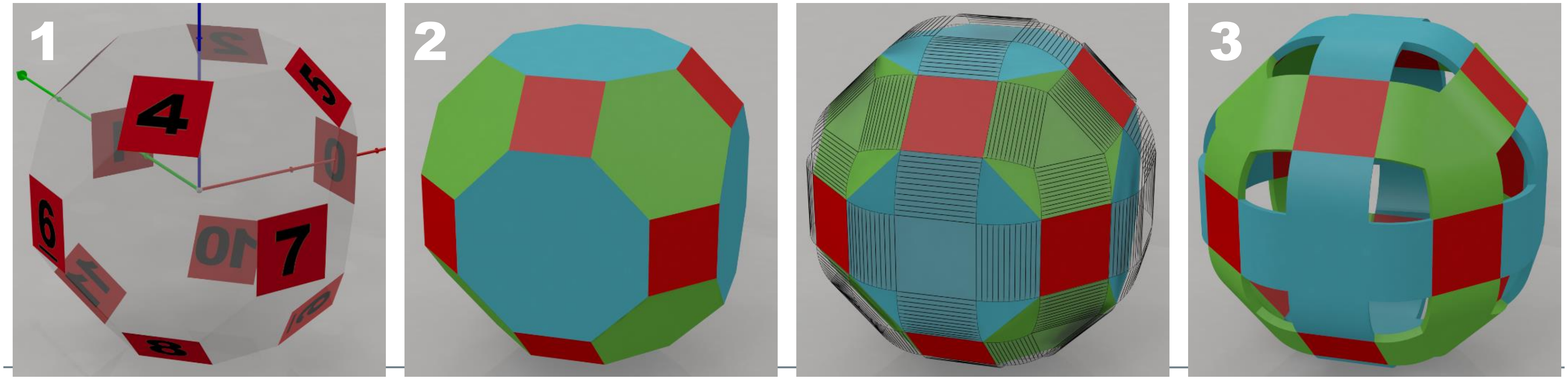
~millimeters (2012)



3D shape

Towards 3D: Geometrical basics

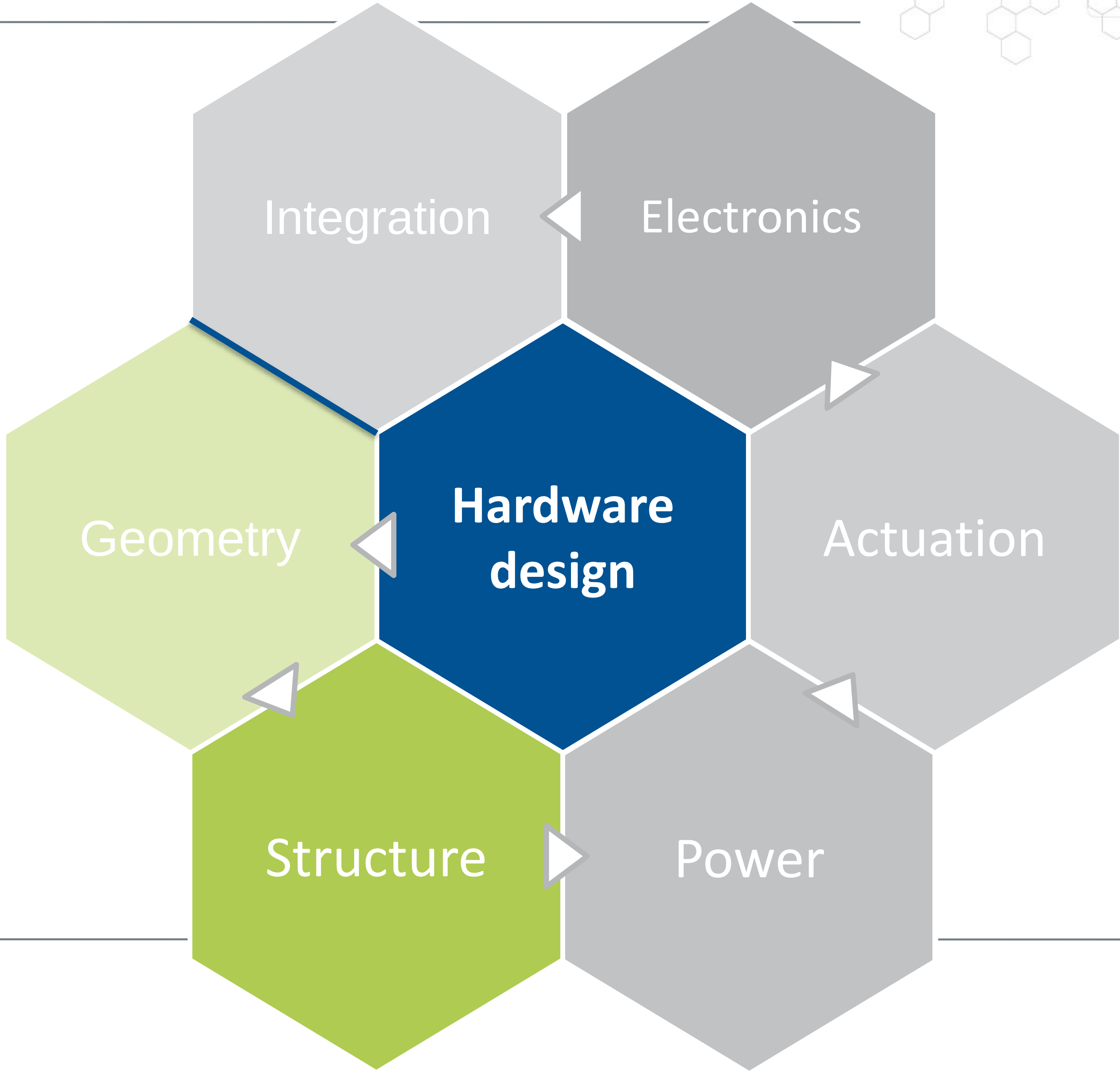
1. We replace connection points by 12 square connectors.
2. Then we can place 8 hexagons and 6 octagons.
   - Truncated cuboctahedron
3. Electrostatic actuators make catoms turning around neighbors.
   - We place curved surface over hexagonal and octagonal faces.
   - These curves are part of cylinders and planes in order to obtain continuous surfaces



Piranda Benoit and Bourgeois Julien, "Geometrical Study of a Quasi-Spherical Module for Building Programmable Matter" *in "2016 13th International Symposium on Distributed Autonomous Robotic Systems (DARS)"*, London, UK, nov. 2016

Motion examples

Outline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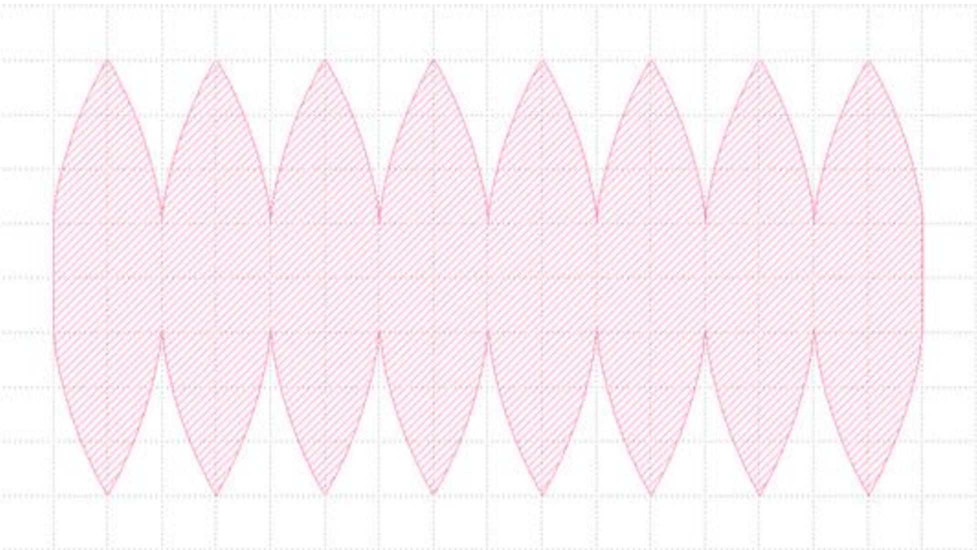
Structure



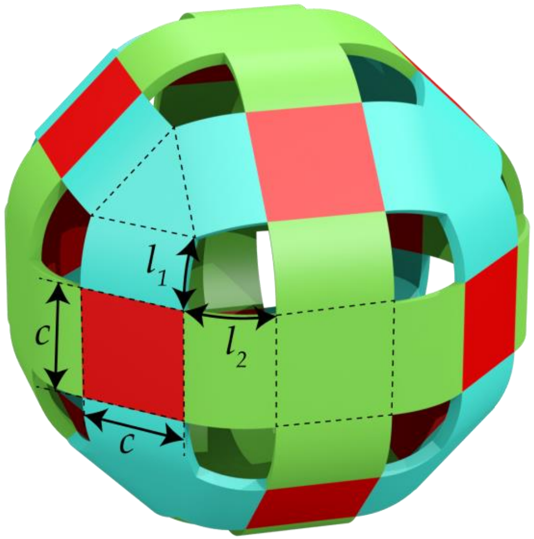
Structure

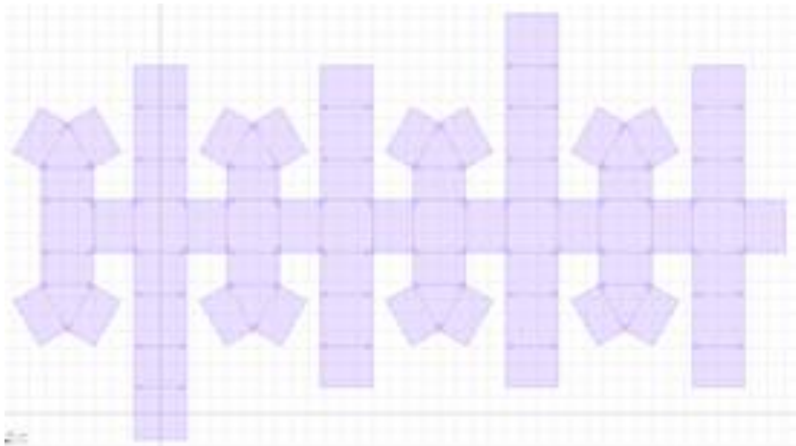






Structure





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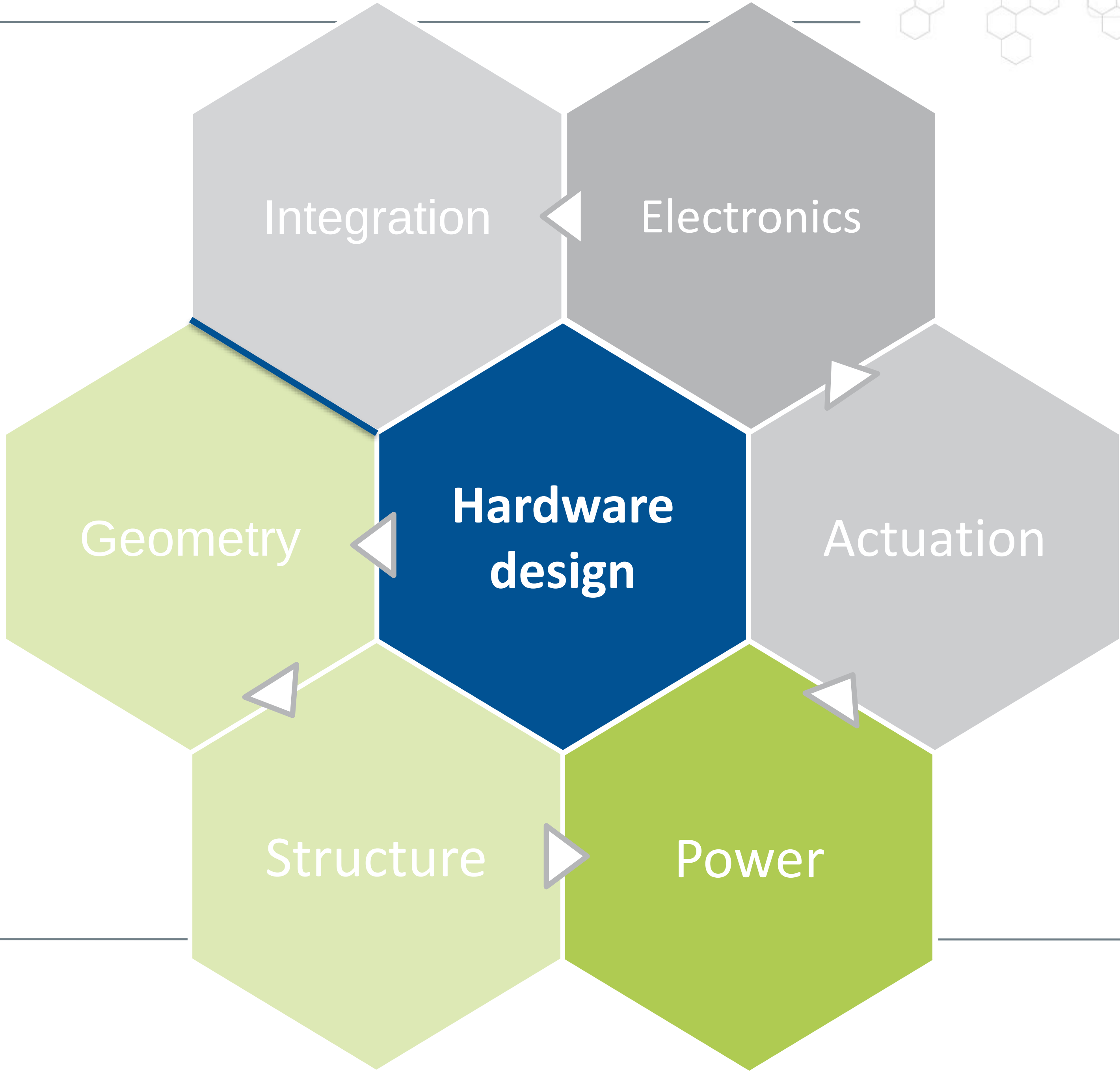

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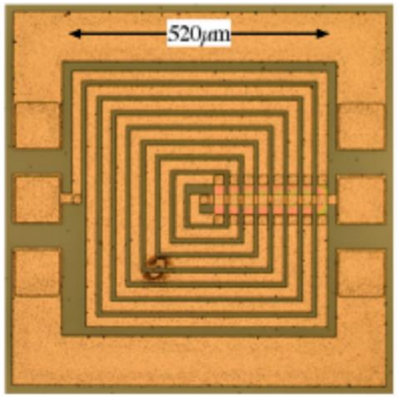
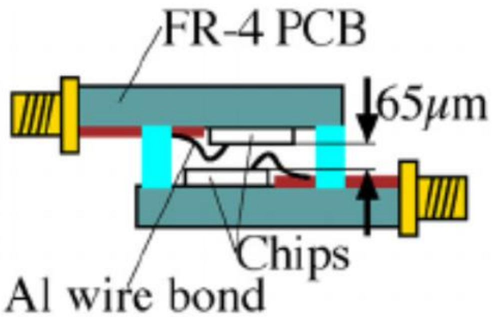
Power

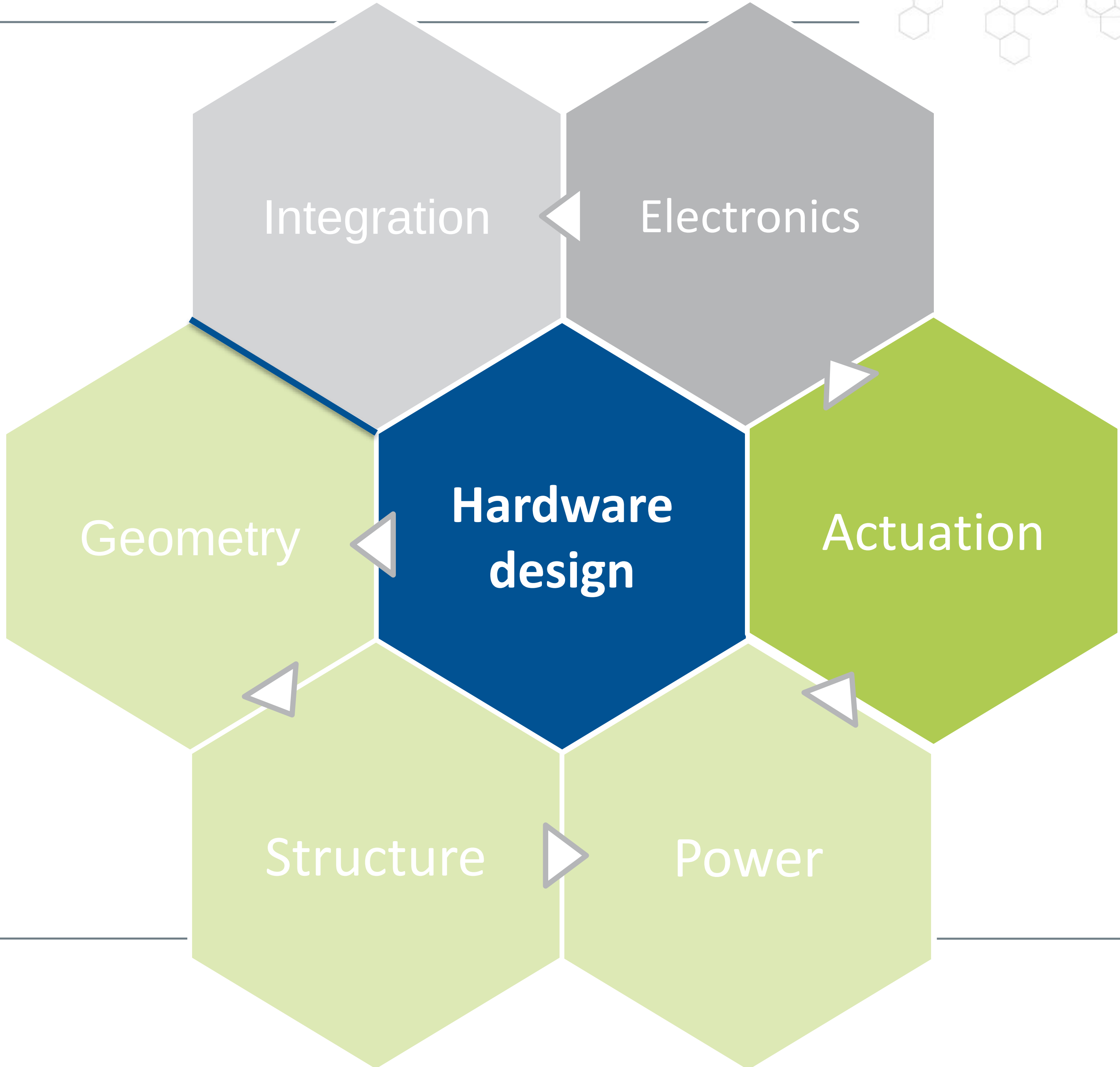
- Experiments with 7.05 mW power consumption by an actuator
- Connected actuators
    - Work using the square of input
    - No need for diode
    - Higher power efficiency





Microscale ultrahigh-frequency resonant wireless powering for capacitive and resistive MEMS actuators, Sensors and Actuators A: Physical (Volume 275, jun 2018, Pages :75 - 87), Mita, Y., Sakamoto, N., Usami, N., Frappé, A., Higo, A, Stefanelli, B., Shiomi, H., Bourgeois, J., Kaiser, A.

Outline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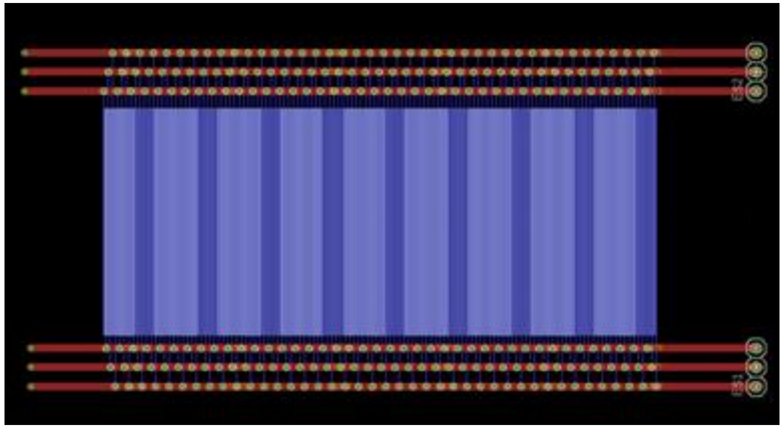
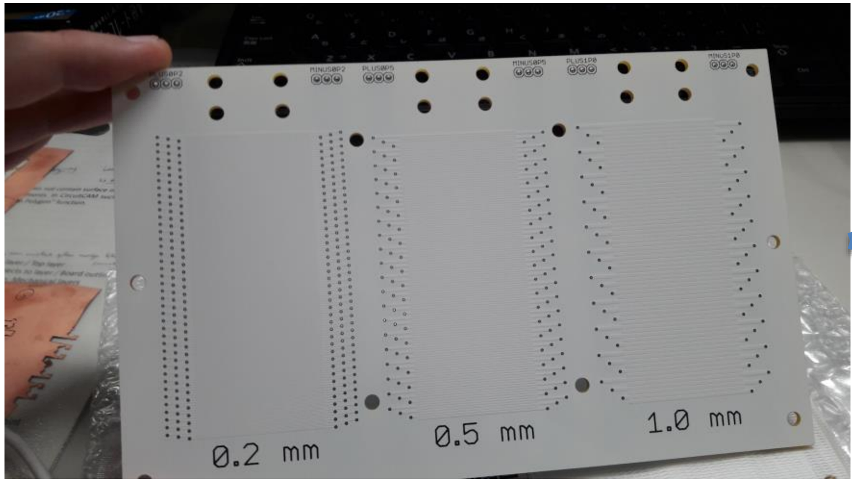
Actuation





Pyralux flexible

LPKF Protolaser U3

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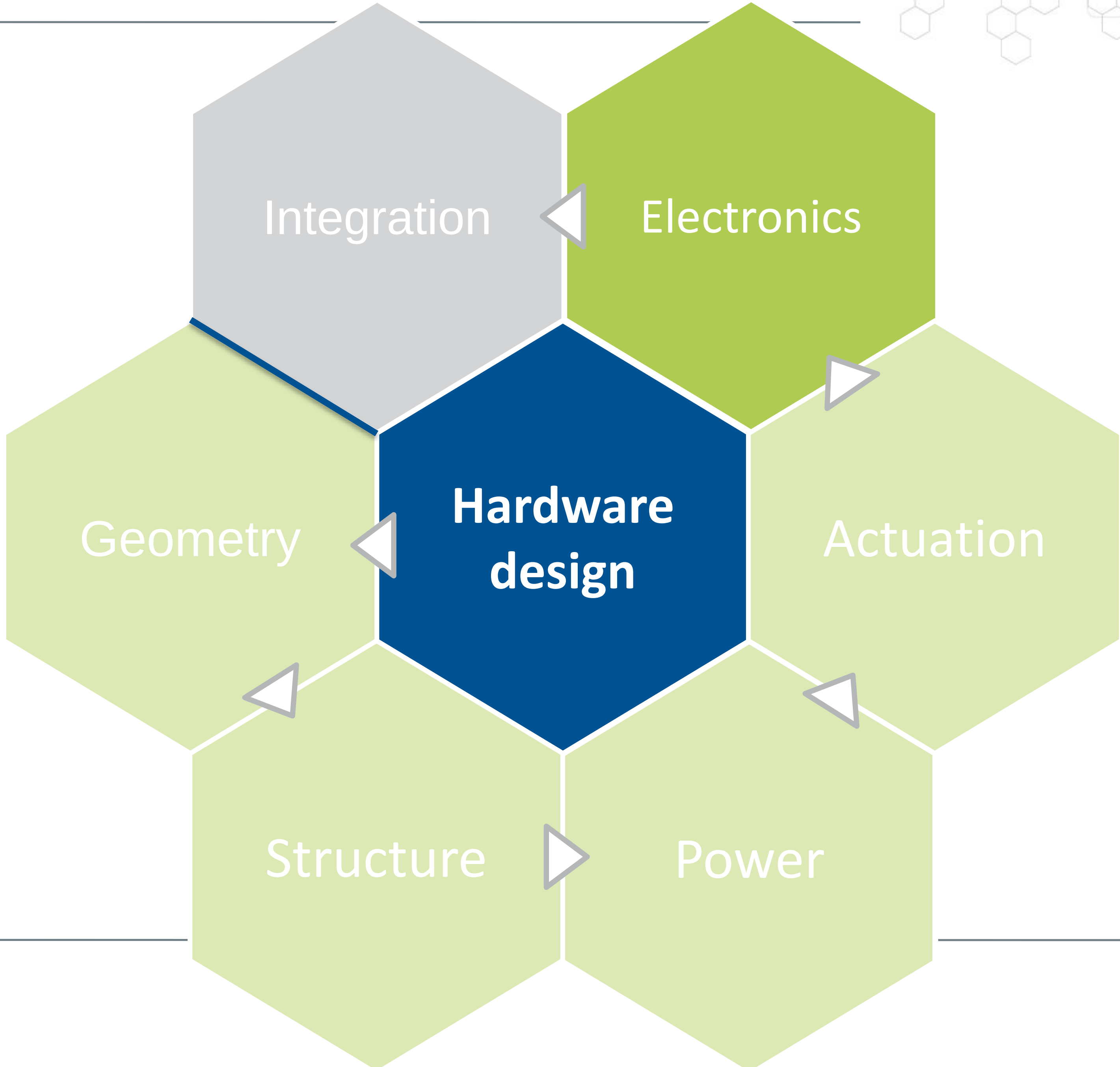
Outline



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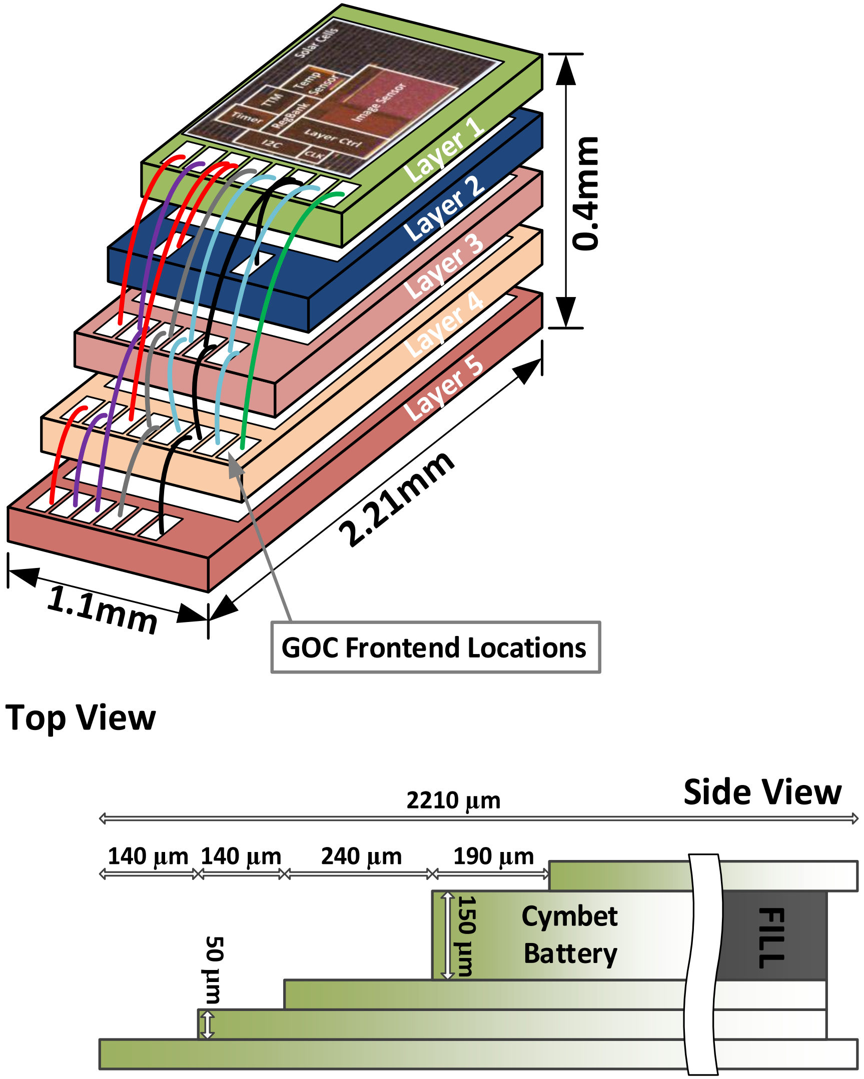
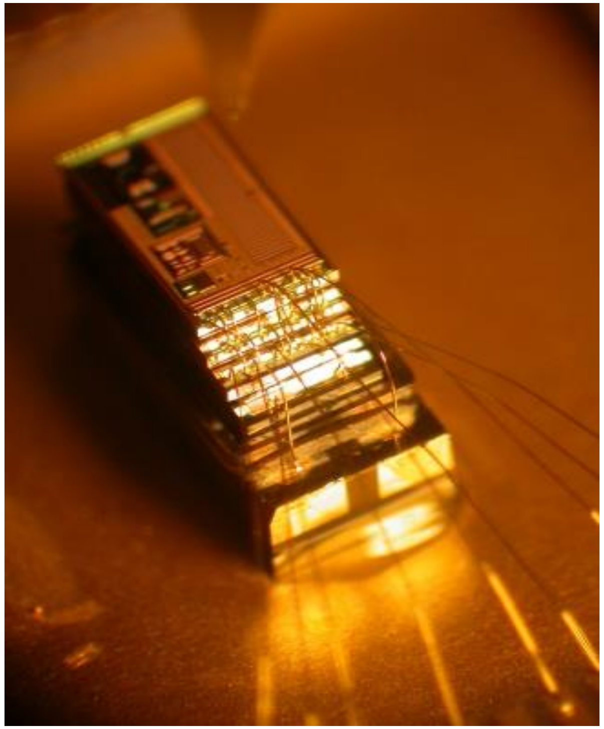
M^3 : Michigan Micro-Mote : A mm^3 Sensing Platform



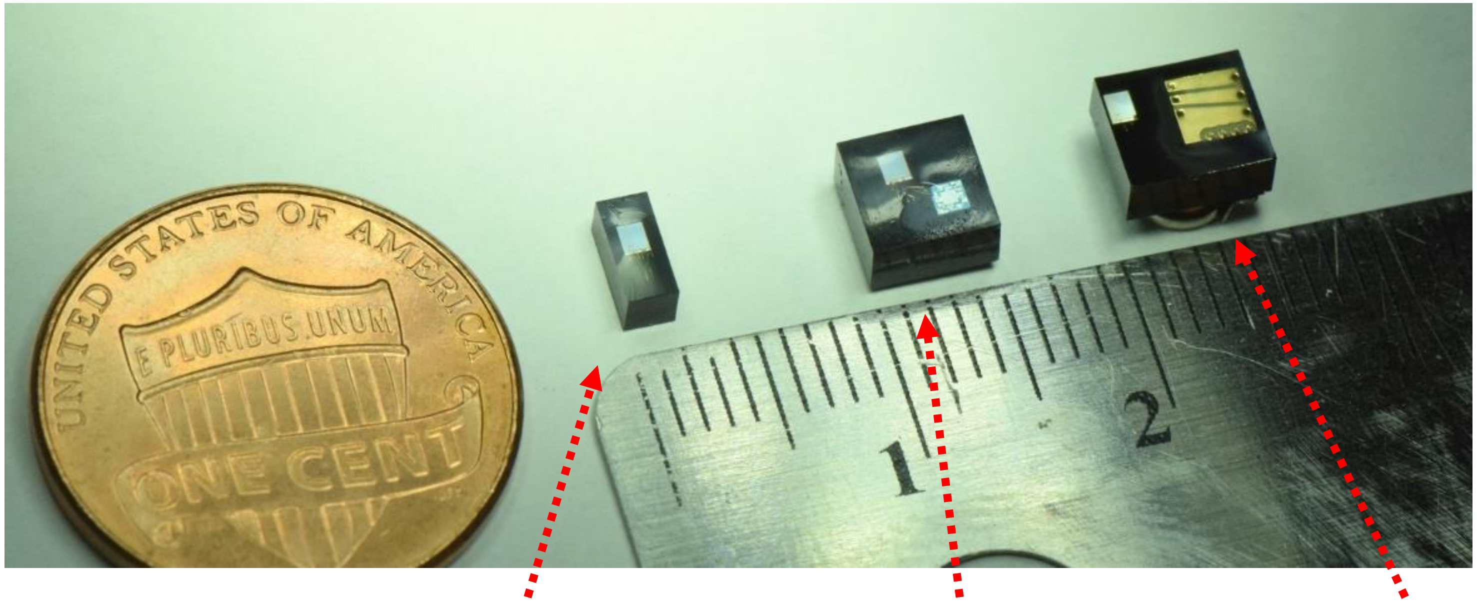
mm^3 generic sensing platform

- Modular die-stacked structure
- Enables diverse technology
- $12.3mm^2$ in $2.5mm^3$
- Swappable layers

Requires standard communication interface between layer



Types of Sensors



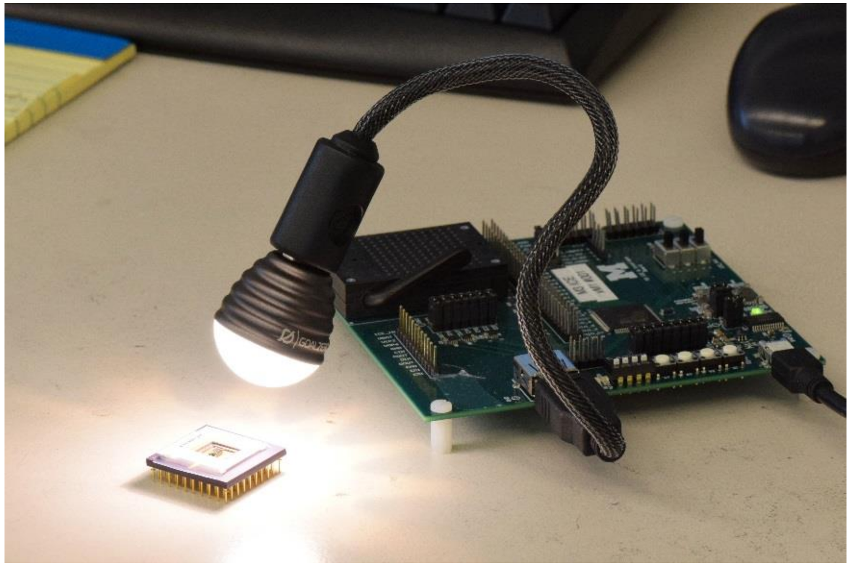
	F Series	P Series	N Series
Dimension	2 x 4 x 2 mm^3	5 x 5 x 3 mm^3	7 x 7 x 5 mm^3
Sensing Modalities	Temp, Pressure, Light	Temp, Pressure, Light	+ Motion, Humidity
Lifetime	1 month 3 years (w/ harvesting)	3 – 5 years	5 – 7 years
Radio Range	5 cm	1 m	20-50m

CubeWorks

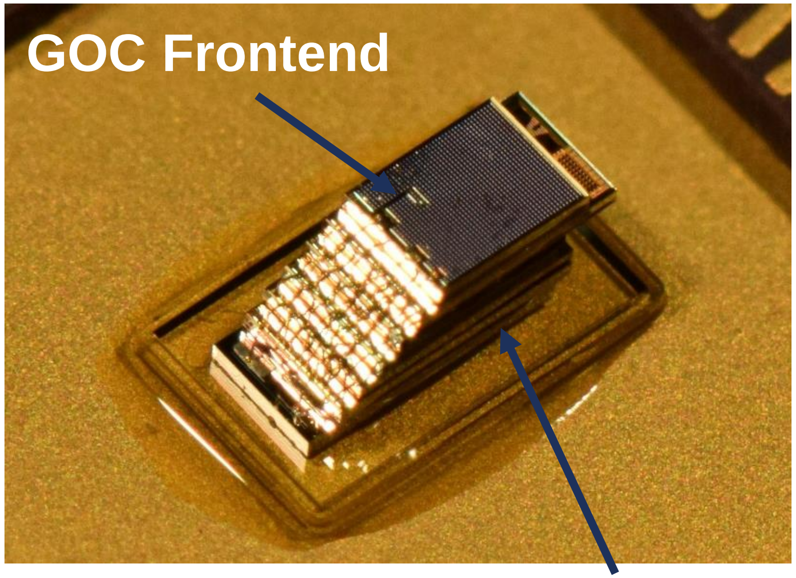
Credit: Cubework

Optical Programming: GOC

- GOC programming interface
  - Separated front-end for isolating light exposure within the system
  - Up to 840bps transmission by faster clock speed and larger frontend diode
  - Tradeoff between programming speed & sleep power

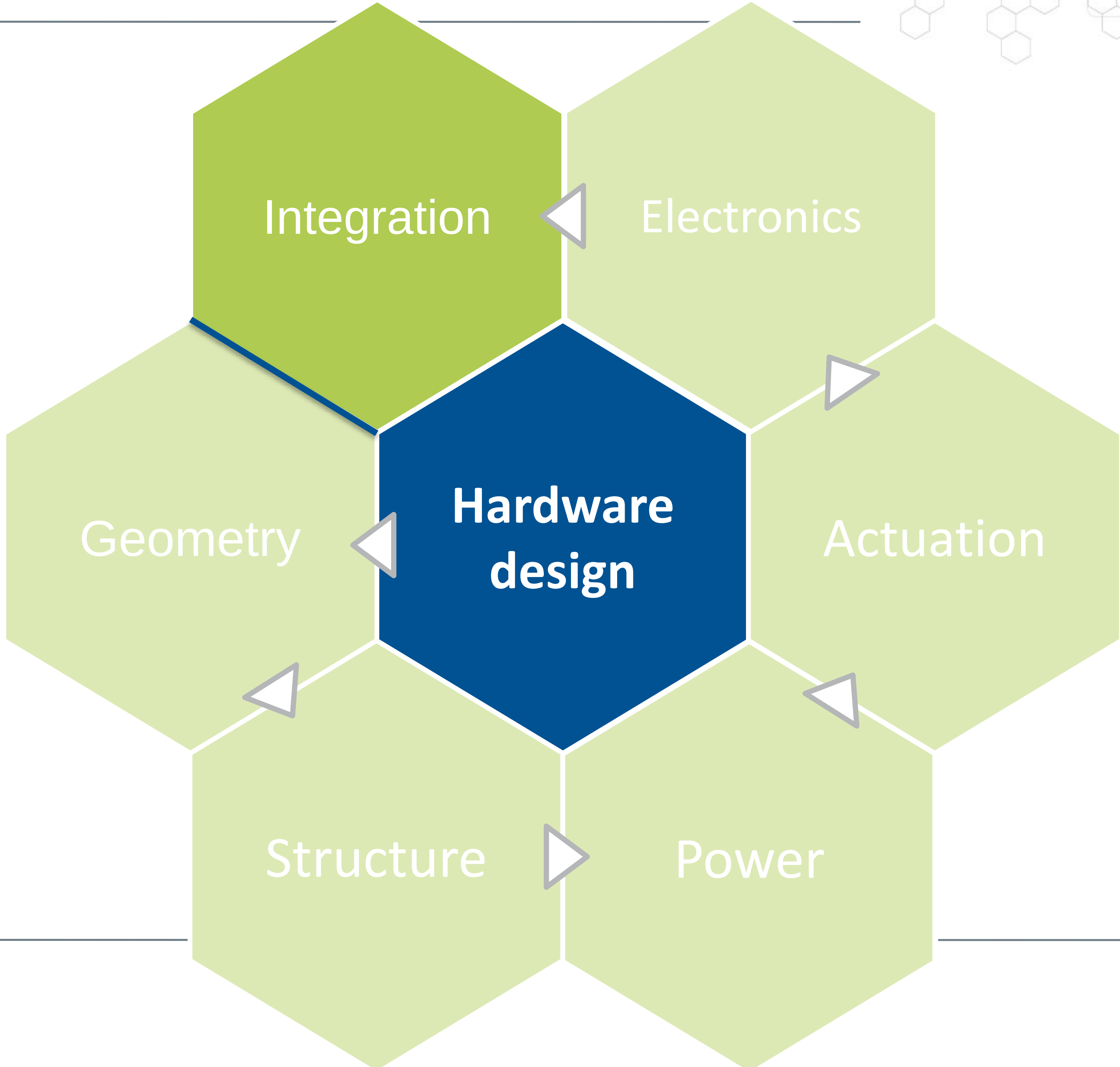


Programming M3 Stack with ICE Board via GOC



M3 Stack with Solar Cell and GOC Frontend on Top Layer

Outline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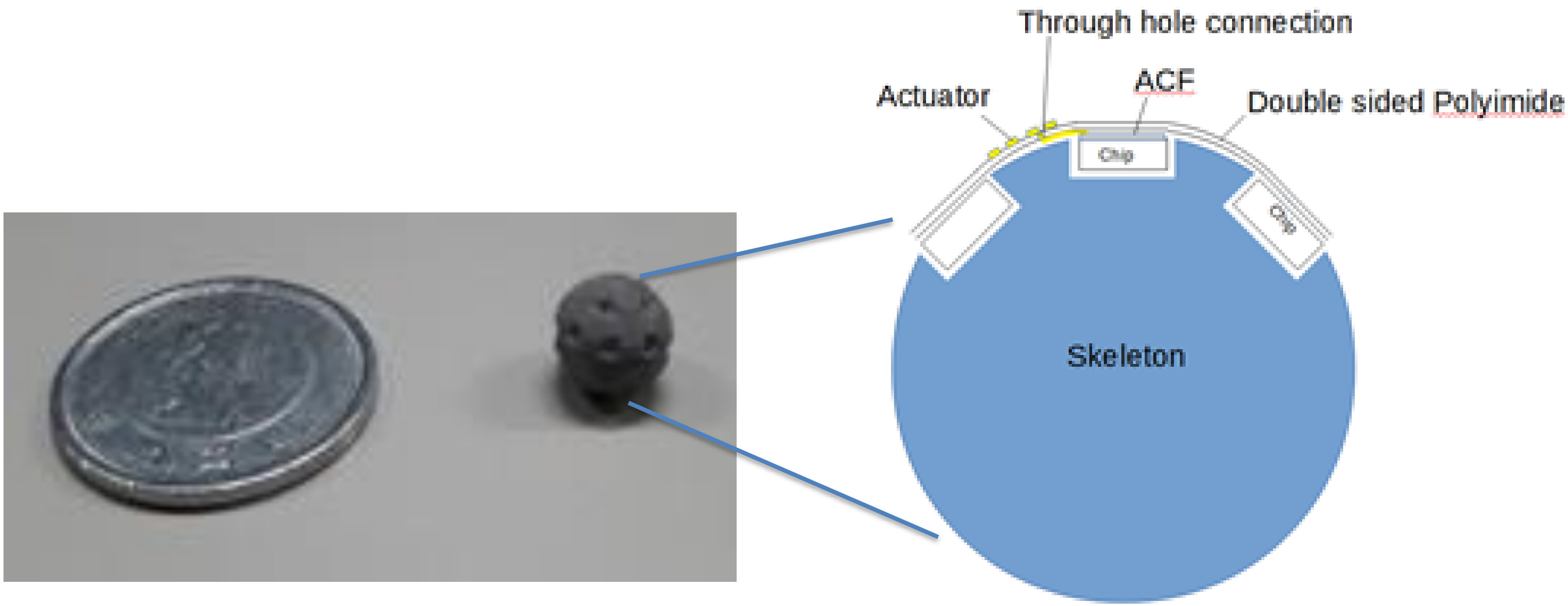
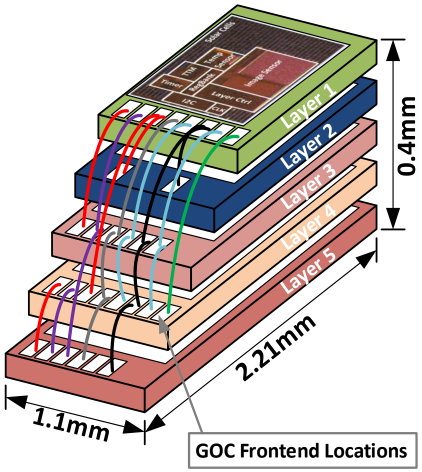
Integration of M3 mote and catom

- Integration on skeleton with flexible printed circuit

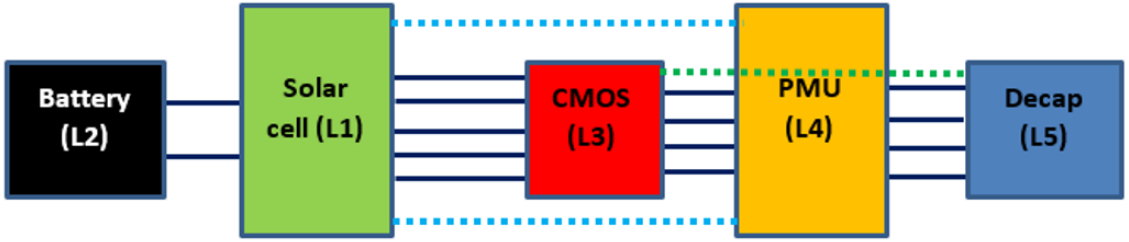


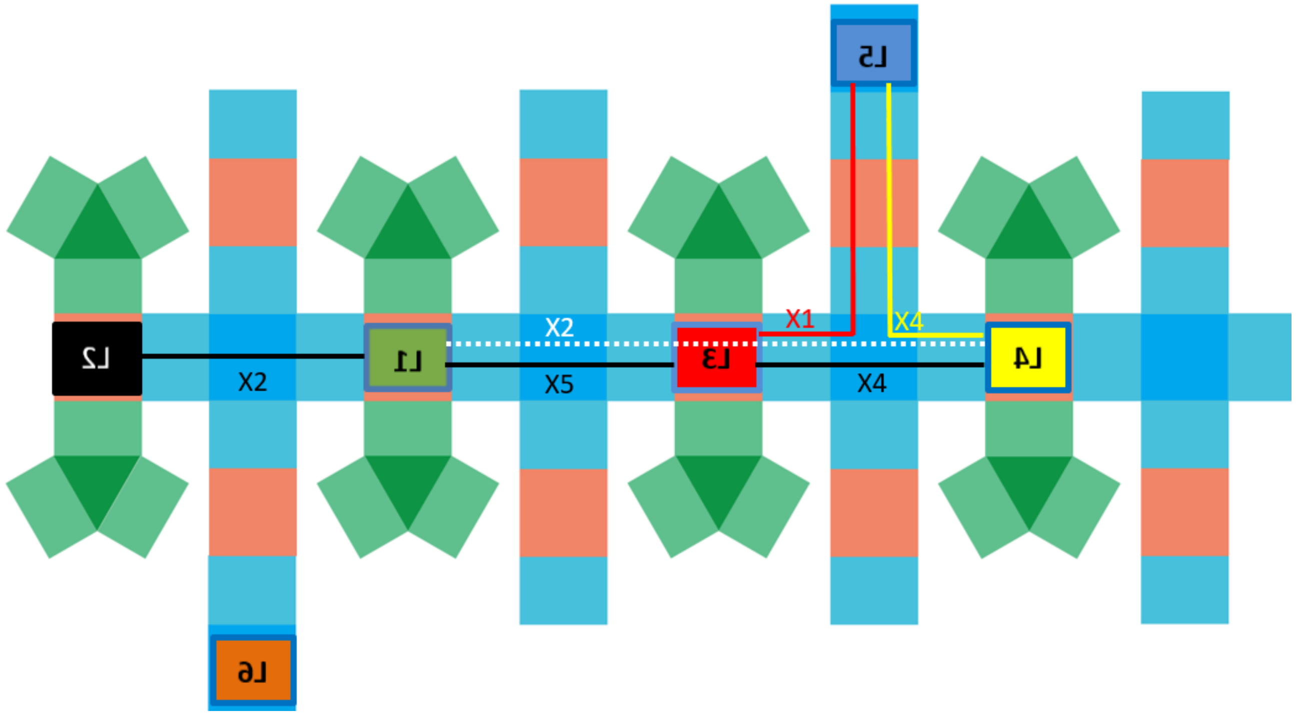
Integration of M3 mote and catom

- Electrical interconnexions



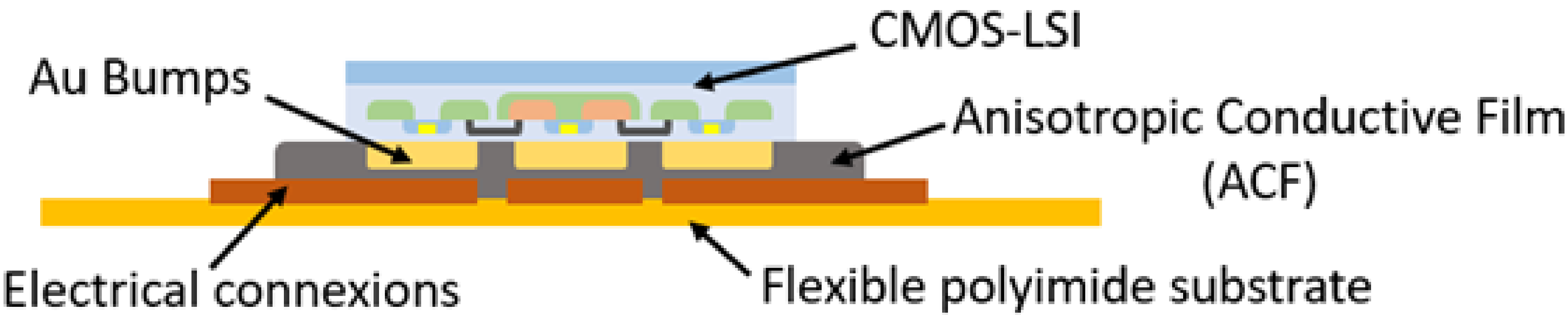
Unstacking



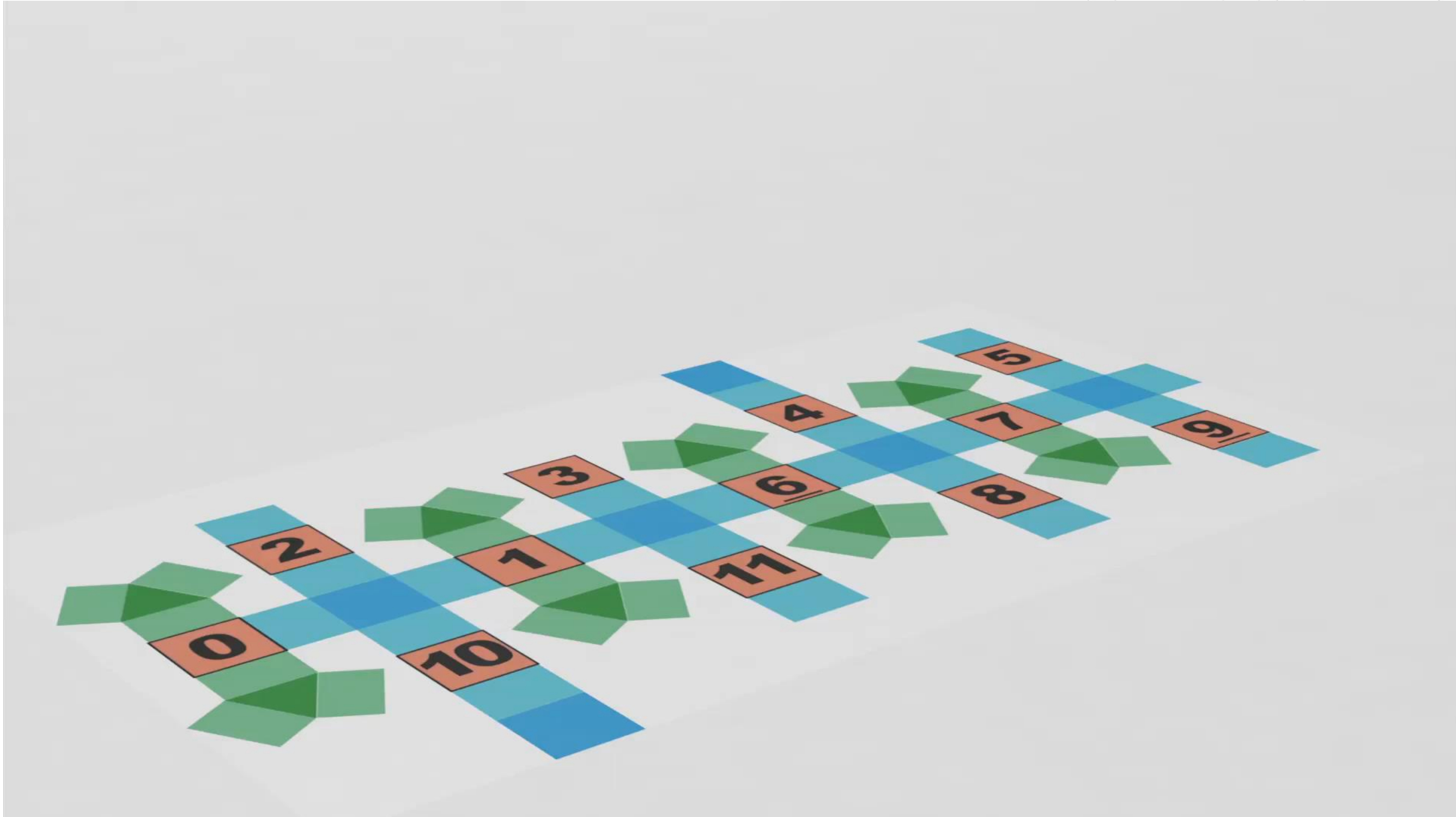


Integration of M3 mote and catom

- Mote unstacking
- Chips bonded on a polyimide film with ACF

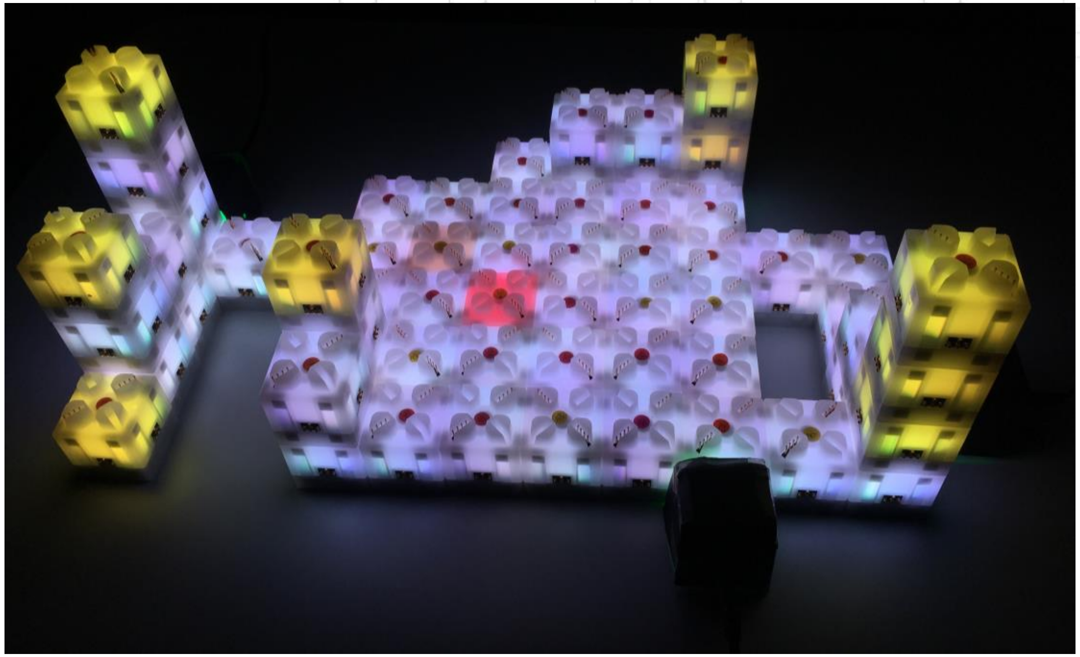


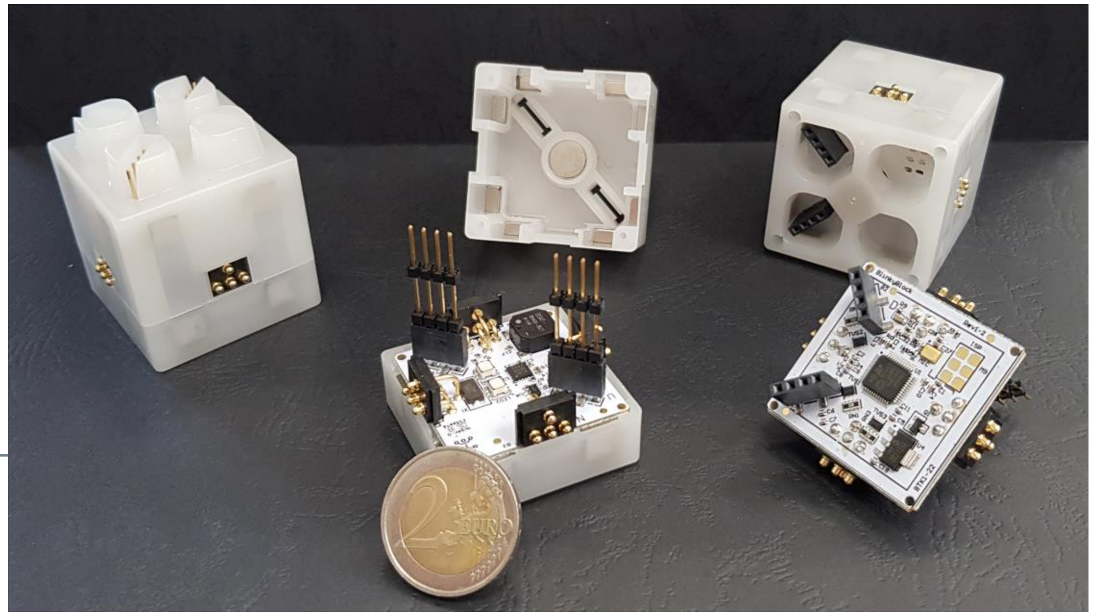
Construction of a 3D Catom from an unfold



The Blinky Blocks

- Micro-controller
  - ARM Cortex M0
- Sensors
  - IMU: Orientation and tapping
  - Microphone: Sound
- Actuators
  - 2 LEDs: Glow in different colors
  - Speaker: Play sounds
- Communications
  - 6 USART communications at 6Mbps max





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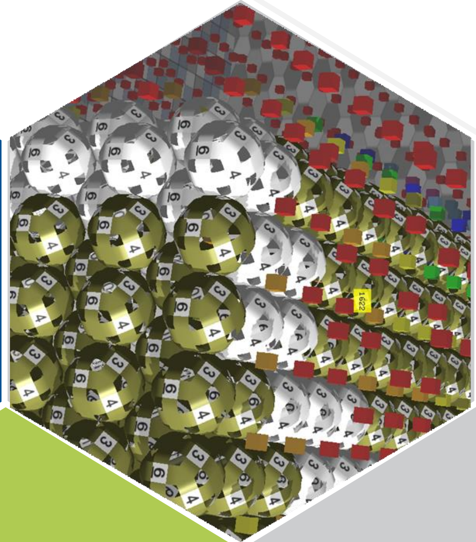

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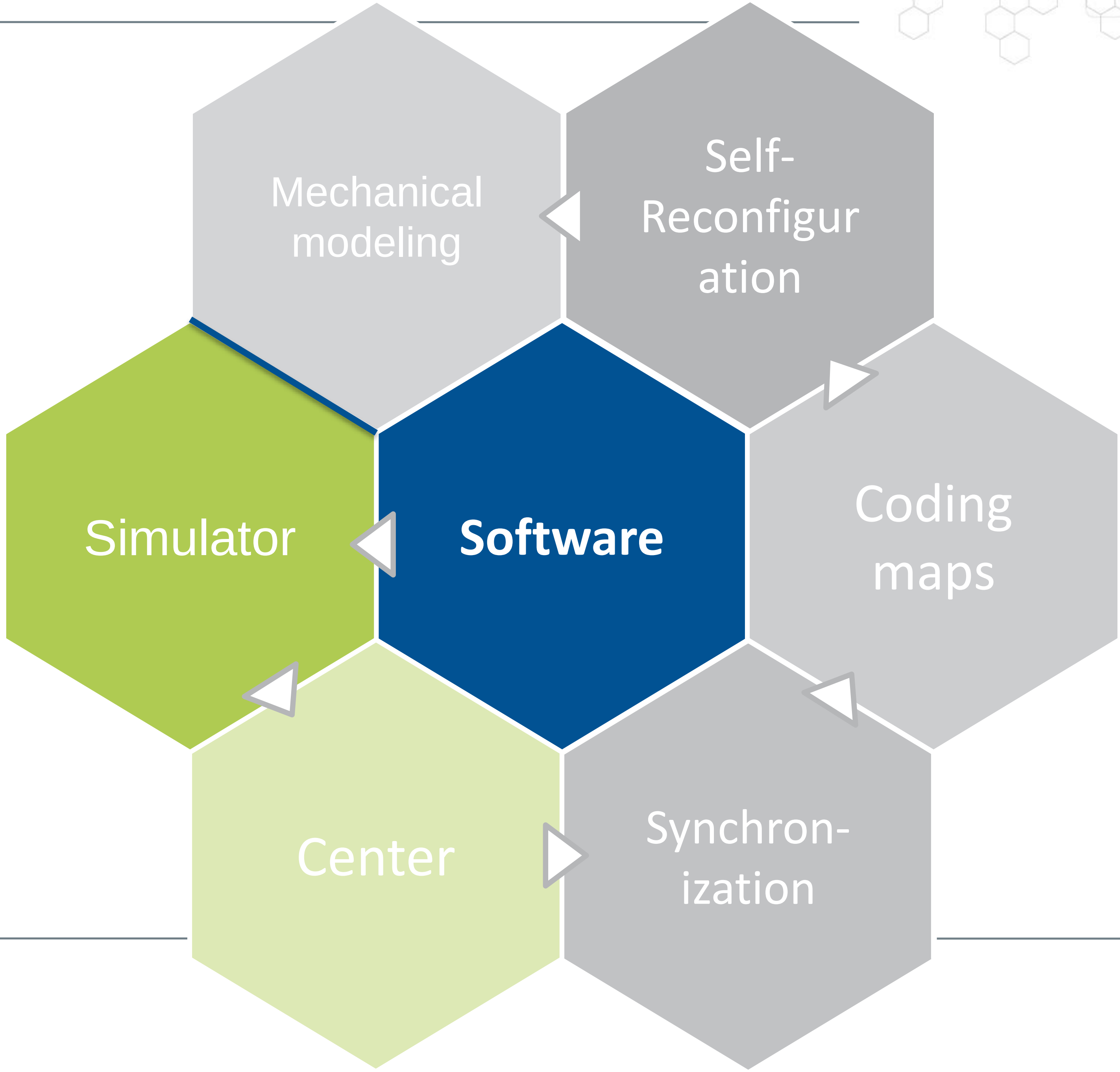

Mechanical modeling
Self-Reconfiguration
Simulator
Software
Coding maps
Center
Synchron-ization

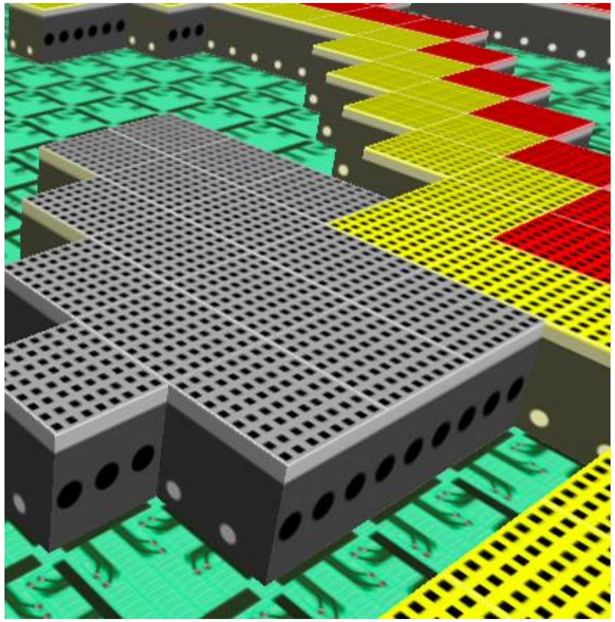
Simulation environment

- VisibleSim (FEMTO-ST, http://projects.femto-st.fr/projet-visiblesim/):
  - Multi-targets (Blinky Blocks, Smart Blocks, Robot Blocks, Claytronics)
  - Multi-languages (C/C++, Meld, Javascript, Python)
  - Interactive
  - Include debugging
  - Available in your web browser online at:
    - http://ceram.pu-pm.univ-fcomte.fr:5015/visiblesim/
  - **First MSR simulator on the web thanks to WebGL!**
- One ambition: make VisibleSim the reference simulator for modular robots and distributed programming initiation

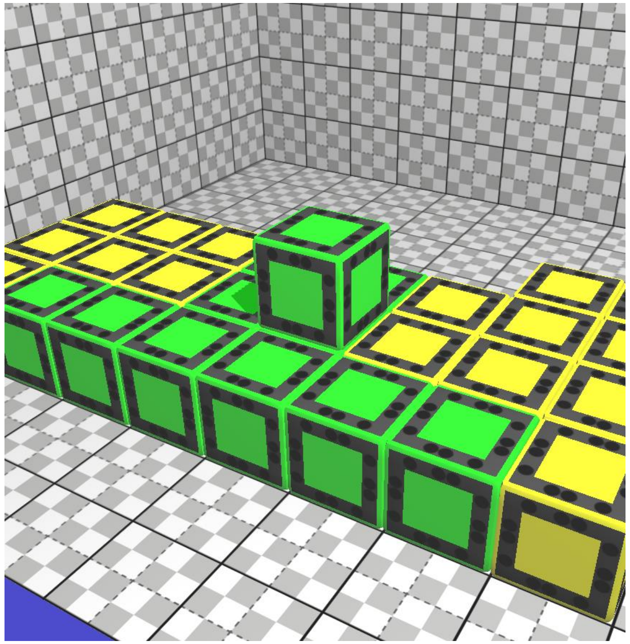
Dhoutaut Dominique, Piranda Benoit and Bourgeois Julien, "Efficient Simulation of distributed Sensing and Control Environments" *in "iThings 2013, IEEE Int. Conf. on Internet of Things"*, Beijing, China, pp. 452--459, aug. 2013

Smart Blocks, Robot Blocks and Blinky Blocks

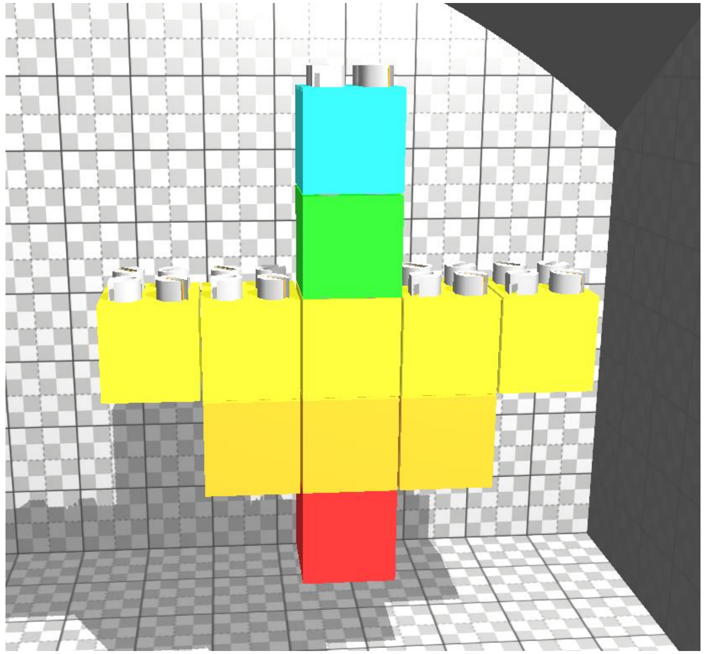
- Smart Blocks



- Robot Blocks

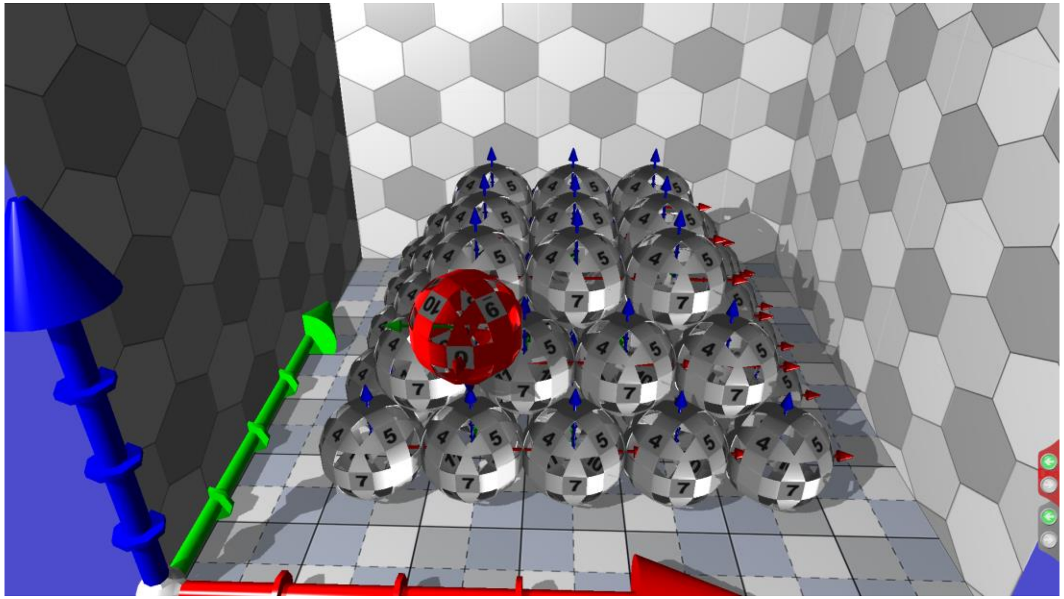


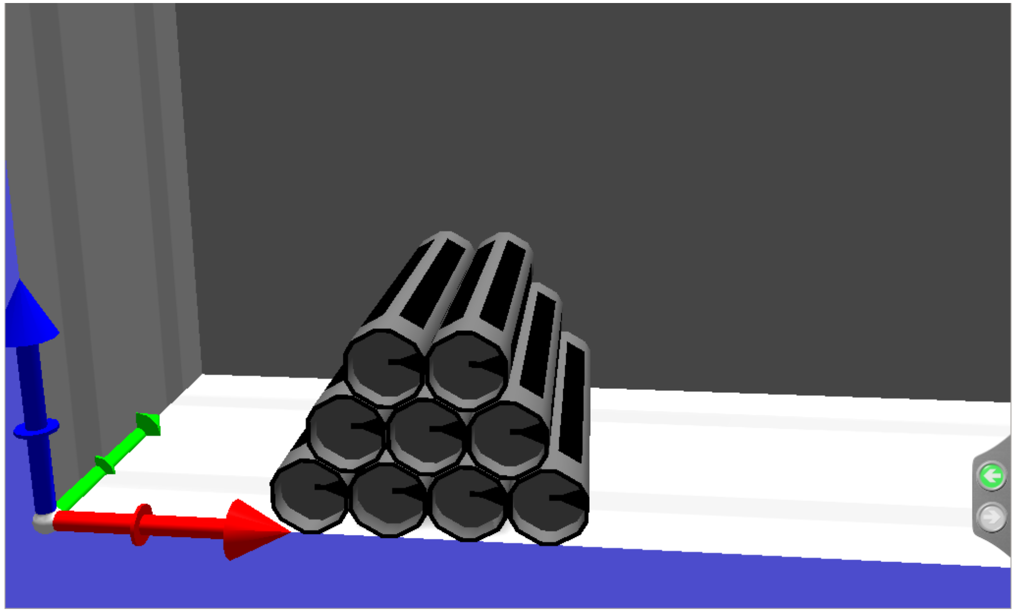
- Blinky Blocks



Catoms

- 3D catoms
- 2D catoms





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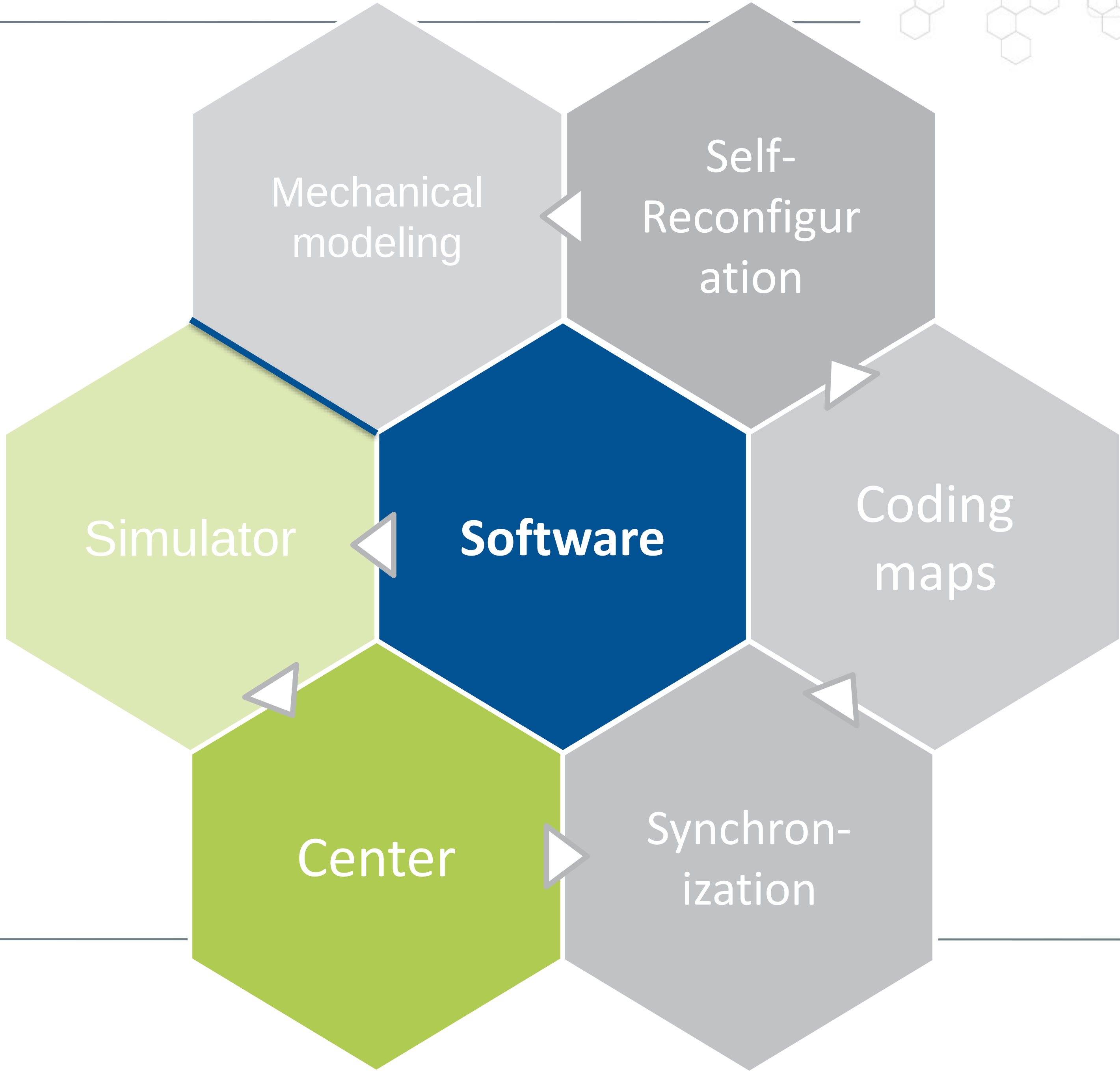


Mechanical modeling
Self-Reconfigur ation
Simulator
Software
Coding maps
Center
Synchron-ization

Algorithms for programmable matter

- Finding the center of a distributed system: ABC-Center, PC2LE, k-BFS-SumSweep *[AINA 16] [IROS 15]*
  - In real time
  - To optimize many algorithms
- Synchronizing large set of micro-robots: MRTP *[JNCA 18] [PDP 16]*
  - For synchronized actions with the external environment
    - Lighting at the same time
    - For mechanical actions
- Memory problem: CSG4PM *[SAC 17]*
  - Coding goal shapes
- Distributed detection of mechanically unsafe reconfiguration
  - Detecting loss of balance and breakage
- Self-assembly algorithms *[AAMAS 18]*
- Self-Reconfiguration algorithms
  - With map of the goal shape *[NCA 16] [IEEE IoT 16] [AIM 14] [ISPA 14]*
  - Without map of the goal shape *[JPDC 15][CN 15][ROBIO 15][JoS 14][PDP 14][JNCA 14][AINA 14][NCA 13][SAC 13][UIC 13] [EUROCON 13]*

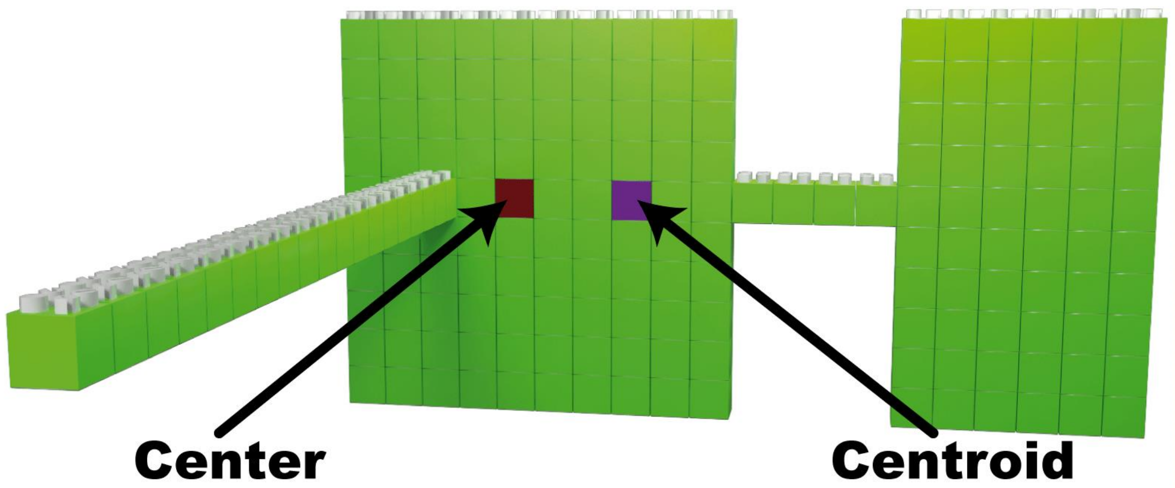
Problem

- Catoms network is forming a graph
  - G(V,E): V = modules, E = connections
- Is it difficult to find a central node?
  - Center: minimizes the maximum distance to all others

$$Center = \underset{v_i \in V}{\text{argmin}}\, ecc(v_i) = \underset{v_i \in V}{\text{argmin}}\, \max_{v_j \in V} d(v_i, v_j)$$

  - Centroid: minimizes the average distance to all others

$$Centroid = \underset{v_i \in V}{\text{argmin}}\, \frac{1}{|V|} \sum_{v_j \in V} d(v_i, v_j)$$



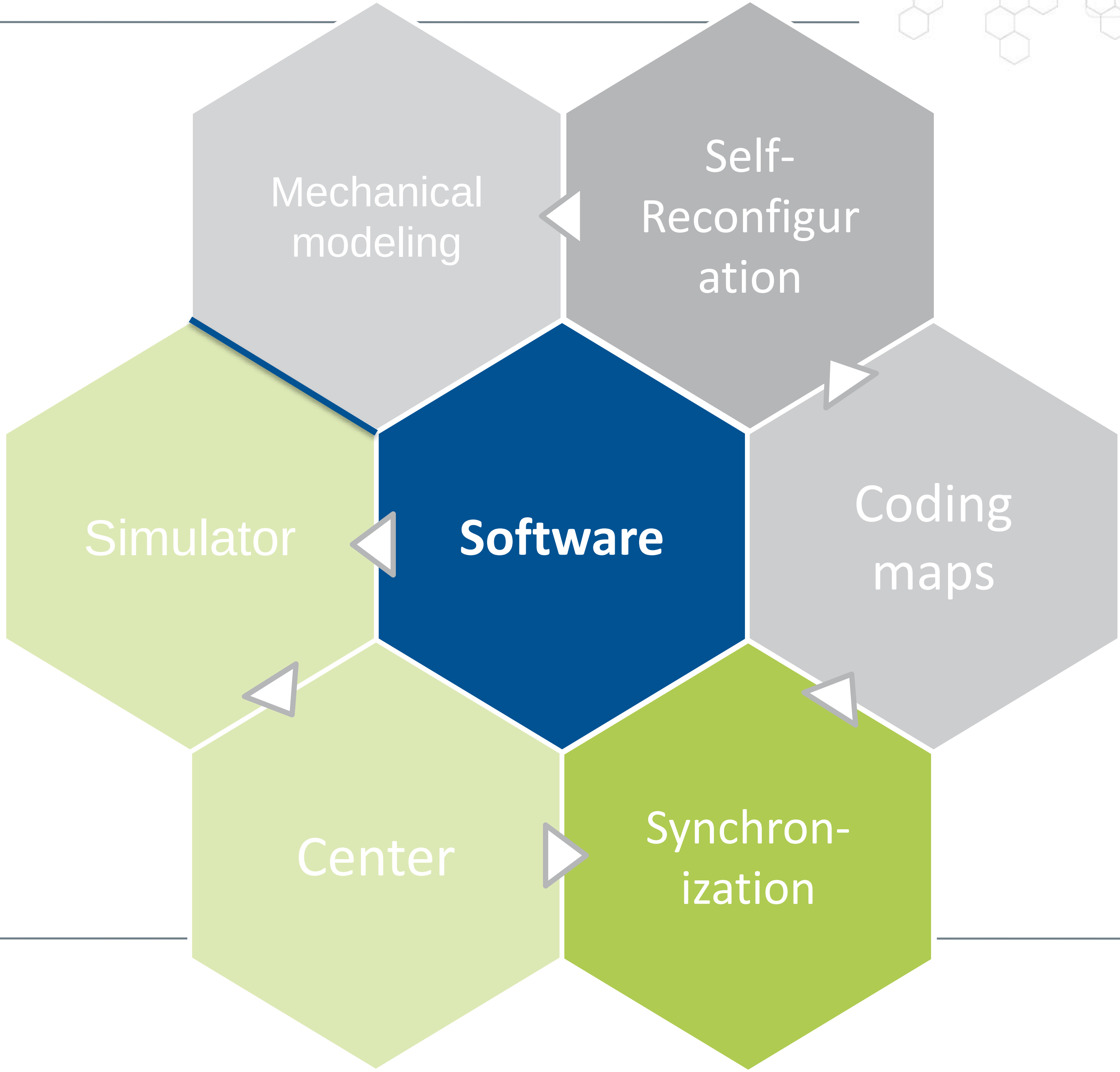
Our contribution

- 3 distributed algorithms
  - K-BFS SumSweep
  - ABC-Center (two versions), ABC-Center-Tree (also known ABC-Center-V2)
  - Probabilistic Counter based Central Leader Election (PC2LE)
- Inspired from existing external-graph analysis algorithms
- All based on intuitive heuristics
- **Experimental evaluation of the accuracy**

Name	Type of center	Time	Memory (per module)	Message
k-BFS SumSweep	center, centroid	$O(k \times d)$	$O(\Delta)$	$O(m \times n^2)$
ABC-CenterV2	center	$\mathrm{O}(\#steps \times d)$	$O(\Delta)$	$O(m \times n^2)$
PC2LE	center, centroid	$\mathrm{O}(d)$	$O(\Delta + \lvert\text{probabilistic counter}\rvert)$	$O(m \times n^2)$

Notation:
$n = \#\text{modules}$, $m = \#\text{ links}$, $d = \text{diameter}$, $\Delta = \text{maximum number of neighbors}$

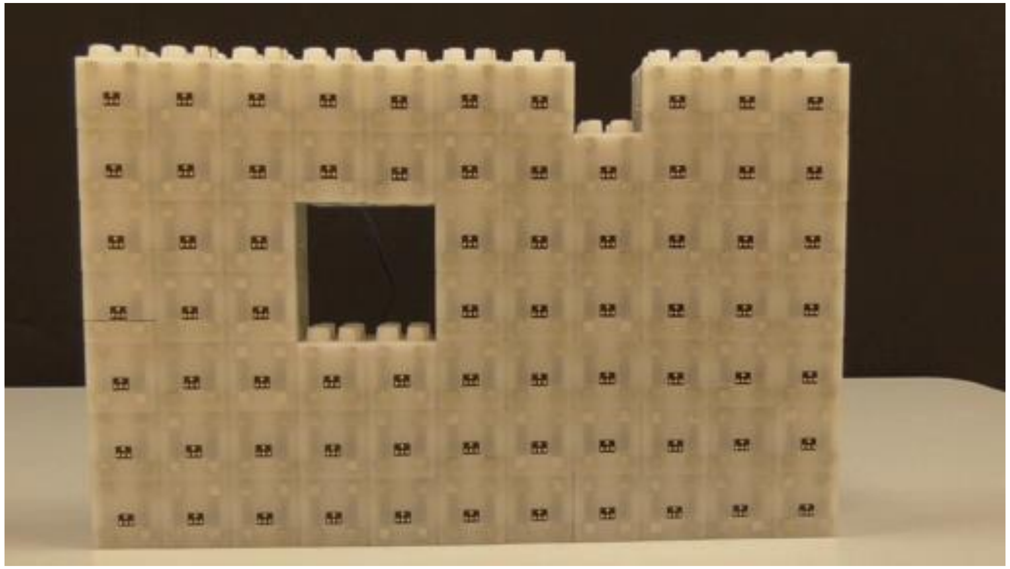
Outline



Mechanical modeling
Self-Reconfiguration
Simulator
Software
Coding maps
Center
Synchron-ization

Time Synchronization

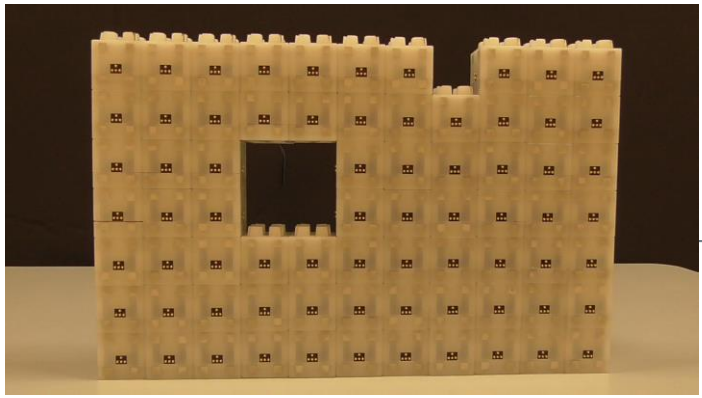
- Needed for distributed coordination



72-Blinky-Blocks scroller synchronized with our protocol (MRTP)

- Unsychronized scroller

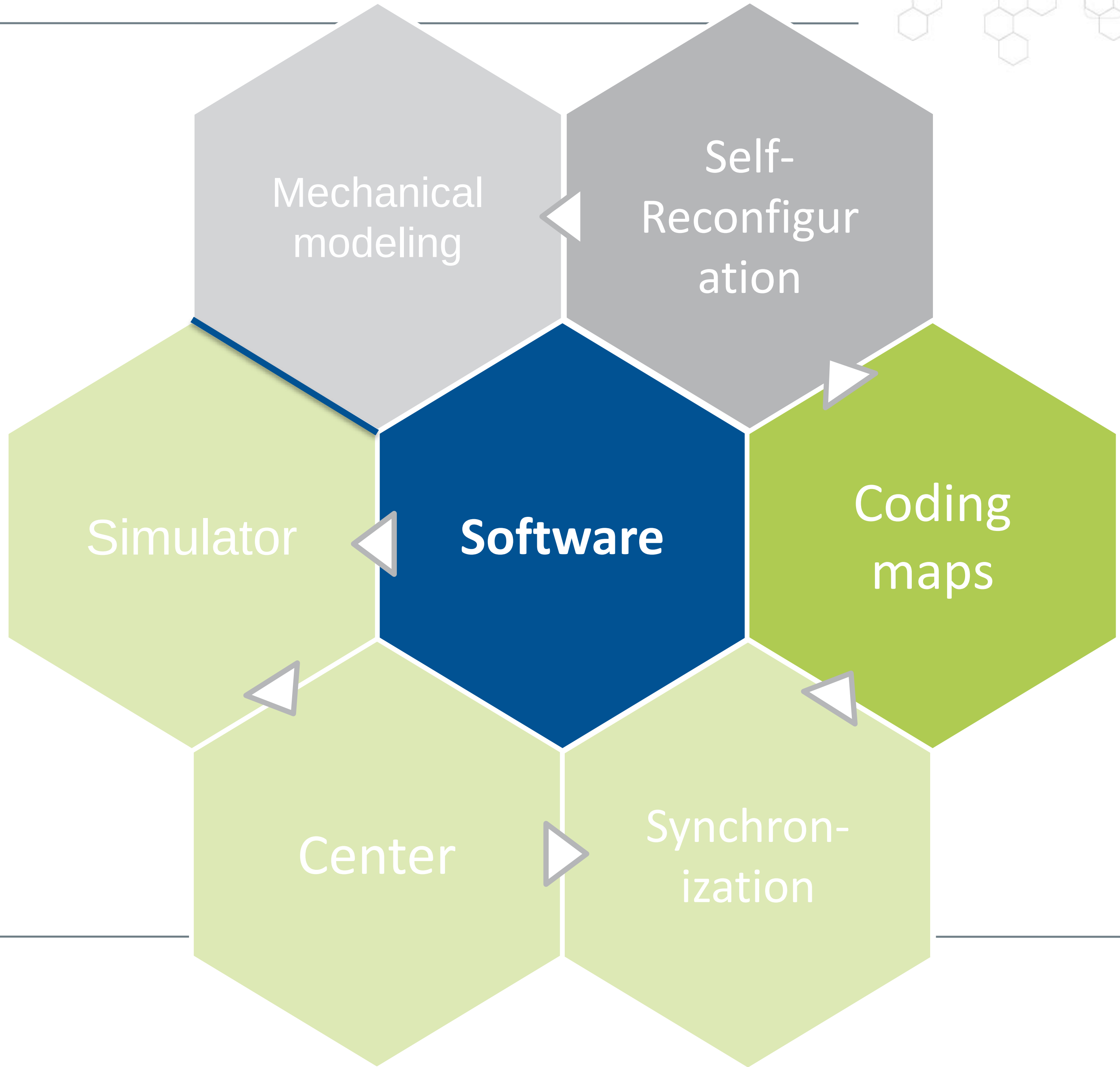
Start



1min20s later

20mins later

Outline


Mechanical modeling
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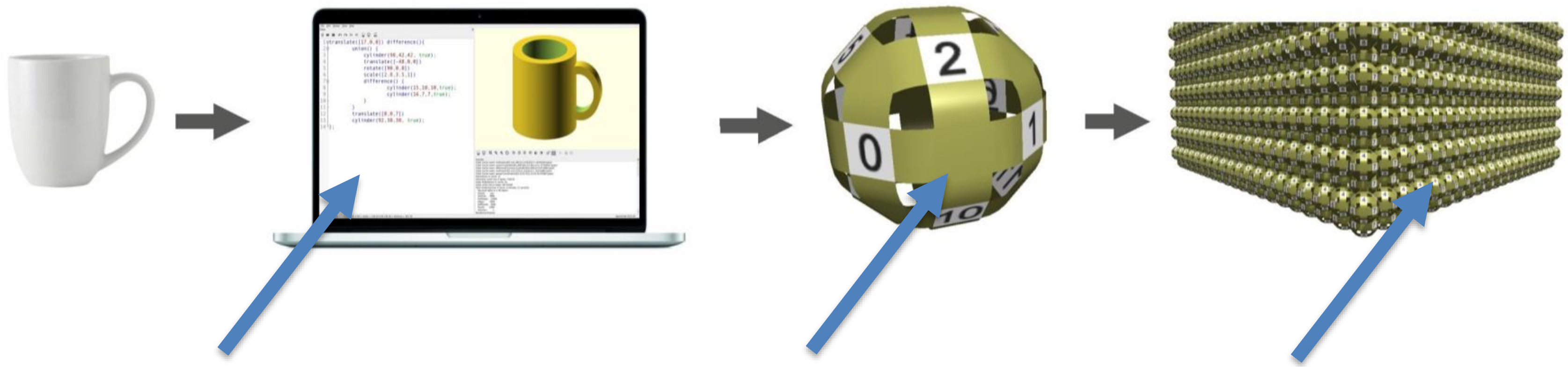
Target shape encoding



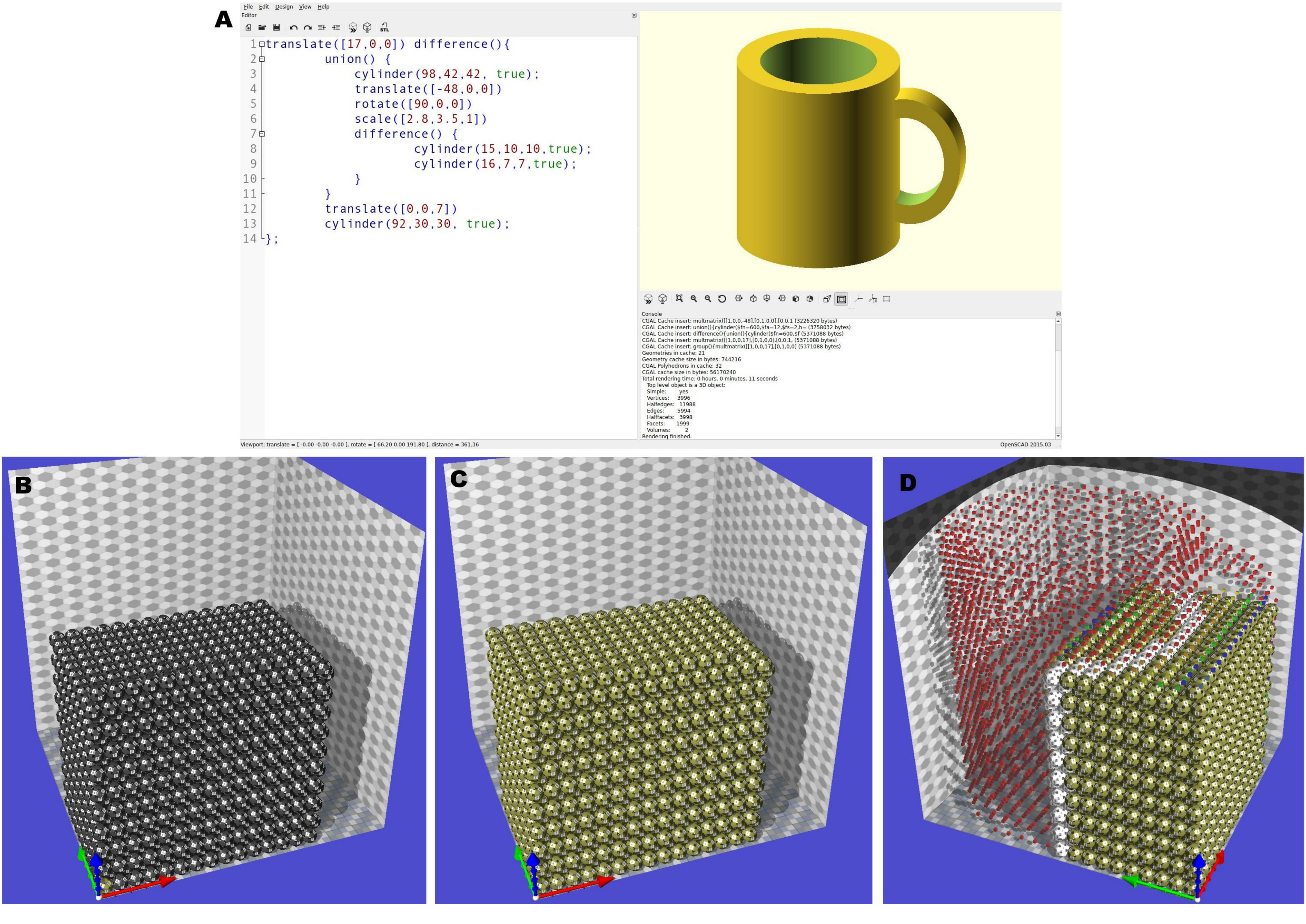
Using Constructive Solid Geometry (CSG) for describing the shape

CSG file is transferred to catoms

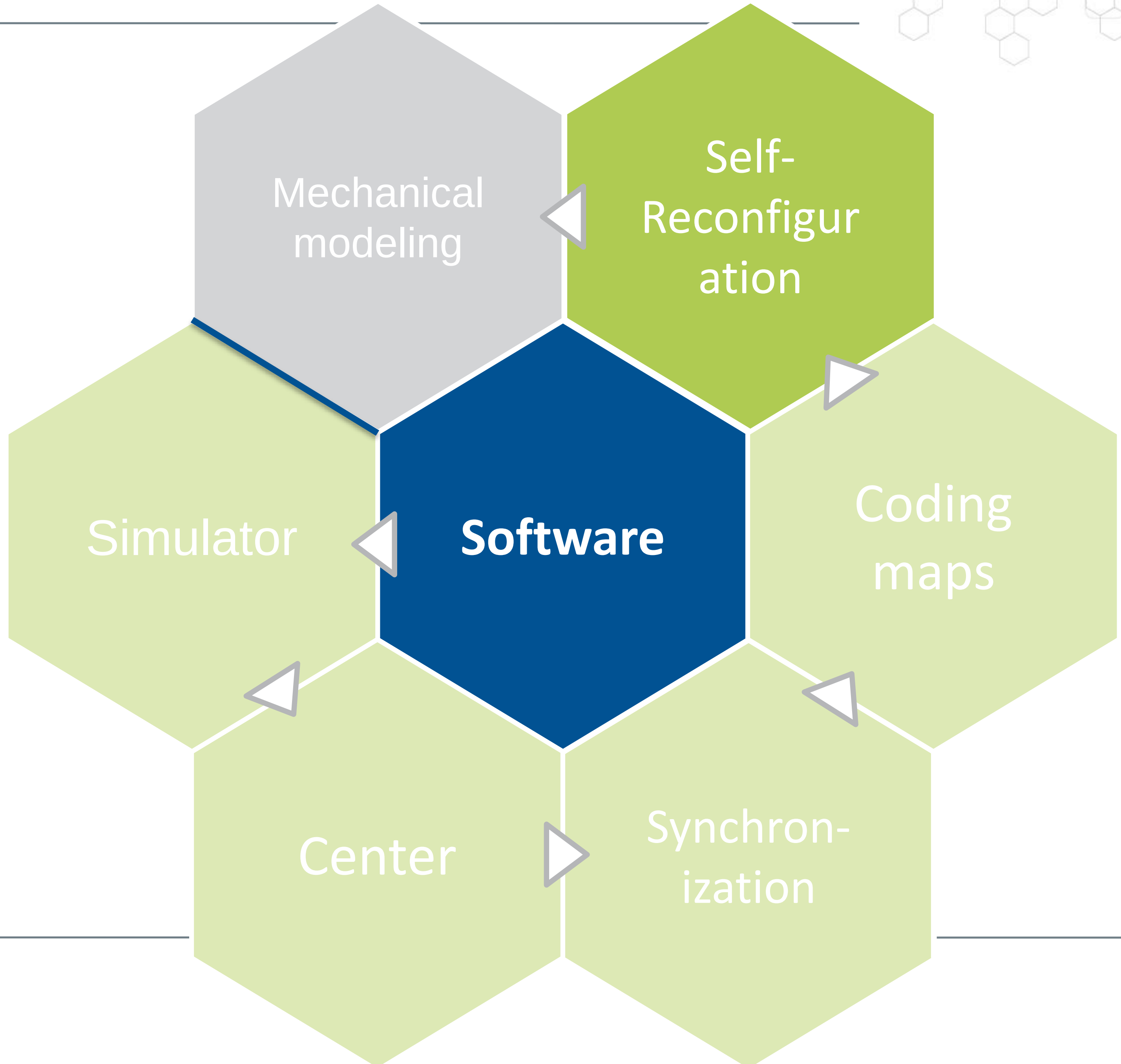
Each catom decides if it is in the shape or not

femto-st SCIENCES & TECHNOLOGIES

Efficient scene encoding for programmable matter self-reconfiguration algorithms
T Tucci, B Piranda, J Bourgeois - ACM SAC, 2017


A
File Edit Design View Help
Editor
translate([17,0,0]) difference(){
union() {
cylinder(98,42,42, true);
translate([-48,0,0])
rotate([90,0,0])
scale([2.8,3.5,1])
difference() {
cylinder(15,10,10,true);
cylinder(16,7,7,true);
}
}
translate([0,0,7])
cylinder(92,30,30, true);
};
Console
CGAL Cache insert: multmatrix([[1,0,0,-48],[0,1,0,0],[0,0,1 (3226320 bytes)
CGAL Cache insert: union(){cylinder($fn=600,$fa=12,$fs=2,h= (3758032 bytes)
CGAL Cache insert: difference(){union(){cylinder($fn=600,$f (5371088 bytes)
CGAL Cache insert: multmatrix([[1,0,0,17],[0,1,0,0],[0,0,1, (5371088 bytes)
CGAL Cache insert: group(){multmatrix([[1,0,0,17],[0,1,0,0] (5371088 bytes)
Geometries in cache: 21
Geometry cache size in bytes: 744216
CGAL Polyhedrons in cache: 32
CGAL cache size in bytes: 56170240
Total rendering time: 0 hours, 0 minutes, 11 seconds
Top level object is a 3D object:
Simple: yes
Vertices: 3996
Halfedges: 11988
Edges: 5994
Halffacets: 3998
Facets: 1999
Volumes: 2
Rendering finished.
Viewport: translate = [-0.00 -0.00 -0.00], rotate = [66.20 0.00 191.80], distance = 361.36
OpenSCAD 2015.03
B
C
D

Outline


Mechanical modeling
Self-Reconfigur ation
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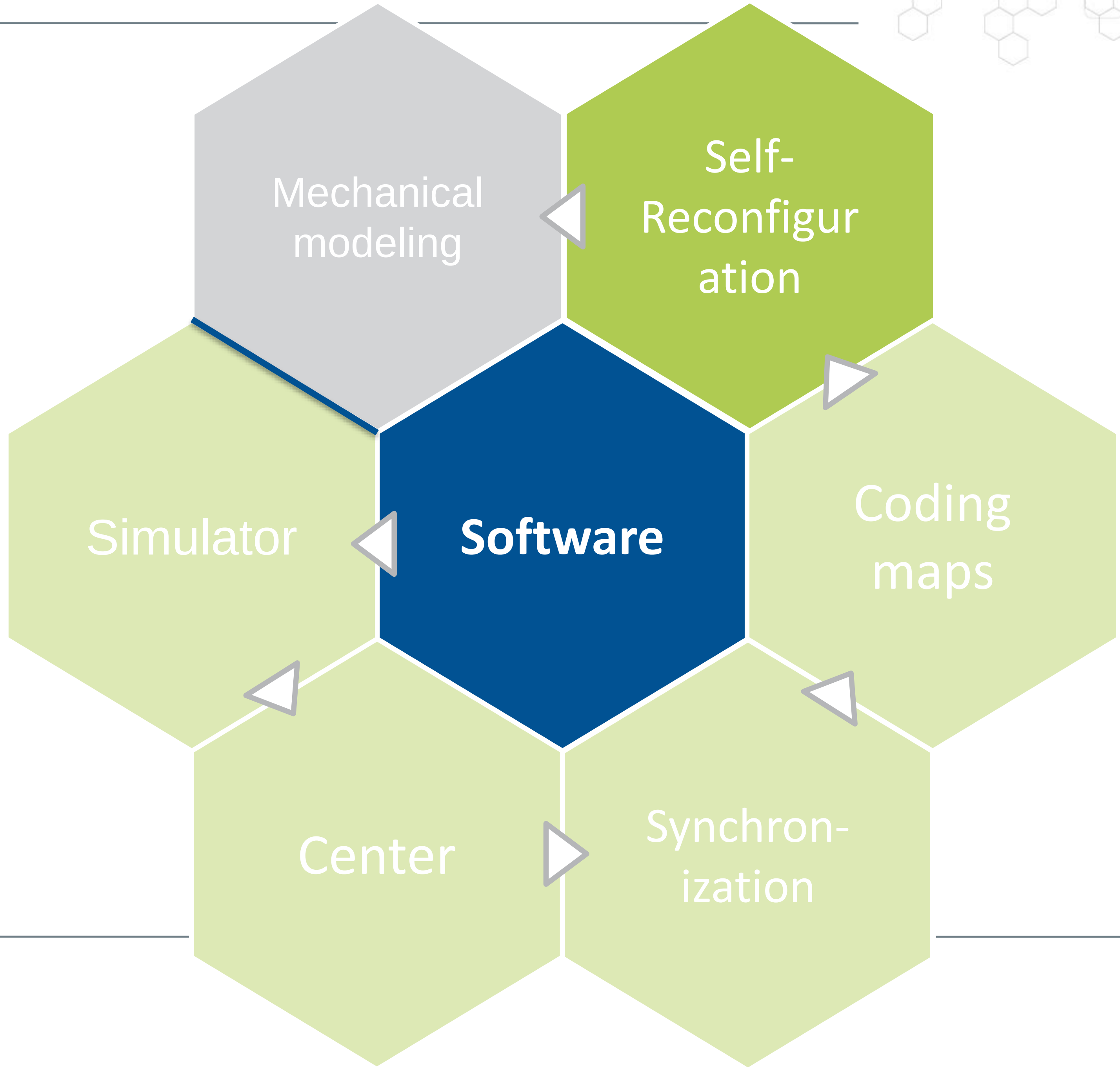
Synchron-ization

Self-reconfiguration and self-assembly

- Self-assembly algorithms
  - With CSG map of the goal shape *[AAMAS 18]*
- Self-Reconfiguration algorithms
  - With map of the goal shape
    - For 2D horizontal shape *[PDP 16]*
    - For 2D Vertical shape *[NCA 16]*
  - Without map of the goal shape
    - Meta algorithm *[IEEE IoT 16] [AIM 14] [ISPA 14]*
    - Chain to square
      - Sequential movements *[NCA 13] [SAC 13] [UIC 13] [JoS 14]*
      - Parallel movements *[JPDC 15] [EUROCON 13] [AINA 14] [PDP 14] [CN 15] [ROBIO 15]*
    - X to square *[JNCA 14]*

Outline



Mechanical modeling
Self-Reconfiguration
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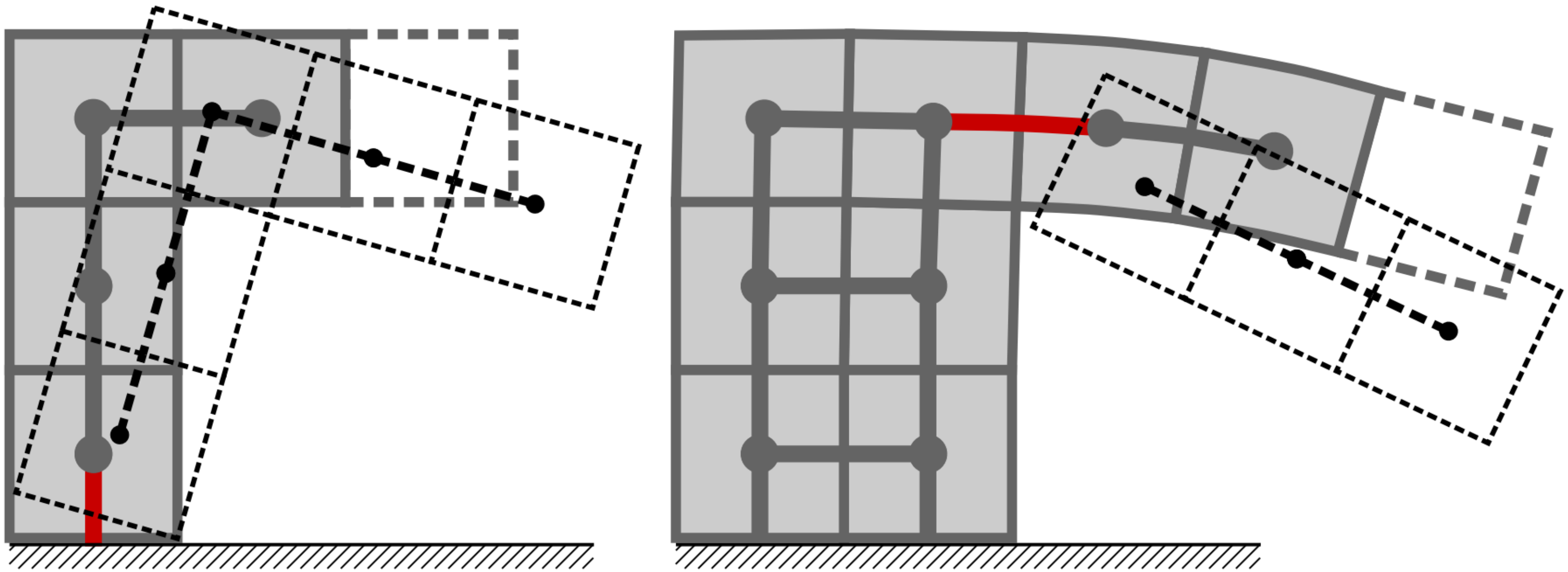
Mechanical modeling

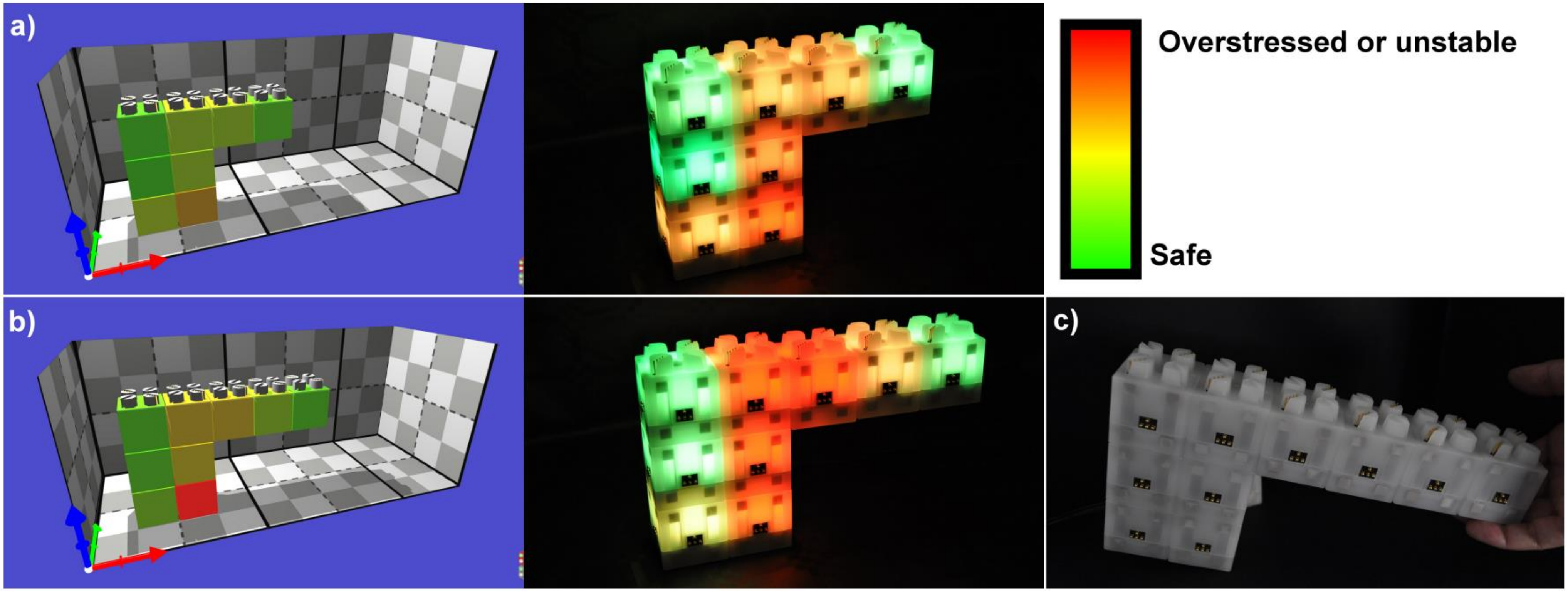
- Distributed detection of mechanically unsafe reconfiguration
  - Detecting loss of balance and breakage



Benoit Piranda, Pawel Chodkiewicz, Pawel Holobut, Julien Bourgeois, Jakub Lengiewicz, « *Distributed autonomous detection of mechanically unsafe reconfiguration scenarios* », in preparation

Mechanical modeling

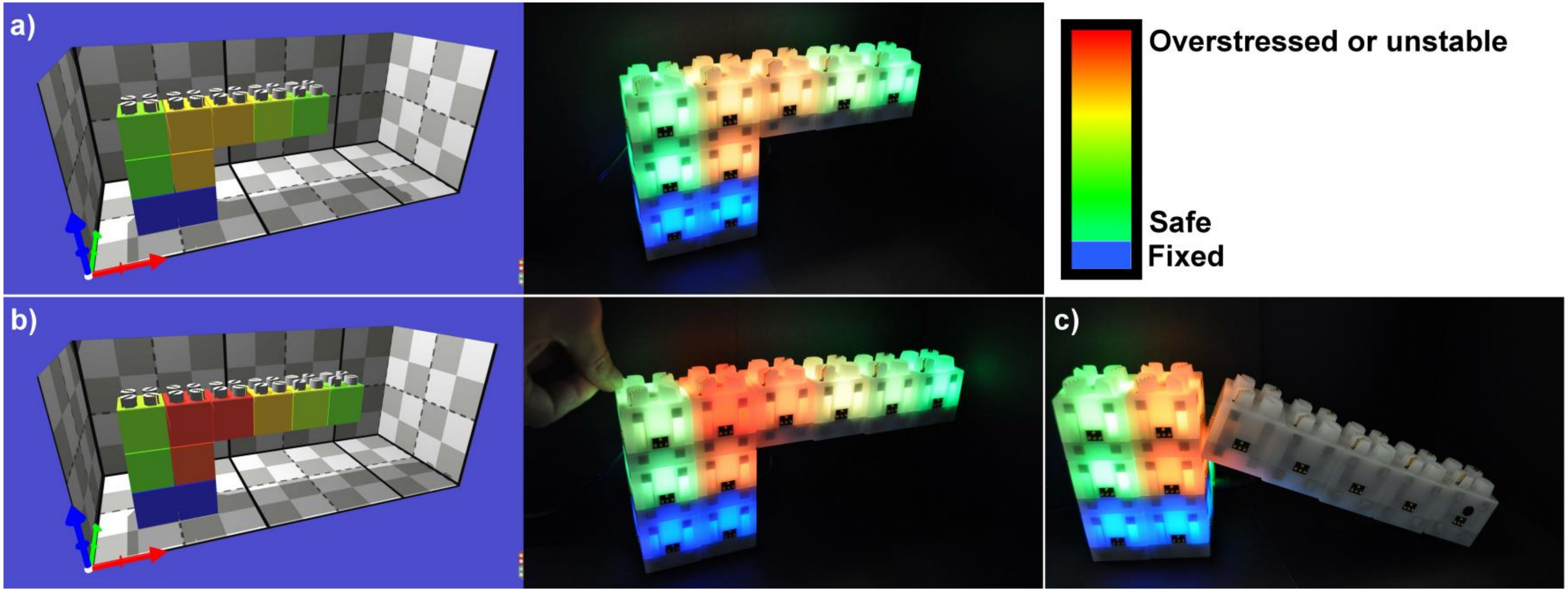
- Detecting loss of balance



Benoit Piranda, Pawel Chodkiewicz, Pawel Holobut, Julien Bourgeois, Jakub Lengiewicz, « *Distributed autonomous detection of mechanically unsafe reconfiguration scenarios* », in preparation

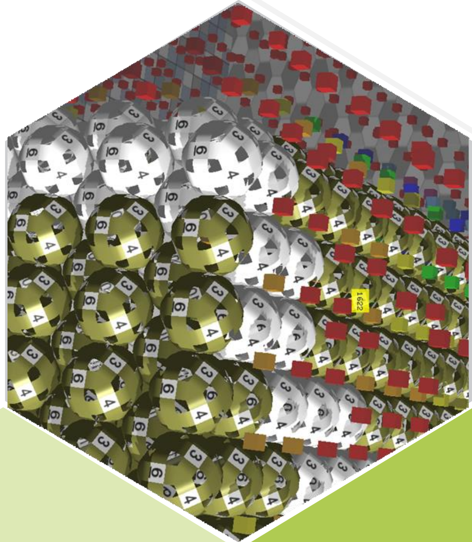
Mechanical modeling

- Detecting breakage



Outline

Our Vision



What's Next?

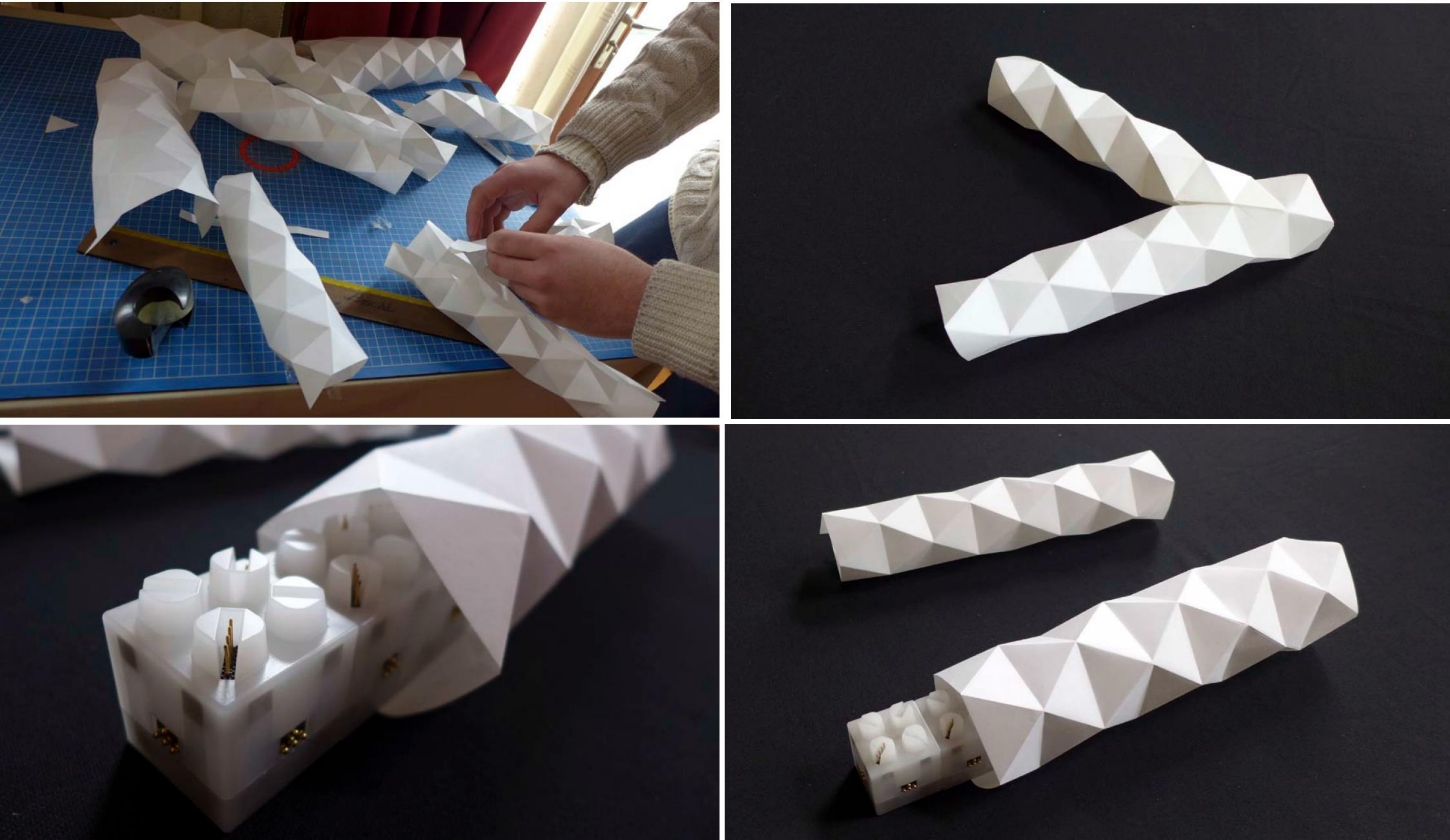
Hardware design

Software

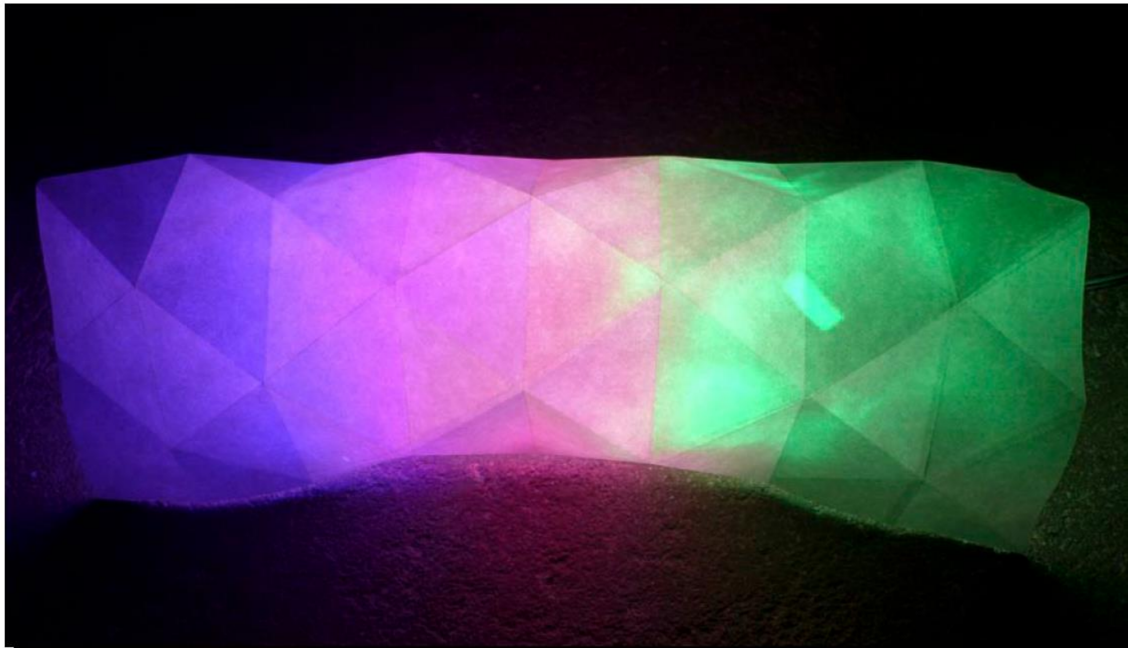
Art

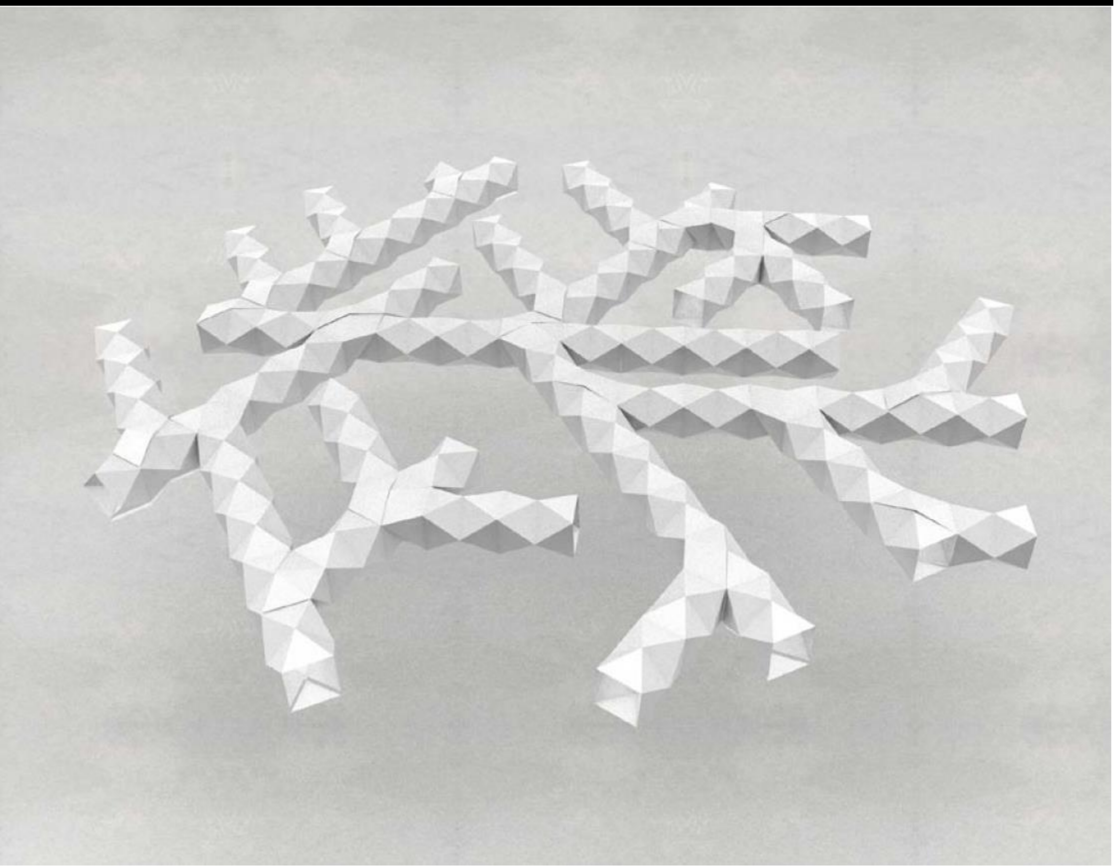
Reactive matter / Interactive sculptures / membranes experimentation

Scenocosme : Grégory Lasserre & Anaïs met den Ancxt

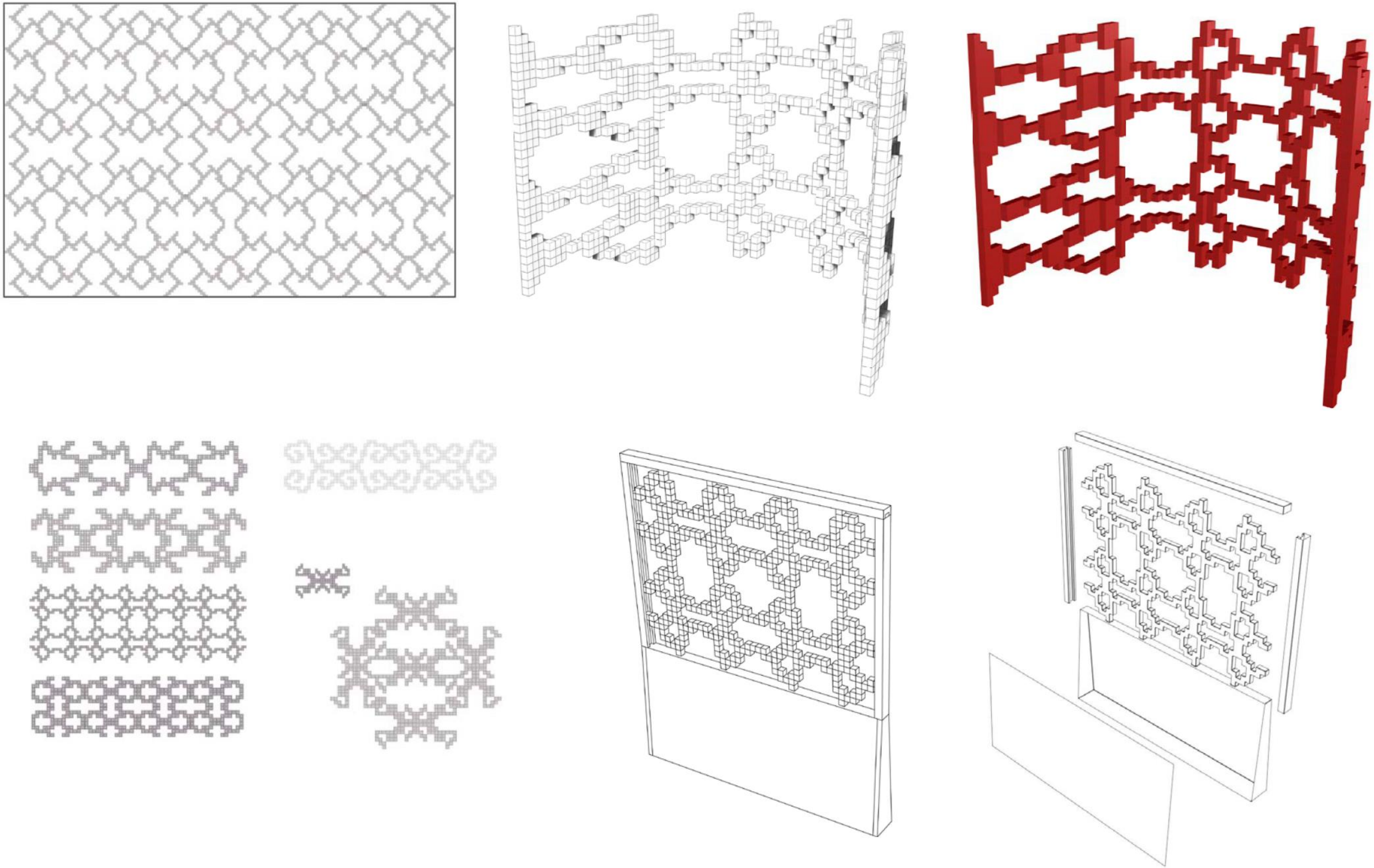


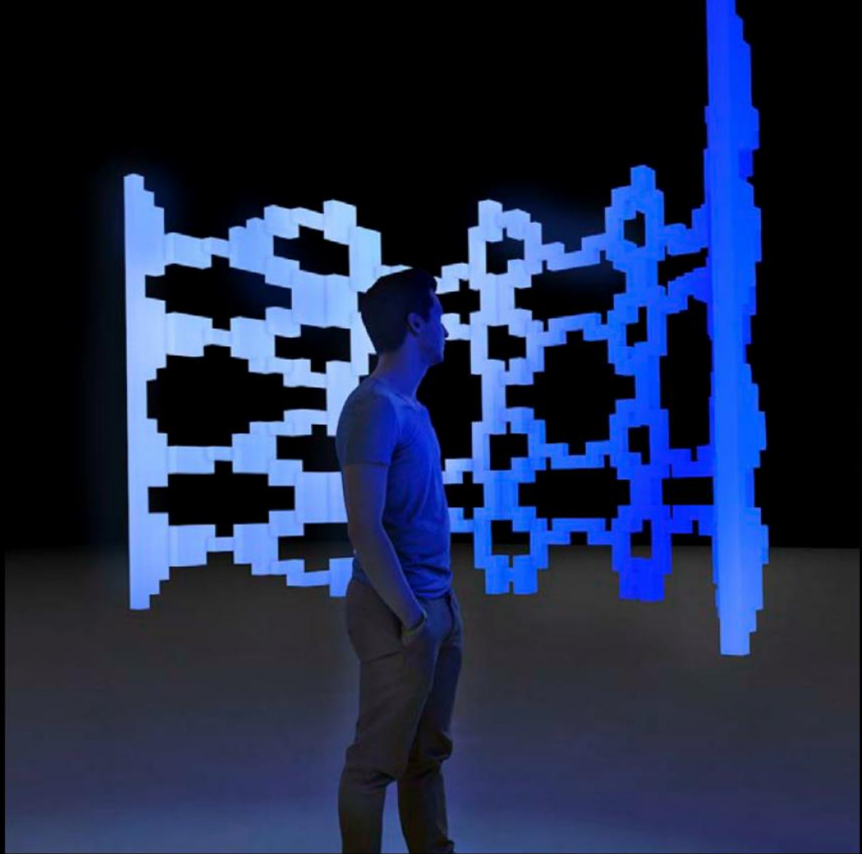
Reactive matter / Interactive sculptures / Lighting and sonorous feedbacks



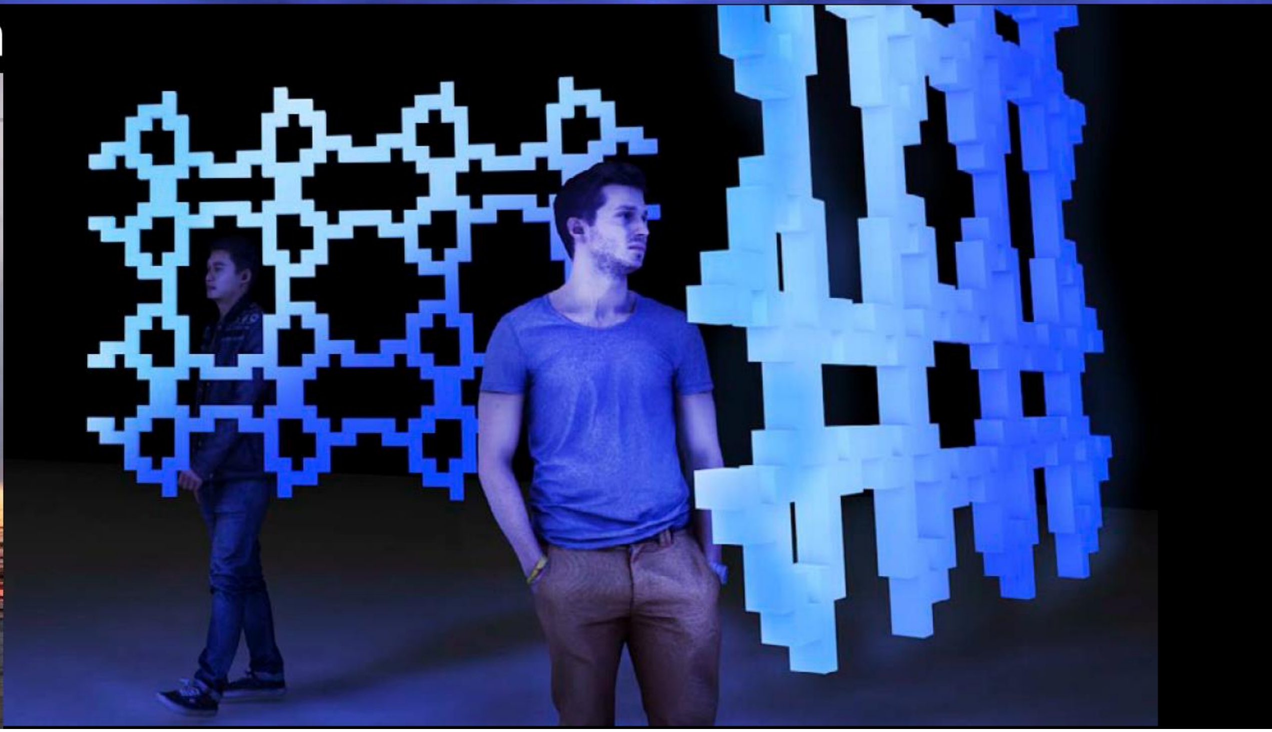


Reactive matter / Interactive sculptures / Mashrabiya design



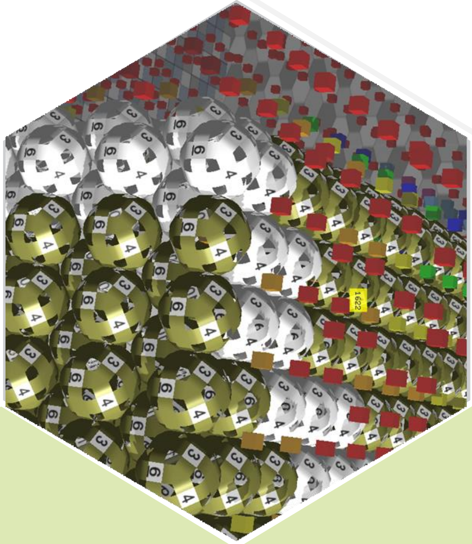


Reactive matter / Murmuration



Outline

Our Vision



What's Next?

Hardware design

Software

Art

What's next?

- Hardware
  – Latching and actuation
  – Integration of the first 3D catoms
  – Scaling down the catom
  – First experiments
  – New catom design (deformation)
- Software
  – 3D Self-reconfiguration algorithm
  – More real test cases (gravity and forces)
  – Comparison between SR algorithms

Bibliography

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- [3] S. Tibbits, C. McKnelly, C. Olguin, D. Dikovsky, and S. Hirsch, “4d printing and universal transformation,” pp. 539–548, 2014.
- [4] K. Gilpin, A. Knaian, and D. Rus, “Robot pebbles: One centimeter modules for programmable matter through self-disassembly.” in IEEE International Conference on Robotics and Automation (ICRA), 3–7 May 2010, pp. 2485–2492.
- [5] W. McCarthy, “Programmable matter,” Nature, vol. 407, no. 6804, pp. 569–569, 2000.
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- [7] J.-W. Kim, J.-H. Kim, and R. Deaton, “Dna-linked nanoparticle building blocks for programmable matter,” Angewandte Chemie International Edition, vol. 50, no. 39, pp. 9185–9190, 2011.

Thank you for your attention!

Questions

All the source code at:
http://github.com/claytronics

More information at:
http://projects.femto-st.fr/programmable-matter/

All videos at:

OMNI Team (FEMTO-ST/DISC/OMNI)

« An adult scientist is a kid that never grew up », Neil DeGrasse Tyson