ROMANDIC Winter School

The configuration space of textiles

JÚLIA BORRÀS SOL - FEBRUARY 2026

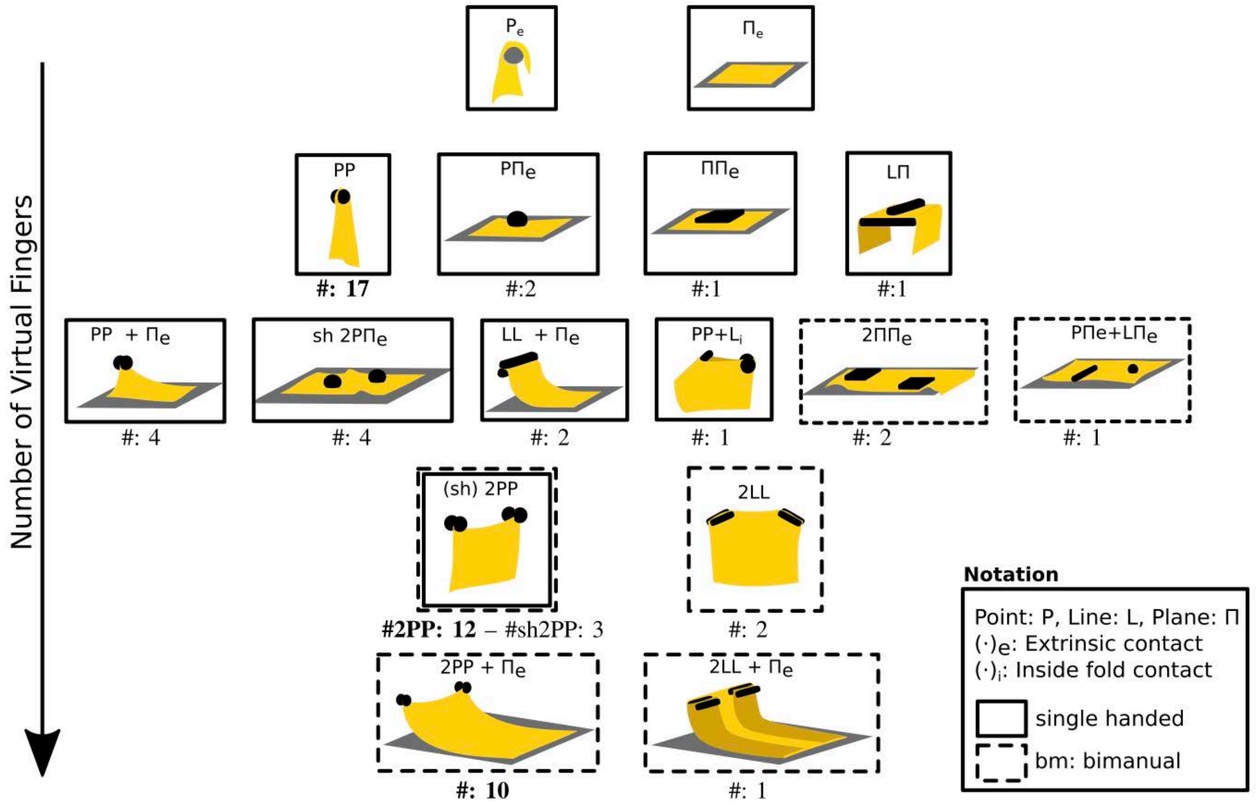
Institut de Robòtica i Informàtica Industrial

CSIC
Consejo Superior de Investigaciones Científicas

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Overview of our research

- Grasp framework for textiles



J. Borràs, G. Alenyà, and C. Torras, "A grasping-centered analysis for cloth manipulation." **IEEE Transactions on Robotics,** 36(3):924-936, 2020.

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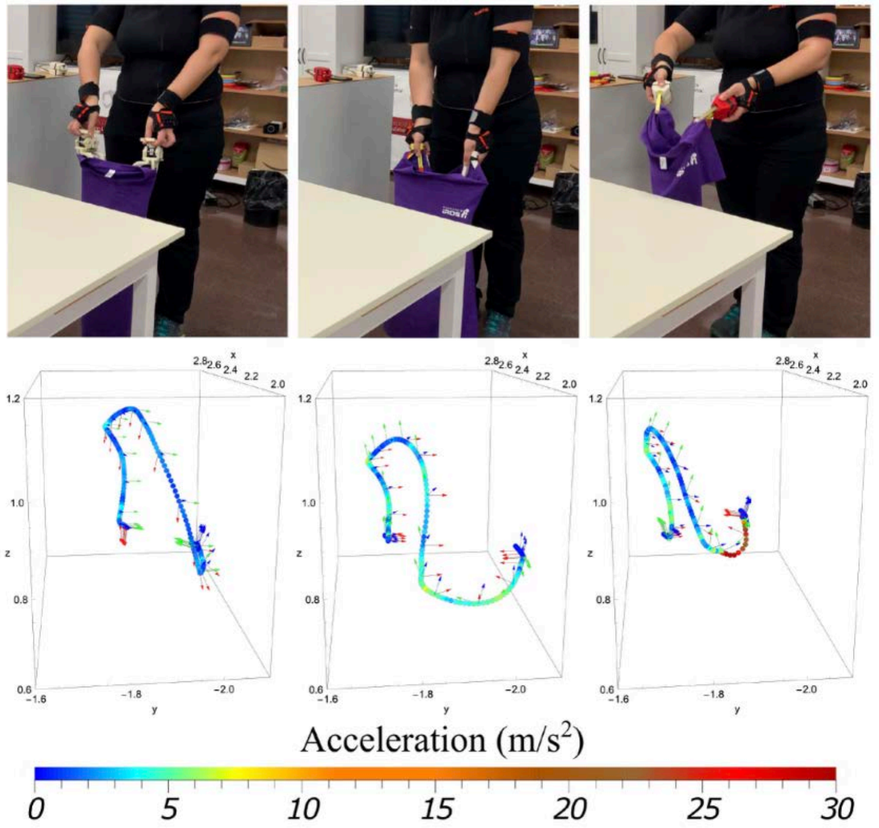

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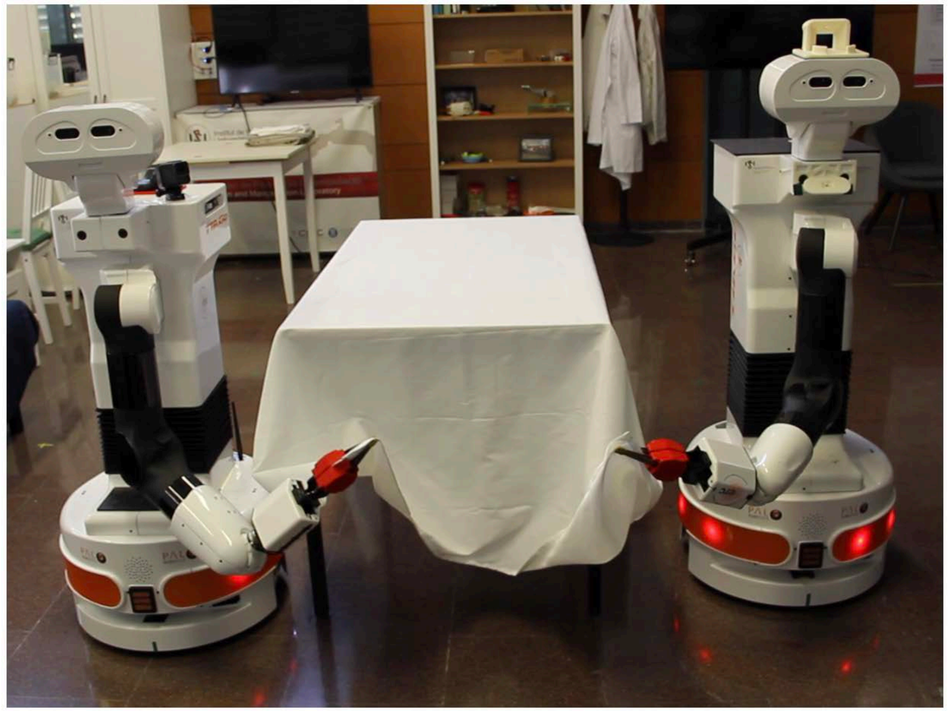

Irene Garcia-Camacho and Guillem Alenyà

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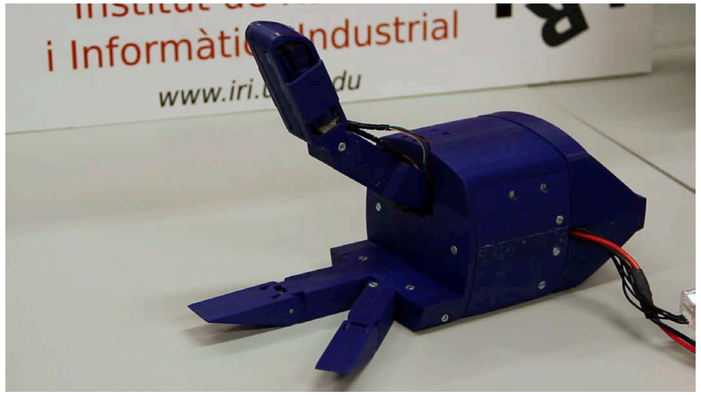
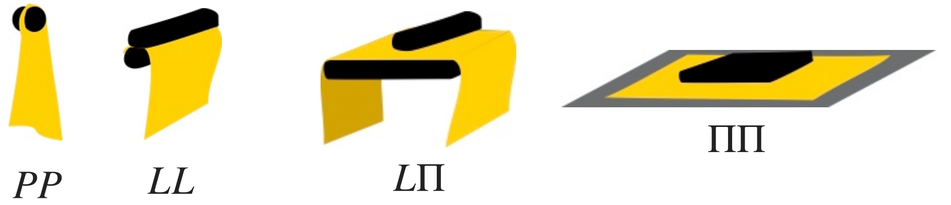
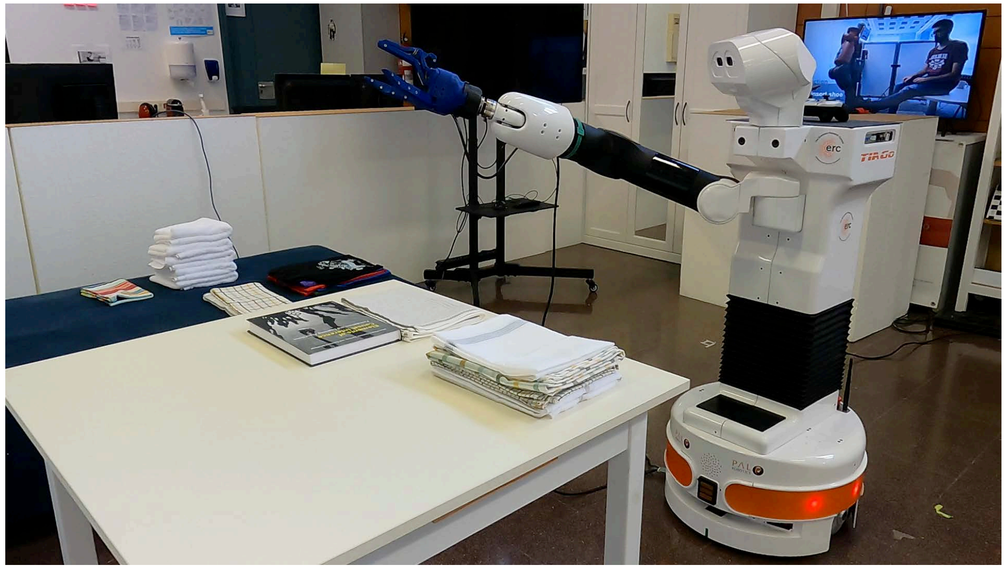
- Design of grippers







S. Donaire, J. Borràs, G. Alenyà, and C. Torras, "A versatile gripper for cloth manipulation."
IEEE Robotics and Automation Letters 5(4): 6520-6527, 2020.

Overview of our research

- Grasp framework for textiles
- Benchmarking cloth manipulation
- Design of grippers
- SoftEnable project:
  - Gripper for opening sealed medical bags

S. Foix, J. Oriol, C. Torras and J. Borràs , A gripper for flap separation and opening of sealed bags, ICRA 2026

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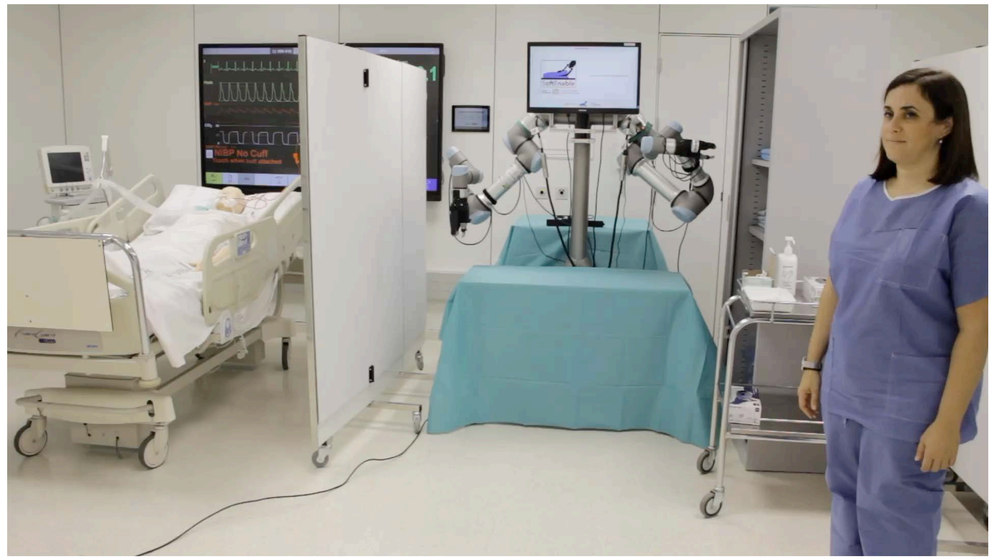
L. Lach, D. Blanco-Mulero and C: Torras



D. Blanco-Mulero, J.Borras and C.Torras, Evaluating the Pre-Dressing Step: Unfolding Medical Garments via Imitation Learning, IROS 2025

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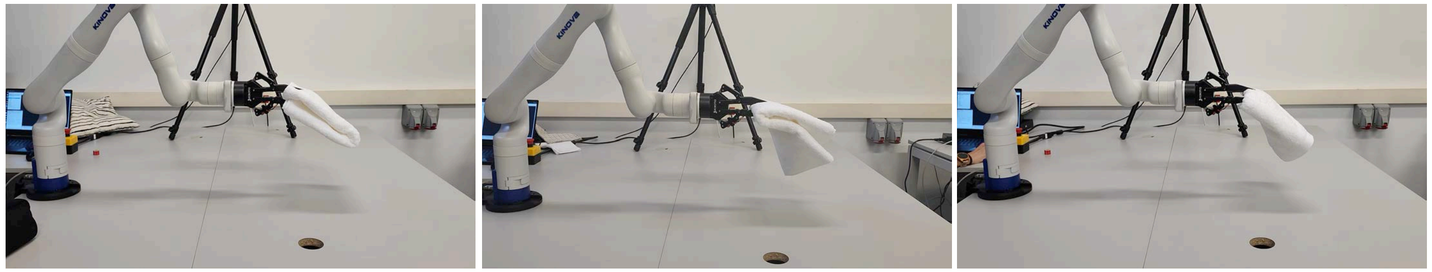

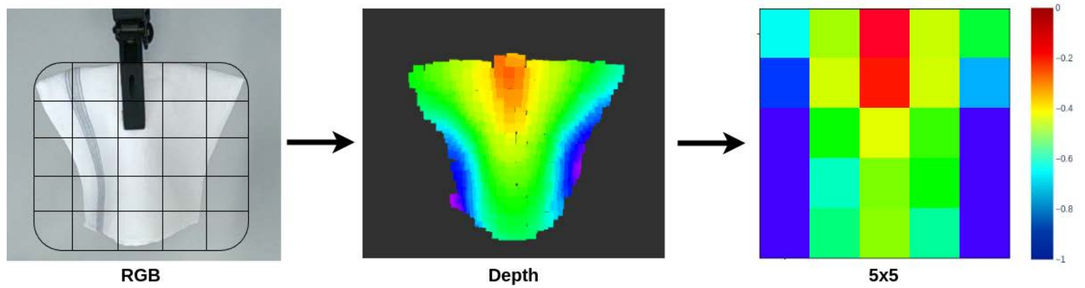

I. Garcia-Camacho, J. Borràs and G. Alenyà, Deformation-aware task and motion planner for piling clothes, in preparation.

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- Dynamics of cloth manipulation (Romandic)

Mahed Dadgostar and Guillem Alenyà

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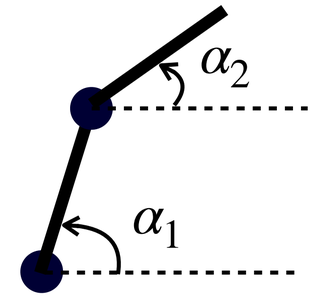
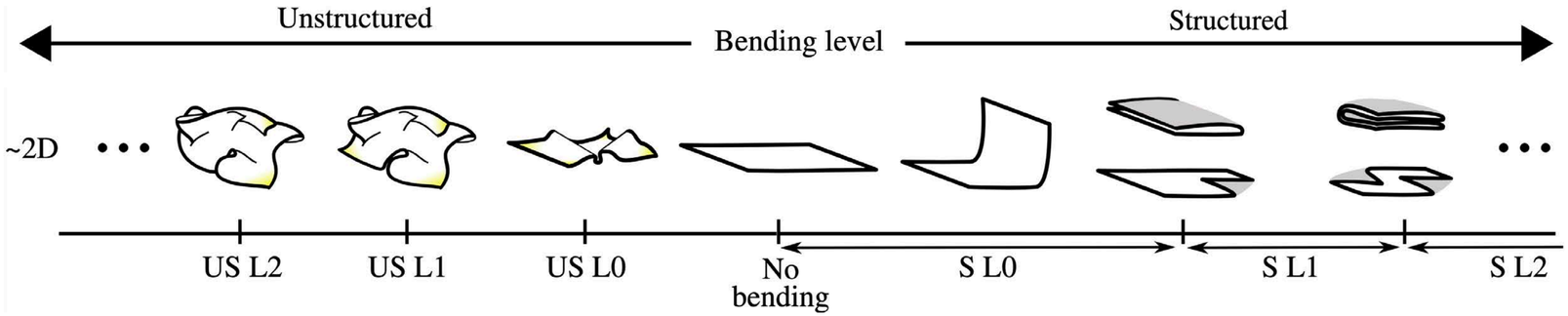
- Dynamics of cloth manipulation (Romandic)
- Representation of the C-space of cloth

Configuration space (C-space)

- A point in the C-space defines a unique configuration of the object in the environment.
- Rigid objects: position and orientation (6 dim)
- Articulated objects: position and orientation + joint angles (6 dim + DOFs)
- What about a piece of fabric? Infinite dimensional space





D Blanco-Mulero, Y Dong, J Borras, FT Pokorny, C Torras ,
T-DOM: A taxonomy for robotic manipulation of deformable objects,
arXiv preprint arXiv:2412.20998, 2025

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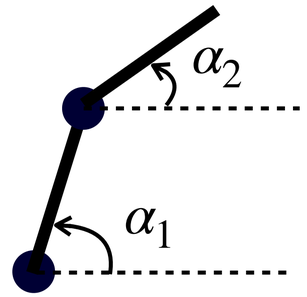

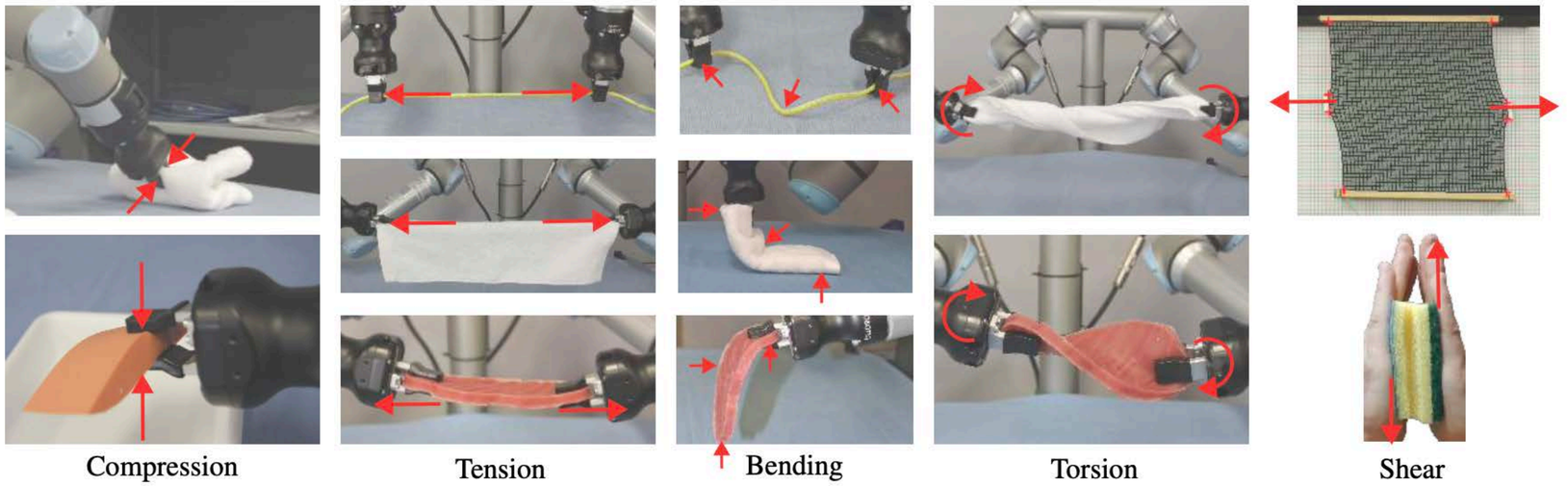

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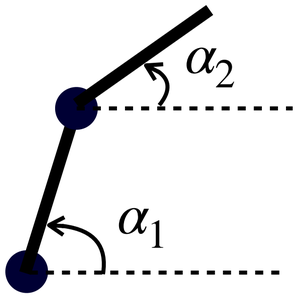

The representation of the objects can lower the dimension

Constructive embeddings

Learned embeddings

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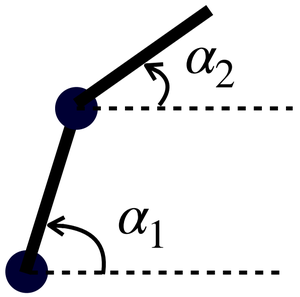

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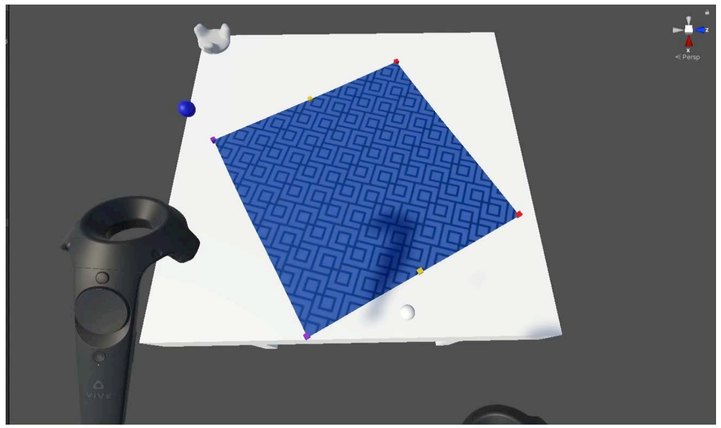

Mesh: number of nodes x 3 dim

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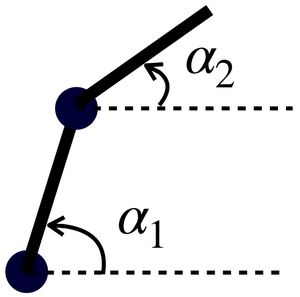

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Constructive embeddings

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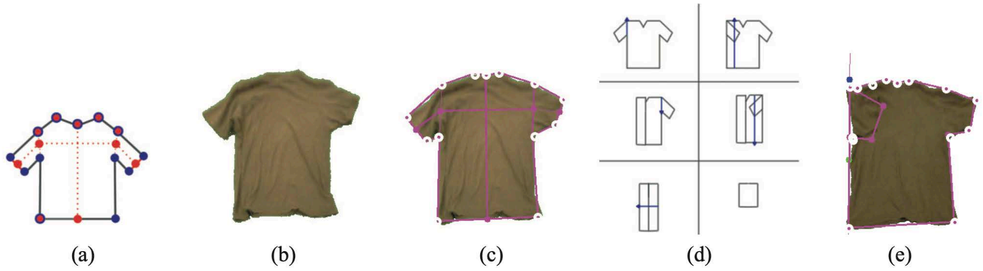
Silhouette /polygons



S. Miller, et al. "A geometric approach to robotic laundry folding." *IJRR*, 2012

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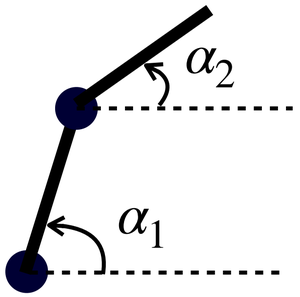

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Constructive embeddings

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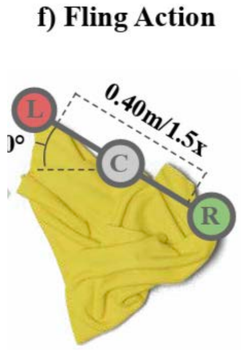

Contour templates with pixels

H. Ha and S. Song. Flingbot: The unreasonable effectiveness of dynamic manipulation for cloth unfolding. CORL 2022

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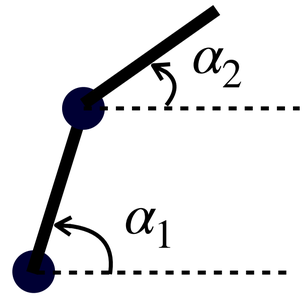

The representation of the objects can lower the dimension

Constructive embeddings

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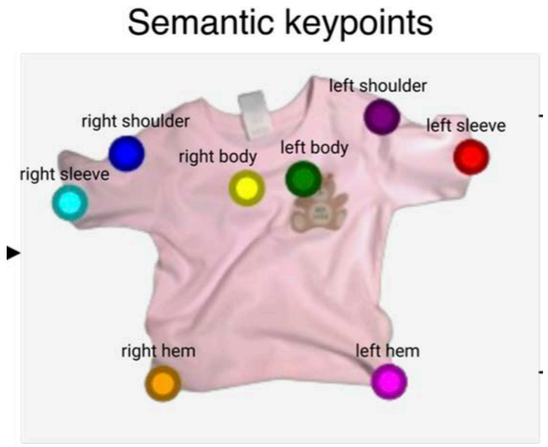

Y. Deng, and D. Hsu. “CLASP: General-purpose clothes manipulation with semantic keypoints”, *ICRA 2025*

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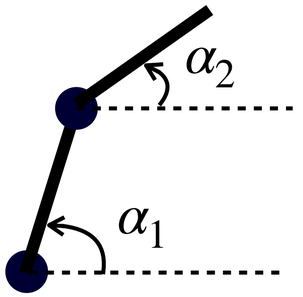
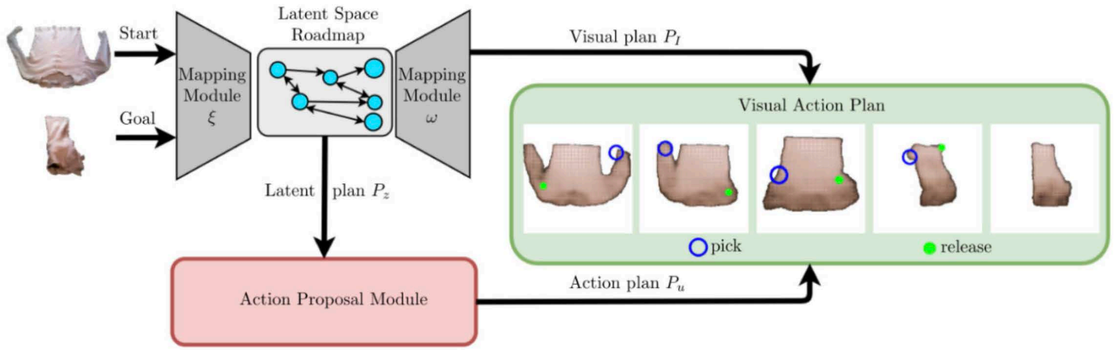


The representation of the objects can lower the dimension

Constructive embeddings

- Mesh
- Silhouette / polygons/contour templates
- Semantic keypoints
- Pixels (RGB or RGB-D)

Learned embeddings



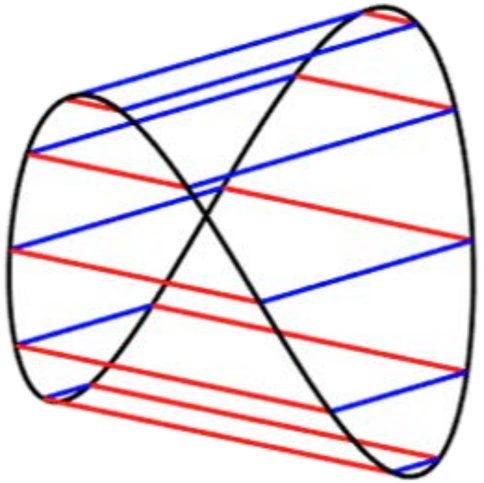
M. Lippi, …, & D. Kragic. Enabling visual action planning for object manipulation through latent space roadmap. TRO, 2022.

Configuration space (C-space)

- Constructive embeddings —> Introduce inductive bias
- Can we define a constructive embedding
  - That uses knowledge of the system?
  - That gives us a sense of metric / distances?
  - That helps us navigate the configuration space?

Assumptions

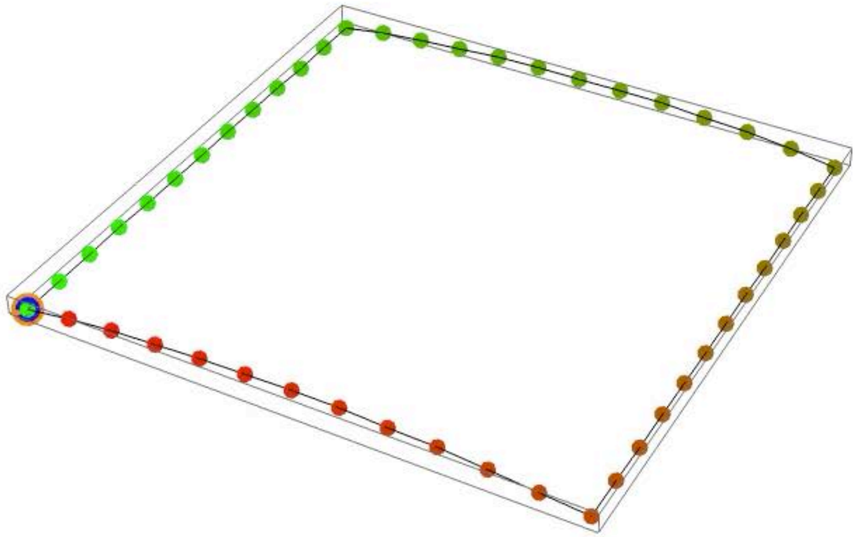
- Cloth under gravity is subject to low stresses —> we can model it as inextensible surfaces
- Original state of cloth is flat —> developable surfaces with 0 curvature
  - Locally isometric to the Euclidean plane $\mathbb{R}^2$
- Clothes are developable surfaces with a boundary
  - Given the boundary, there is not a unique developable surface
  - But, there is a finite set of solutions separated by a non-trivial jump

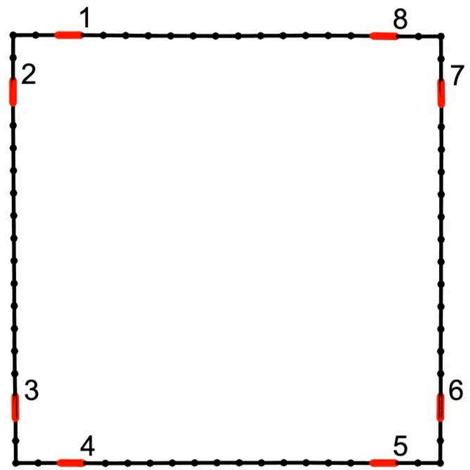


M. Alberich-Carramiñana, J. Amorós and F. Coltraro. Developable surfaces with prescribed boundary, GEOMVAP 2019

Assumptions

- So.. can we (robots) understand the state of cloth just looking at the border?





2D curves in space —> Topology, Knot theory

The Gauss Linking Integral

- Given 2 curves γ_1 and γ_2 the Gauss Linking Integral (GLI) between them gives the **linking number** between the curves

$$GLI(\gamma_1, \gamma_2) = \frac{1}{4\pi} \int \int \frac{(\gamma_2 - \gamma_1) \cdot [\gamma_2' \times \gamma_1']}{\|\gamma_2 - \gamma_1\|^3}$$

- The GLI(γ, γ) between a curve and itself gives the **writhe** or writhing number of γ
- Both values are **geometic invariants of the curves**

R. L. Ricca and B. Nipoti. Gauss linking number revisited. Journal of Knot Theory and Its Ramications, 2011.

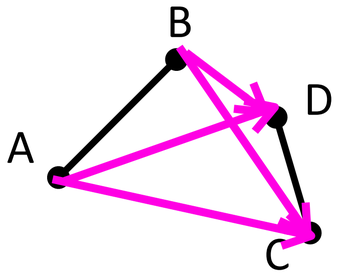
- In 1983, a version for polygonal curves appeared in the context of DNA protein structures

M. Levitt. Protein folding by restrained energy minimization and molecular dynamics. Journal of molecular biology, 1983.

- Many applications
  - S. Ho Thesis 2011: to identify and synthesize animated characters in intertwined positions
  - Ivan et al. IJRR2013: To guide path planning through holes with representative curves of the workspace
  - Pokorny et al ICRA2023: To guide caging grasps in
  - Yuan et al ICRA 2019: To guide reinforcement learning for humanoid motions.

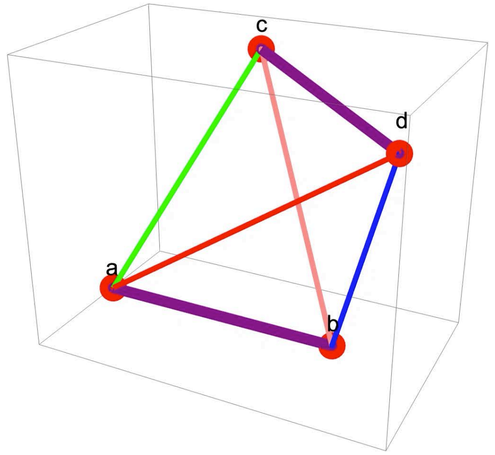
The Gauss Linking Integral: the Levitt formula

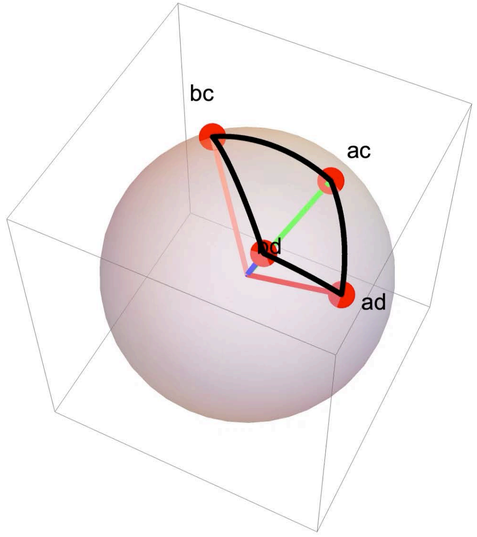
- The GLI between two segments:



$$GLI(\vec{AB},\vec{CD}) = \arcsin(\vec{n}_A\vec{n}_D) + \arcsin(\vec{n}_D\vec{n}_B) + \arcsin(\vec{n}_B\vec{n}_C) + \arcsin(\vec{n}_C\vec{n}_A)$$

$$\vec{n}_A = \|\vec{AC} \times \vec{AD}\|,\ \vec{n}_B = \|\vec{BD} \times \vec{BC}\|,$$
$$\vec{n}_C = \|\vec{BC} \times \vec{AC}\|,\ \text{and}\ \vec{n}_D = \|\vec{AD} \times \vec{BD}\|.$$

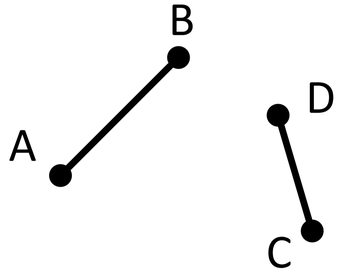




The GLI between two segments is the area of the spherical quadritaleral defined by the unit vectors $\|AC\|, \|AD\|, \|BC\|, \|BD\|$

The Gauss Linking Integral: the Levitt formula

- The GLI between two segments:



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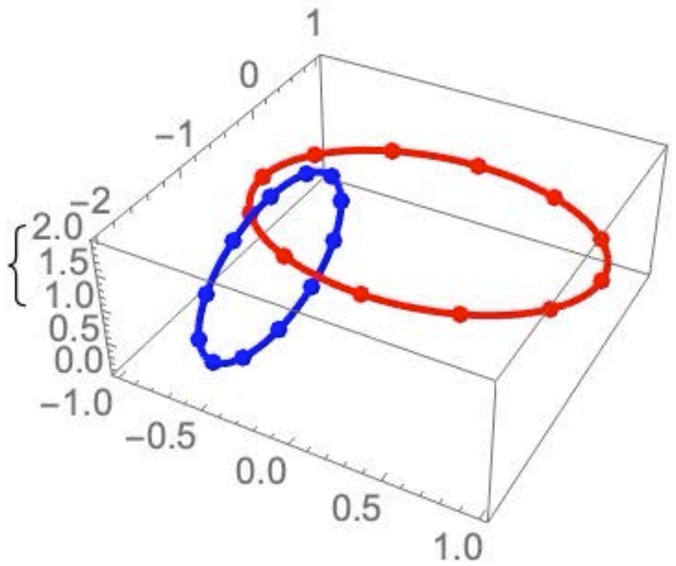
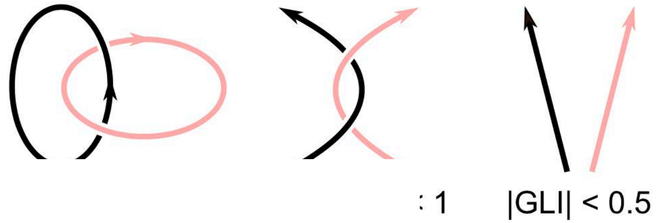
$$\vec{n}_A = \|\vec{AC} \times \vec{AD}\|,\ \vec{n}_B = \|\vec{BD} \times \vec{BC}\|,$$
$$\vec{n}_C = \|\vec{BC} \times \vec{AC}\|,\ \text{and}\ \vec{n}_D = \|\vec{AD} \times \vec{BD}\|.$$

- For two curves $\gamma_1 = \{s_i, i = 1,\ldots N\}$ and $\gamma_2 = \{e_i, i = 1,\ldots N\}$

$$\mathcal{G}(\gamma_1,\gamma_2) = \sum_{s_i \in \gamma_1} \sum_{r_i \in \gamma_2} GLI(s_i, r_i)$$

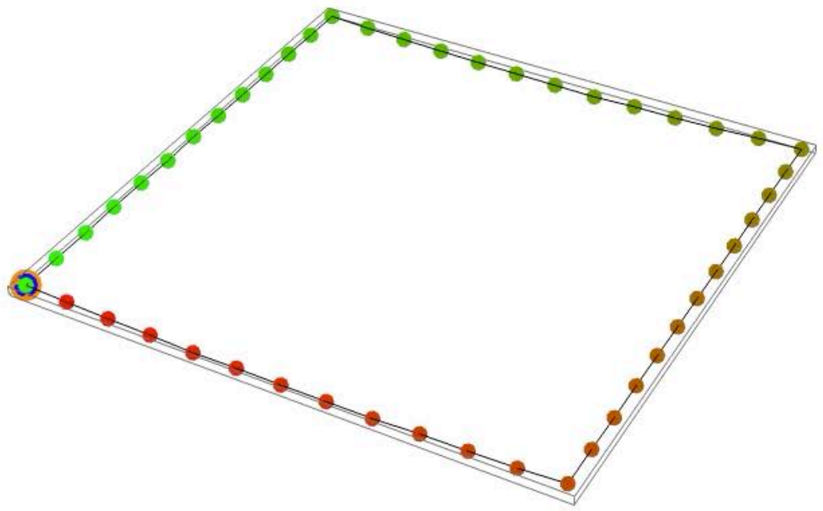




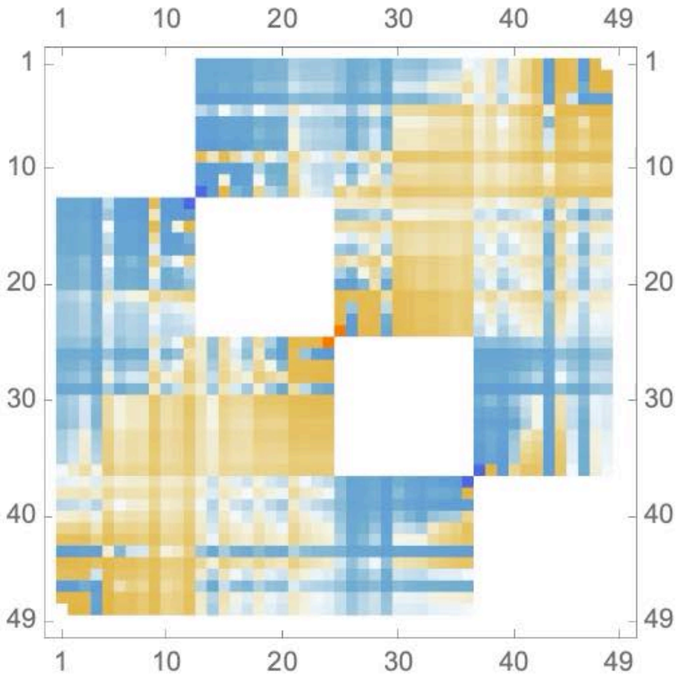
: 1 |GLI| < 0.5

What about clothes?

- Can we apply this concept to the border of the cloth?

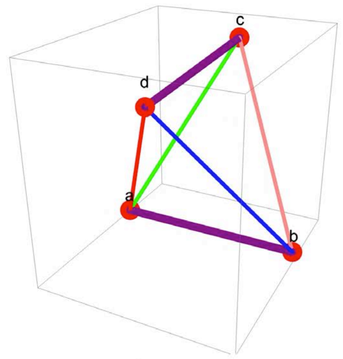


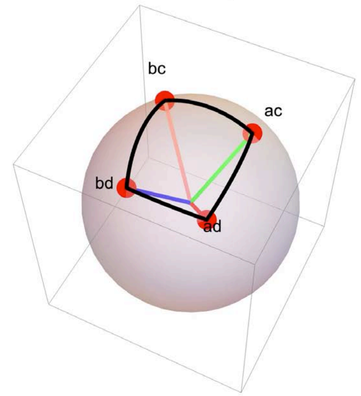
Simulation of grasping a cloth by a corner



The corresponding GLI matrix at each frame

The GLI between two coplanar segments is not defined!

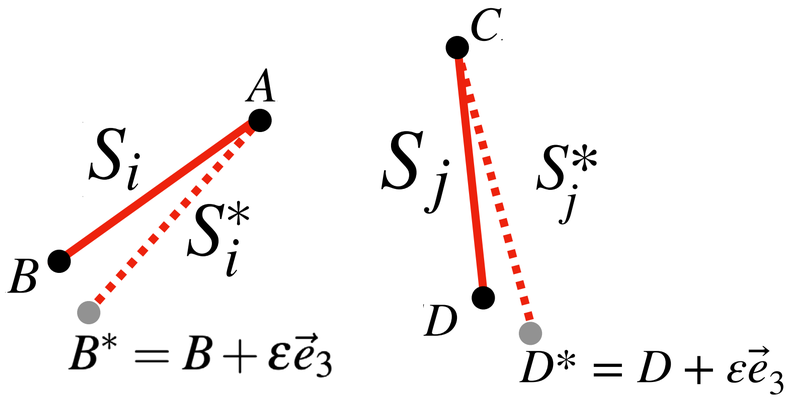


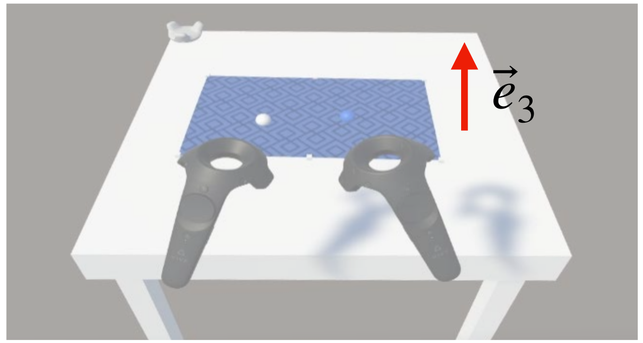


Derivative of the GLI: dGLI

- We use a derivative of the GLI between two segments

$$dGLI(S_i, S_j) = \frac{GLI(S_i^*, S_j^*) - GLI(S_i, S_j)}{\varepsilon}$$



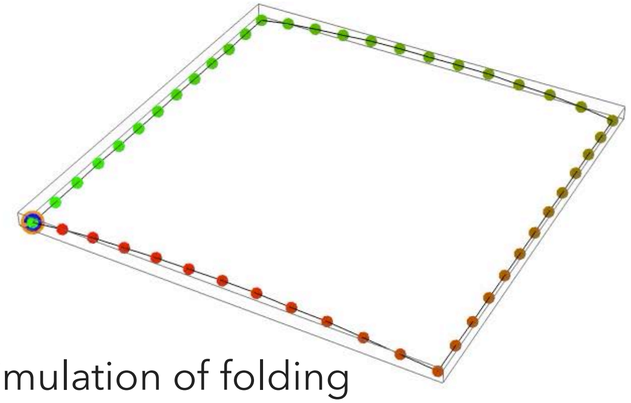


F. Coltraro, J. Fontana, J. Amorós, M. Alberich-Carramiñana, J. Borràs and C. Torras.

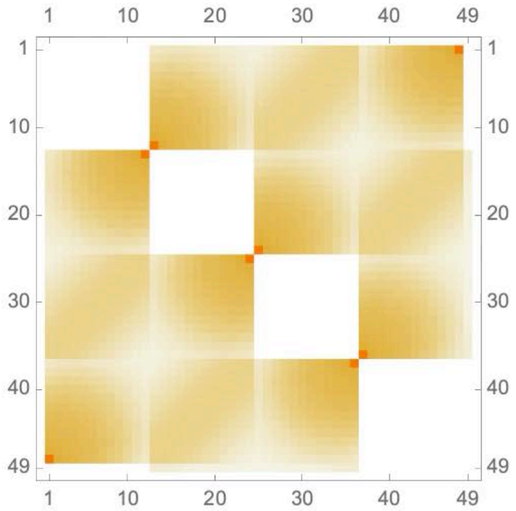
A representation of cloth states based on a derivative of the Gauss Linking Integral.

Applied Mathematics and Computation, 2023.

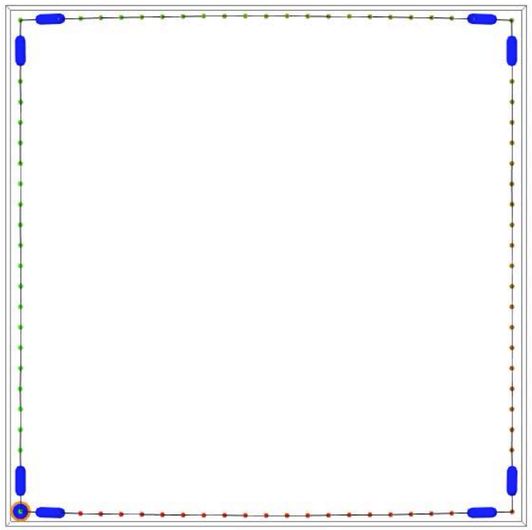
Derivative of the GLI: dGLI

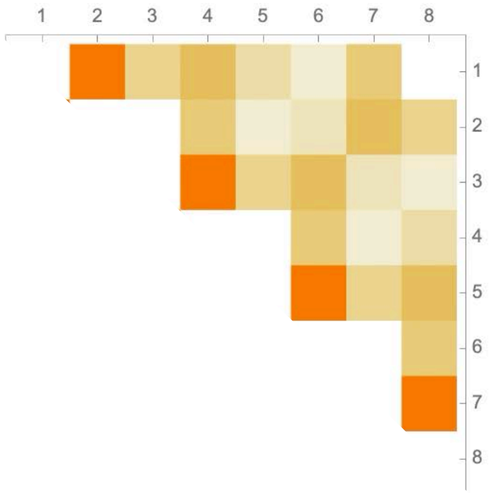


Simulation of folding sequence



dGLI matrix: each element is the dGLI between two segments





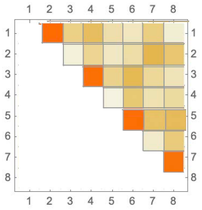
We select only 8 edges close to the corner

28 coordinates

The dGLI coordinates embedding

- The 28-dim coordinates represent different cloth states
- Each coordinate can be very big (for close to intersect edges)
- What is relevant is what values are bigger, positive and negative, not the actual value of each coordinate
  - Bigger edges lead to bigger values
- Spearman's distance.
  - ρ is the Pearson correlation coefficient
  - $R(x)$ is the rank variable of x
    - Ordering the coordinates of x
    - Each coordinate value is its position in the ranking
- Bounded with values between 0 and 2
- Ignores scaling factors between different clothes

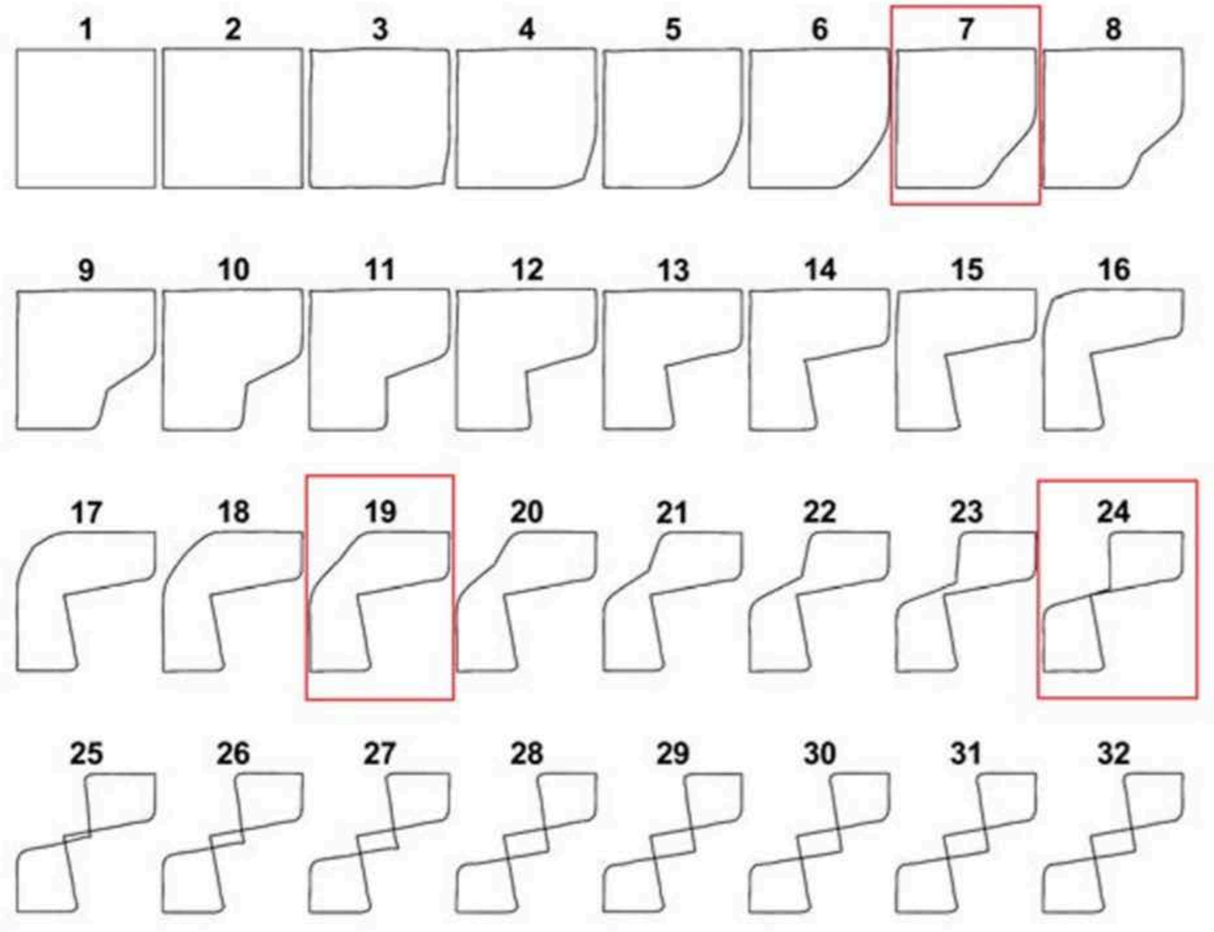
C_{dGLI} in matrix form



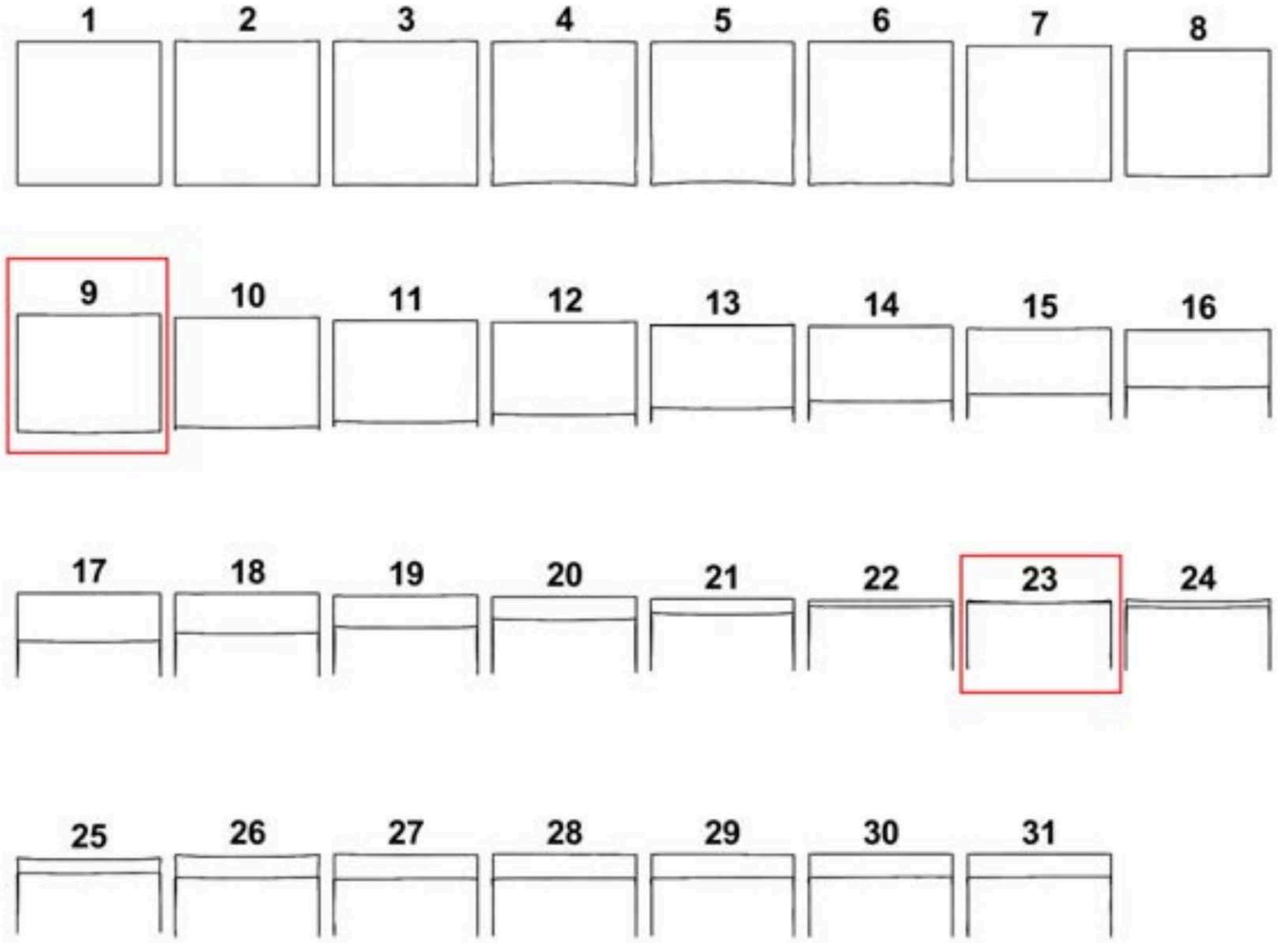
$$C_{\text{dGLI}} = \Big(\qquad \Big)$$

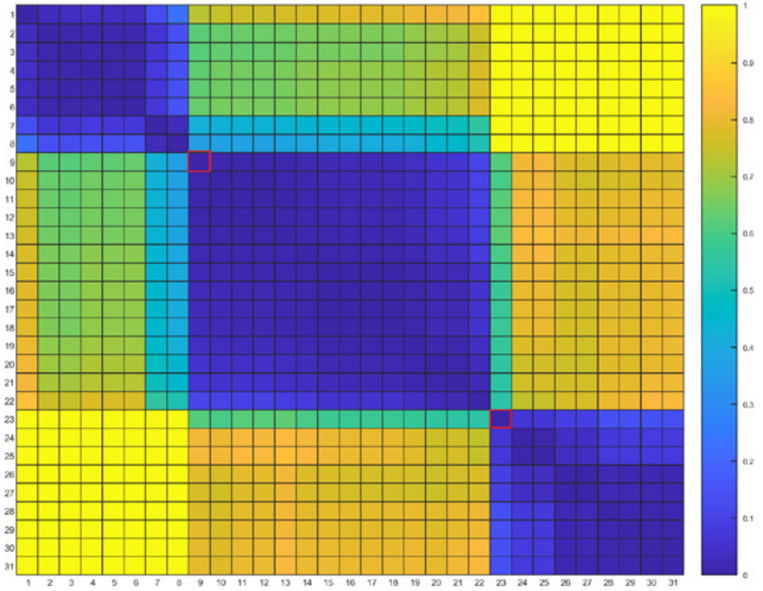
$$d(x, y) = 1 - \rho(\mathrm{R}(x), \mathrm{R}(y)).$$

Classification of cloth semantic states by distance



Classification of cloth semantic states by distance



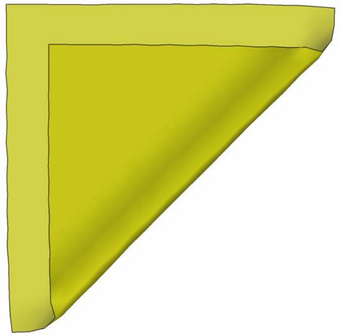


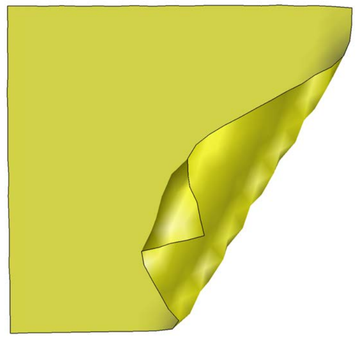
Distance matrix

$$M(i,j) = d(f_i, f_j)$$

Classification of cloth semantic states by distance

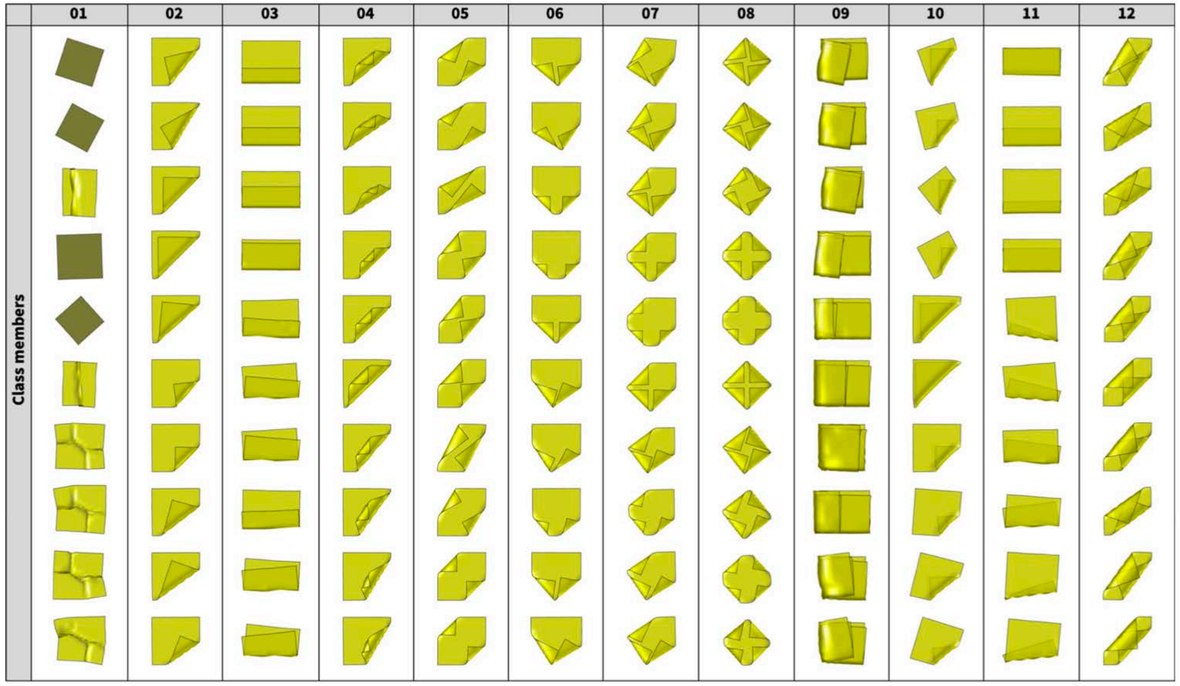
- What is a semantic state?
  - Not well defined
- “One corner folded” / “Folded in half” / “Bottom side folded” / “Wrinkled?”

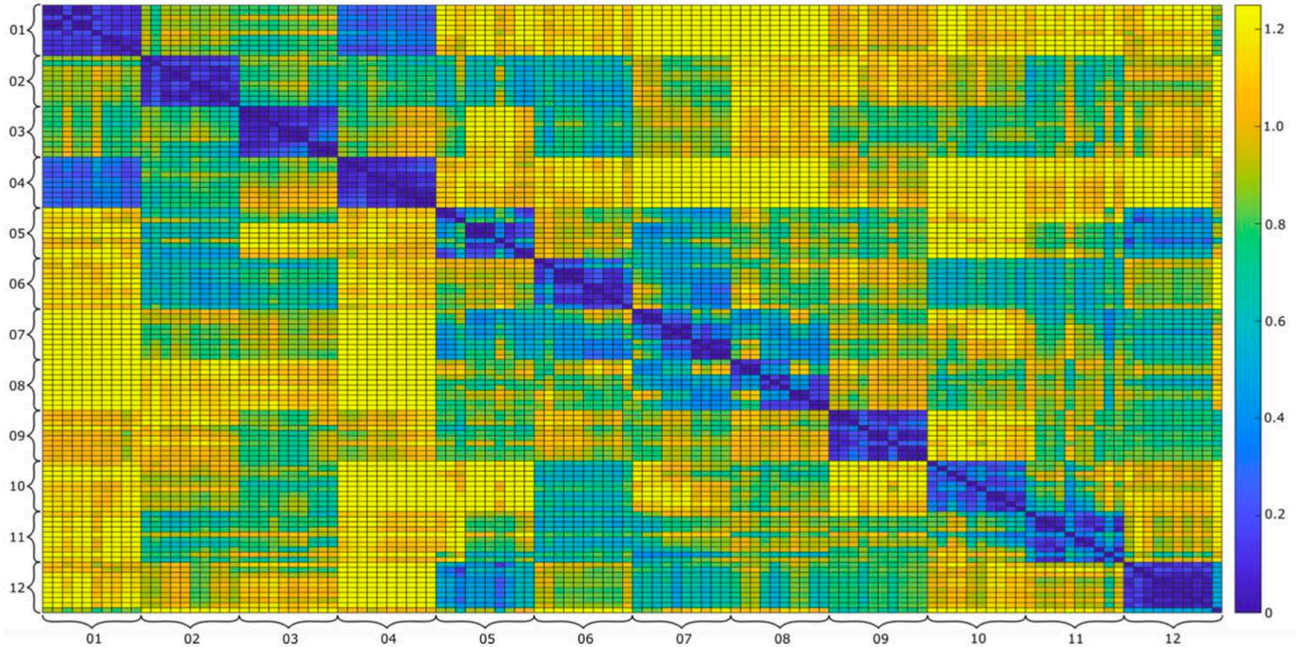




- The choice of edges defines the semantic states we can identify

Classification of cloth semantic states by distance





Comparison between different shape representations*.

	Database	Seq. I	Seq. II	Seq. III	Seq. IV
dGLI	**0.73**	**0.27**	**0.18**	**0.21**	**0.52**
Edges	1.60	0.68	0.77	0.51	1.91
Corners	2.49	0.98	1.61	3.14	1.86
Fréchet	0.99	0.69	0.76	0.48	0.90
Hausdorff	1.45	0.71	0.84	0.49	0.90

*Each number is the Davies-Bouldin index introduced in Eq. 10, that measures cluster separation quality. A smaller value means a better separation. We mark in bold the smallest values in each column.

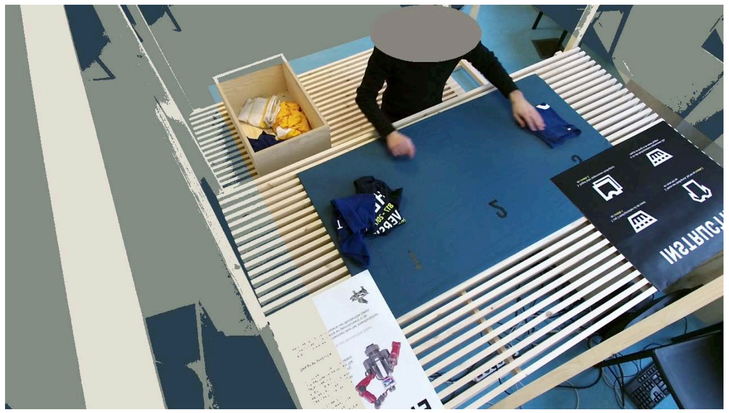
Data collection: virtual reality framework

Unity's 3D platform, Obi Cloth & HTC Vive Pro system

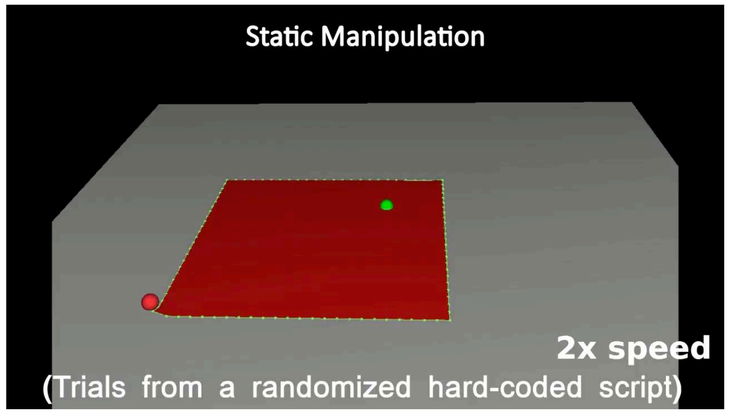
J. Borràs, A. Boix-Granell, S. Foix, and C. Torras, A Virtual Reality Framework For Fast Dataset Creation Applied to Cloth Manipulation with Automatic Semantic Labelling, ICRA 2023.

Data collection: virtual reality framework

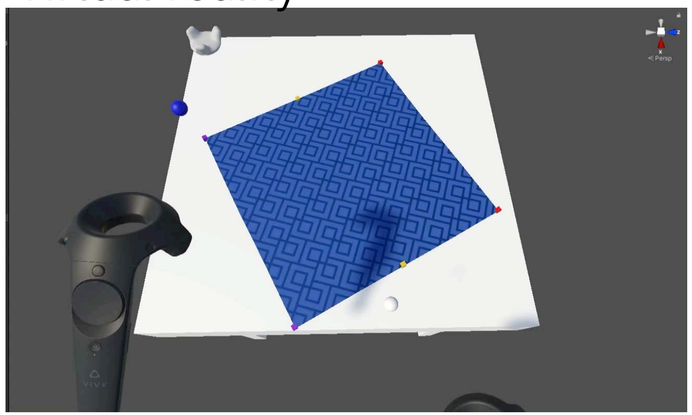
Real video



Cloth simulation

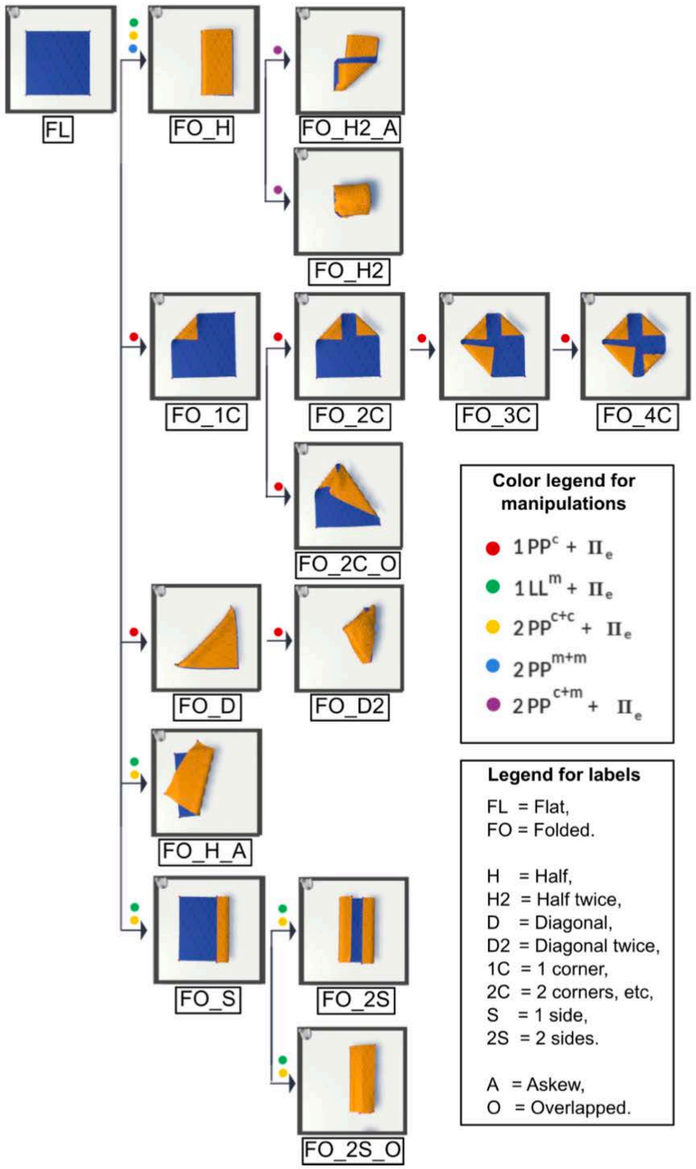


Virtual reality



	Real video	Simulation	Virtual reality
Realistic cloth dynamics	✓	✗	
Ground truth of cloth 3D pose	✗	✓	
Realistic mani. trajectories	✓	✗	
Exploits human visual feedback	✓	✗	
Variability in repetitions	✓	~	
Online error correction	✓	✗	
Fast/easy data acquisition	✓	✗	

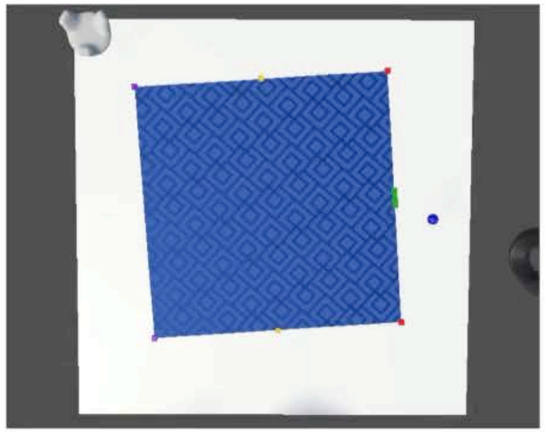
Dataset of cloth manipulations



123 sequences of foldings with fixed position and orientation
81 sequences of foldings with random position and orientation

Label	Possible different samples
FO_1C	
FO_2C	
FO_3C	
FO_S	
FO_H	
FO_H2	
FO_H_A	

Learning semantic labels in the virtual reality

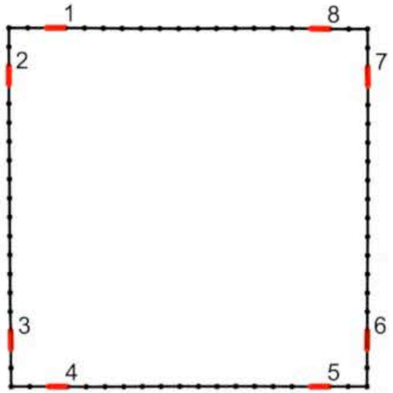


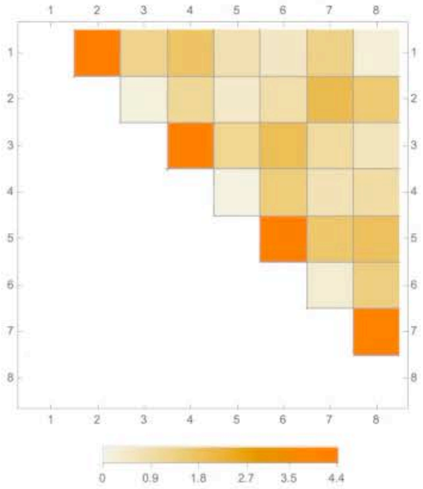
Filename:
02_1LM_2PCM_03.xml

Grasp 1: None
Grasp 2: None

Predicted class:
FL

We learn the mapping
{ dGLI cloth coordinates → SemanticLabel }





Comparing with different representations

dGLI

{ dGLI cloth coordinates → SemanticLabel }

$$\mathscr{G} = (g_1, \ldots, g_{28})$$

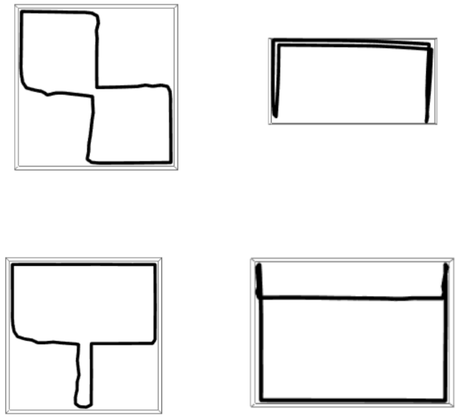
Border coordinates

{ cloth border coordinates → SemanticLabel }

$$\mathscr{B} = \{p_i - p_1, i = 1, \ldots n\}$$

Image representation

{ image of border → SemanticLabel }

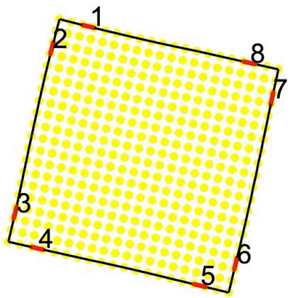


	Cloth representation used for training		
Accuracy	**dGLI**	**Norm. border**	**Image**
Test dataset	$98.5\% \pm 0.6\%$	$97.2\% \pm 1.0\%$	$90.7\% \pm 1.3\%$
Rand. P&R dataset	$88.3\% \pm 1.6\%$	$60.3\% \pm 2.1\%$	$16.0\% \pm 1.9\%$

Semantic labels during cloth manipulation

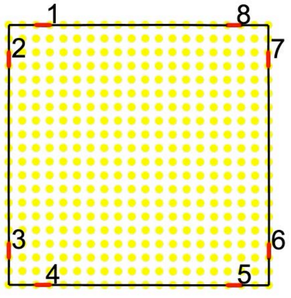
- Fully labeled dataset with more than 200 cloth manipulation sequences.

04_1PC_1PC_07.xml



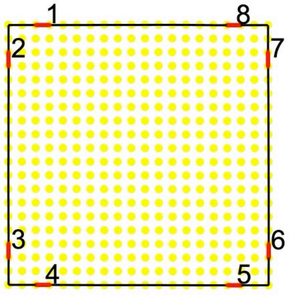
Predicted class: FL
Grasp 1: None,
Grasp 2: None

02_2PC_2PCM_11.xml



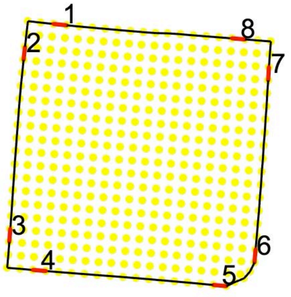
Predicted class: FL
Grasp 1: None,
Grasp 2: None

01_2PM_2PCM_18.xml



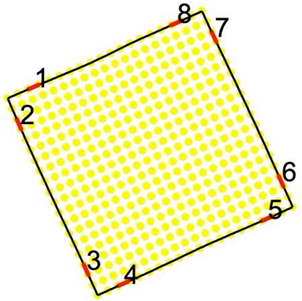
Predicted class: FL
Grasp 1: None,
Grasp 2: None

06_2PC_08.xml



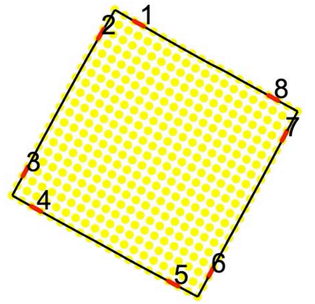
Predicted class: FL
Grasp 1: None,
Grasp 2: None

07_2PC_2PC_02.xml



Predicted class: FL
Grasp 1: None,
Grasp 2: None

04_1PC_1PC_09.xml

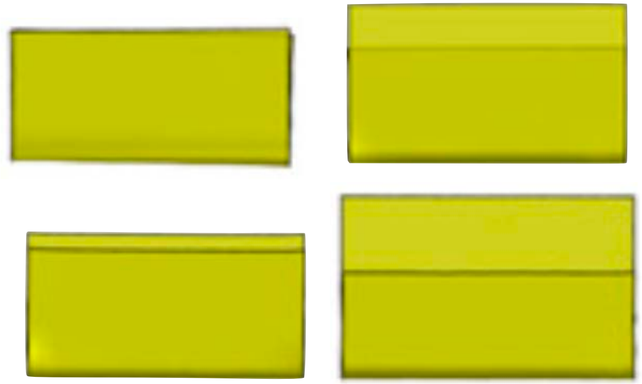


Predicted class: FL
Grasp 1: None,
Grasp 2: None

http://www.iri.upc.edu/groups/perception/#VR_Framework_Dataset

So far...

- dGLI coordinates
  - Low dimensional representation of cloth
  - Give a metric in space -> sense of distance between folding states : Classification
  - Suitable to learn semantic labels (supervised learning)
- BUT
  - Given the dGLI coordinates, we CAN'T compute what is the cloth state
  - We need to choose the edges to compute the dGLI coordinates
    - If there is noise on this particular edges its a problem
    - It doesn't capture the rest of the border
  - Configs close to the border of classes are very "far"

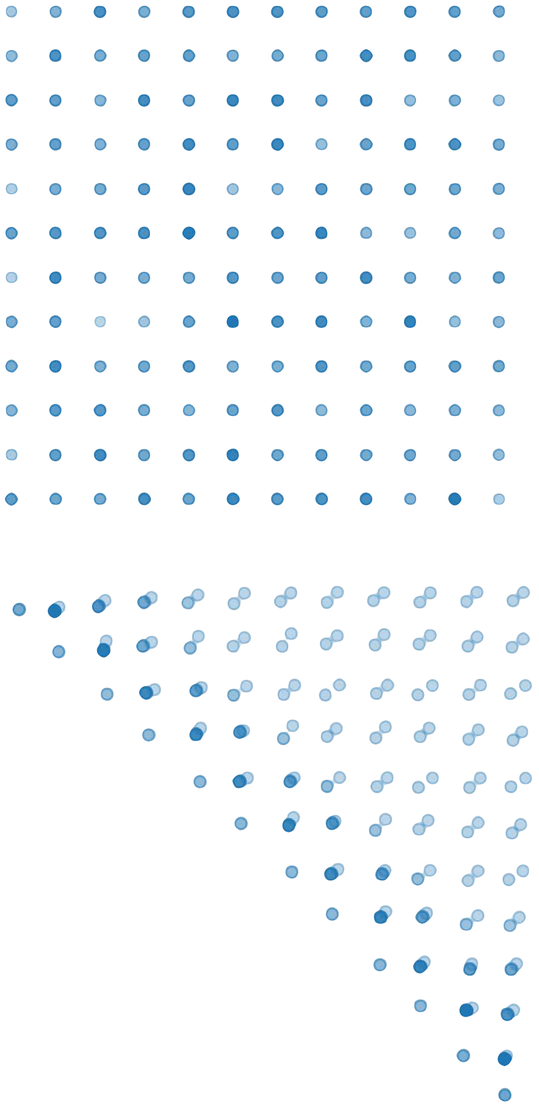


Class 11

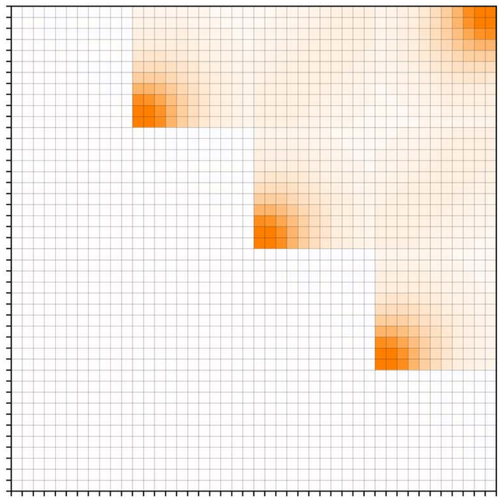
Class 3

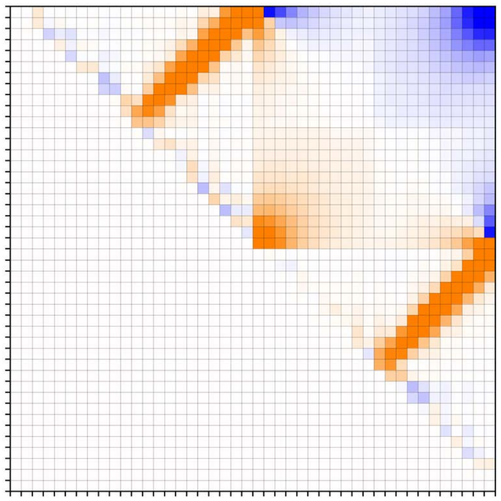
From the dGLI coordinates to the dGLI disk

Mesh



dGLI Matrix

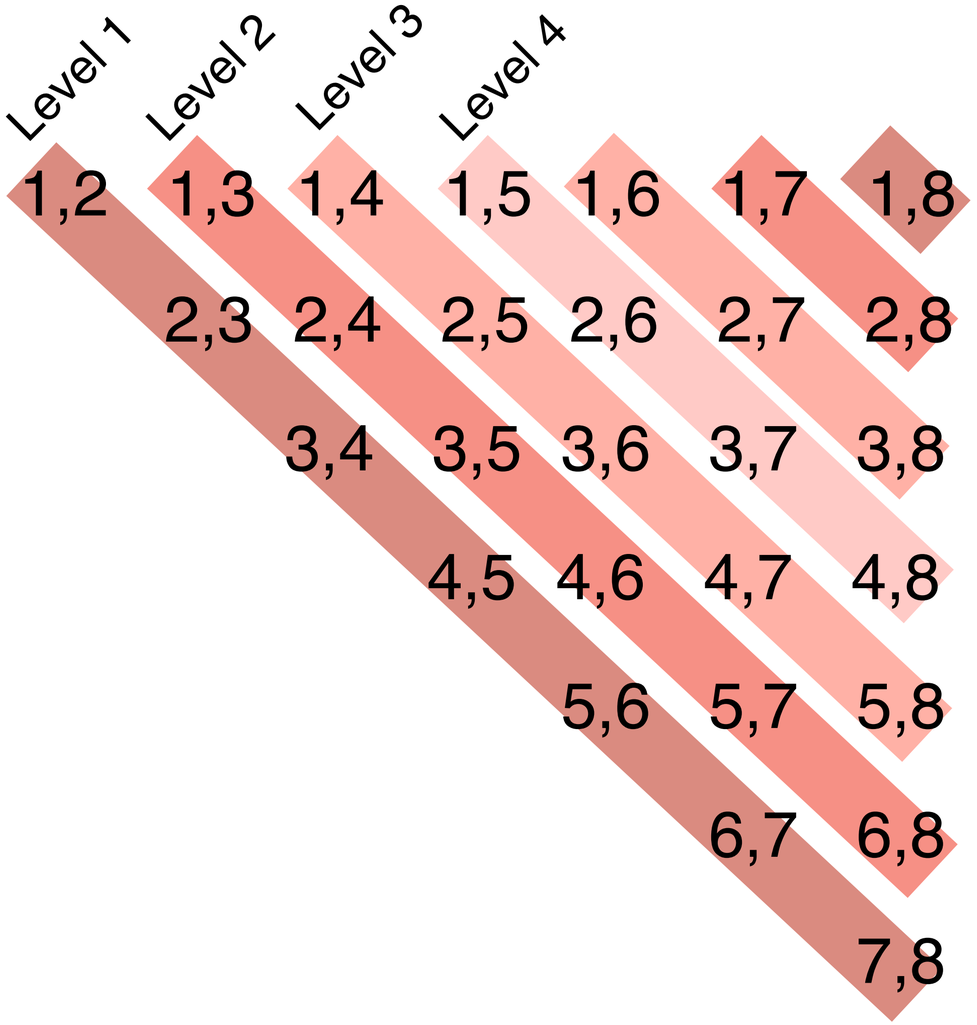




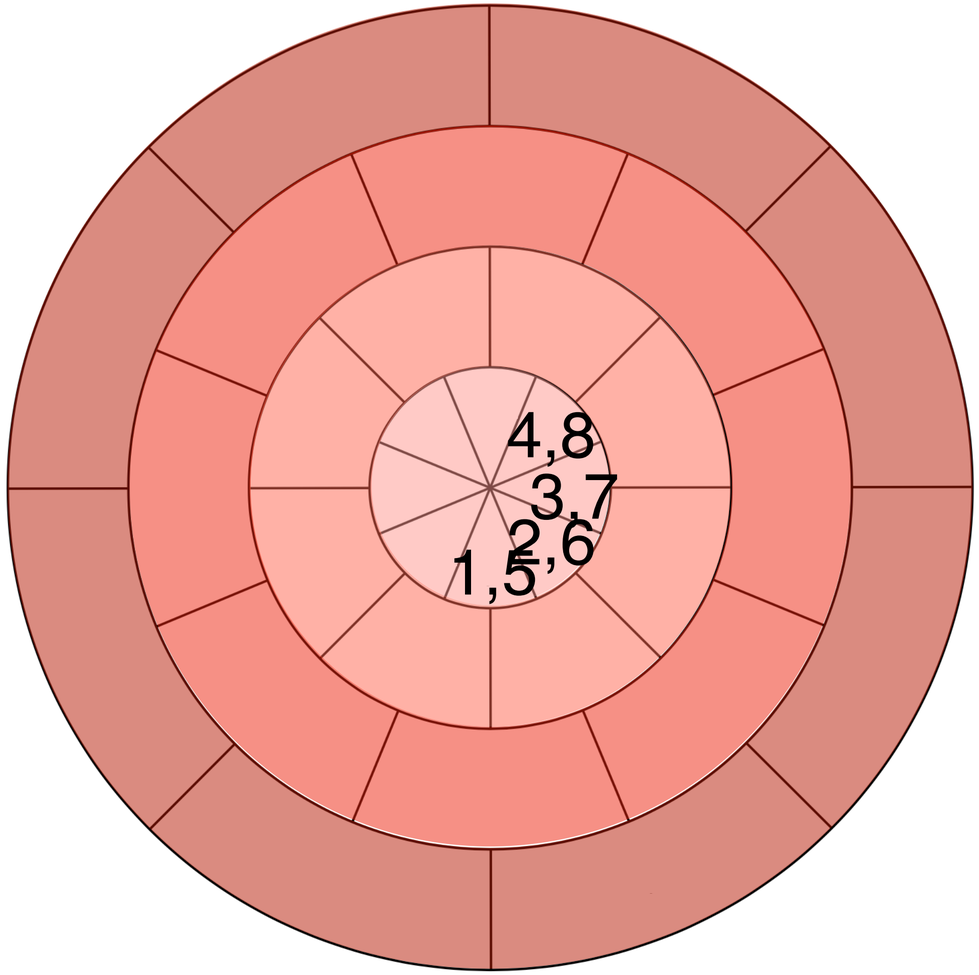
- New idea
  - Use all edges of the border
  - Work with the patterns on the dGLI matrix
  - This patterns seem to have a circular symmetry

J. Kamat, J. Borràs, C .Torras, CloSE: A Geometric Shape-Agnostic Cloth State Representation, ICRA 2026

Mapping of the half matrix to the circle



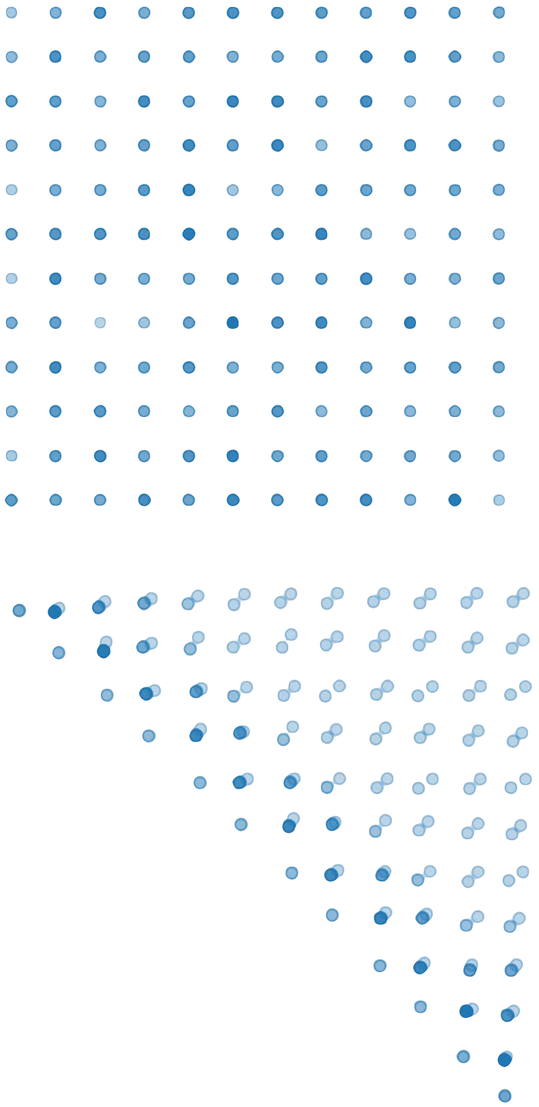
Usual matrix mapping



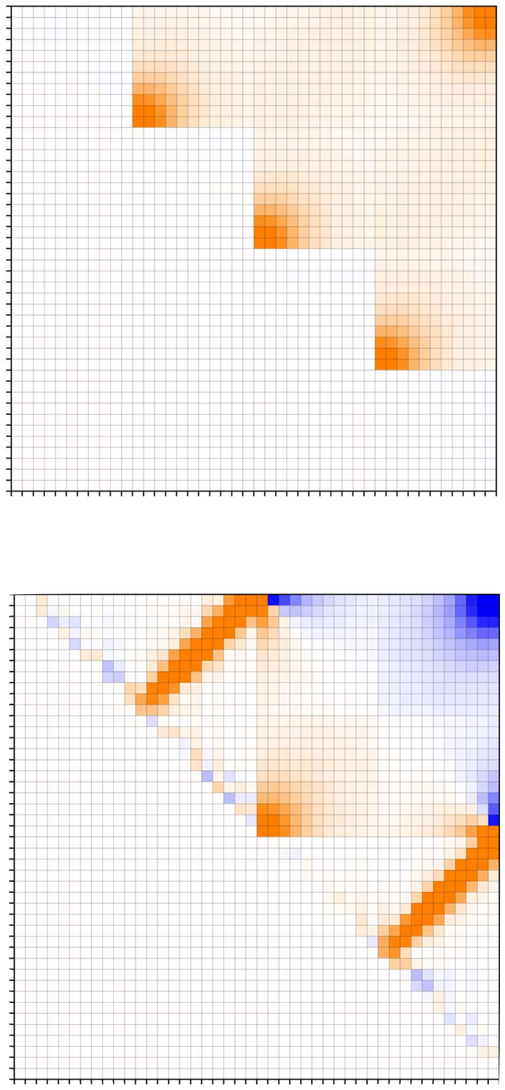
Circular mapping

From the dGLI coordinates to the dGLI disk

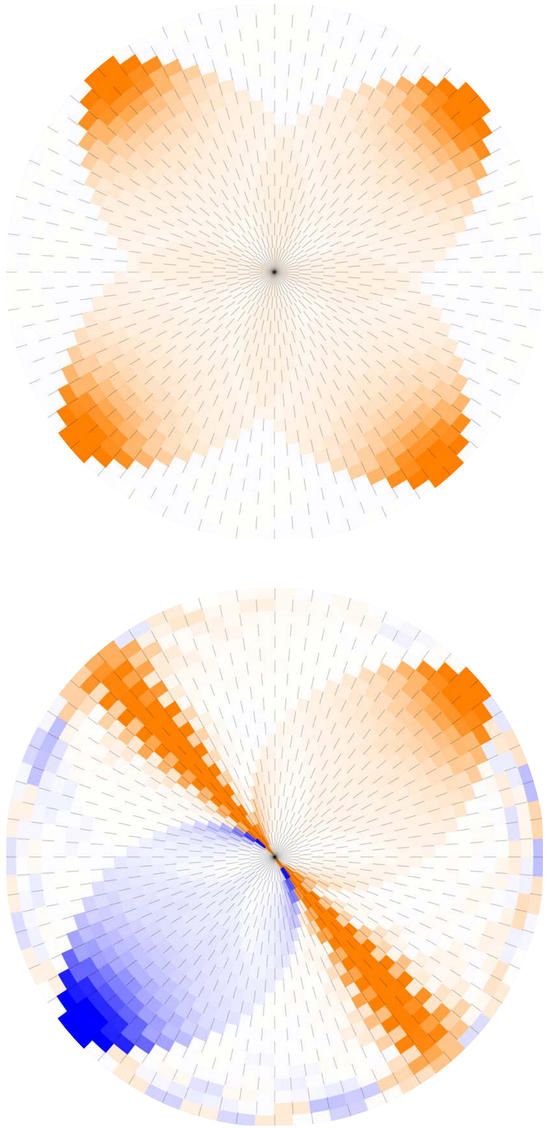
Mesh



dGLI Matrix



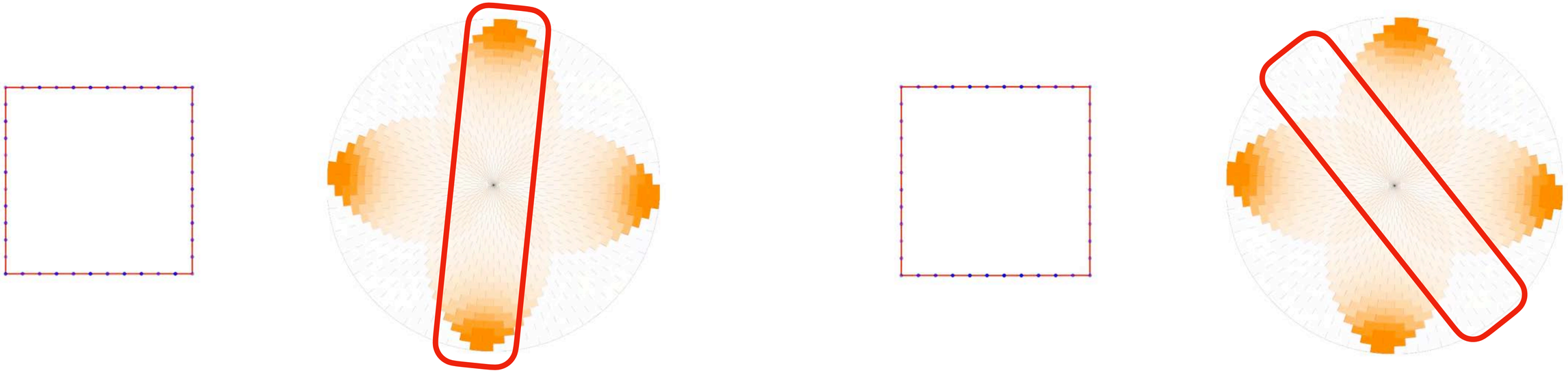
dGLI Disk



Uncovers easy to identify geometries!

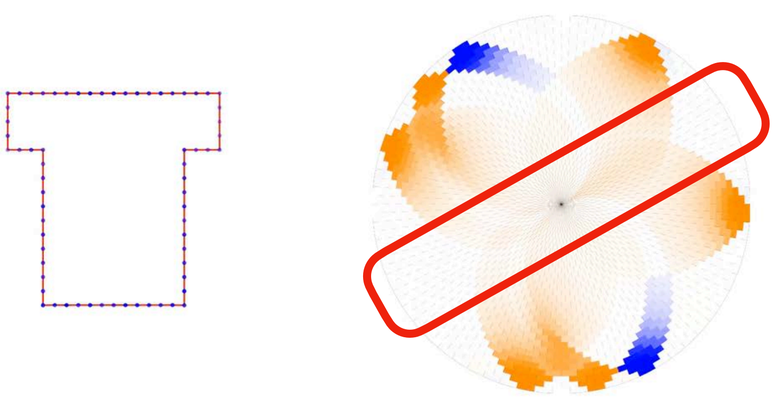
Half folds patterns on the dGLI disk

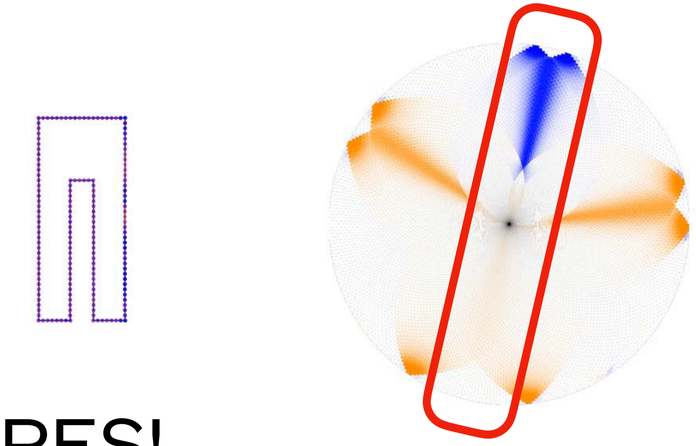
Initial frames: a petal for each corner → End frames: a line appears



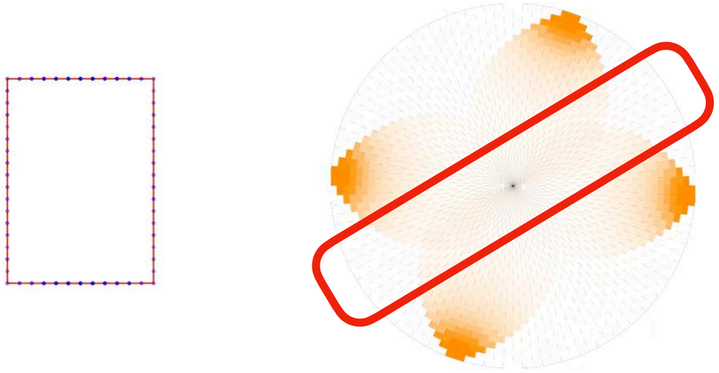
Half folds patterns on the dGLI disk

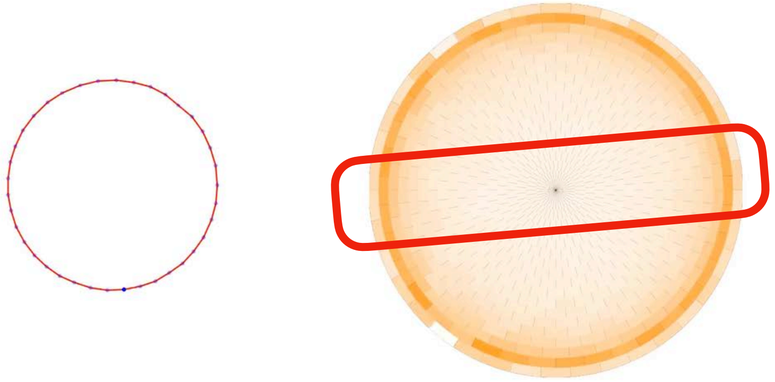
Initial frames: a petal for each corner → End frames: a line appears



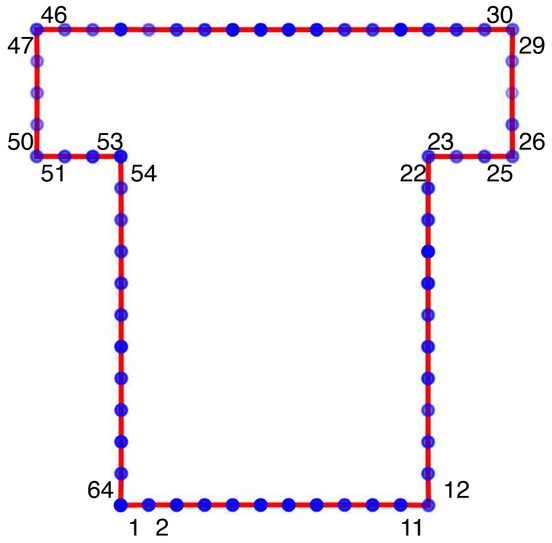


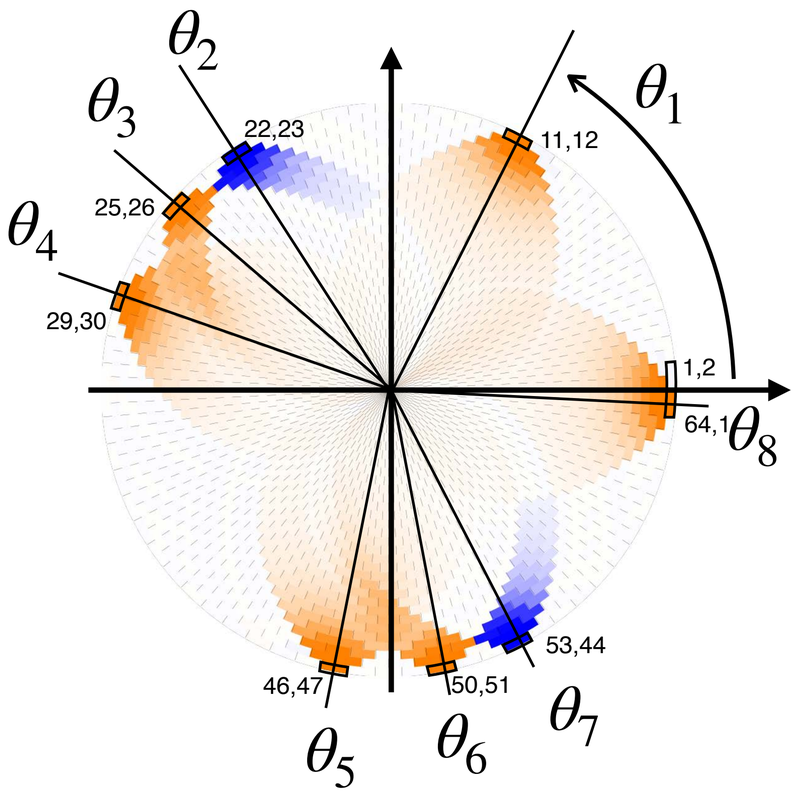
FOR ALL SHAPES!

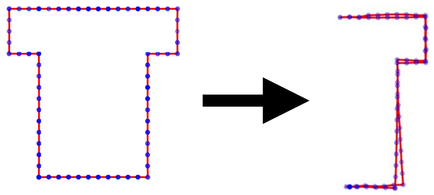




CloSE: abstraction captured from the dGLI disk

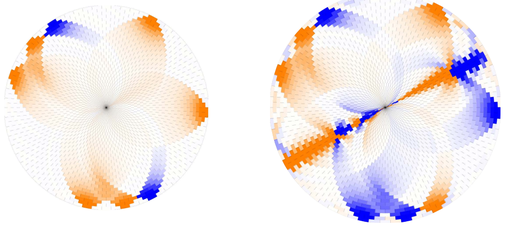


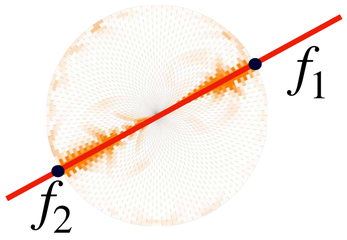




D_0 dGLI disk$_0$ D_1 dGLI disk$_1$

$|D_1| - |D_0| =$ dGLI disk diff





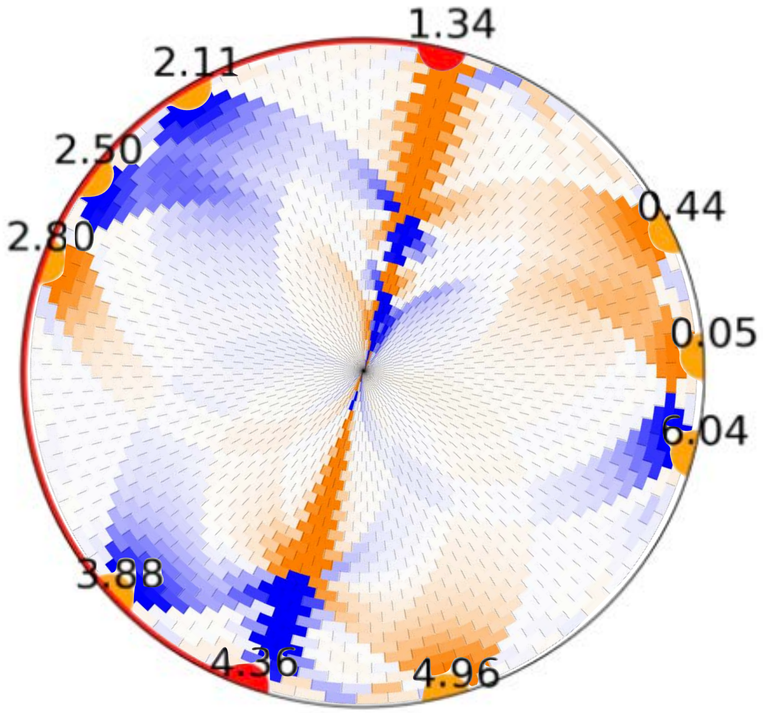
Corners represented by $(\theta_1, \ldots, \theta_n)$

Folds represented by (f_1, f_2)

Folded corners included $f_1 \longrightarrow f_2$

The CloSE representation

CloSE: Cloth StatE representation



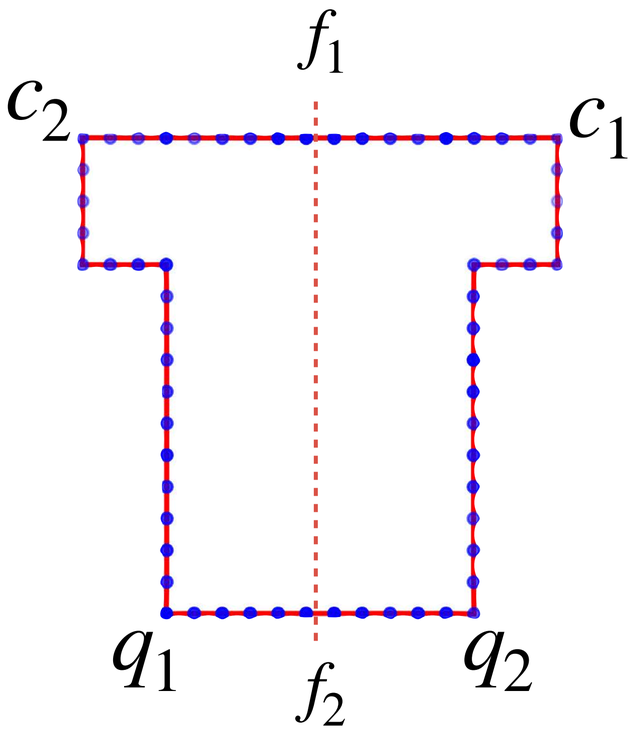
Corners represented by $(\theta_1, \ldots, \theta_n)$

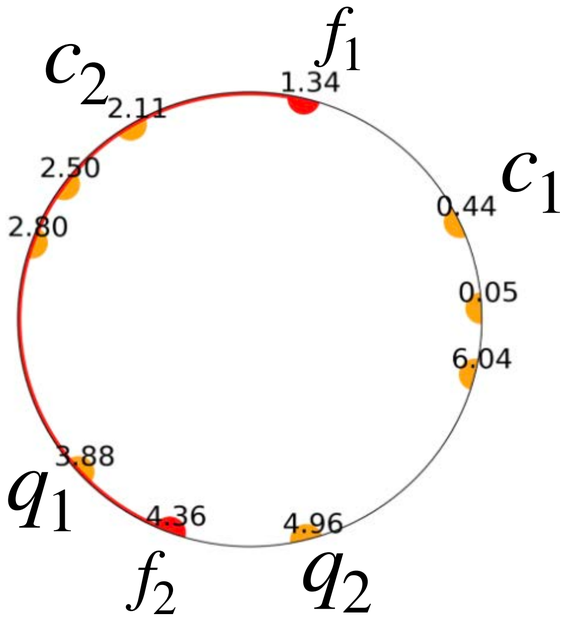
Folds represented by (f_1, f_2)

Folded corners included $f_1 \longrightarrow f_2$

The CloSE representation

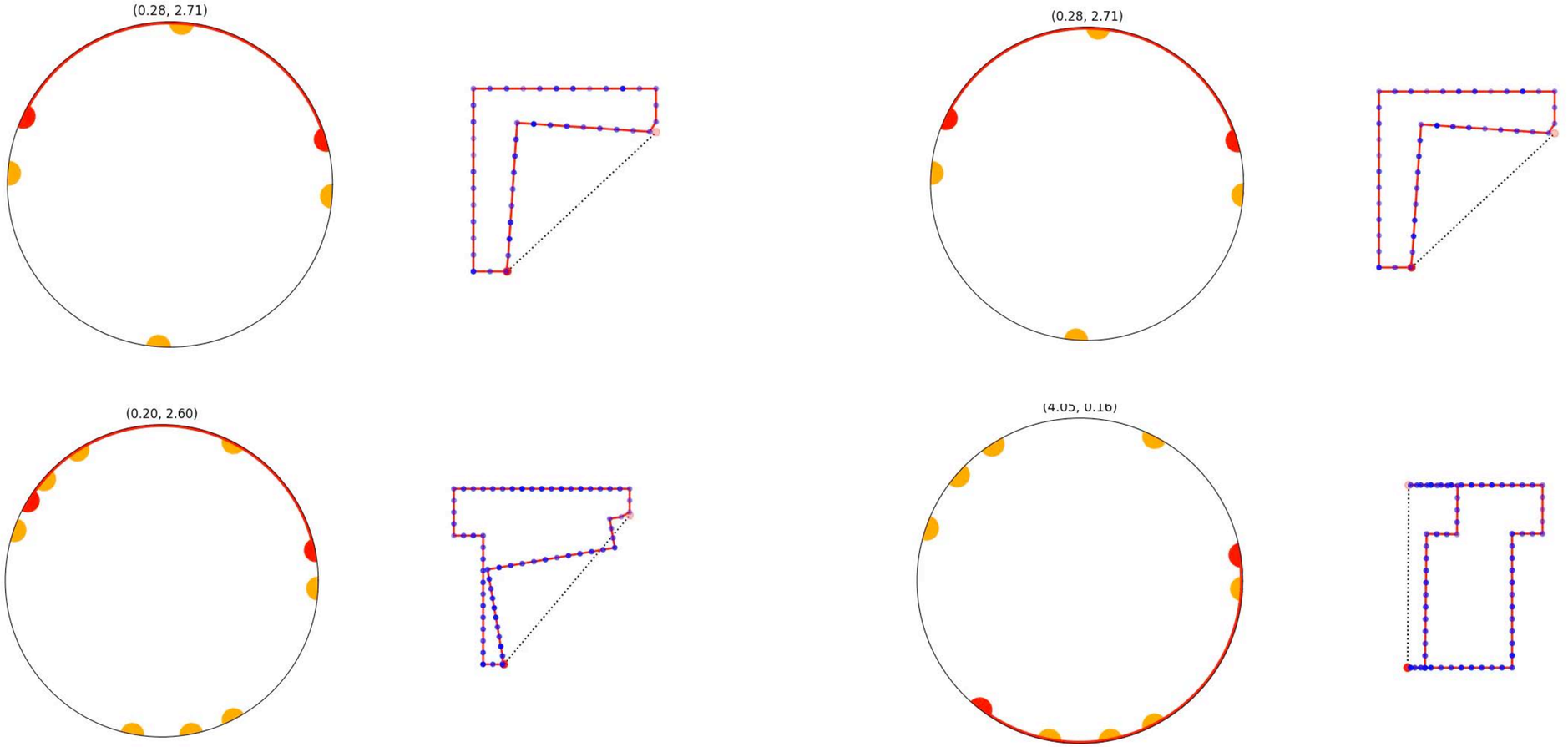
CloSE: Cloth StatE representation





We can recover the border mesh from the CloSE

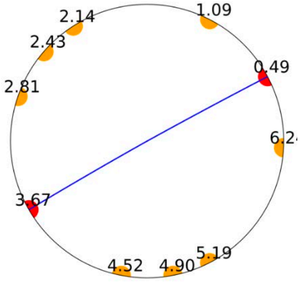
The CloSE representation is continous



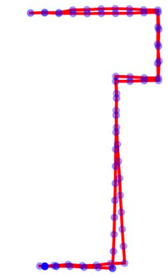
Animations are reconstructed borders from the CloSE representation

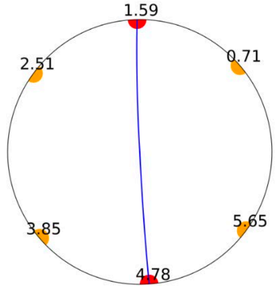
Automatic semantic labeling

CloSE rep. → Generated label — GT border

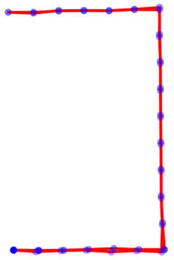


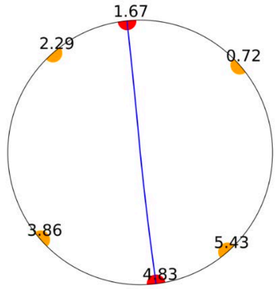

```
Cloth has 8 corners.
Corners {5, 6, 7, 8} are folded.
Cloth is folded in half
Side 45 is 49.9% folded
Side 81 is 47.2% folded
```



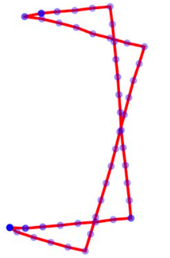


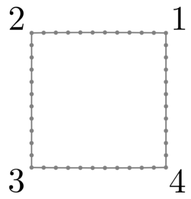

```
Cloth has 4 corners.
Corners {2, 3} are folded.
Cloth is folded in half
Side 12 is 50.9% folded
Side 34 is 51.9% folded
```

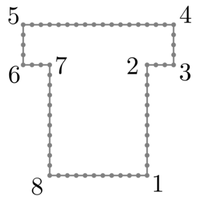




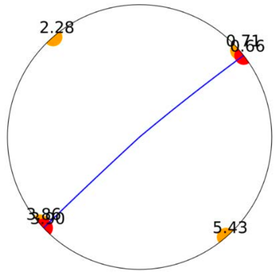

```
Cloth has 4 corners.
Corners {2, 3} are folded.
Folded in half-askew.
Side 12 is 39.4% folded
Side 34 is 61.8% folded
```



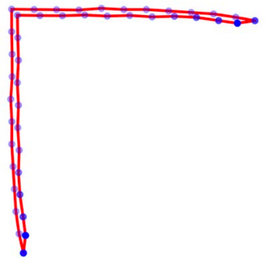


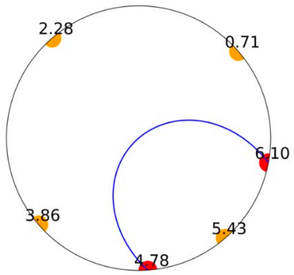


CloSE rep. → Generated label — GT border

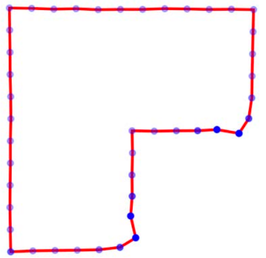


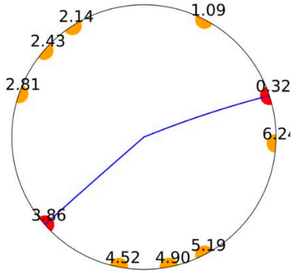

```
Cloth has 4 corners.
Corner 4 is folded.
Diagonally folded in half
Corner is 97.% folded.
```



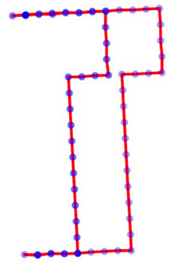



```
Cloth has 4 corners.
Corner 4 is folded.
Corner is 41.9% folded.
```





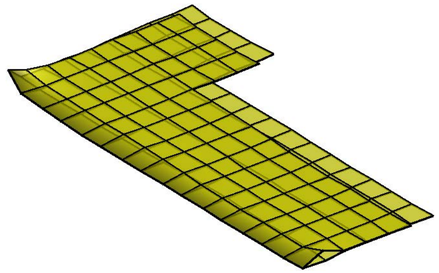

```
Cloth has 8 corners.
Corners {5, 6, 7, 8} are folded.
One side folded
Side 45 is 38.4% folded
Side 81 is 32.1% folded
```



Planning with the CloSE representation II

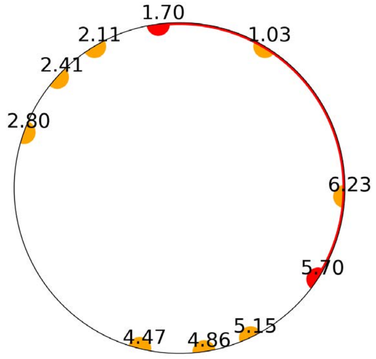
Inputs:

Initial mesh



+

CloSE goal

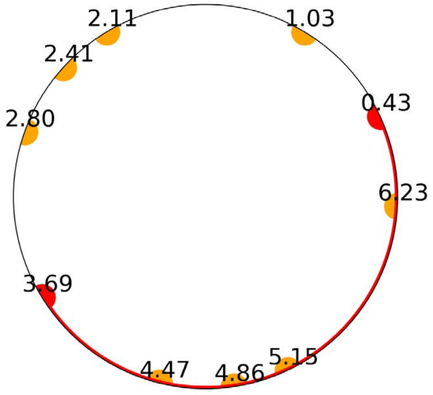


Planner

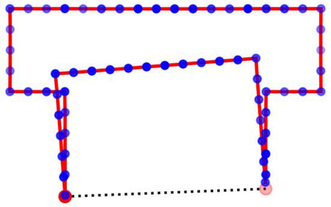
```
Step 1: Unfold corner(s): [5, 6, 7, 8]
across line: (3.69, 0.43)

Step 2: Fold corner(s): [1, 8]
across line: (5.70, 1.70)
```

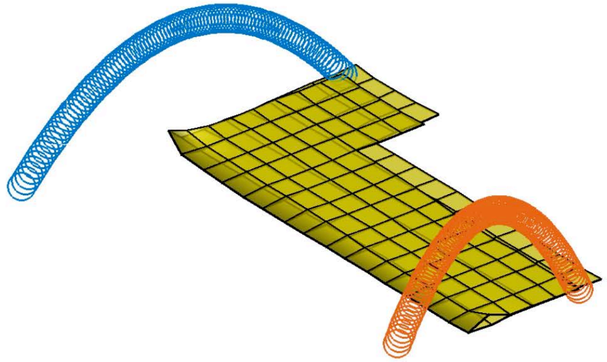
CloSE init



Predicted goal border

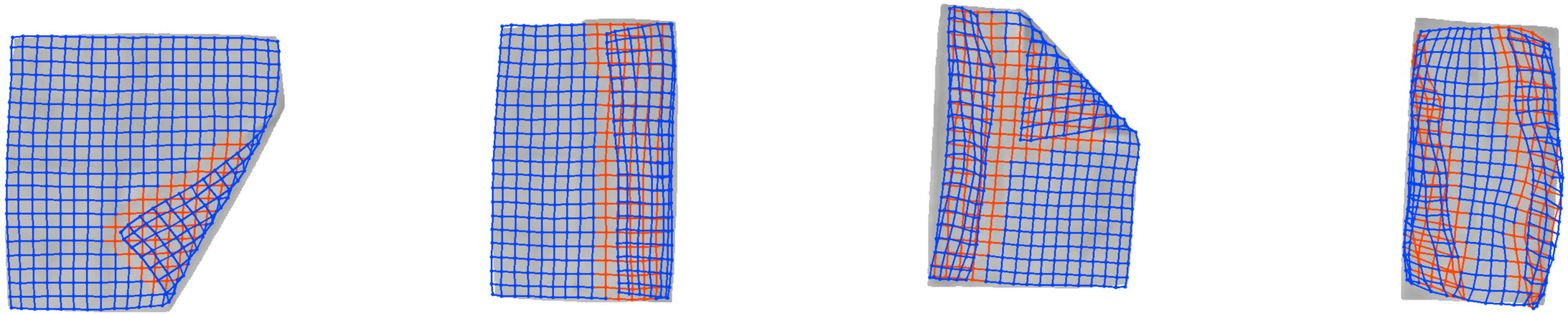


Execution of the plan in simulation:



Tracking the border of clothes

- CloSE representation is useful in simulation to
  - Pre-train models
  - To automatically label datasets
- To work with real robots, we need to track/estimate the border of clothes
  - W. Wang, G. Li, M. Zamora, & S. Coros; TRTM: Template-based reconstruction and target-oriented manipulation of crumpled cloths. ICRA 2024



Conclusions
The C-space of cloth

- Simple and structured representation
- For single folds—> We are extending it to more configurations.
- The representation itself gives generalization across different shapes, pose and orientation.
- By construction we can plan and identify states (semantic labels and classification)
- We are working on integrating the dGLI disk and the CloSE into learning methods to evaluate advantages.