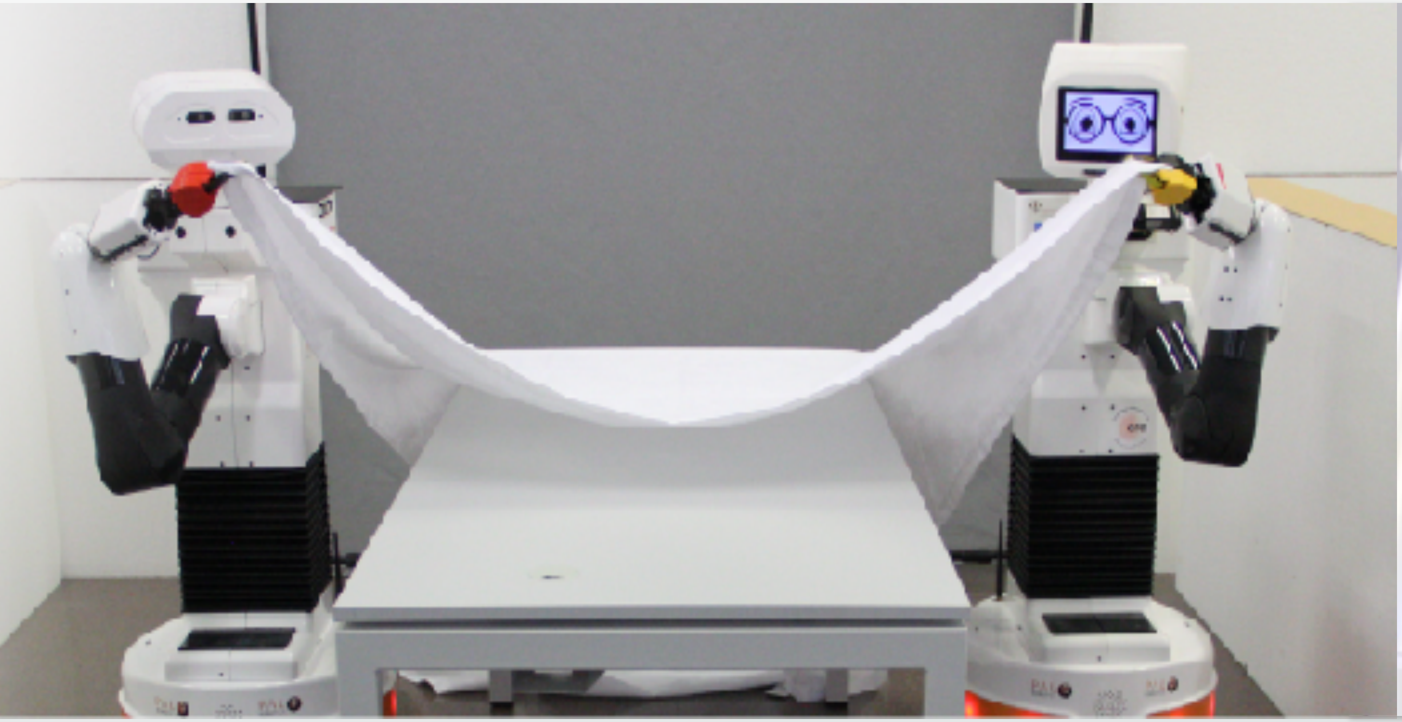
The puzzle of endowing robots with cloth manipulation skills



Institut de Robòtica i Informàtica Industrial

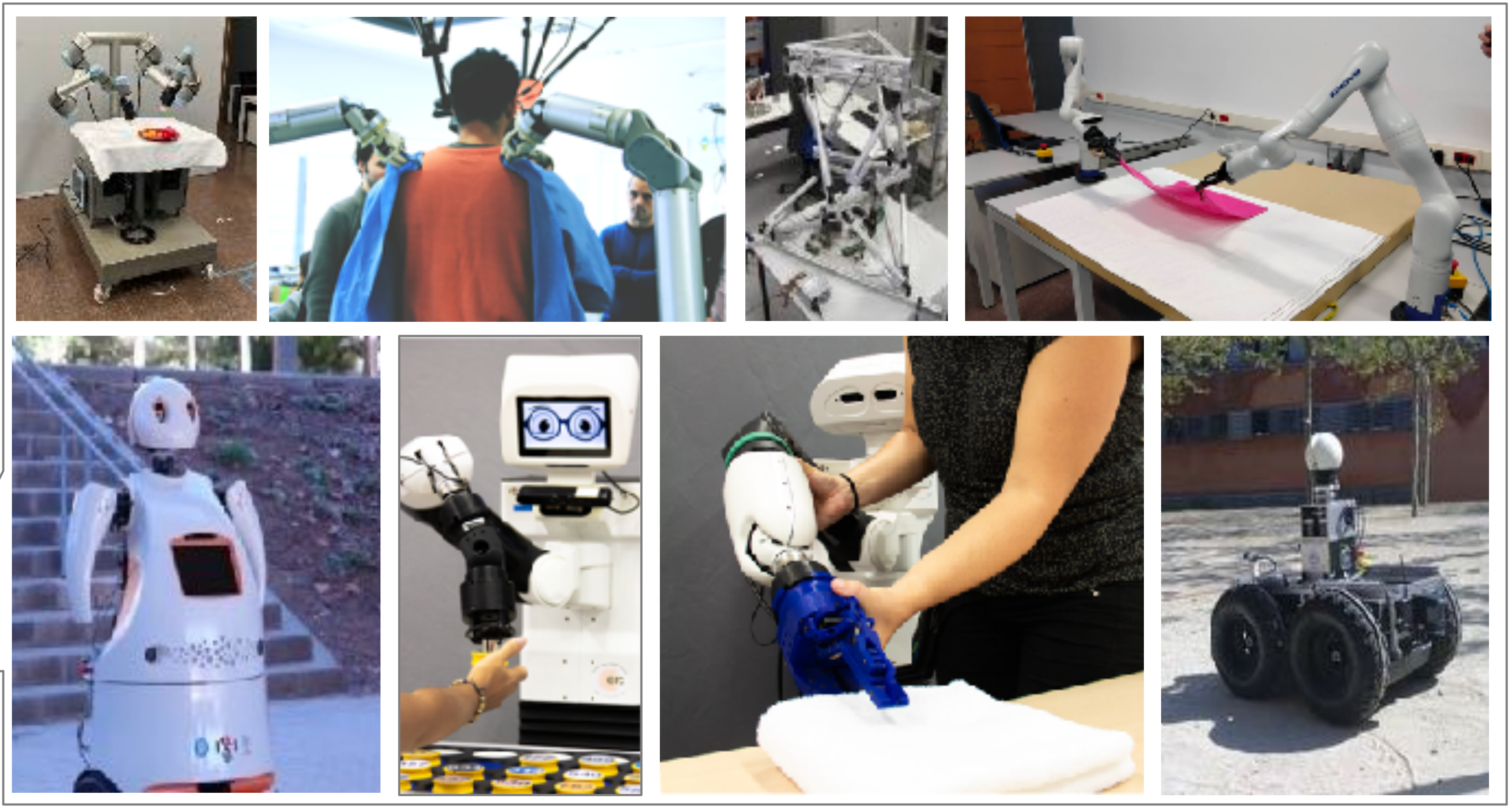
Carme Torras @ ELLIIT

CSIC UPC

Institut de Robòtica i Informàtica Industrial

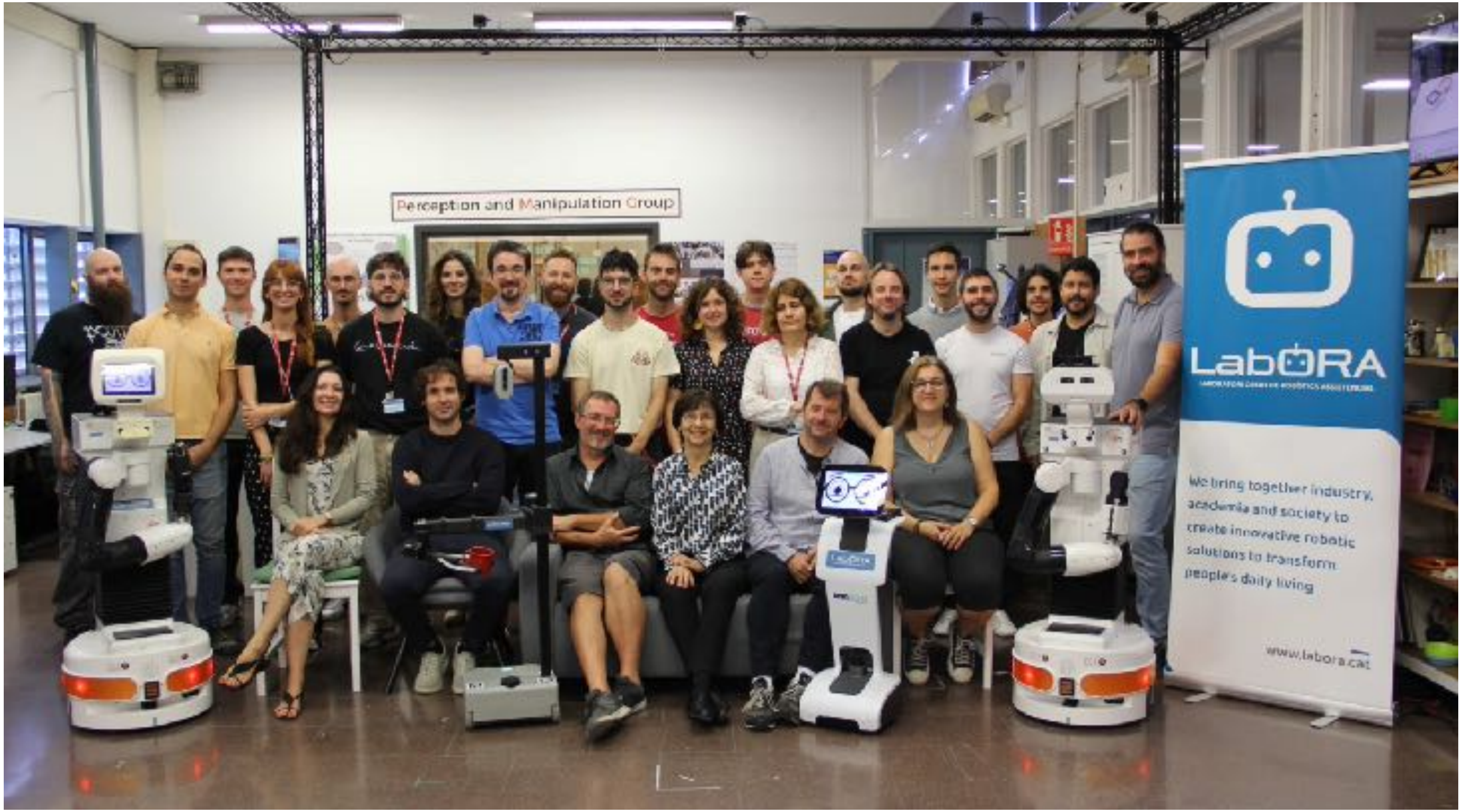
CSIC UPC

- 43 Doctors
- 46 PhD students
- 10 MSc students
- 12 Technicians
- 18 Support
- > 25 Robots



Research Group RobIRI: Robot Perception and Manipulation at IRI

Permanents	11 (4)
Postdocs	9 (3)
Predocs	23 (3)
Tècnics	8 (0)
Màster	8 (2)
TOTAL…	59 (12)



Research Group RobIRI: Robot Perception and Manipulation at IRI

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CLOTH manIpulation Learning from DEmonstrations

SOCRATES
Social Cognitive Robotics in The European Society

I-DRESS
Assistive interactive robotic system for support in dressing

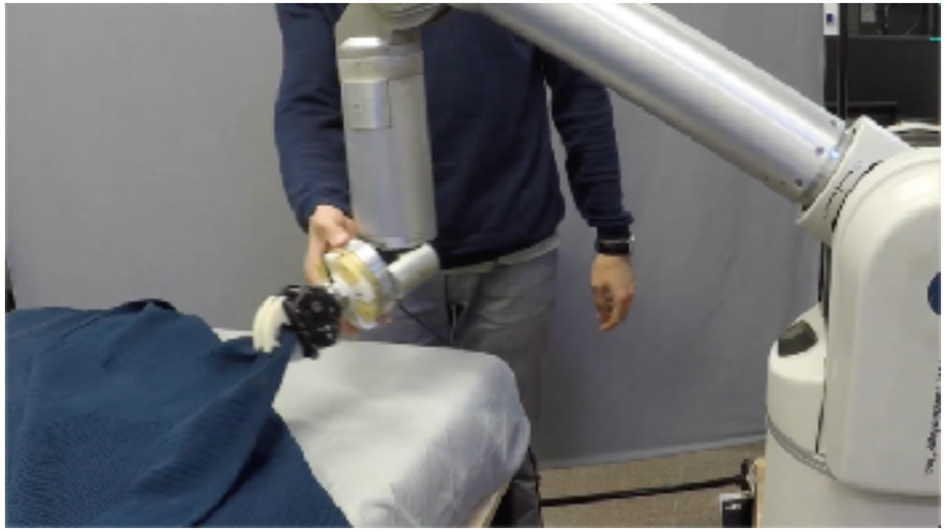
SoftEnable

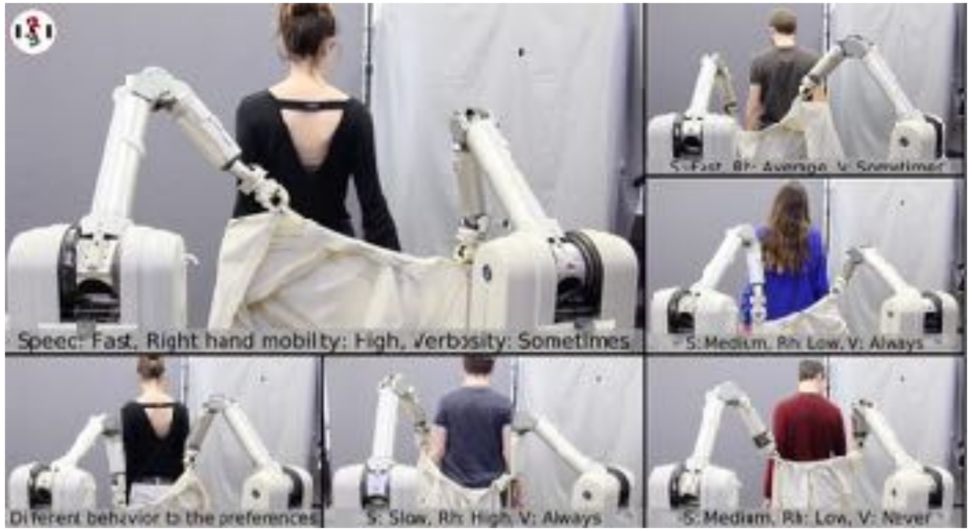
Research challenges of assistive robotics

User modelling

Adaptation and safety

Easy teaching





Human-robot collaboration

Versatile cloth manipulation requires:

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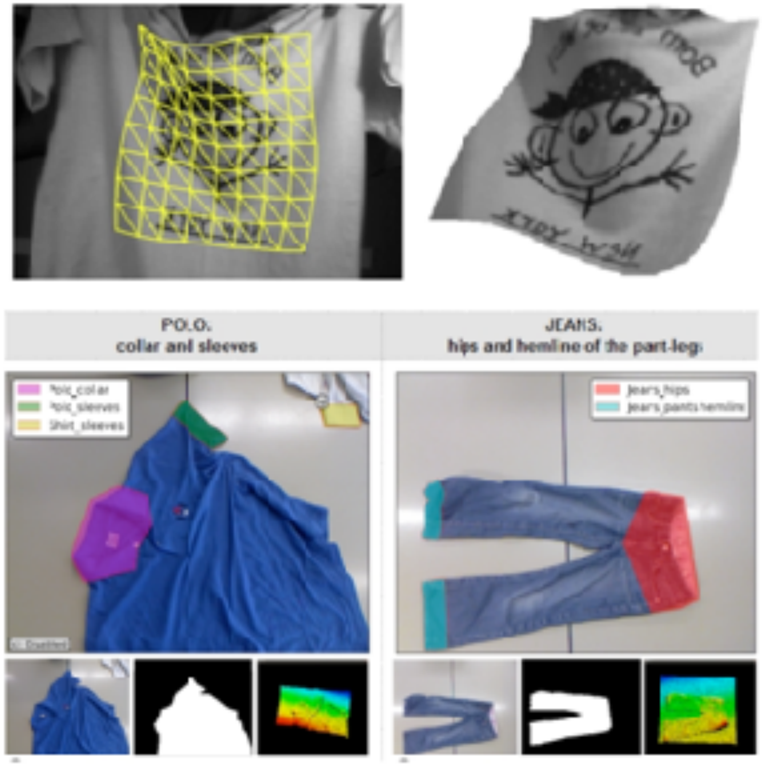
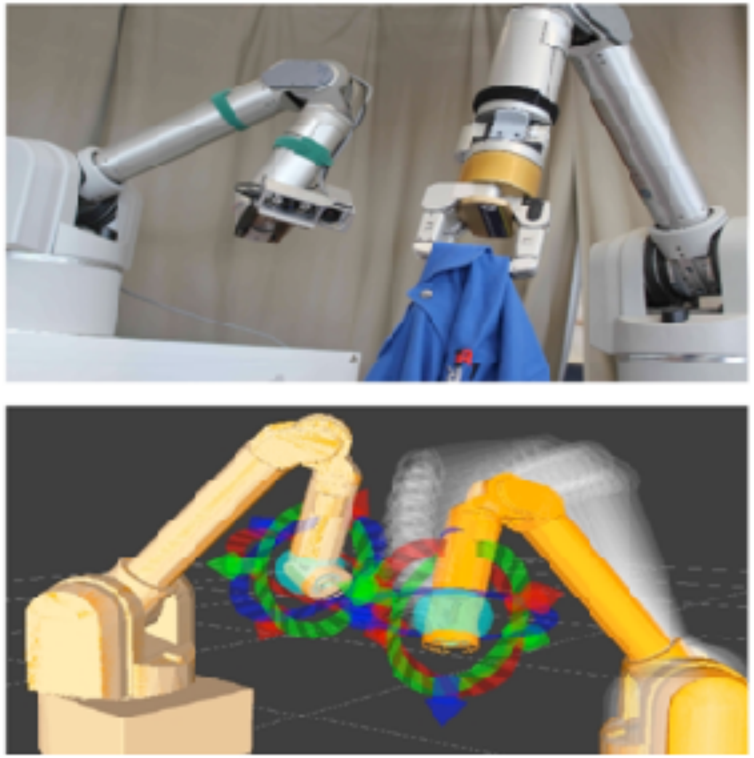
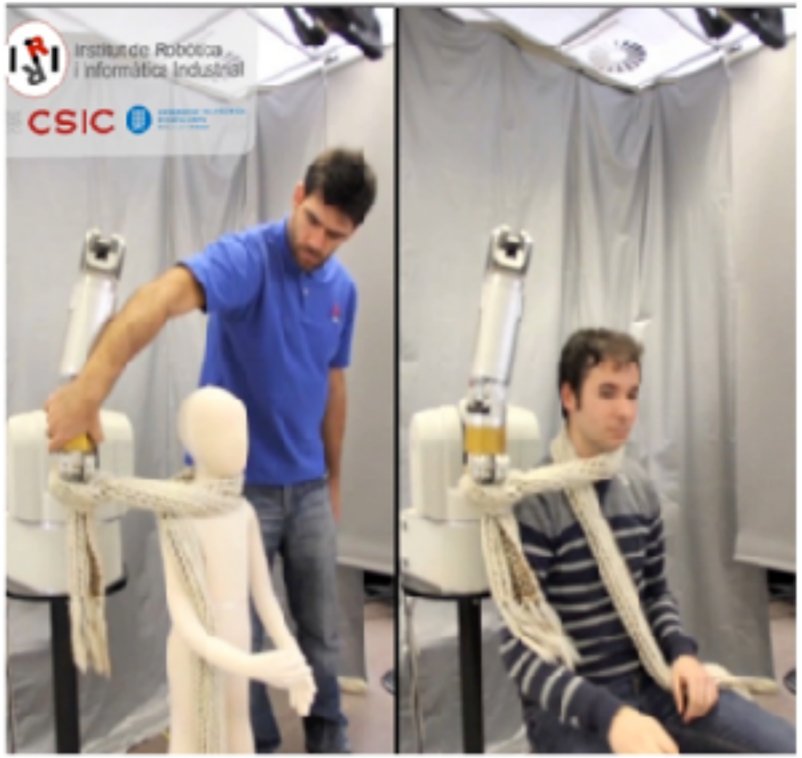
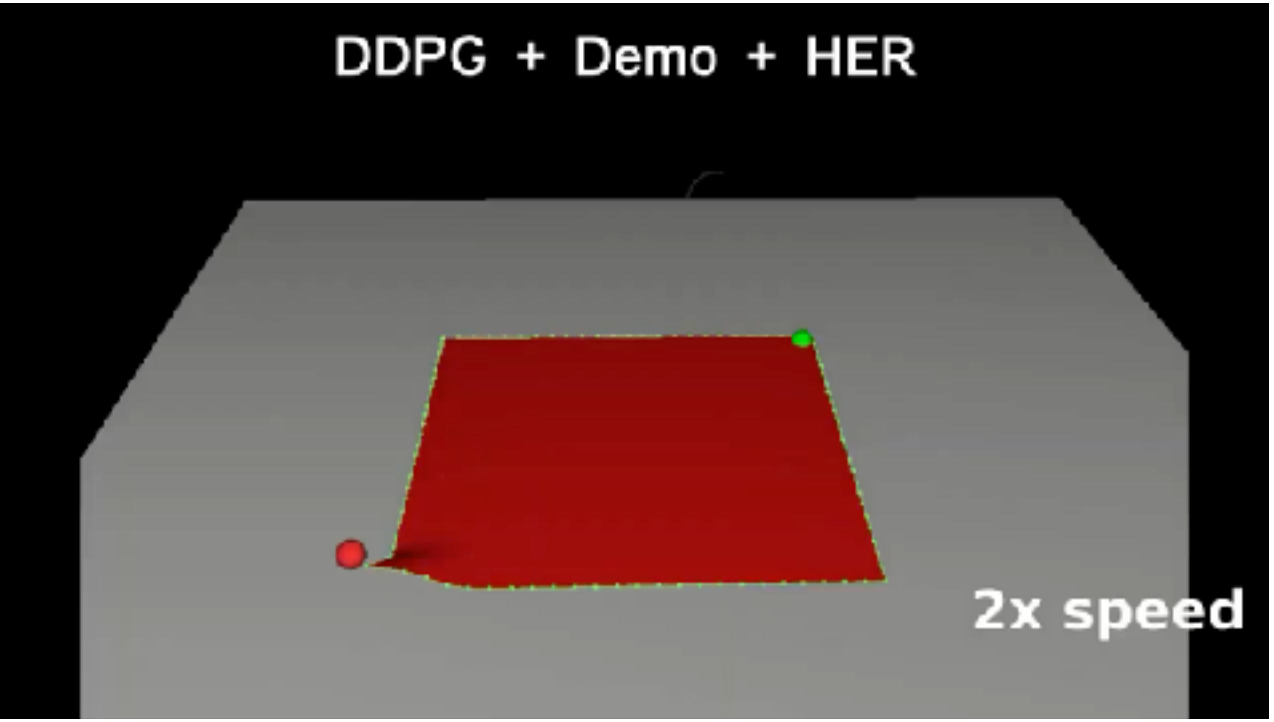
Cloth/Motion **Representation** | **Manipulation,** Plan & Control | **Learning** from Demos & RL

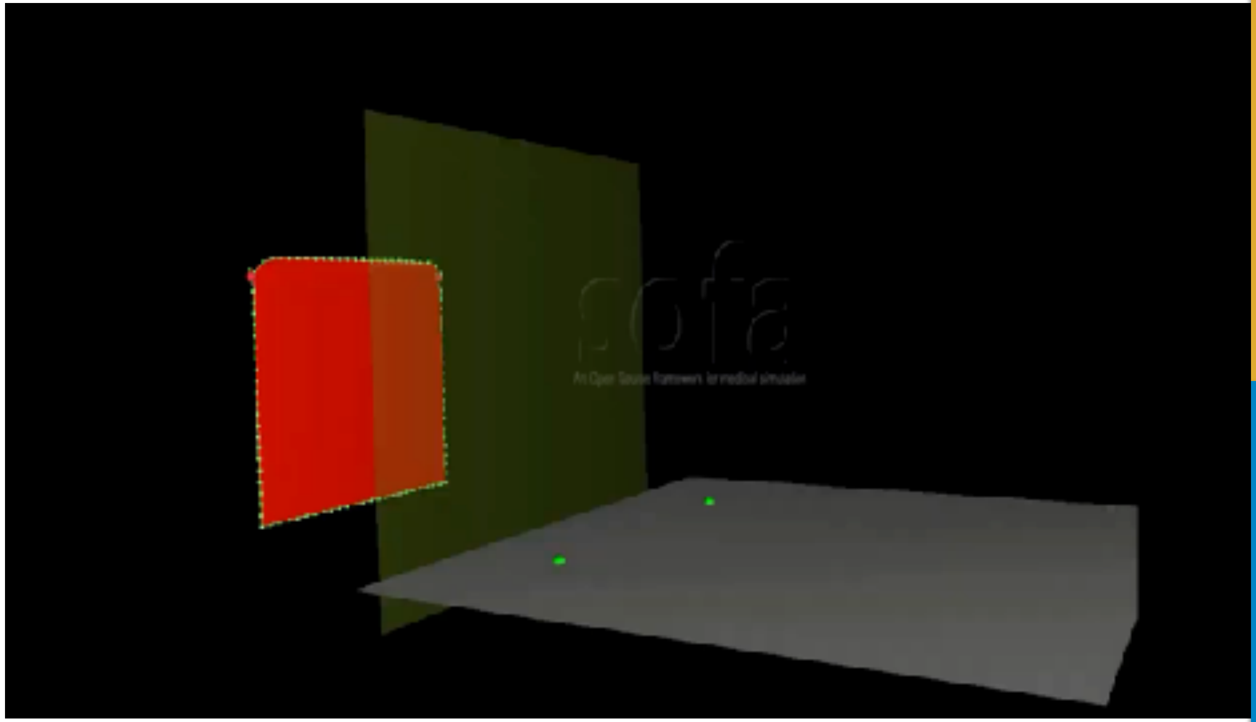






Quasi-static vs. **dynamic** cloth manipulation





R. Jangir, G. Alenyà and C. Torras. Dynamic cloth manipulation with deep reinforcement learning. *IEEE International Conference on Robotics and Automation (ICRA)*, Paris, pp. 4630-4636, 2020.

Our research on cloth manipulation

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	Quasi-static manipulation	**Dynamic manipulation**
Cloth/Motion **Representation**	- Cloth macro-states (C-space, dGLI) - Capturing cloth states (Color/depth vision, Optitrack…) - Capturing motion (VR…)	
Manipulation, planning and control	- Grippers - Grasping/Manipulation primitives - Planning state transitions	
Learning (perception, motion)	- Cloth state estimation (from template, border…) - Learning transitions from VR	

Topology + Machine Learning for versatile cloth manipulation

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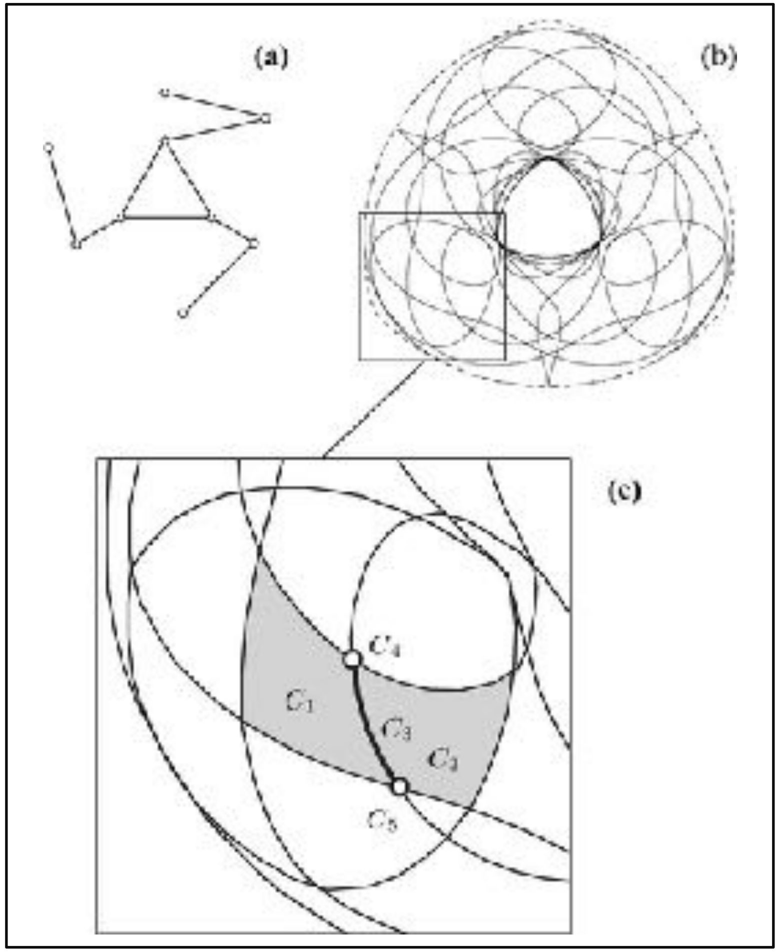
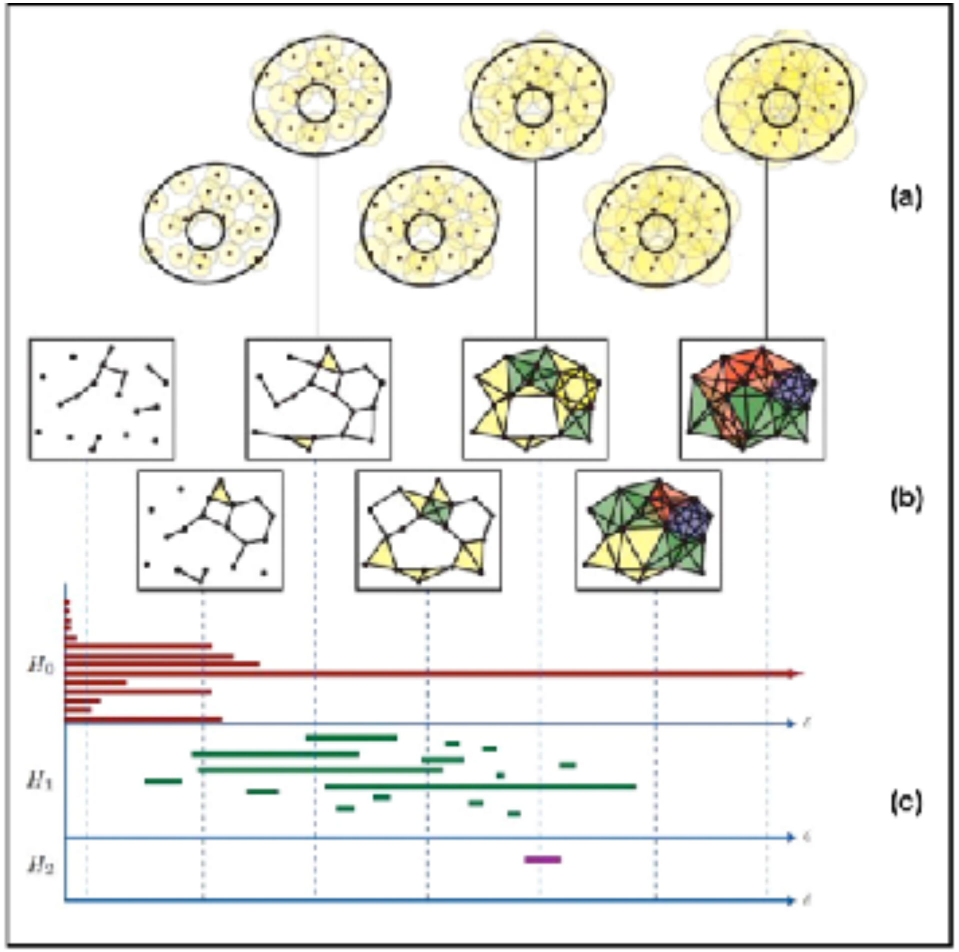
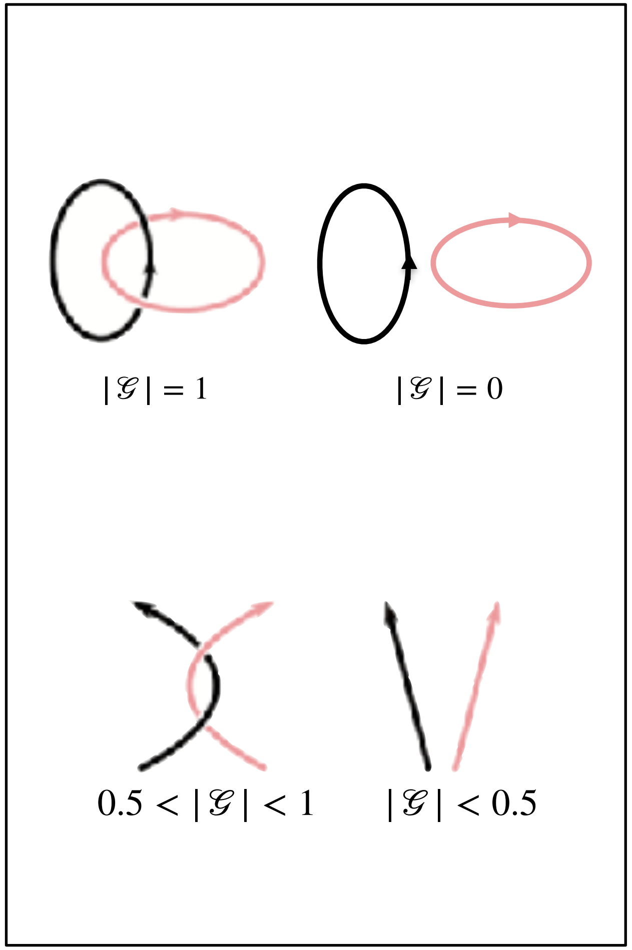
Cell complexes



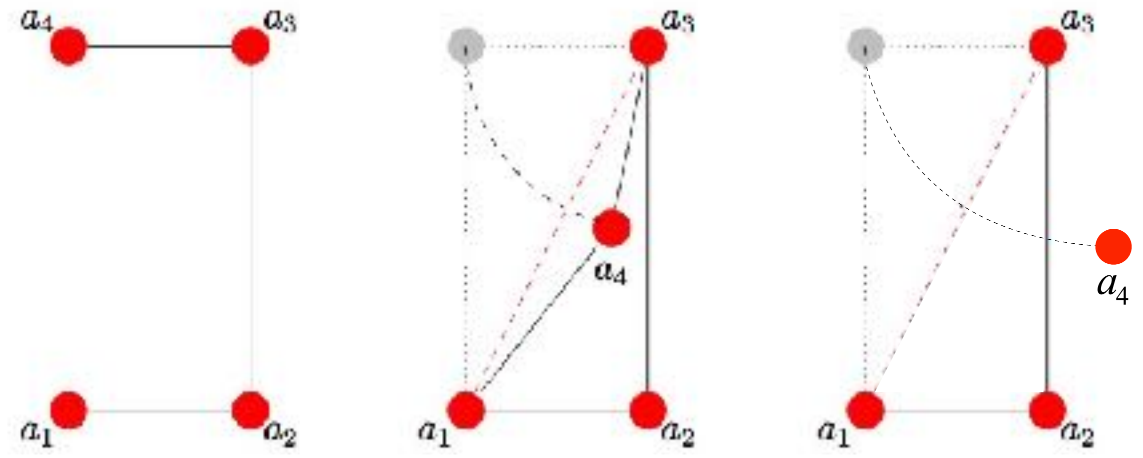
Persistent homology



Gauss Linking Integral



Topology of cloth configuration space - **Cell complexes**



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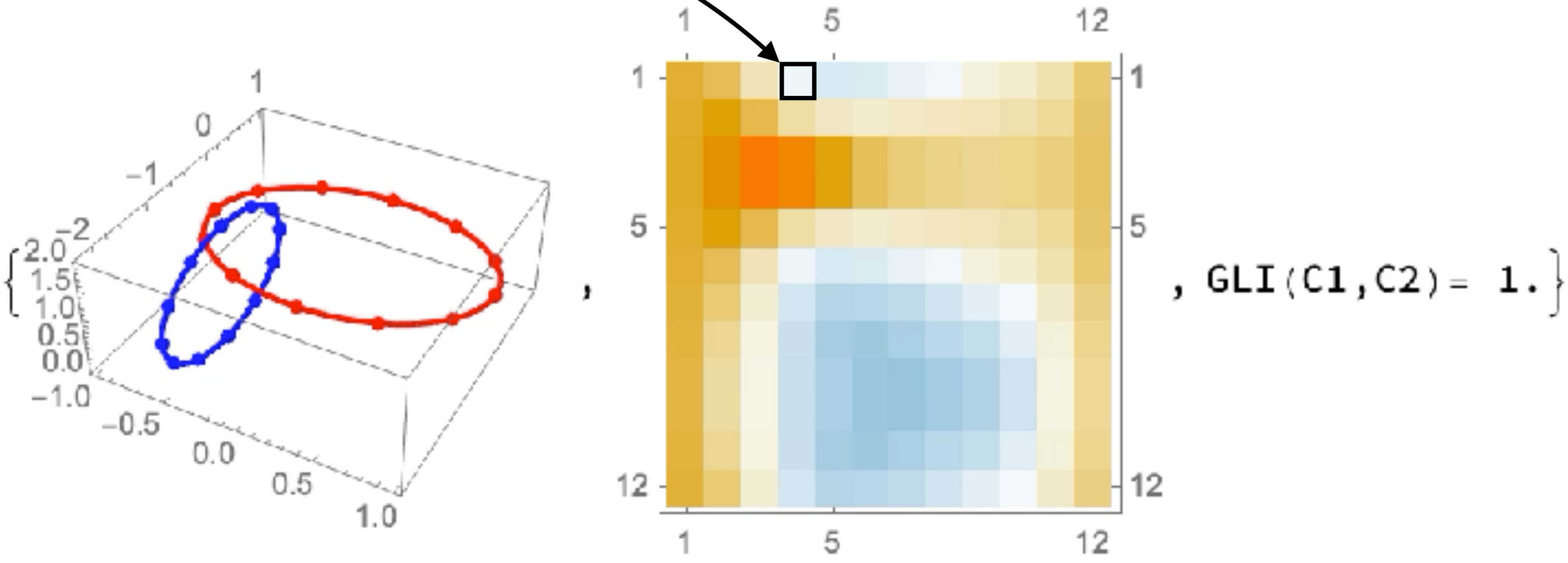
F. Strazzeri and C. Torras. Topological representation of cloth state for robot manipulation. ***Autonomous Robots***, 45: 737–754, 2021.

Topology of cloth deformation - Gauss Linking Integral

$$\mathcal{G}(C_1, C_2) = \sum_{s_i \in C_1} \sum_{r_i \in C_2} \boxed{GLI(s_i, r_i)}$$



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*** 457: 128165, 2023.

Topology of cloth deformation - Gauss Linking Integral

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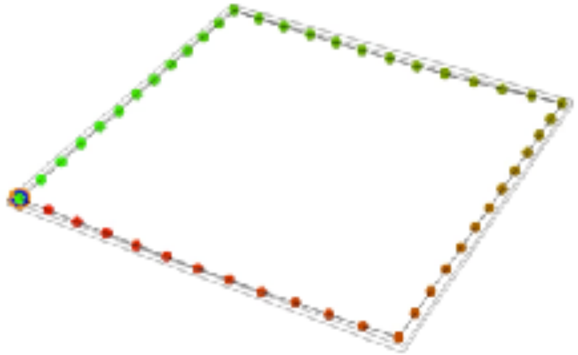
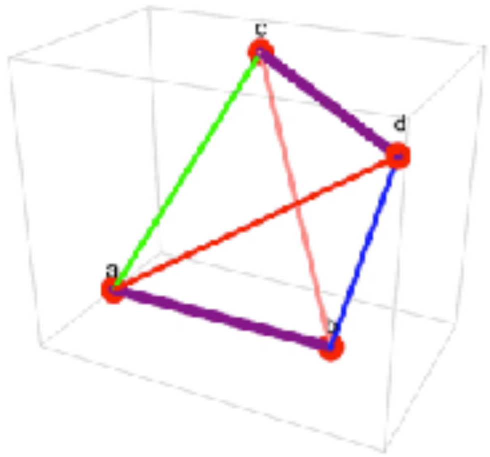
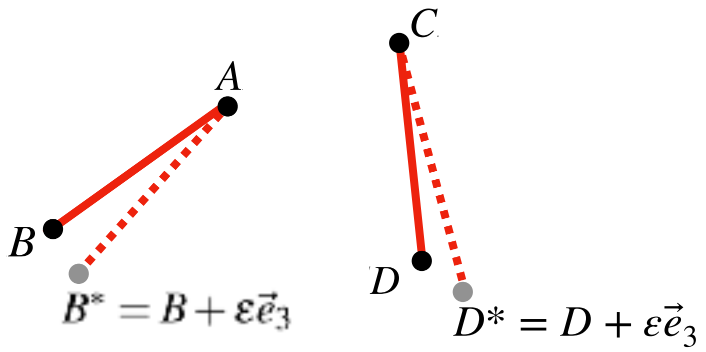




$$GLI(\vec{AB}, \vec{CD}) = \det(\vec{AB}, \vec{AC}, \vec{AD}) \frac{1}{4\pi} \int \int \frac{1}{\|\gamma_{CD} - \gamma_{AB}\|^3}$$

$$\boxed{dGLI(\gamma_{AB}, \gamma_{CD})} := \lim_{\varepsilon \to 0} \frac{GLI(\gamma_{AB^*}, \gamma_{CD^*}) - GLI(\gamma_{AB}, \gamma_{CD})}{\varepsilon}$$



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*** 457: 128165, 2023.

Topology of cloth deformation - **Gauss Linking Integral**

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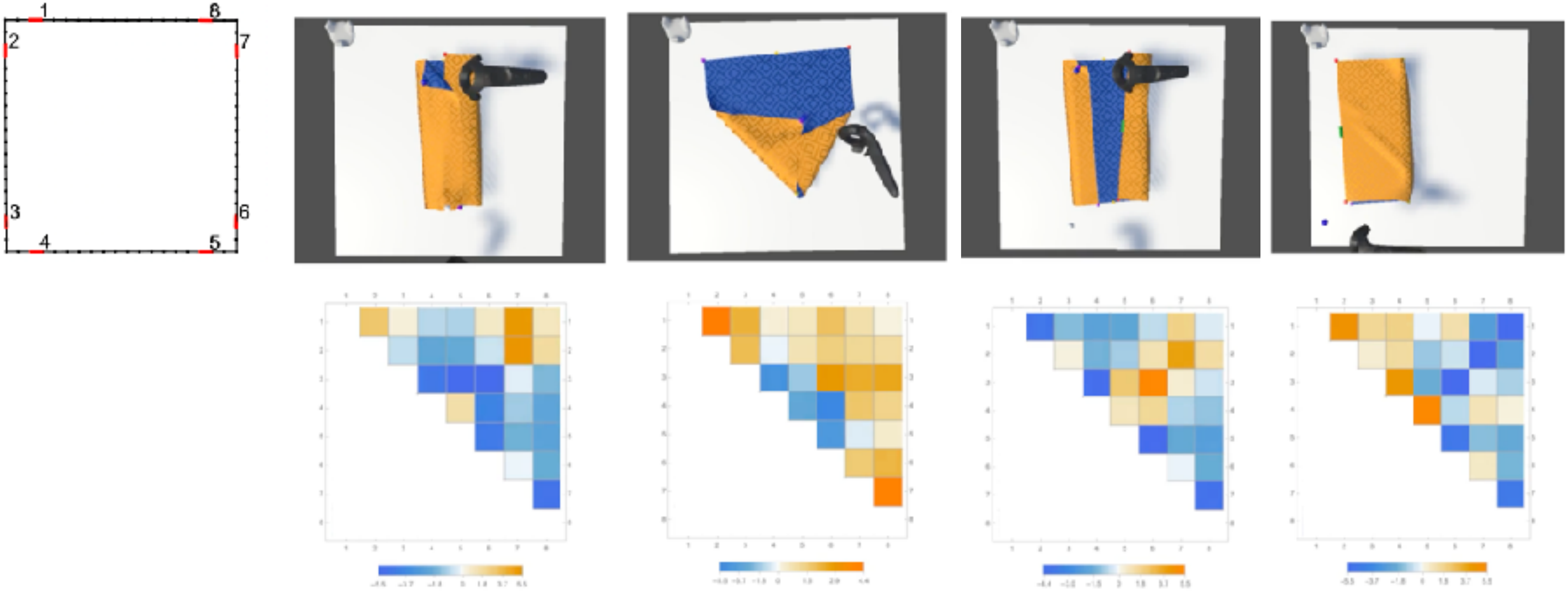
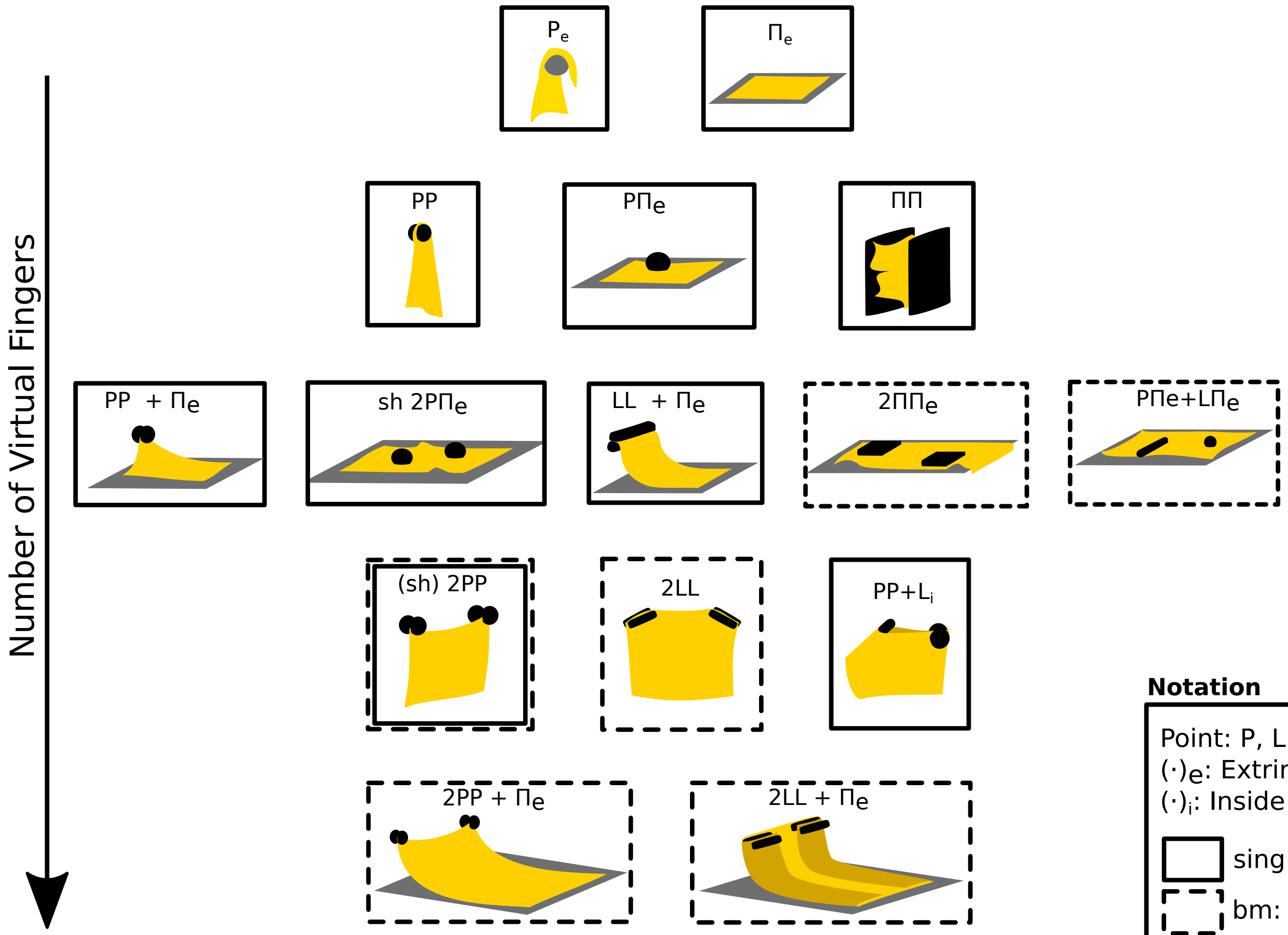


F. Coltraro, J. Fontana, J. Amorós, M. Alberich-Carramiñana, J. Borràs and C. Torras. A Representation of Cloth States based on a Derivative of the Gauss Linking Integral. ***Applied Mathematics and Computation*** 457: 128165, 2023.

Taxonomy of grasps and gripper functionalities



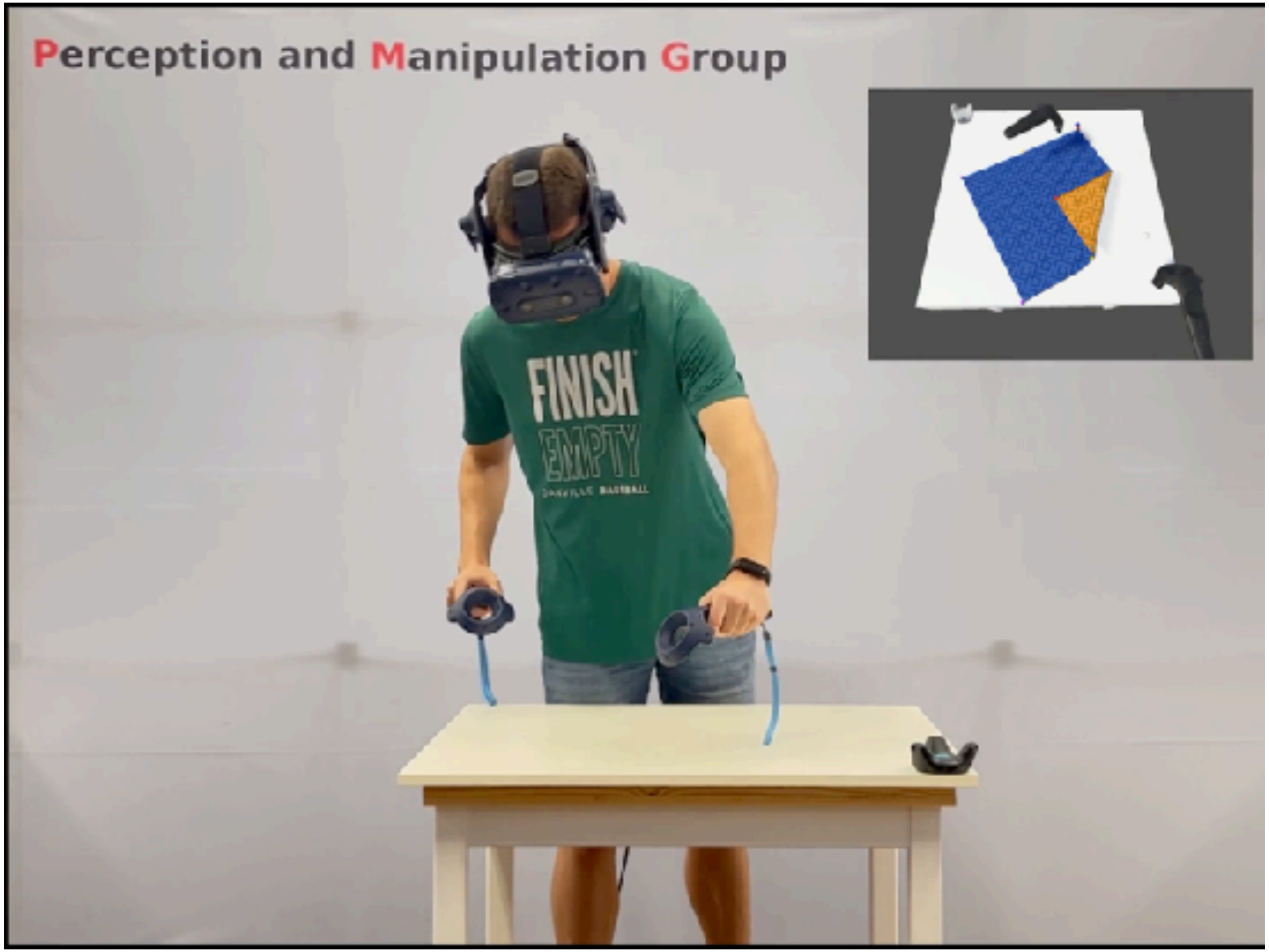
Notation

Point: P, Line: L, Plane: Π
$(\cdot)_e$: Extrinsic contact
$(\cdot)_i$: Inside fold contact

single handed
bm: bimanual

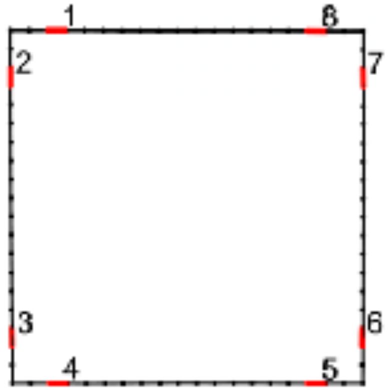
J. Borràs, G. Alenyà, and C. Torras. A grasping-centered analysis for cloth manipulation. *IEEE Transactions on Robotics*, 36(3):924-936, 2020.

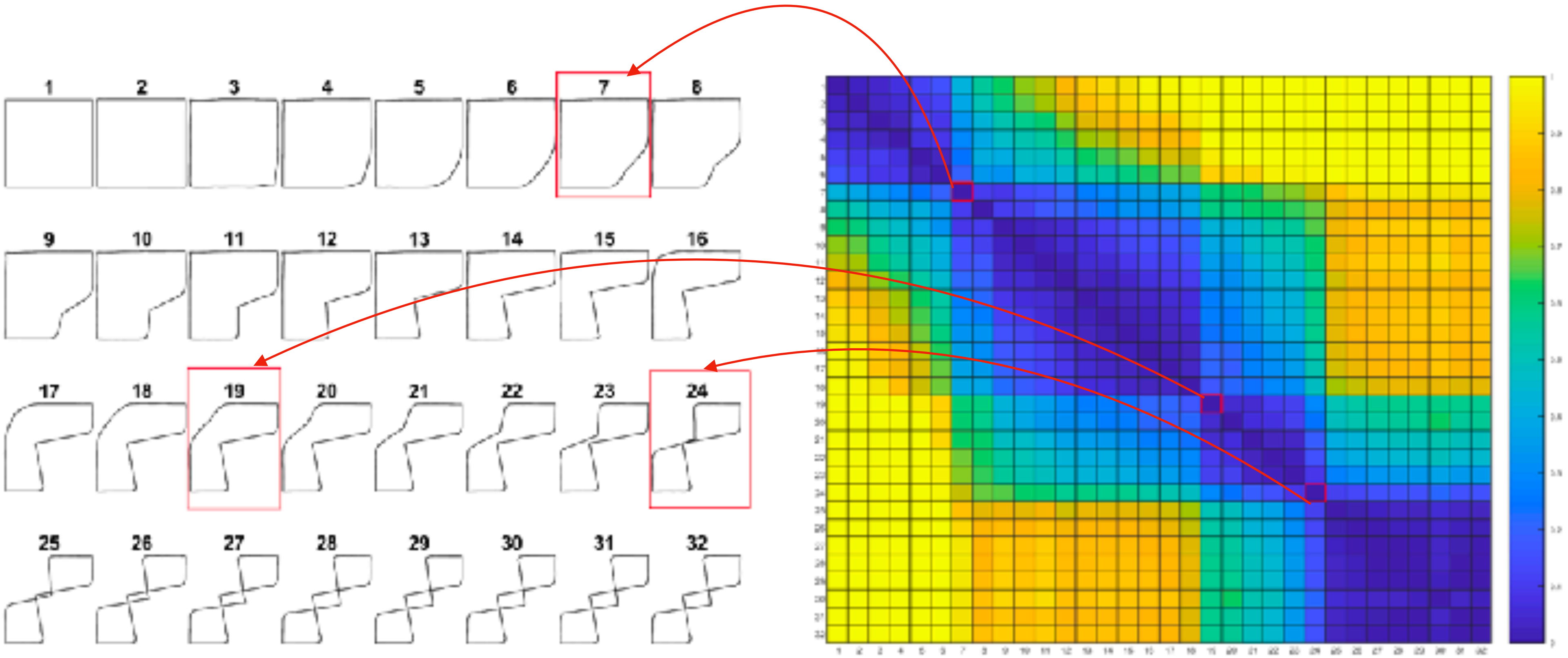
Learning cloth folding sequences using Virtual Reality



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, ***IEEE International Conference on Robotics and Automation***, London, May 2023.

Topology of cloth deformation - **Gauss Linking Integral**





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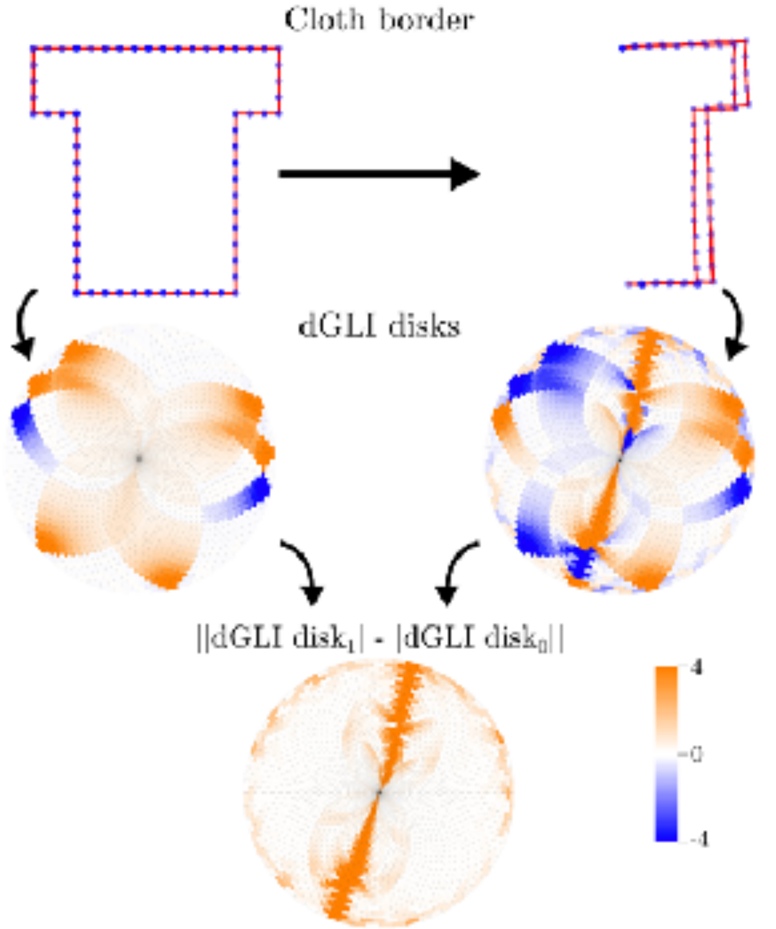
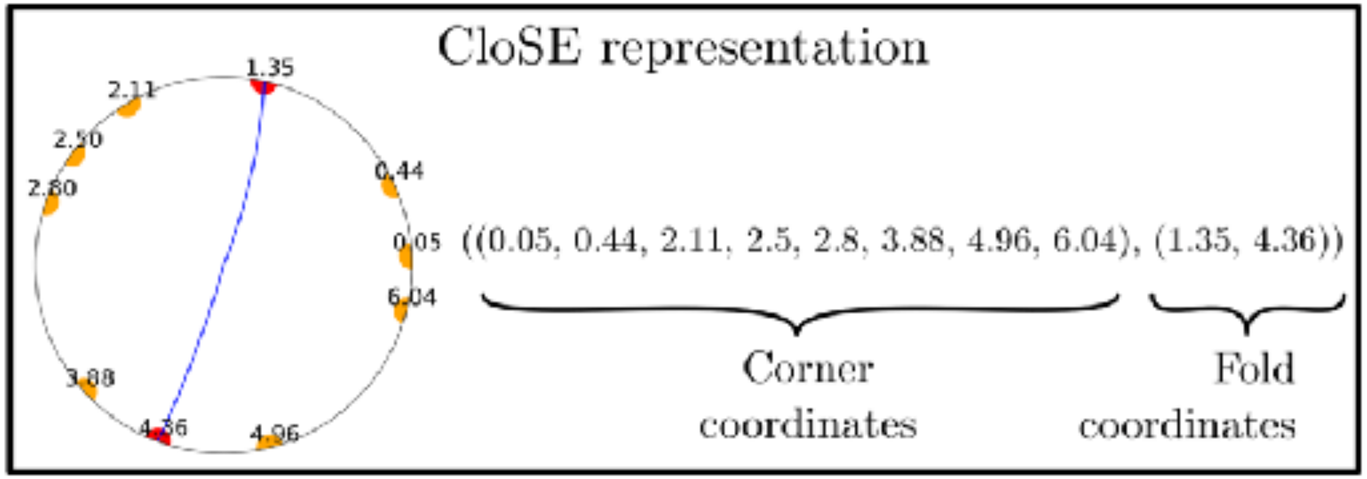
Work in progress: dGLI-based, compact representation

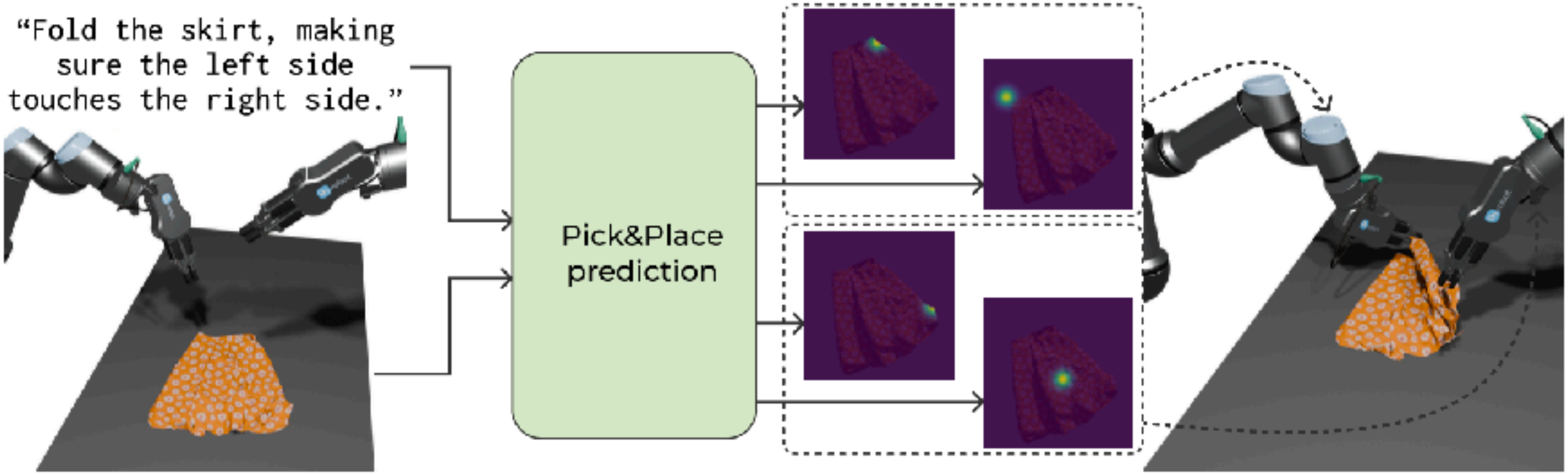




J. Kamat, J. Borràs and C. Torras. CloSE: A Compact Shape-and Orientation-Agnostic Cloth State Representation. ***arXiv preprint*** arXiv:2504.05033, 2025.

Work in progress: predicting cloth manipulation actions using VLM

Language-conditioned model to predict folding actions from cloth state + text instruction



https://barbany.github.io/bifold/

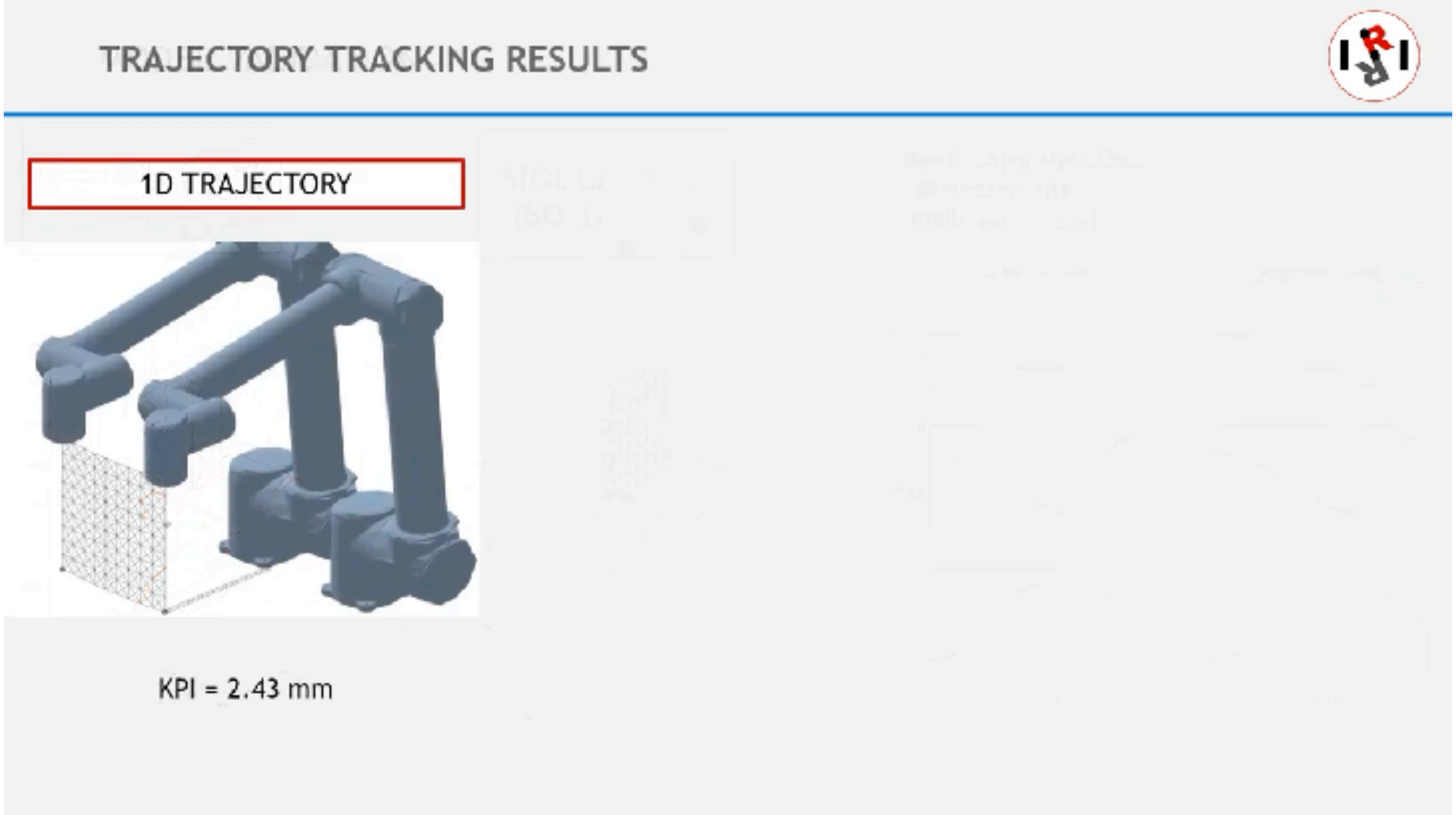
O. Barbany, A. Colomé and C. Torras. BiFold: Bimanual Cloth Folding with Language Guidance. ***IEEE International Conference on Robotics and Automation* (*ICRA*), *arXiv preprint*** arXiv:2501.16458, 2025.

Our research on cloth manipulation

CLOTHILDE
ERC Advanced Grant Cloth manipulation learning from demonstrations
erc Advanced Grant

	Quasi-static manipulation	**Dynamic manipulation**
Cloth/Motion **Representation**	- Cloth macro-states (C-space, dGLI) - Capturing cloth states (Color/depth vision, Optitrack…) - Capturing motion (VR…)	- Modeling cloth as an inextensible surface - Representing motions (DMPs, writhe…)
Manipulation, planning and control	- Grippers - Grasping primitives - Planning state transitions	- Simulation of cloth dynamics - Controling cloth manipulation using GP and MPC - Variable impedance control
Learning (perception, motion)	- Cloth state estimation (from template, border…) - Learning transitions from VR	- Learning robot skills from demonstration & reinforcement (trajectories and force profiles)

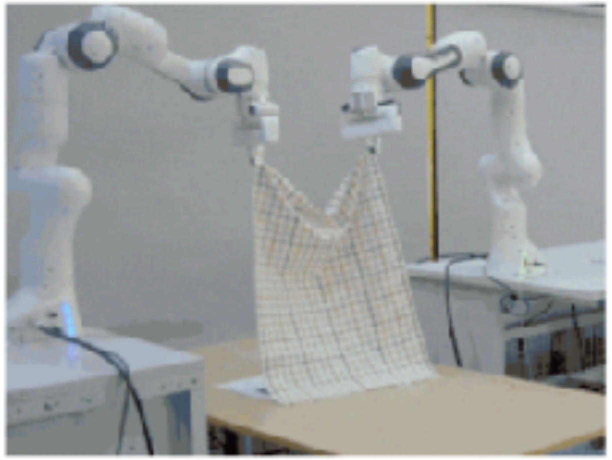
Controlling dynamic cloth manipulation using MPC



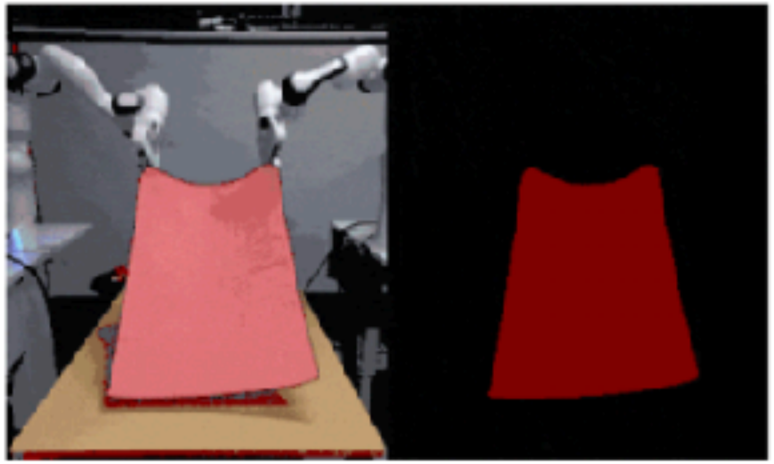
A. Luque, D. Parent, A. Colomé, C. Ocampo-Martínez and C. Torras. Model predictive control for dynamic cloth manipulation: Parameter learning and experimental validation. ***IEEE Transactions on Control Systems Technology*** 32(4): 1254-1270, 2024.

Sim-to-Real Gap in Cloth Simulators

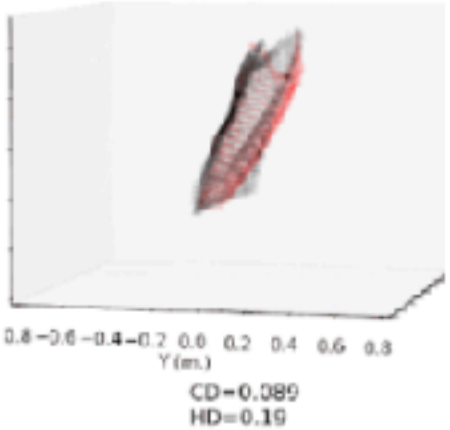
- 3 objects: rags of different materials
- 2 manipulation tasks: dynamic & quasi-static
- 4 simulators: MuJoCo, Bullet, Flex, SOFA
- Real-world dataset: Depth and RGB images from Kinect
- 2 metrics: Chamfer Distance & Hausdorff Distance



Record Dataset



Pre-process RGB-D data



Measure the Reality Gap in Simulated Environments

D. Blanco-Mulero, O. Barbany, G. Alcan, A. Colomé, C. Torras, V. Kyrki. Benchmarking the Sim-to-Real Gap in Cloth Manipulation *IEEE Robotics and Automation Letters*, Paris, pp. 2981-29886, 2024.

Sim-to-Real Gap in Cloth Simulators

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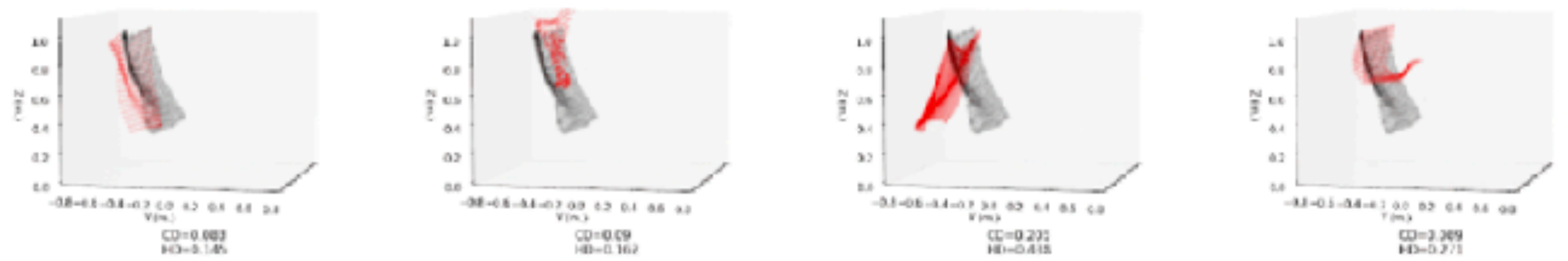
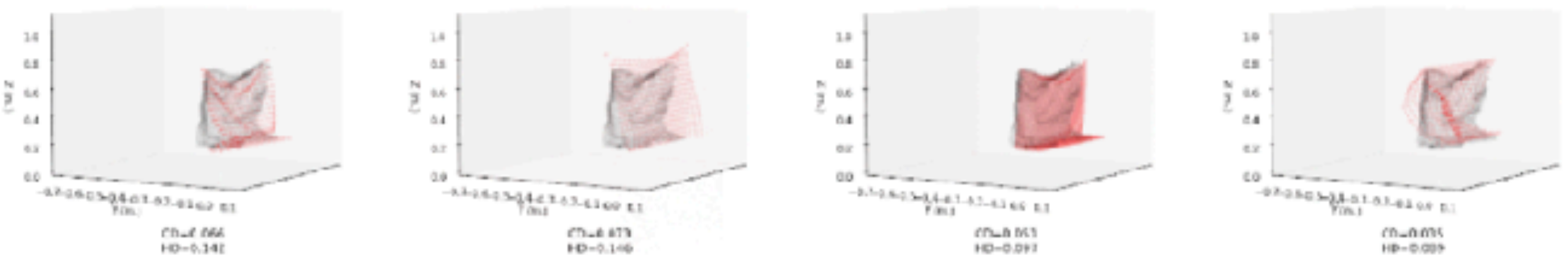
Linen Rag — Dynamic motion



MuJoCo | Bullet | Flex | SOFA

Inaccurate aerodynamic effects

Linen Rag — Quasi-static motion with friction



MuJoCo | Bullet | Flex | SOFA

Collisions cause locking

D. Blanco-Mulero, O. Barbany, G. Alcan, A. Colomé, C. Torras, V. Kyrki. Benchmarking the Sim-to-Real Gap in Cloth Manipulation *IEEE **Robotics and Automation Letters***, Paris, pp. 2981-29886, 2024.

CLOTHILDE Simulator - Equation of motion with inextensibility, contacts and aerodynamics

$$\begin{cases} \rho \mathbf{M} \ddot{\varphi} = -\delta \mathbf{M} \mathbf{g} - \kappa \mathbf{K} \varphi - (\alpha \mathbf{M} + \beta \mathbf{K}) \dot{\varphi} - \nabla \mathbf{C}(\varphi)^{\mathsf{T}} \boldsymbol{\lambda} \\ \mathbf{C}(\varphi) = 0, \ \text{(inextensibility)} \\ \mathbf{H}(\varphi) \geq 0, \quad \gamma \geq 0, \quad \gamma^{\mathsf{T}} \cdot \mathbf{H}(\varphi) = 0, \ \text{(contacts)} \end{cases}$$

PARAMETER	MEANING
ρ	Density (inertial mass)
δ	Virtual (gravitational) mass
κ	Bending/stiffness
α	Damping of slow oscillations
β	Damping of fast oscillations

F. Coltraro, J. Amorós, C. Torras and M. Alberich-Carramiñana. A practical aerodynamic model for dynamic textile manipulation in robotics. ***Mechanism and Machine Theory***, 209: 105993, 2025.

CLOTHILDE Simulator

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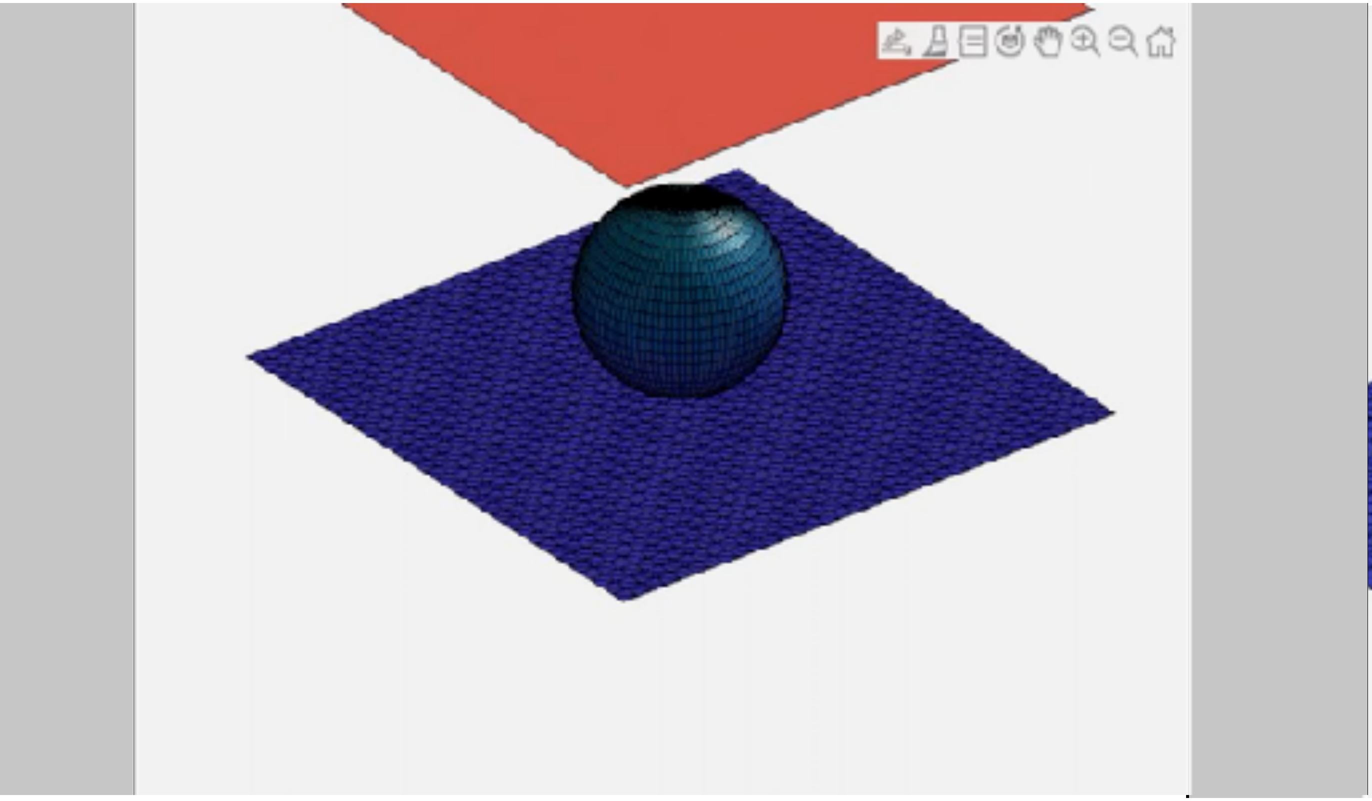
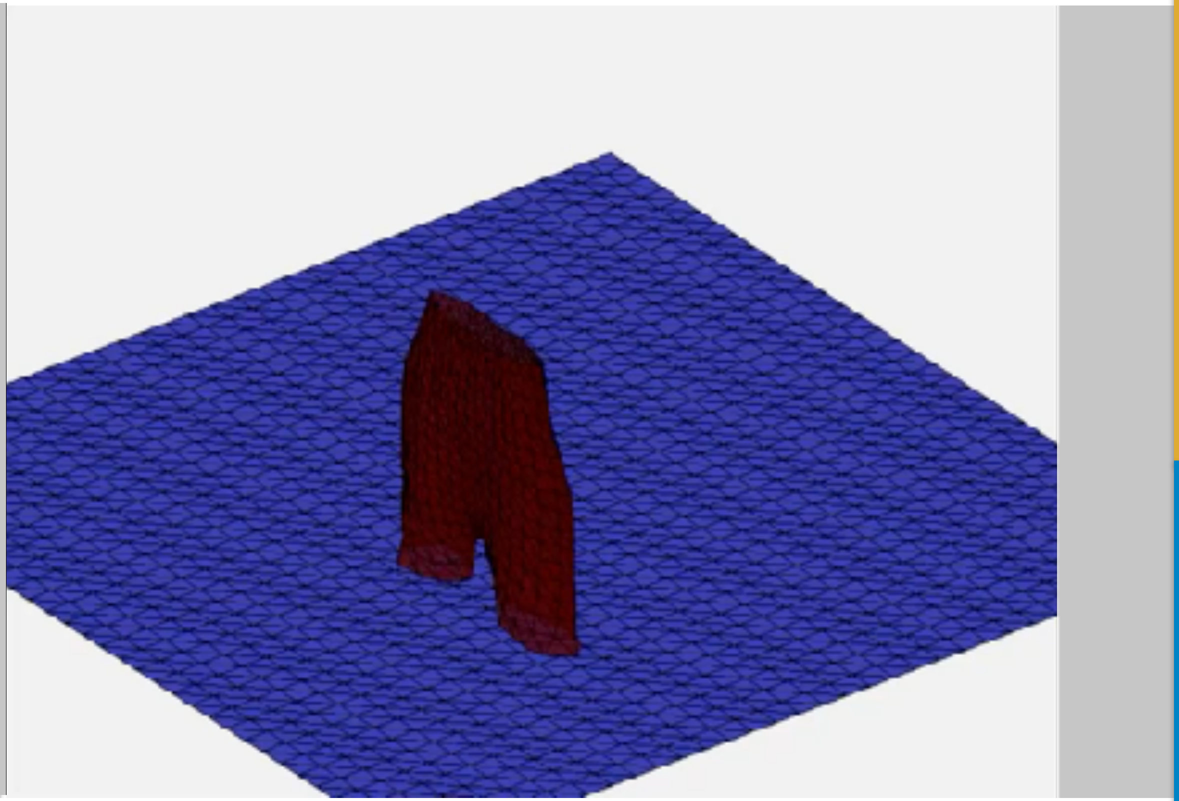
- simple (few parameters)
- easy to calibrate (physical parameters)
- faithful to reality (fast and slow dynamic motion)
- accounting for aerodynamic effects
- accounting for friction and self-collisions
- fast

F. Coltraro, J. Amorós, M. Alberich-Carramiñana and C. Torras. An inextensible model for the robotic manipulation of textiles. ***Applied Mathematical Modelling*** 101, 832-858, 2022.

F. Coltraro, J. Amorós, M. Alberich-Carramiñana and C. Torras. A novel collision model for inextensible textiles and its experimental validation. ***Applied Mathematical Modelling*** 128: 287-308, 2024.

Modeling cloth dynamics as an inextensible surface





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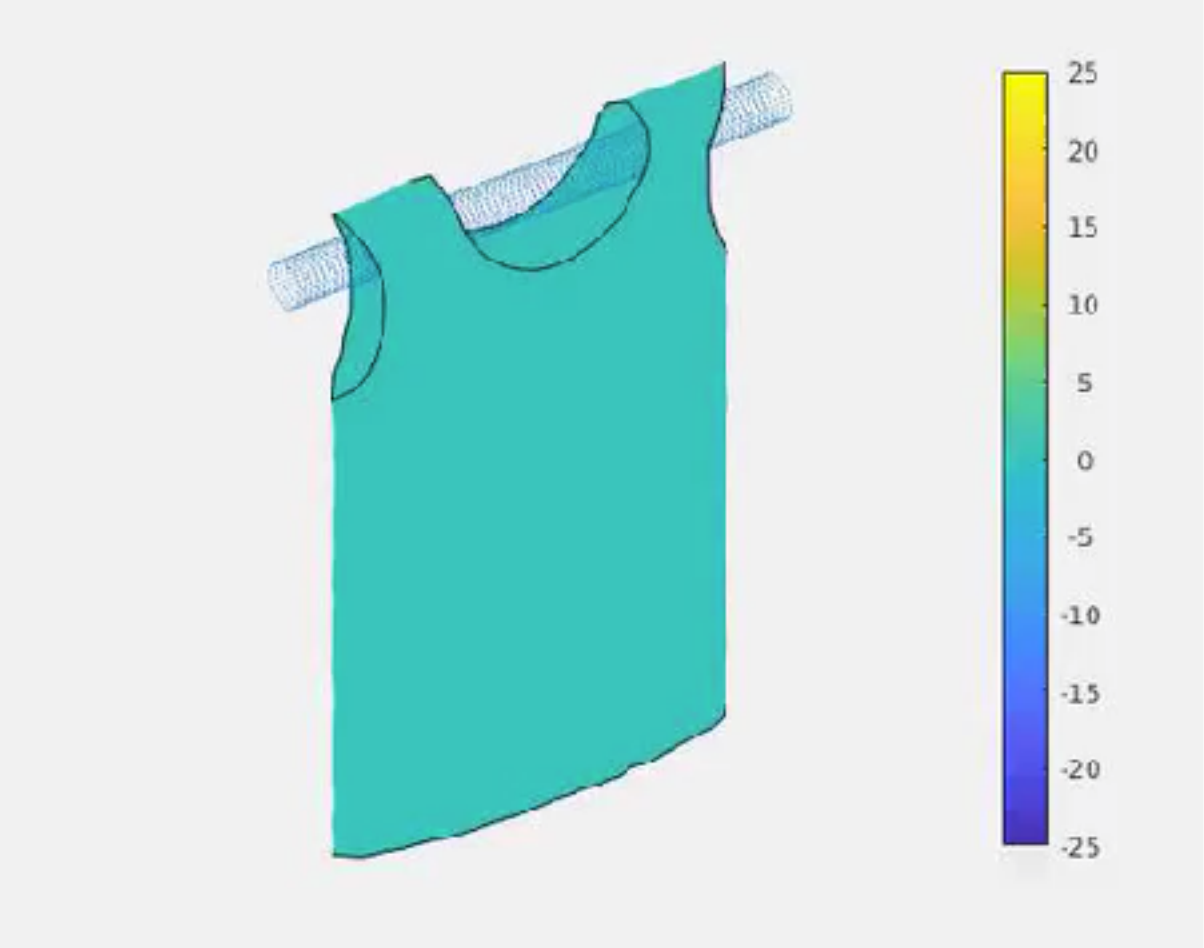
CLOTHILDE Simulator - Validation



Simulation of shaking with a hanger of a meshed tank-top with 1676 triangles during 4.5s.
Area error with sign of each individual triangle for each time instant. Total area error almost zero.

Our research on cloth manipulation

	Quasi-static manipulation	Dynamic manipulation
Cloth/Motion **Representation**	- Cloth macro-states (C-space, dGLI) - Capturing cloth states (Color/depth vision, Optitrack…) - Capturing motion (VR…)	- Modeling cloth as an inextensible surface - Representing motions (DMPs, writhe…)
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Learning (perception, motion)	- Cloth state estimation (from template, border…) - Learning transitions from VR	- Learning robot skills from demonstration & reinforcement (trajectories and force profiles)

Learning folding skills by demonstration and reinforcement

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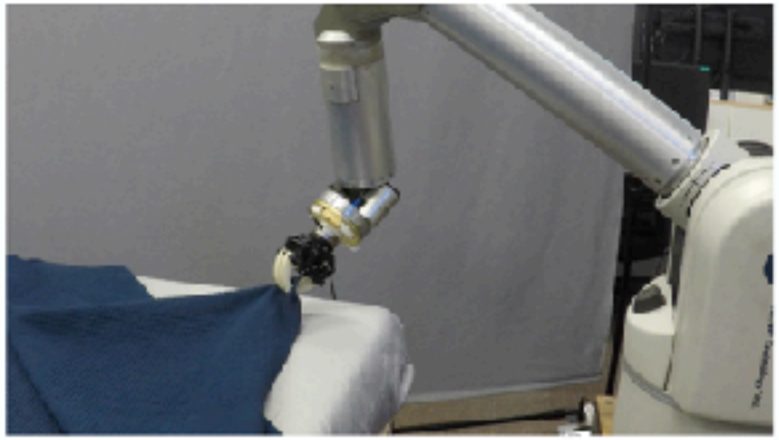
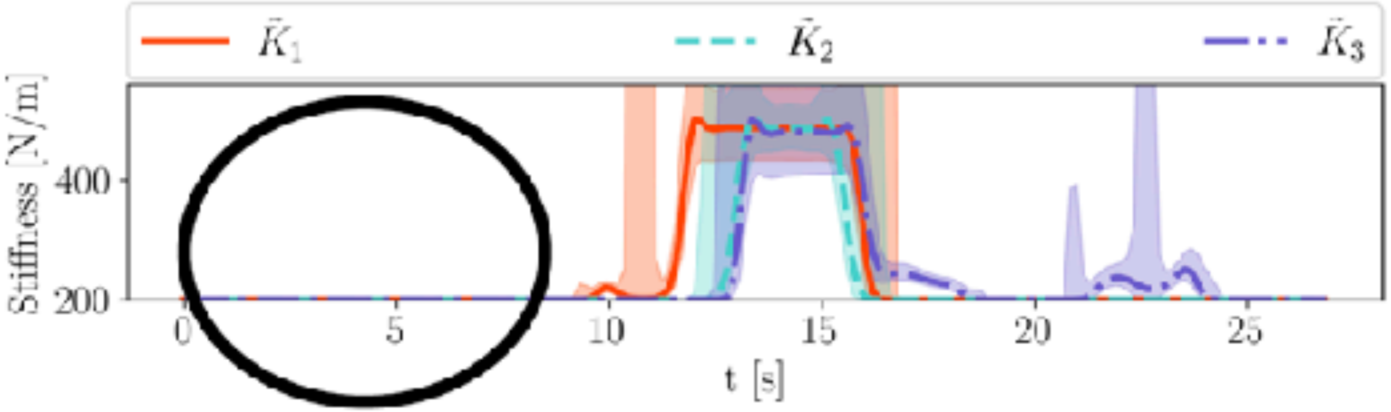
A. Colomé, C. Torras. Reinforcement Learning of Bimanual Robot Skills. ***Springer Tracts in Advanced Robotics*** 134, 2020.

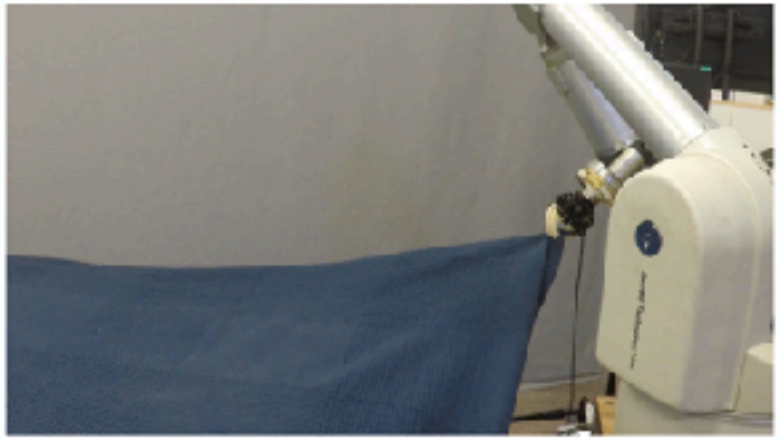
Learning force profiles through demonstration

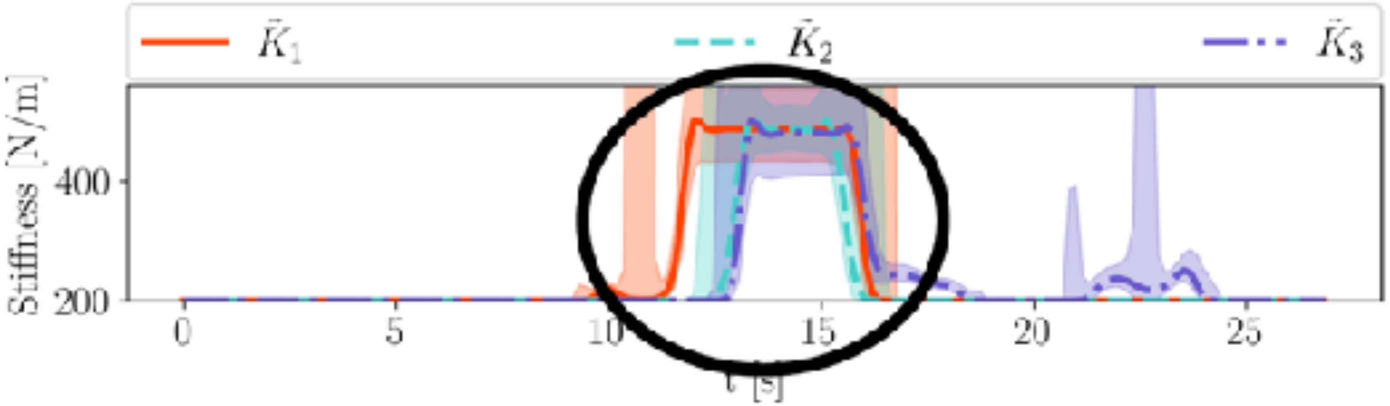




E. Caldarelli, A. Colomé and C. Torras. Perturbation-Based stiffness inference in variable impedance control. ***IEEE Robotics and Automation Letters***, 7(4): 8823-8830, 2022.

Learning force profiles through demonstration





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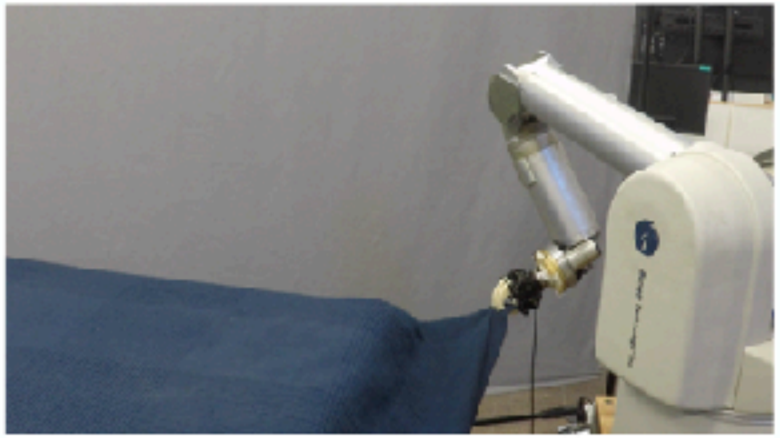
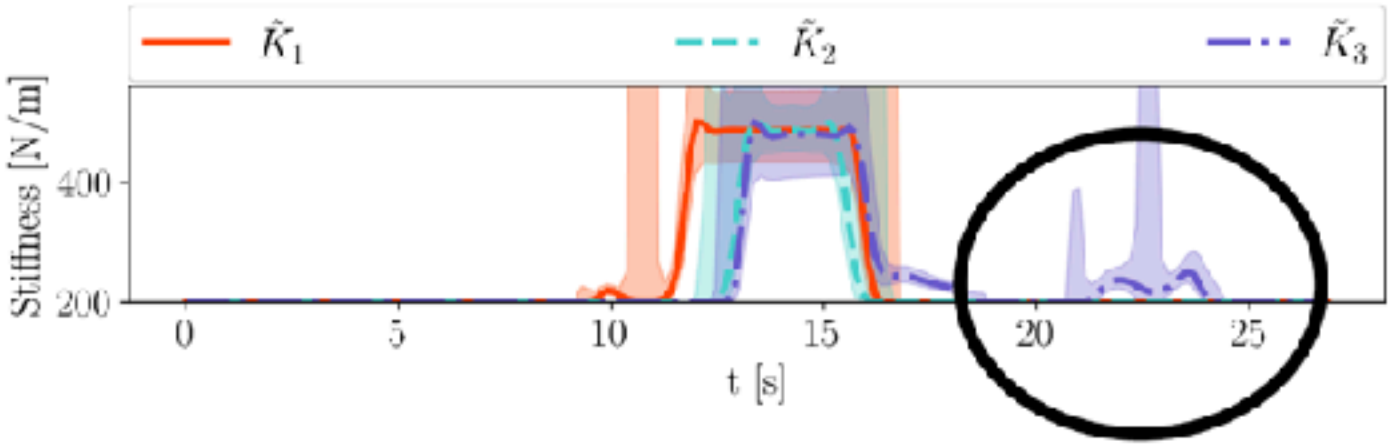
Learning force profiles through demonstration





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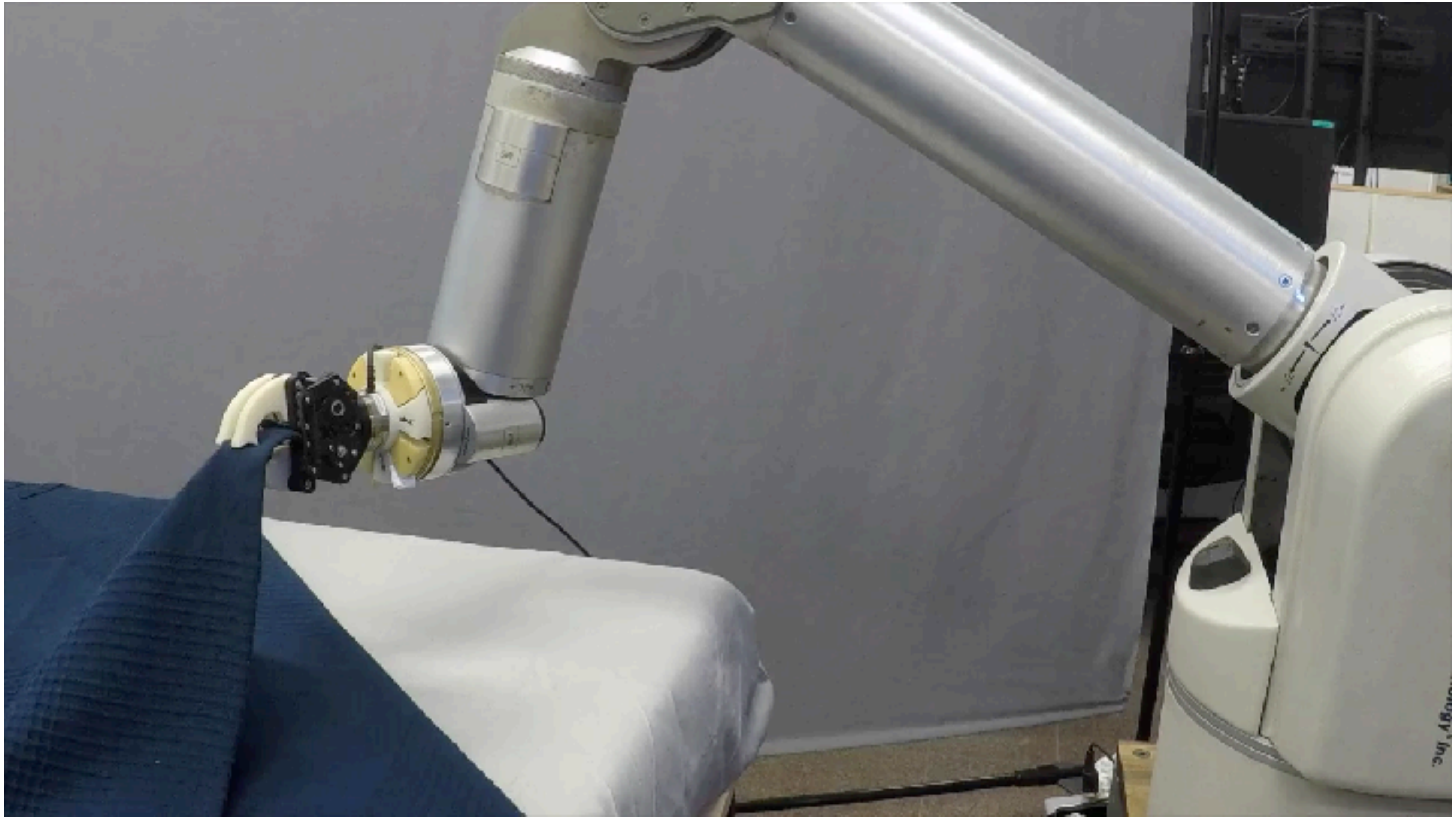
Learning force profiles through demonstration



Our current research on cloth manipulation

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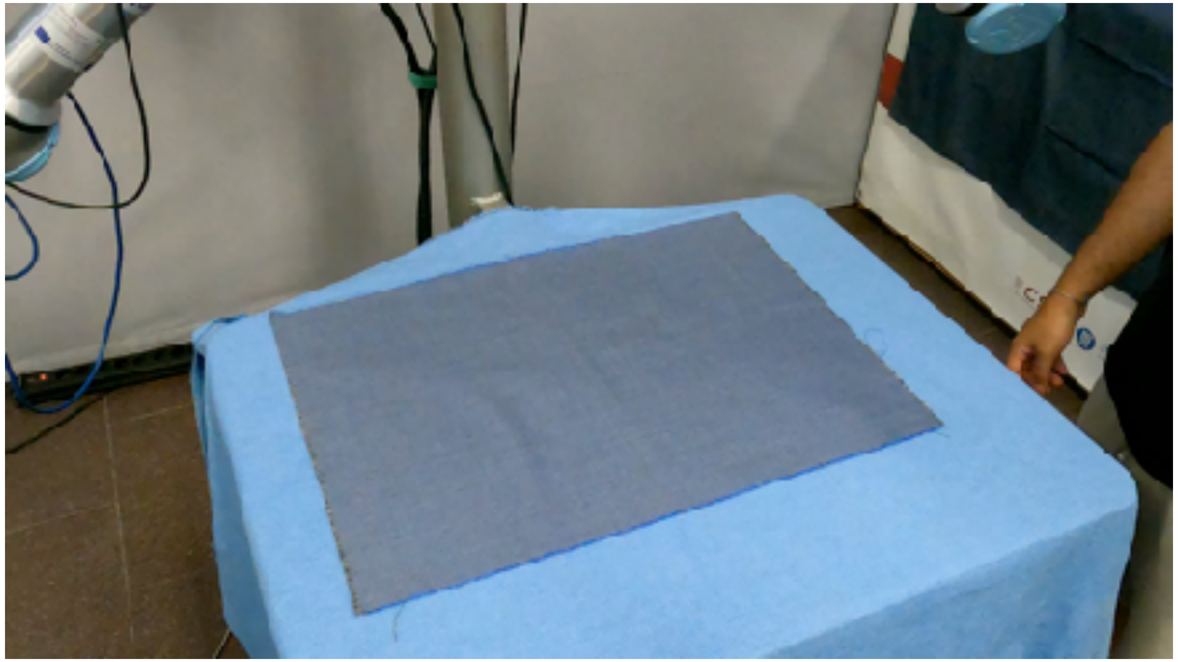
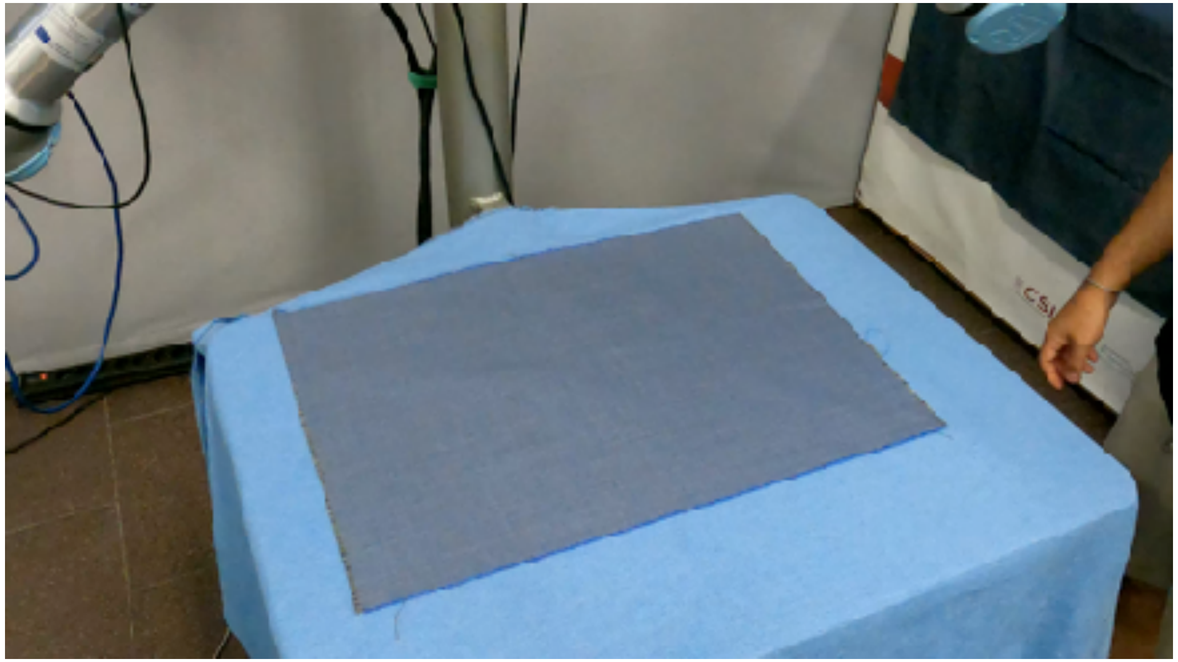
Work in progress: Fast cloth manipulation exploiting dynamics





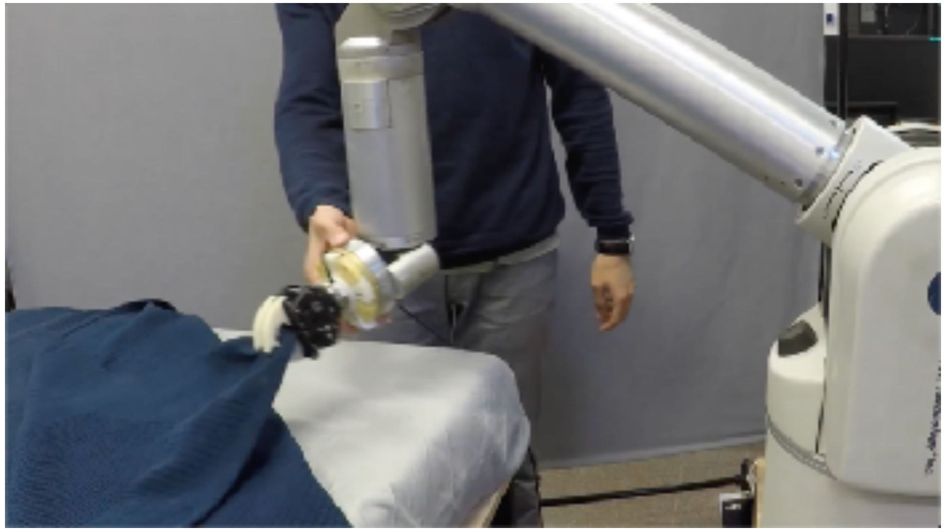
Kernel-based Koopman operator regression + high-fidelity simulator + model predictive control

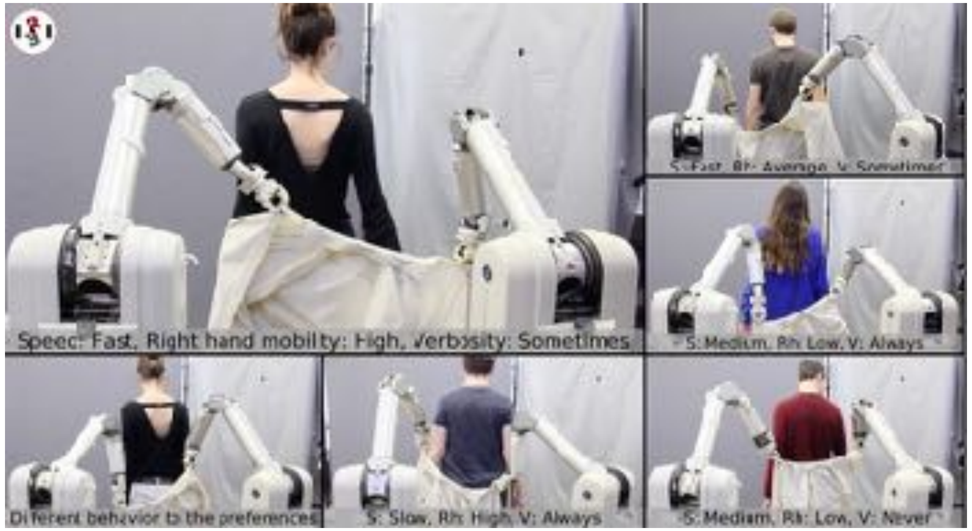
Prototypes of assistive robots

Cognitive training

Feeding

Bed making





Helping to dress

Co-creation with all the involved stakeholders

Fundació ACE

- Management
- Neurologist
- Clinical Therapist
- Social Worker

Parc Sanitari Pere Virgili

- Management
- Innovation
- Medical Personnel
- Nursing Pers.
- Caregivers

Helping nursing personnel in stressful routine tasks

SoftEnable

Clínic Barcelona

Co-creation

- Management
- Innovation
- Medical Personnel
- Nursing Pers.

Human-robot interaction → learn and discuss about **techno-ethics**

C. Torras. Ethics of social robotics: Individual and societal concerns and opportunities. ***Annual Review of Control, Robotics, and Autonomous Systems*** 7: 1-18, 2024.

1. Including ethics in the curricula

«By making ethical reasoning a central element in the curriculum, students can <u>learn to think not only about what technology they could create, but also whether they should create that technology.</u>»

2. Engage students

«Using fiction to teach ethics allows students to safely discuss and <u>reason about difficult and emotionally charged issues without making the discussion personal</u>.»

Teaching materials on **Social Robotics and AI**

- A **novel** about a future society in which people rely on personal-assistant robots to navigate daily life
- An **appendix** with 24 ethics questions
- An **online teacher's guide**
- A **100-slide presentation**

Educational levels:

University: https://mitpress.mit.edu/books/vestigial-heart

https://www.iri.upc.edu/people/torras/vestigial.html

High school: https://www.pageseditors.cat/es/guia-didactica-la-mutacio-sentimental.html

Encouraging future perspectives

Social services are beginning to invest in social robots:

- Population ageing & shortage of caregiving personnel.
- Elderly people could **live longer at home** with some technological help.
- Robots can take on routine **tasks with no added human value**.
- Increase the **autonomy of the elderly**.
- Raise the **qualification of caregiving jobs**.
- Reduce **burden for the healthcare system & for families**.

Carme Torras
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European Social Services Conference

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