From Swarm Robotics to Smart Materials

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The ultimate robotic swarm: a liquid that thinks

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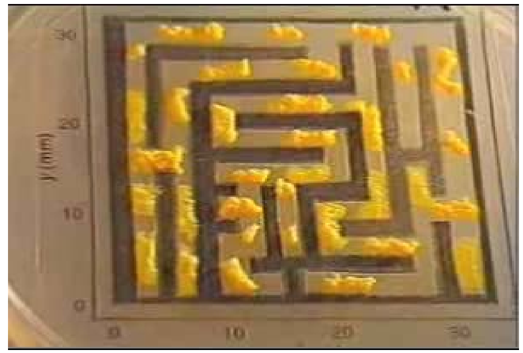
Subsets of Liquids that think

Construction

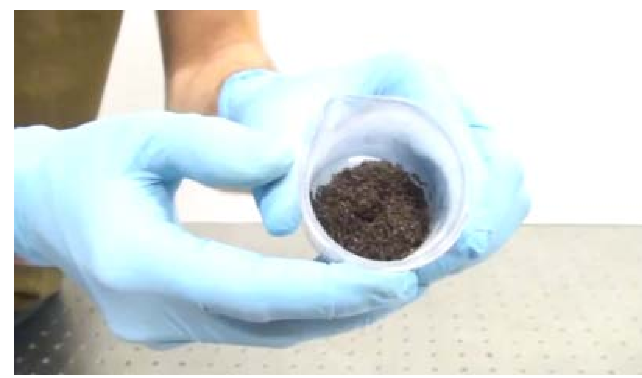
Distributed Computing



Collective Motion

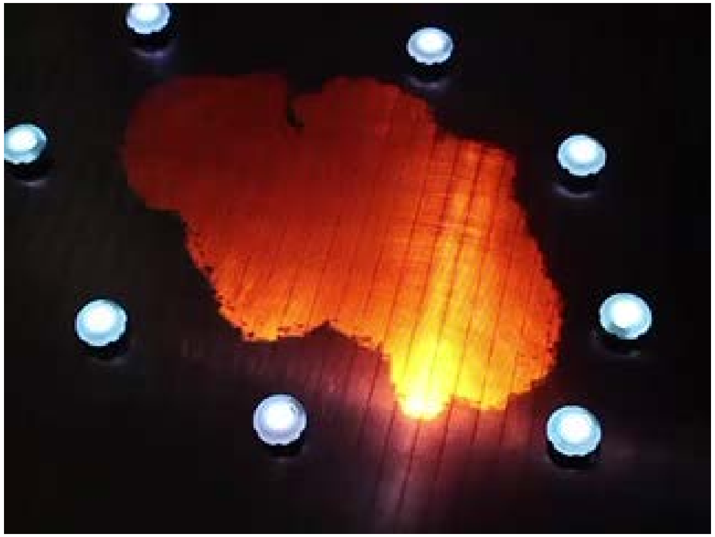
Appearance Change

Intelligent function



Viscoelasiticy

Making a liquid that thinks



"Droplets"

"Liquid that thinks"

Liquid that thinks

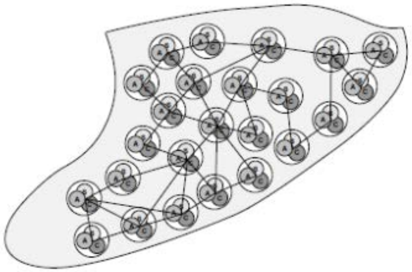
"Droplets"

Useful novel materials?

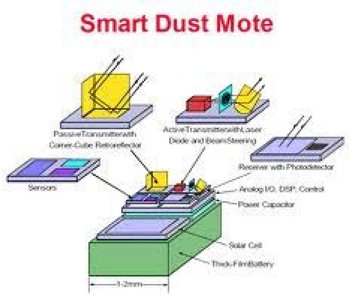
"Liquid that thinks"

Background: Materials that think

- Embedded…
  - Actuation
  - Sensing
  - Computation
  - Communication
- Periodic, amorphous



Distributed MEMS (Berlin, 1997)



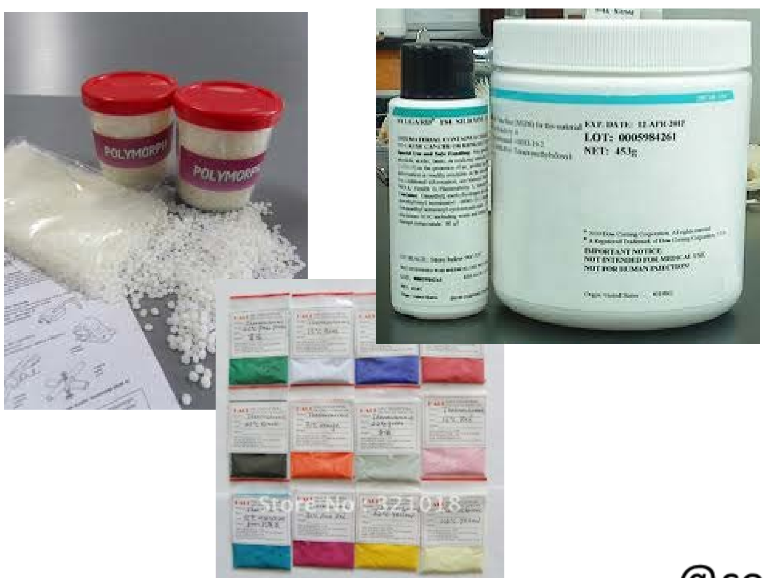
Smart Dust (Pister, 1999)

Programmable Matter (Goldstein, 2005)

Amorphous Computing (Abelson, 2000)

Enablers

- Cheap sensing, computation, actuation
- Cheap manufacturing
- Available polymers

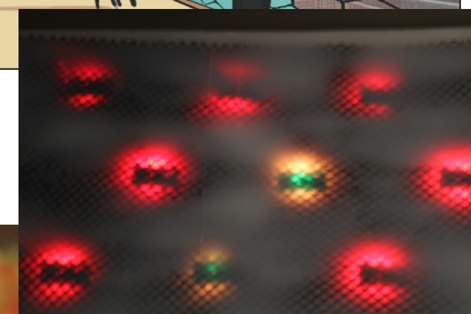


Materials that Sense

- Prosthetic / augmented limbs
- Improved situational awareness for robots
- More subtle Human / Robot Interaction
- Structural monitoring

Materials that change Appearance

- Smart facades
- Camouflage
- Smart clothes



Materials that change Shape

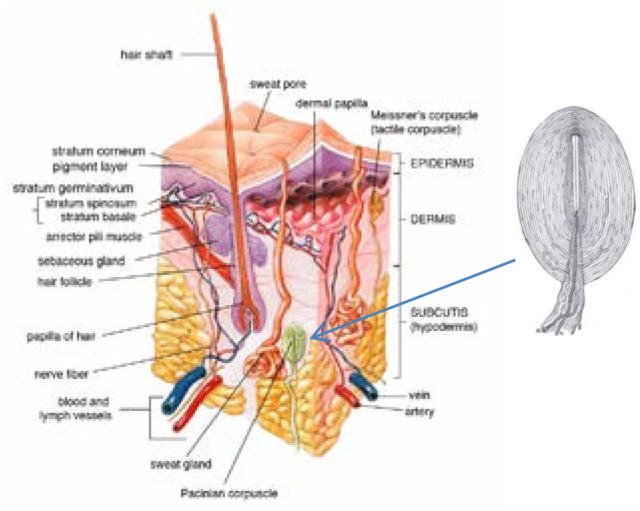
- Reconfigurable airplane wings
- Reconfigurable aerodynamic structures
- Reconfigurable architecture
- Reconfigurable furniture

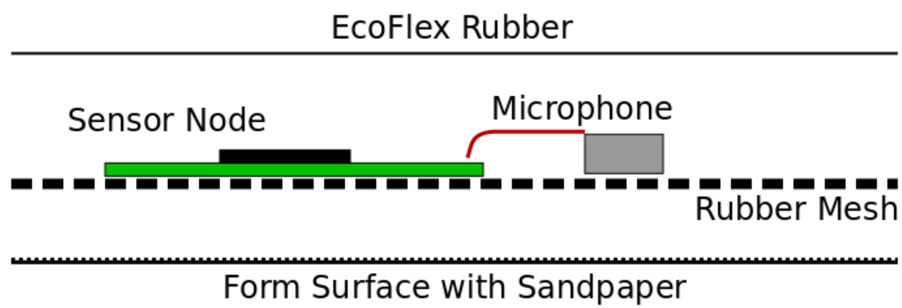
New forms of artistic expression

K. Sugawara, K. Hata, N. Correll, M. Theodore (2013): 群れ行動の数理モデルとその応用～ 群れお絵かきツールとSwarm Wall ～. 1st International Conference on Human Agent Interaction (HAI), Sapporo, Japan, 2013.

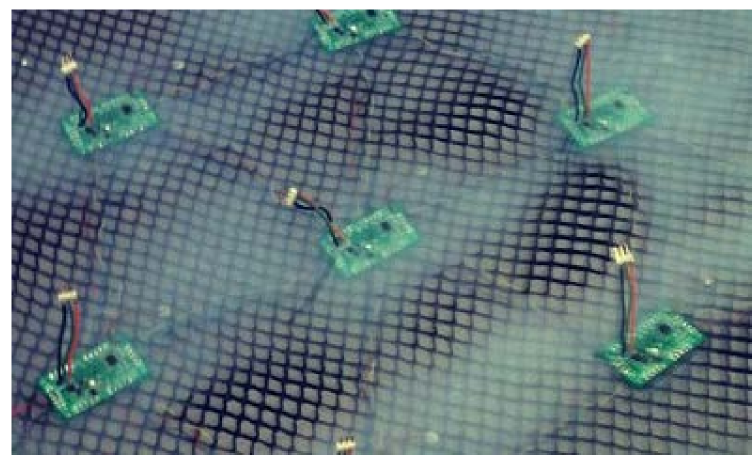
Materials that Sense

Soft Sensing Skin





- Sensor network woven in rubber mesh
- Embedded in EcoFlex silicone rubber
- Surface textured using 60-grit sandpaper during curing



D. Hughes, N. Correll (2014): A Soft, Amorphous Skin that can Sense and Localize Texture . IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, 2014.

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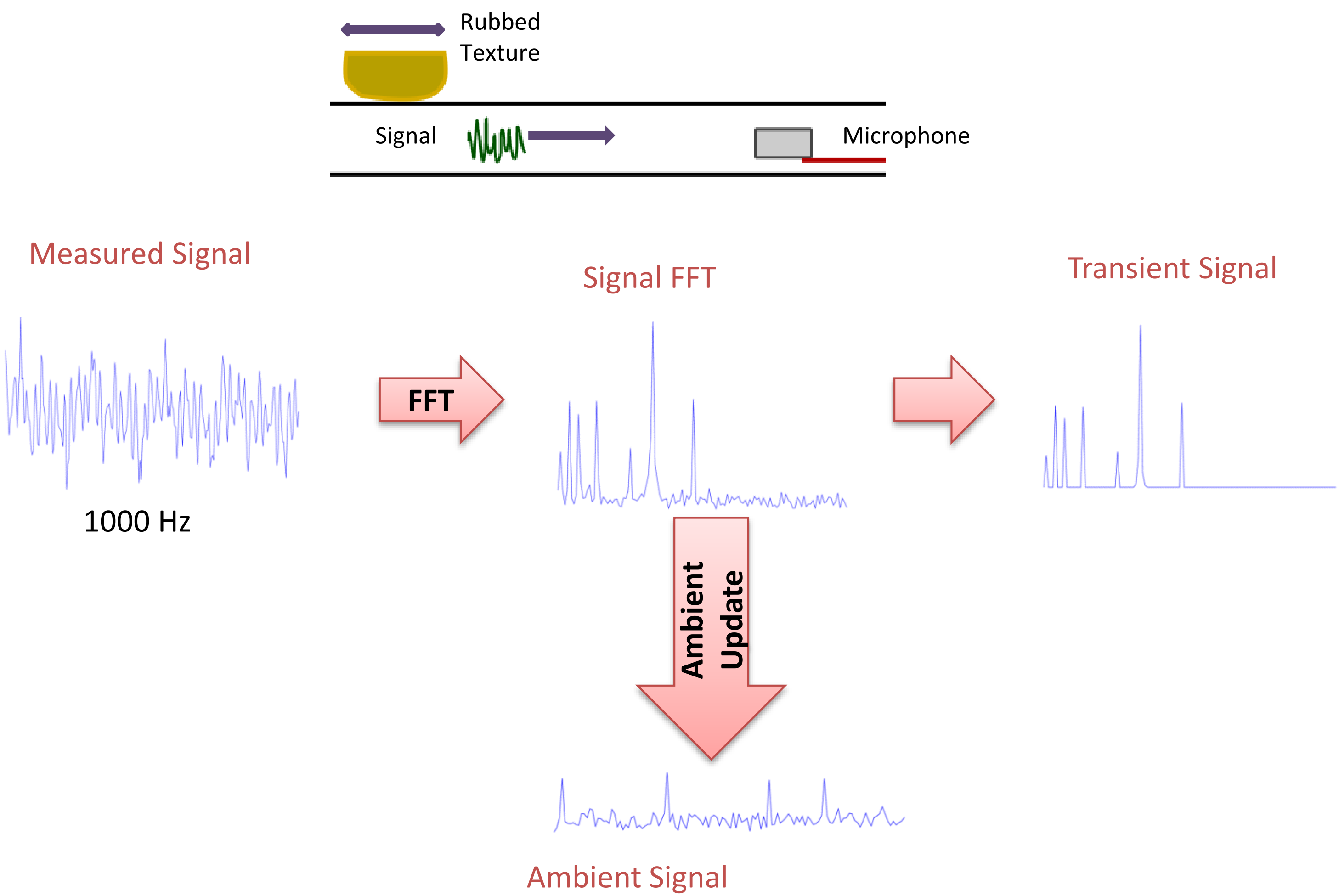
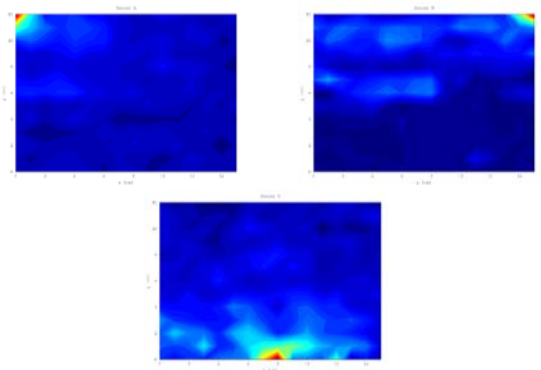
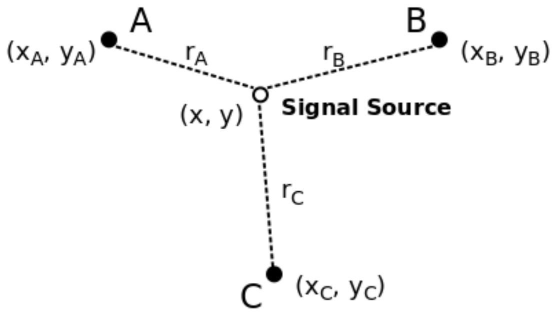
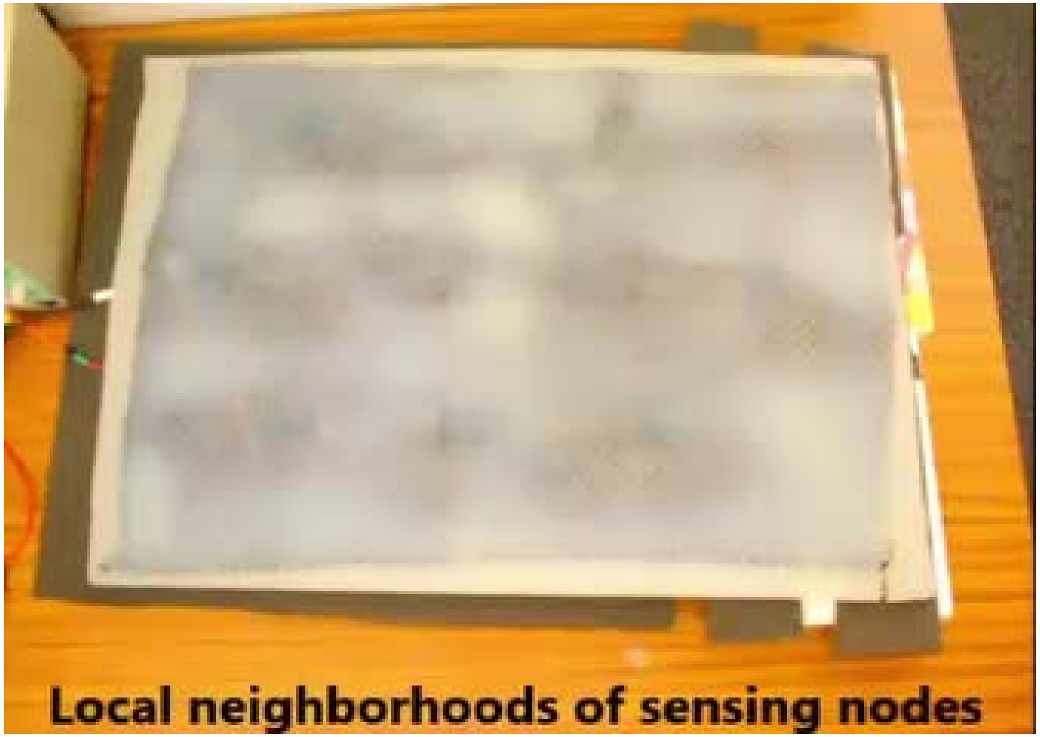
Soft Sensing Skin



1. Texture localization

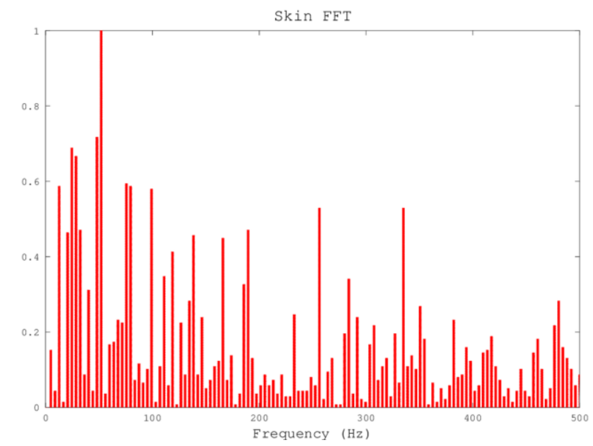






2. Texture Classification

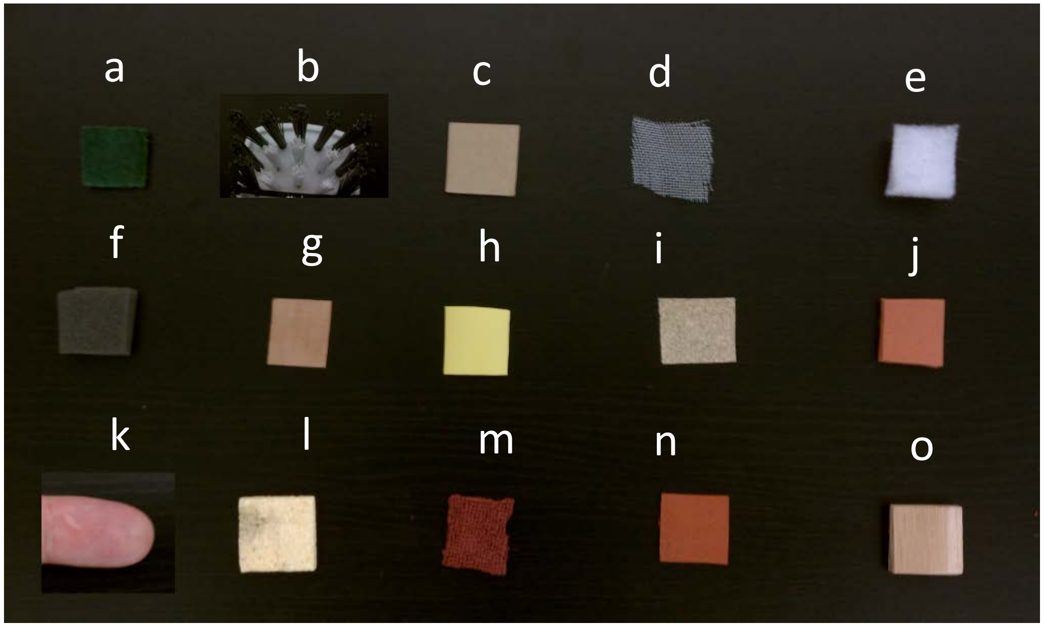
- Logistic regression
- Classifier trained on 15 predefined textures
- 128 inputs
- 15 outputs
- 1935 weights stored on board



$$y = g(\theta_0 + \theta_1 f_1 + \theta_2 f_2 + \cdots + \theta_n f_n)$$

Brillo: 2.4%
Skin: 93.5%
…

Classifier Training



a) brillo
b) brush
c) cardboard
d) coarse wire mesh
e) cotton
f) dense foam
g) fine wire mesh
h) plastic
i) sandpaper
j) silicone foam
k) skin
l) sponge
m) terry cloth
n) textured silicone
o) wood

- Classifiers trained using 15 textures
- 100 samples per texture
- 10-fold cross-validation used to determine accuracy

Classification Results Summary

- Logistic Regression
  - Overall Classification Accuracy: 71.2%
  - Total Number of Weights: 1,935
- Possible improvements
  - Multi-modal sensing
  - Joint classifiers
  - Better classifiers

Predicted Textures

Actual Textures	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
Brillo Pad (a)	89	4	0	1	0	0	0	1	2	0	0	0	1	1	1
Brush (b)	2	59	4	6	0	3	0	1	9	2	1	3	6	4	0
Cardboard (c)	1	1	77	0	2	2	5	2	1	1	4	3	0	0	1
Coarse Wire Mesh (d)	3	7	3	64	2	[illegible]	1	4	2	1	5	2	3	1	0
Cotton (e)	0	1	2	1	69	15	[illegible]	1	1	0	1	3	2	1	3
Dense Foam (f)	2	3	3	2	14	54	3	0	4	3	1	3	3	1	4
Fine Wire Mesh (g)	2	1	4	2	0	0	80	3	2	0	2	1	2	1	0
Plastic (h)	1	3	1	0	3	0	2	78	6	1	4	0	1	0	0
Sandpaper (i)	1	8	0	6	2	4	0	3	58	1	4	6	3	0	4
Silicone Foam (j)	1	1	1	1	2	3	2	0	3	77	1	3	1	4	0
Skin (k)	0	1	0	3	2	1	2	1	1	1	81	3	2	0	2
Sponge (l)	0	3	5	5	4	3	1	1	0	2	3	65	3	2	3
Terry Cloth (m)	2	2	1	6	2	4	1	1	2	0	0	[illegible]	70	2	3
Textured Silicone (n)	2	2	1	4	0	5	1	1	0	5	0	3	[illegible]	72	1
Wood (o)	1	3	1	0	1	0	0	2	4	1	0	5	2	5	75

Confusion Matrix

Non-trivial, material-centric computation

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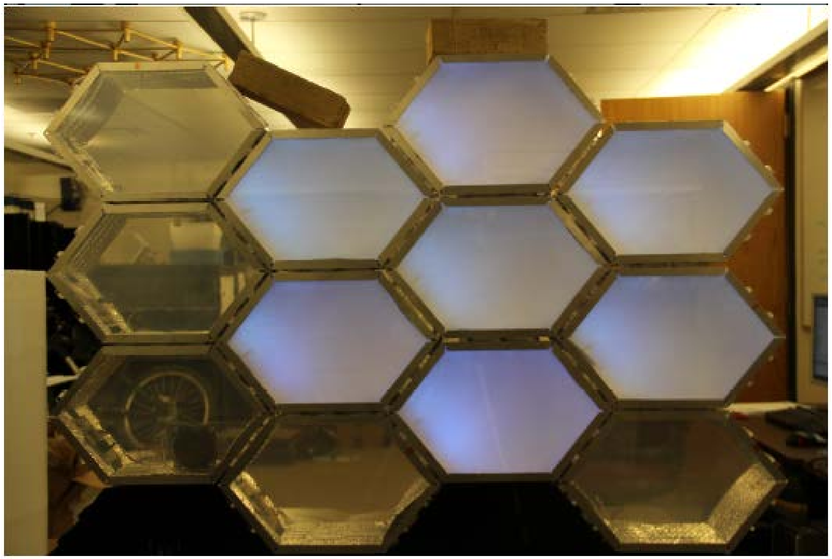
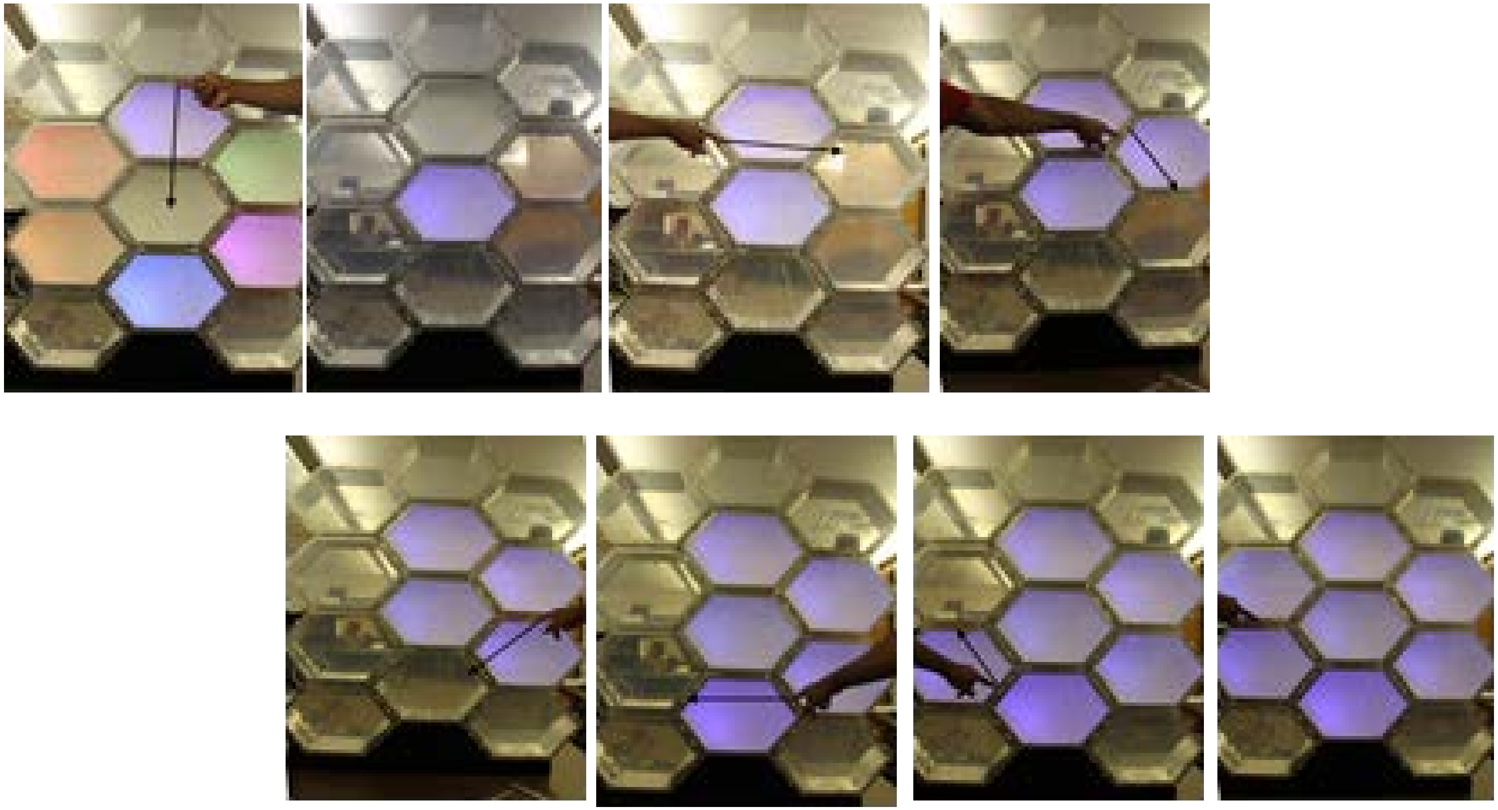
Materials that Change Appearance

Appearance changing materials

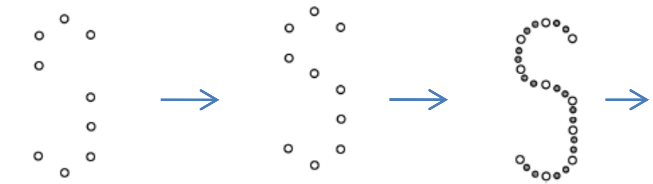


Interacting with a Distributed System



N. Farrow, N. Sivagnanadasan, N. Correll (2014): Gesture Based Distributed User Interaction System for a Reconfigurable Self-Organizing Smart Wall. In: Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI), pp. 245-246 , ACM 2014.

Distributed Gesture Recognition



1. Sample 2. Dilate 3. Interpolate

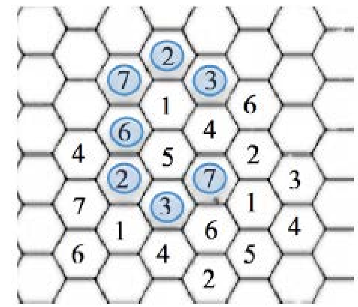
$$\vec{v}_x = [v_x(1), v_x(2), \ldots, v_x(N)]$$
$$\vec{v}_y = [v_y(1), v_y(2), \ldots, v_y(N)]$$

4. Encode

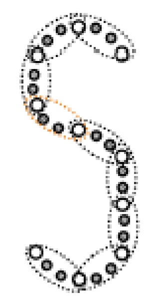
k-NN

5. Consensus

“S”



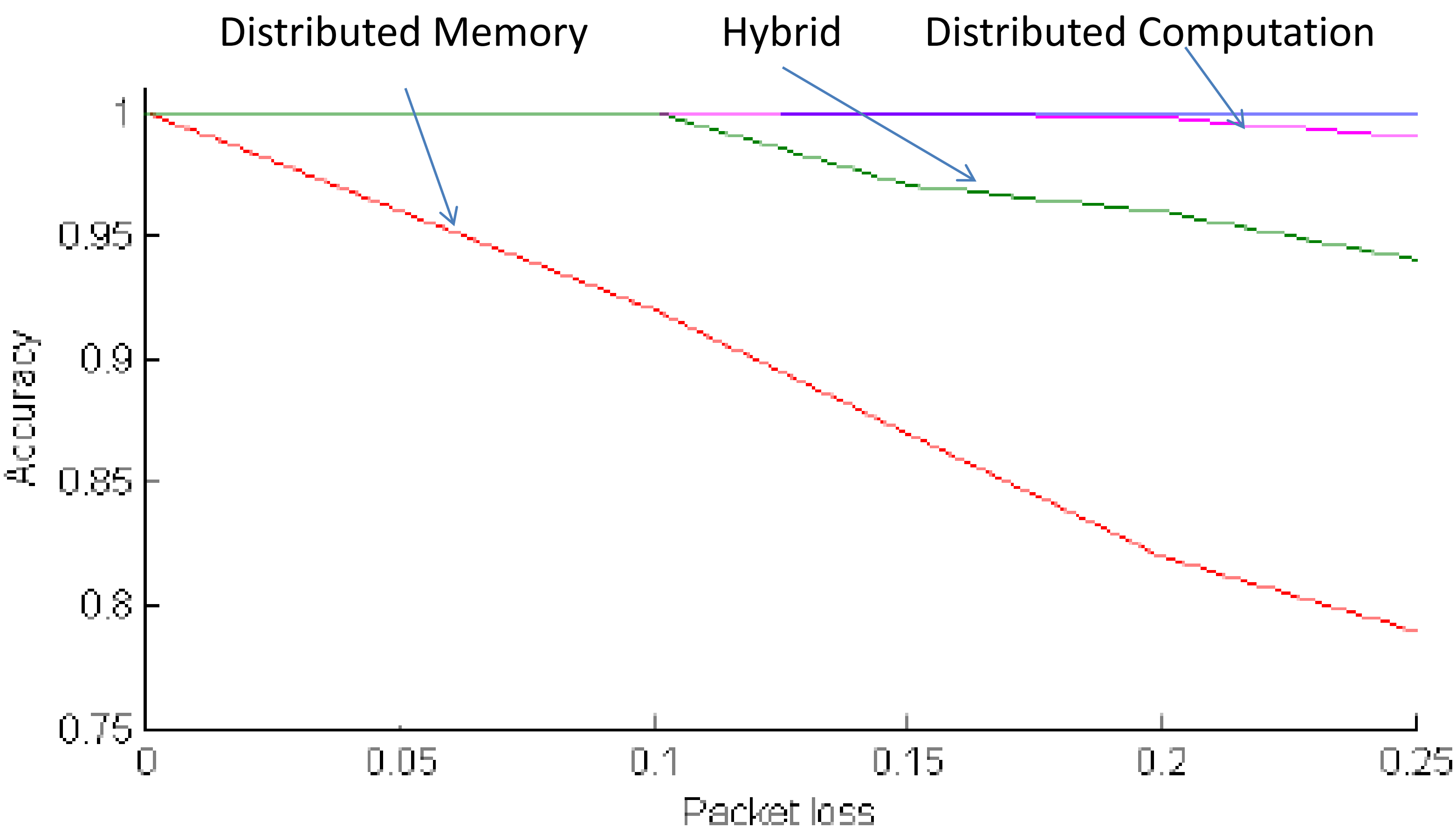
Distribute Memory



Distribute Computation

with Rick Han

Accuracy vs. Packet loss



Tight relationship between material and algorithm design trade-offs

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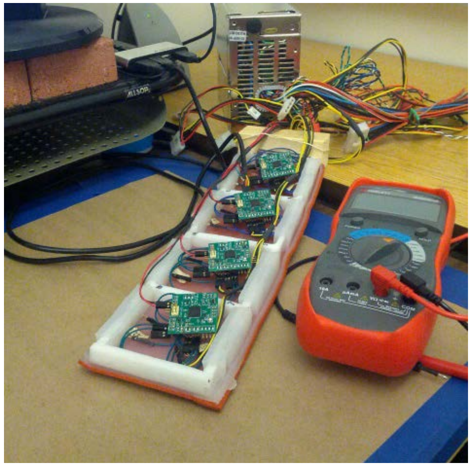
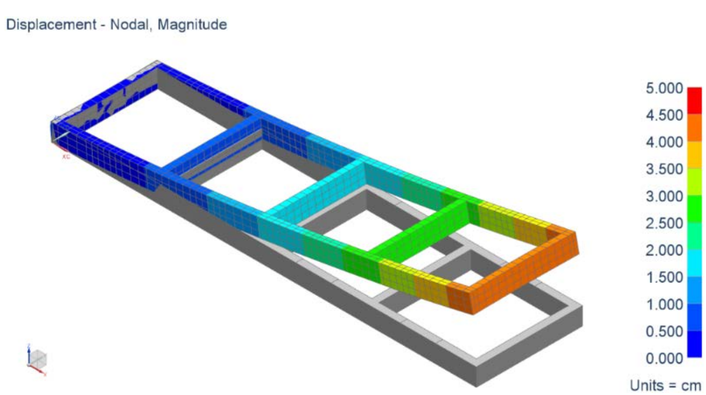
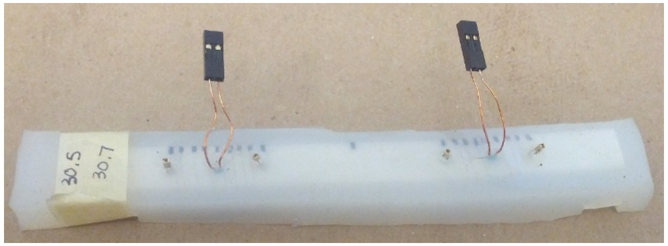
Materials that Shape Change

Variable Stiffness Control

- Stiffness control = shape control
- Melting of PCL
- 2-200MPa change in Youngs' M.
- Local feedback temperature control
- Global distributed shape control

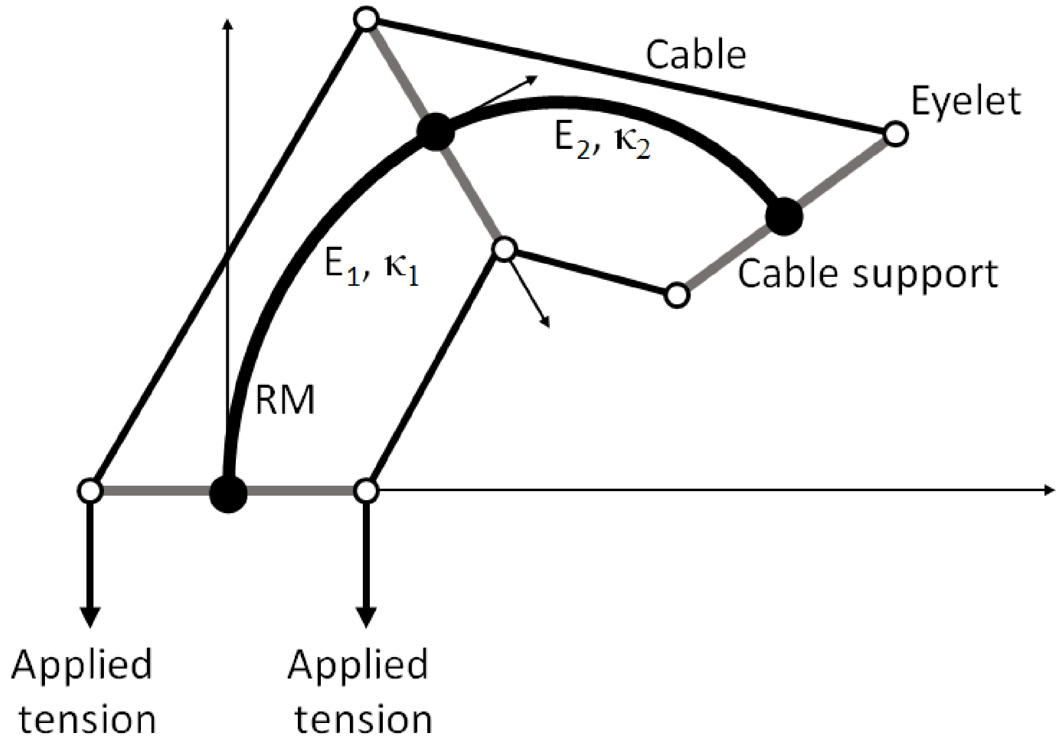






M. A. McEvoy, N. Correll (2014): "Thermoplastic variable stiffness composites with embedded, networked sensing, actuation, and control. In: Journal of Composite Materials, 2014.

Principle of Operation



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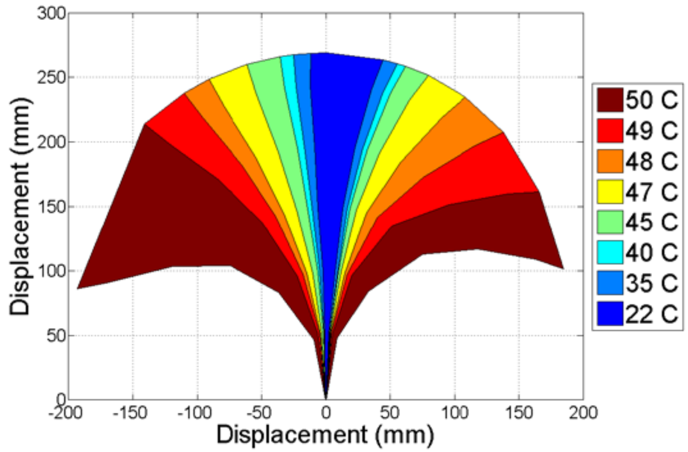
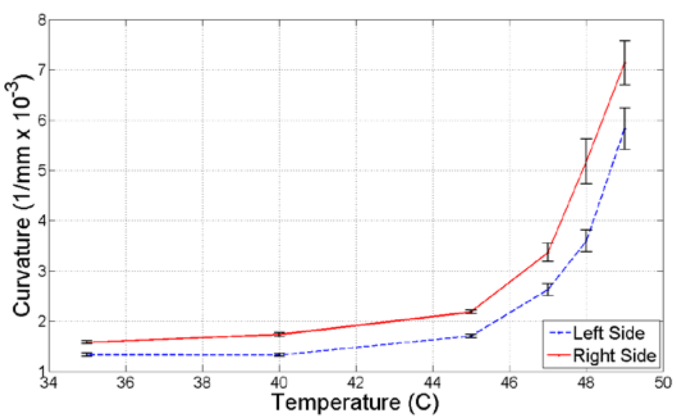
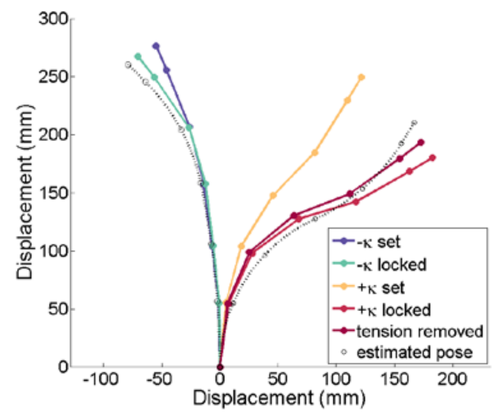
Resulting Shape Change

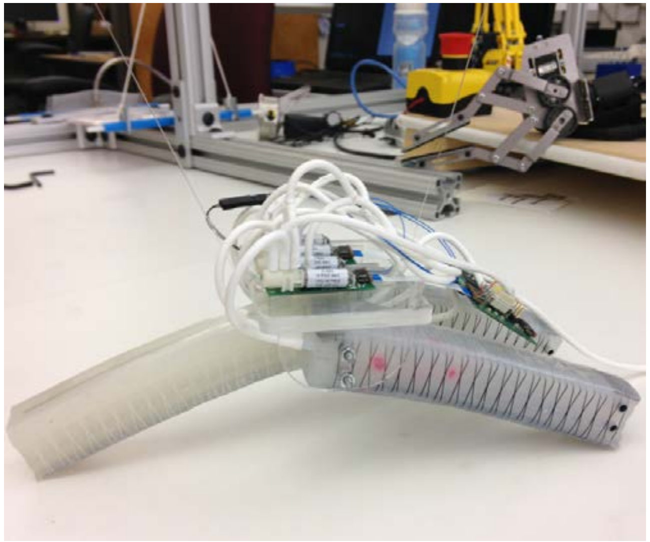




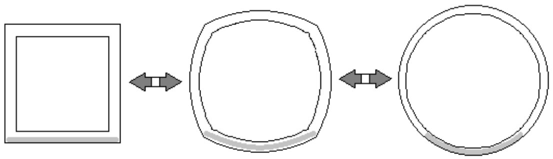


M. A. McEvoy, N. Correll (2014): Shape Change Through Programmable Stiffness. International Symposium on Experimental Robotics (ISER), Springer Verlag, Marrakech, Morocco, 2014.

Pneumatic Shape Change



Modular soft robotic actuator with embedded sensing and control



Modeling

- Geometry
- Material properties
- Pressure
- Curvature
- Resulting force

Outside   Inside

$$\int_0^h \int_0^w \frac{E}{L}\left(\frac{yL}{r}\right) dx\, dy - \int_{h_t}^{h-h_t} \int_{w_t}^{w-w_t} \frac{E}{L}\left(\frac{yL}{r}\right) dx\, dy = \int_{h_t}^{h-h_t} \int_{w_t}^{w-w_t} P\, dx\, dy$$

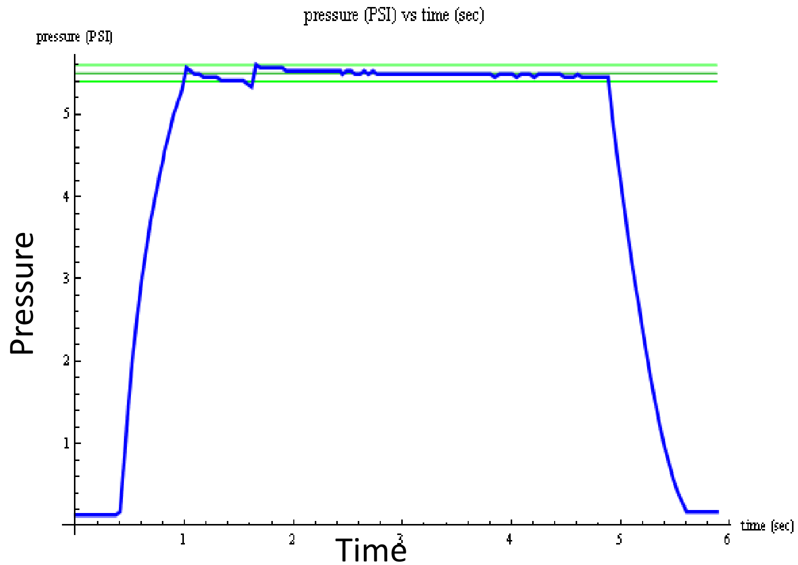
Contraction force   Expansion force

$$\kappa = \frac{1}{r} = \frac{(h-2h_t)(w-2w_t)P}{(h(w-2w_t)h_t + h^2 w_t)E}$$

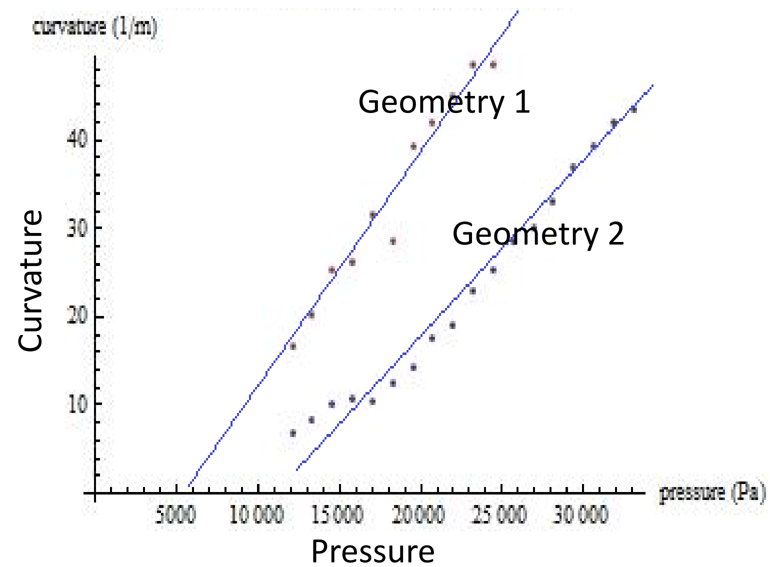
Curvature   Geometry

Pneumatic Shape Change

Feedback control



Model prediction



Tight interaction between distributed control and material physics

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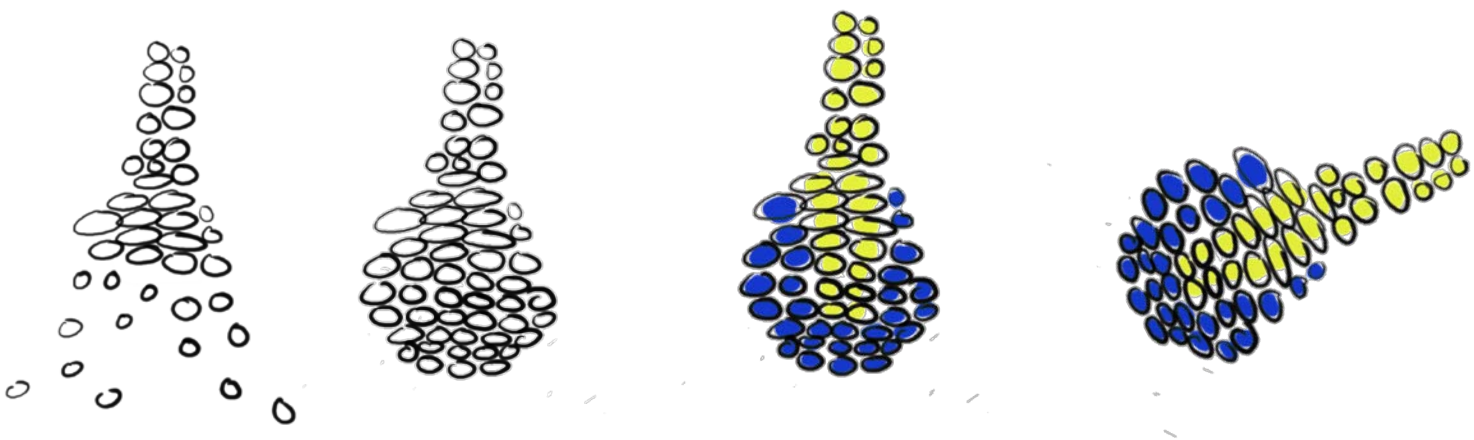
Materials that Self-Assemble

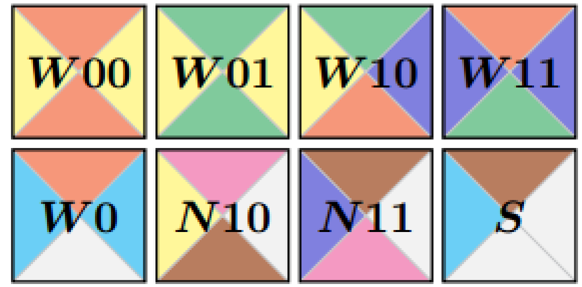
Vision



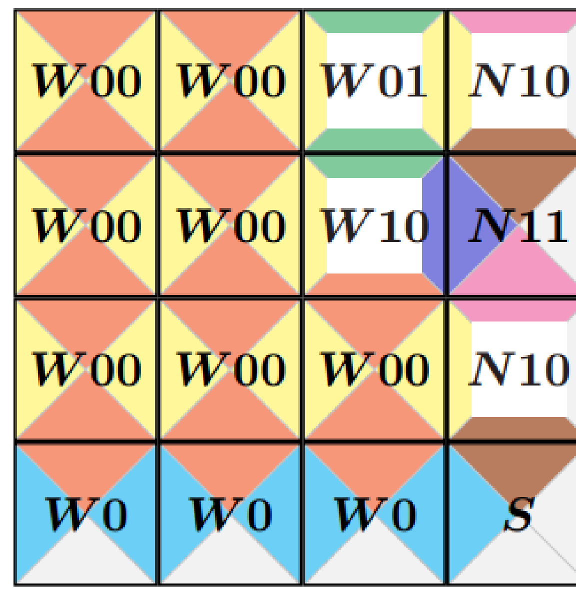
1. Self-assembly 2. Cell differentiation 3. Collective behavior

DNA Tile Assembly Model

- Rules to encode neighborhood relationships
- Maximal N rules for structures with N tiles
- Many interesting structures can be made with fewer rules!

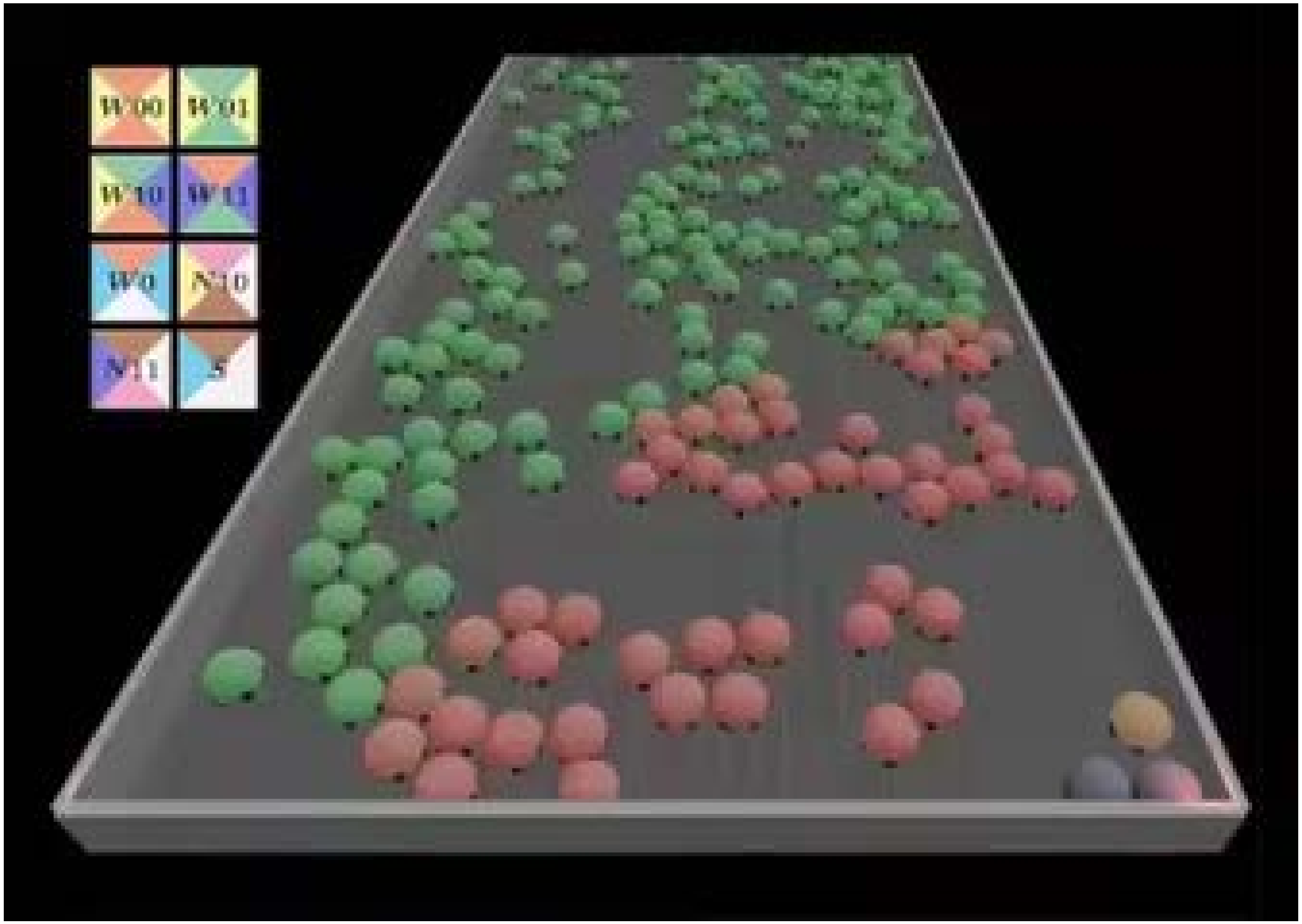


Rules

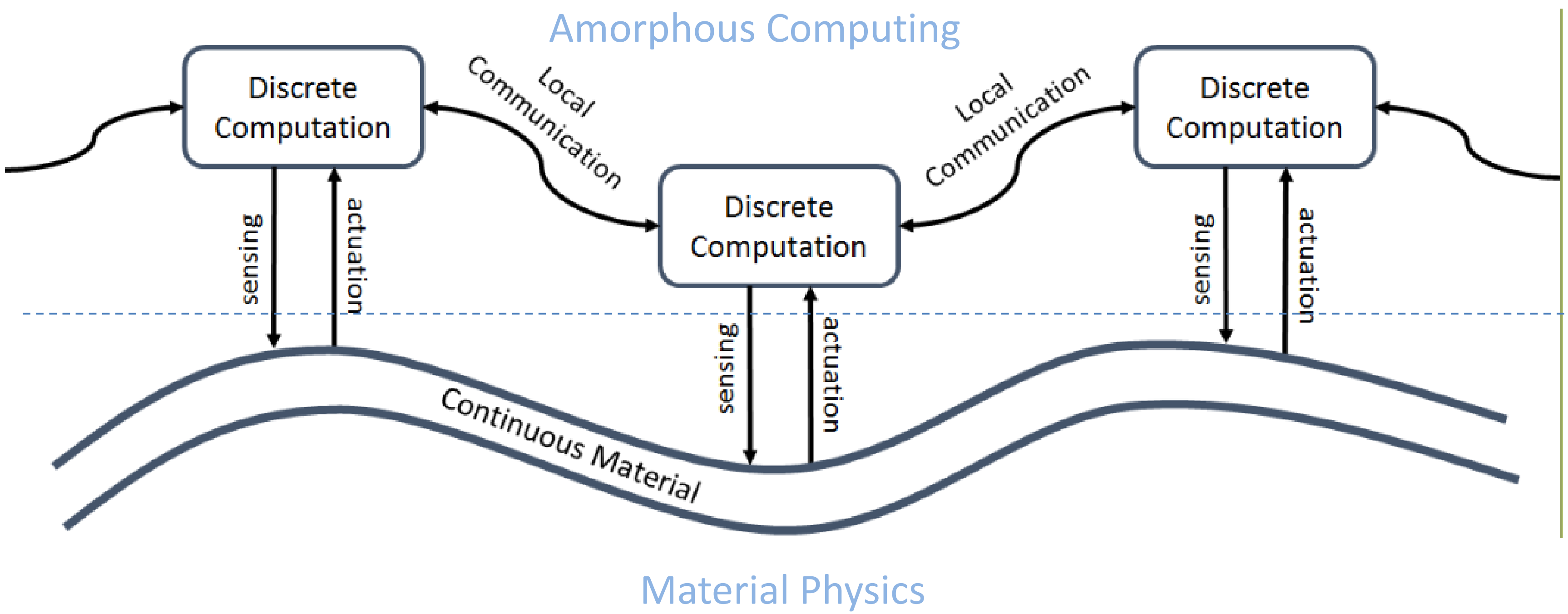


Yuriy Brun. Solving np-complete problems in the tile assembly model. Theoretical Computer Science, 395(1):31–46, 2008.

Example



Robotic Materials



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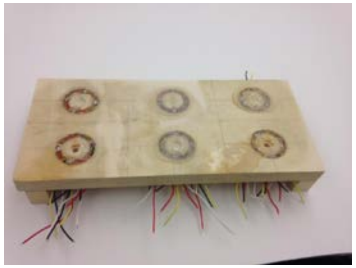
Robotic Materials: New challenges for Education

A soft skin that can
sense distance and force

Variable Stiffness by
Sheet Jamming

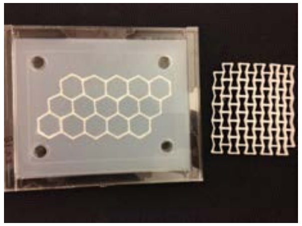
Shortest path routing
in a distributed system

Computation X Materials



An interactive Sushi tray

Wireless data transmission
powered by Seebeck effect



Shape-changing materials that
can self-restore

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Conclusion

- Robotic Materials pose new opportunities and challenges in distributed algorithms
- Understanding the link between “crowd dynamics” and “material physics”
- Timely problems:
  - Novel capabilities for robots
  - Novel materials with revolutionary functionality for every-day applications

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Acknowledgements