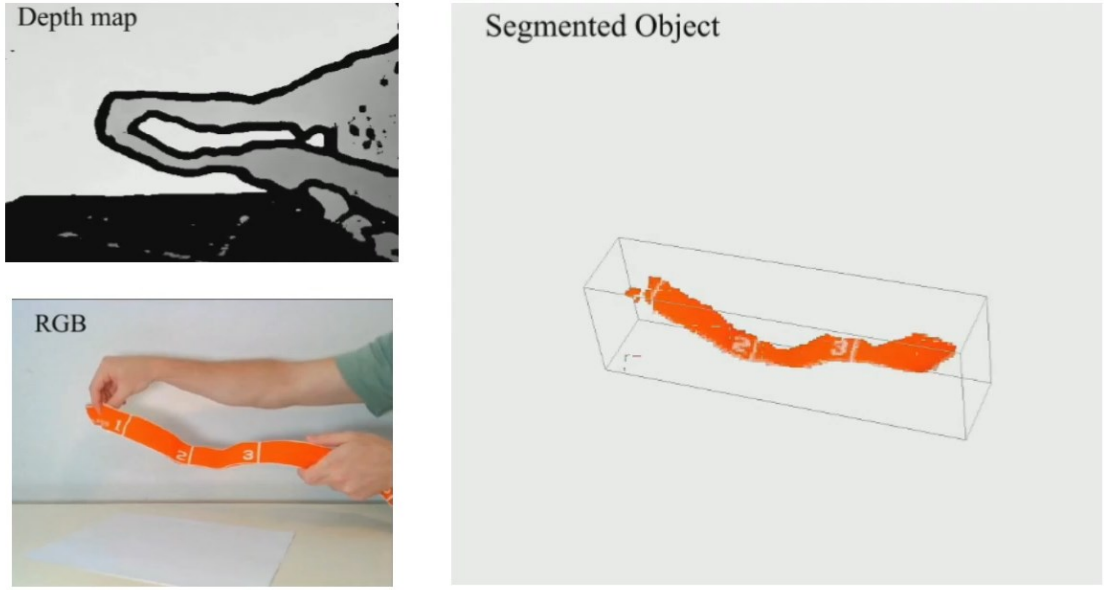
Data-driven manipulation and control of deformable objects

Ignacio Cuiral Zueco

ELLIIT 15 years



Focus Period
Lund University
2025

Lund University
LTH Faculty of Engineering
Interreg Sudoe REMAIN
Co-funded by the European Union
Interreg Sudoe COMMANDIA
I3A Instituto Universitario de Investigación en Ingeniería de Aragón
Universidad Zaragoza
Faculdade de Ciências e Tecnologia Universidade de Coimbra
République Française
Clermont Auvergne INP

Deformable object manipulation: a hot topic

Medical and surgical

Logistics, and transport

Automotive/aerospace industries

Food industry and agriculture

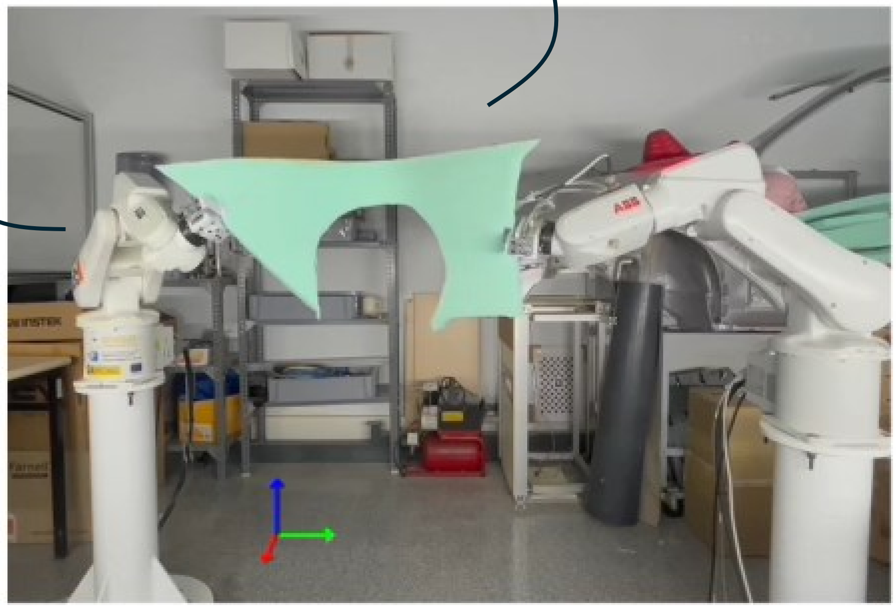
Electric industry/electronics

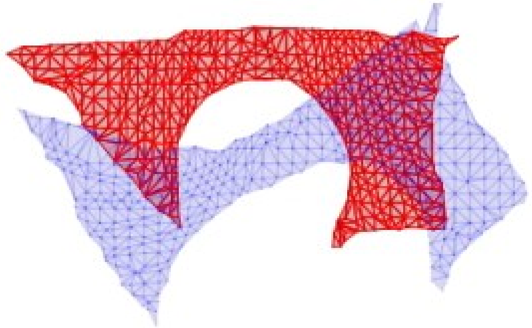
Textile and clothing industry

Central to deformable object manipulation: The shape control problem

deformable object
(foam piece)

robots

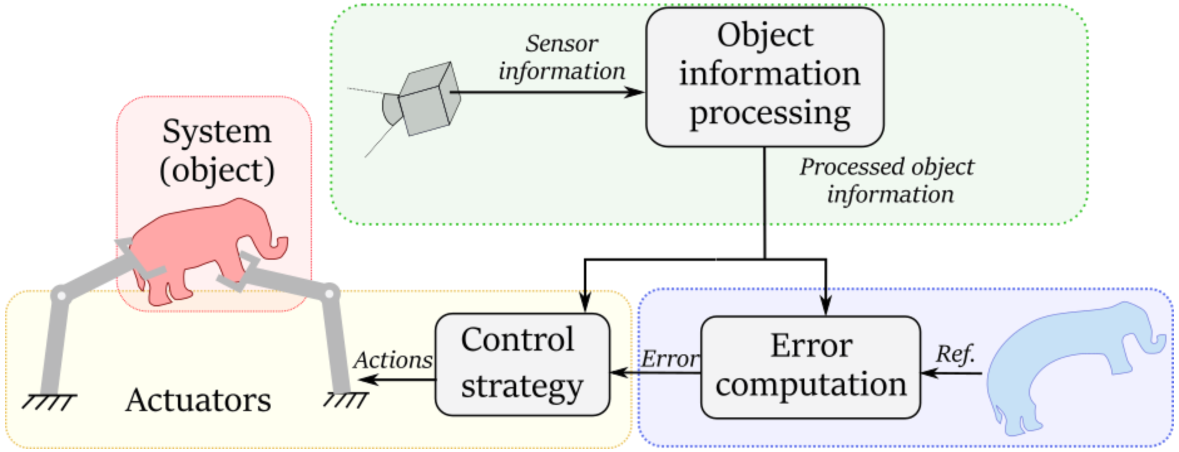




initial shape
current shape
target shape

Objectives and structure

General goal: Enhance deformable object manipulation by developing advanced **perception, shape analysis, and control** techniques.



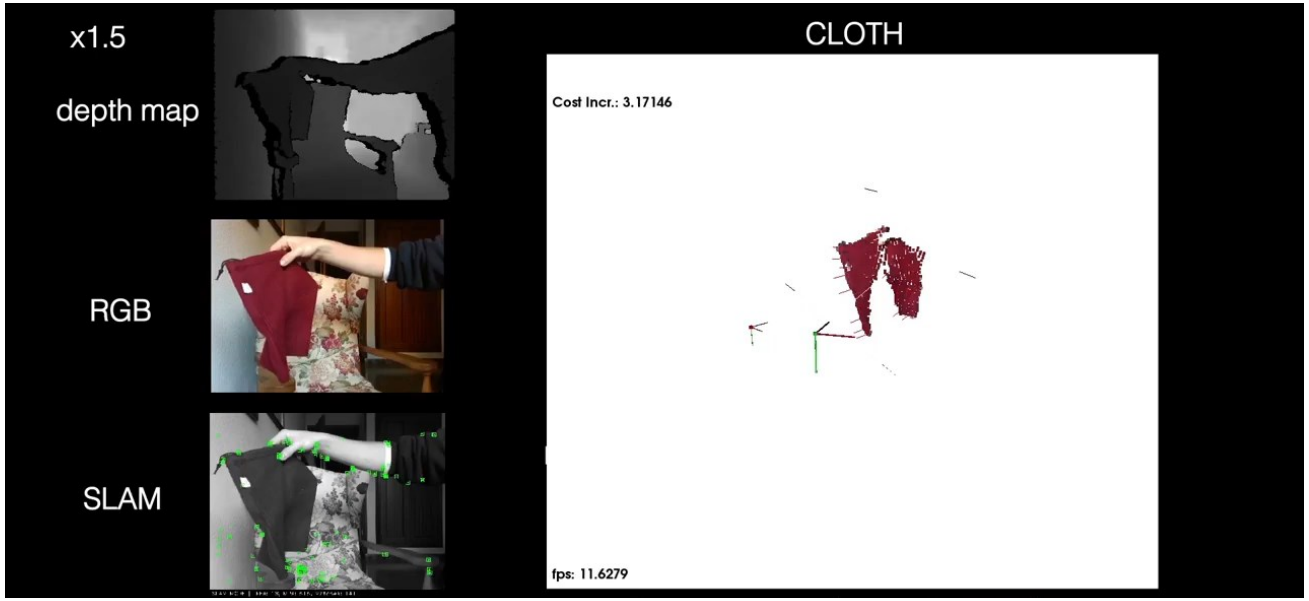
Cuiral-Zueco, I., et al., *IEEE Robotics and Automation Letters*, 2024.

Objectives and structure

- Segment and track the object
- Locate camera pose
- Compute optimal camera pose for best perception

RGB-D video → Active deformable object perception → tracked object point cloud, optimal camera pose

Active deformable object perception

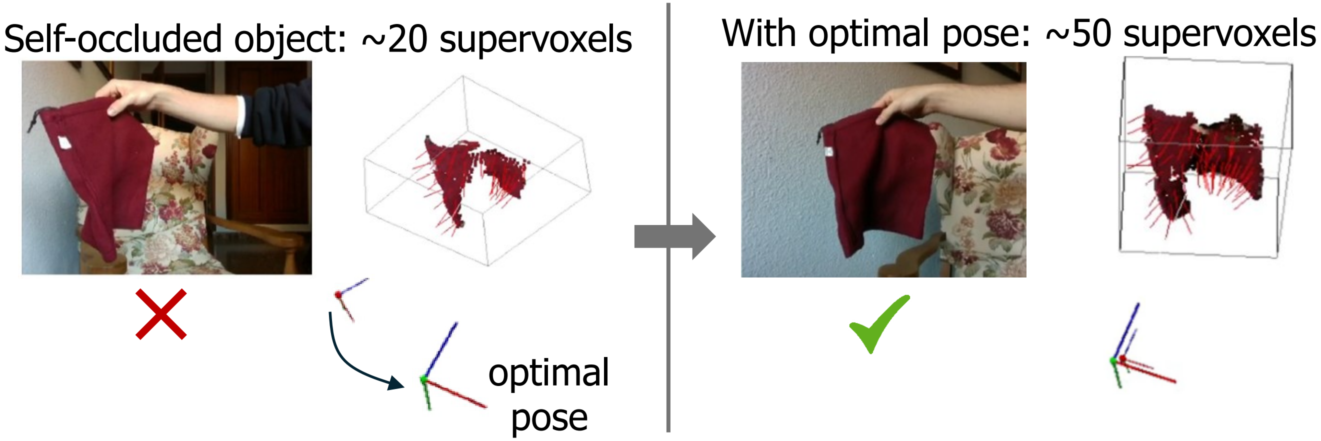


Challenges

- Large deformations, and occlusions
- Lack of distinctive visual features
- Noisy/incomplete information

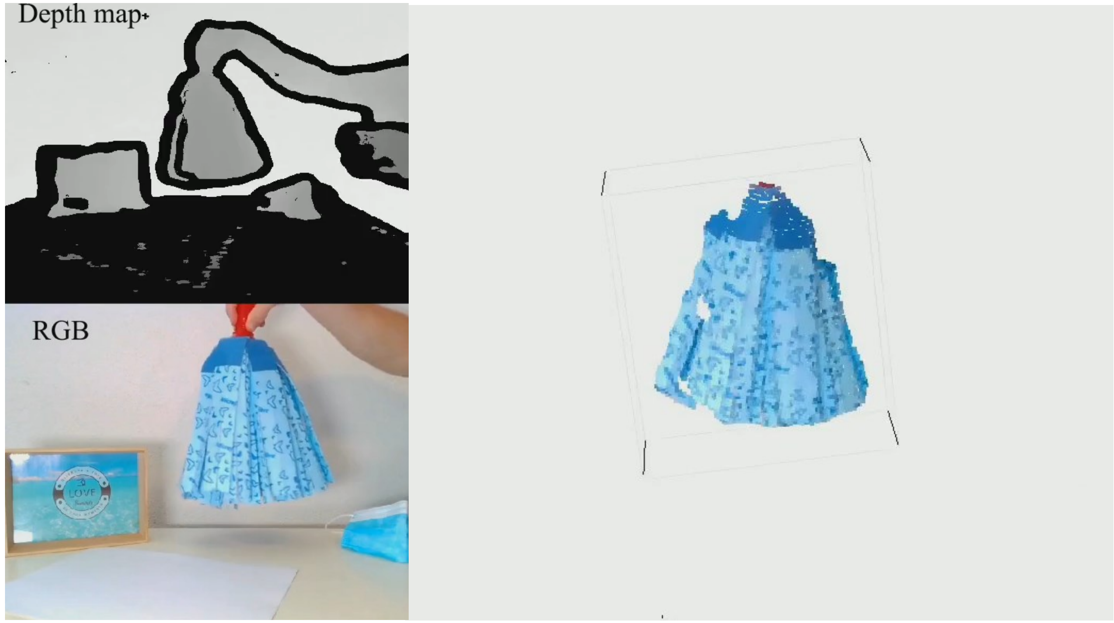
Our perception system:

- Super-voxel dynamic graphs + SLAM
- C++ implementation
- Non-linear (online) Next-Best-View optimisation

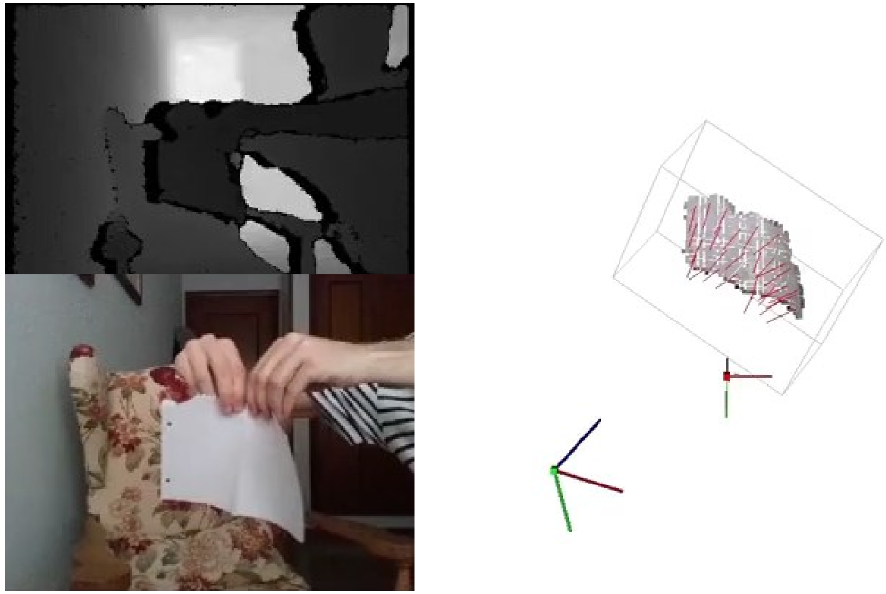


Cuiral-Zueco, I., et al., *IEEE Access, 2020.*
Cuiral-Zueco, I., et al., *IEEE ICRAE, 2020.*
Cuiral-Zueco, I., et al., Workshop, *IEEE IROS, 2021.*

Deformable object active perception results



Mop head manipulation



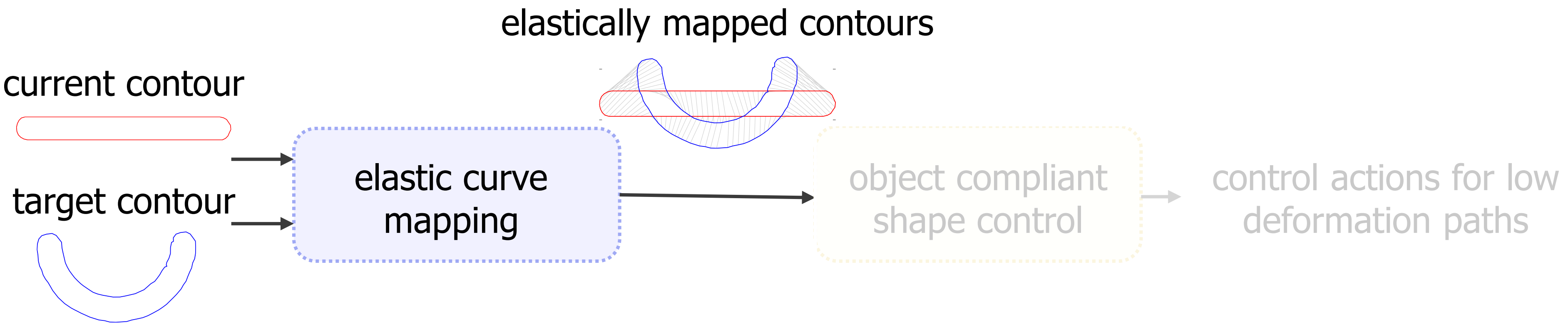
Paper tearing process

Cuiral-Zueco, I., et al., *IEEE Access, 2020*.
Cuiral-Zueco, I., et al., *IEEE ICRAE, 2020*.
Cuiral-Zueco, I., et al., Workshop, *IEEE IROS, 2021*.

Objectives and structure

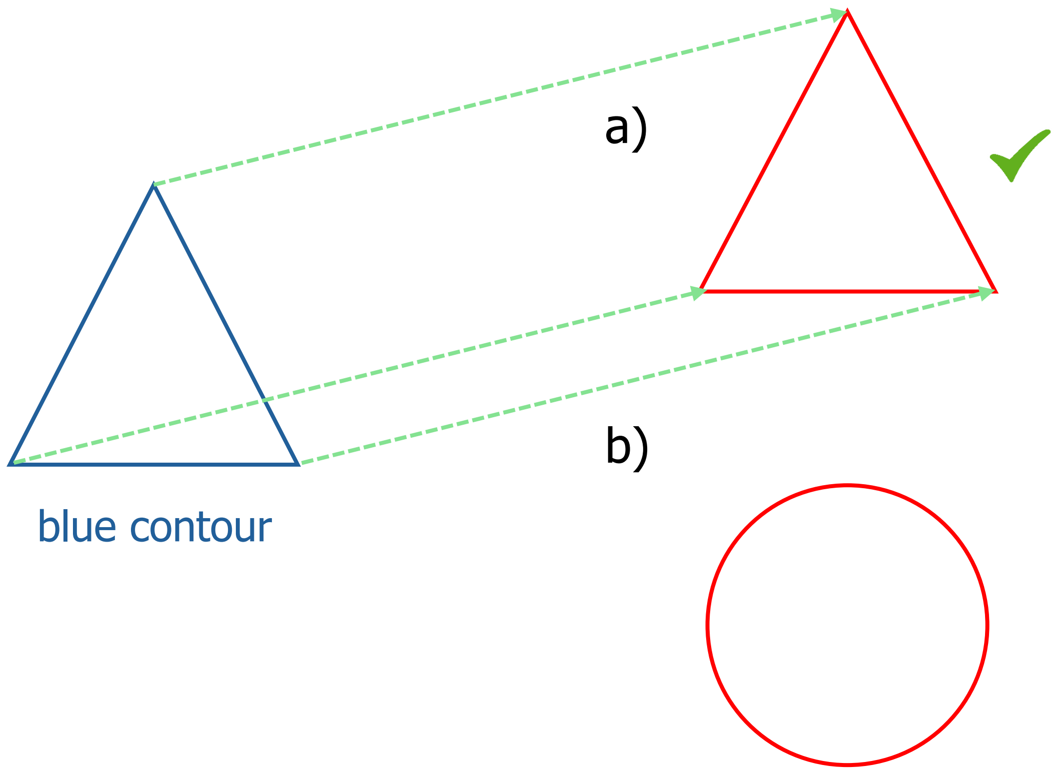
- II. Deformable object perception
- **III. Shape as curve: mapping and control**
- IV. Shape as surface: mapping and control
- V. Shape trajectory control

- Map curves to infer realistic deformations between shapes
- *Gently* guide objects along low deformation paths



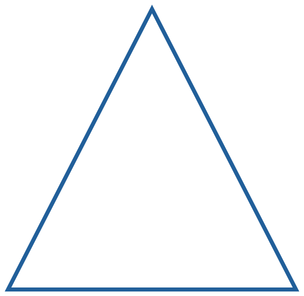
Shape comparison quiz

Level 1

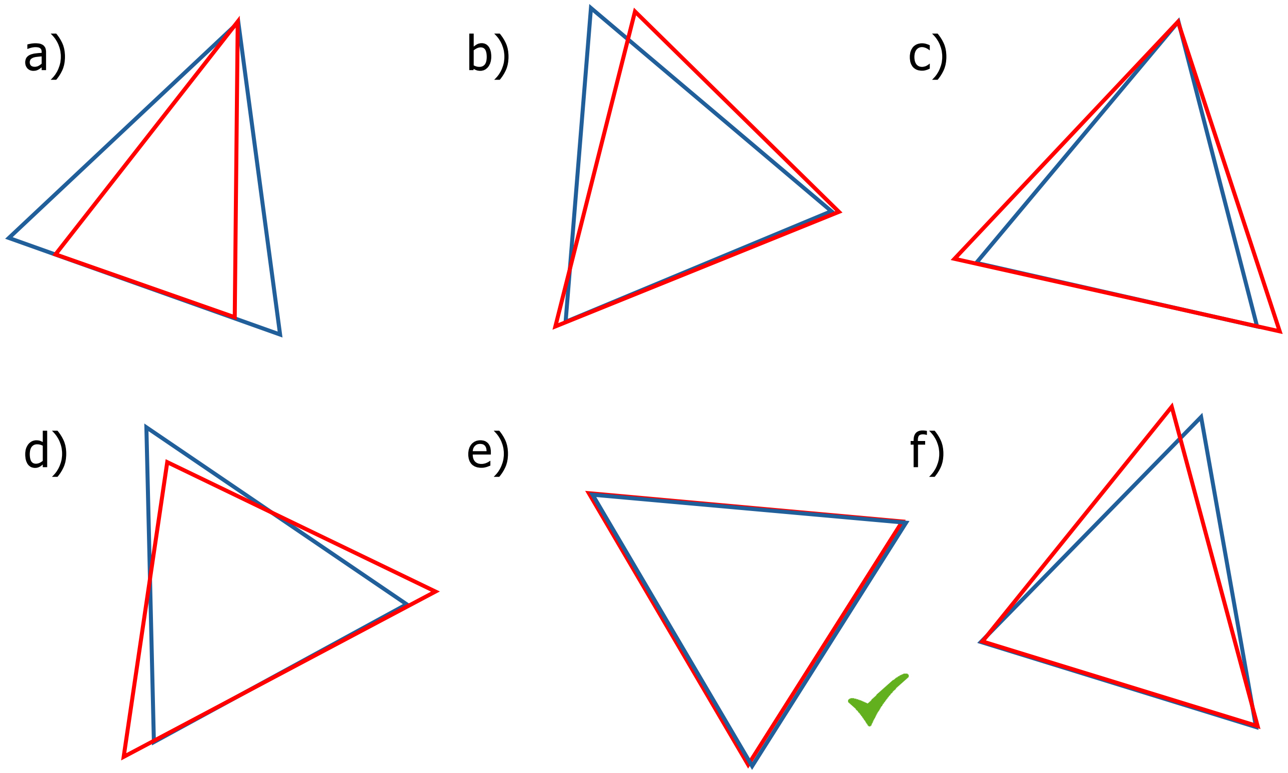


Shape comparison quiz

Level 2

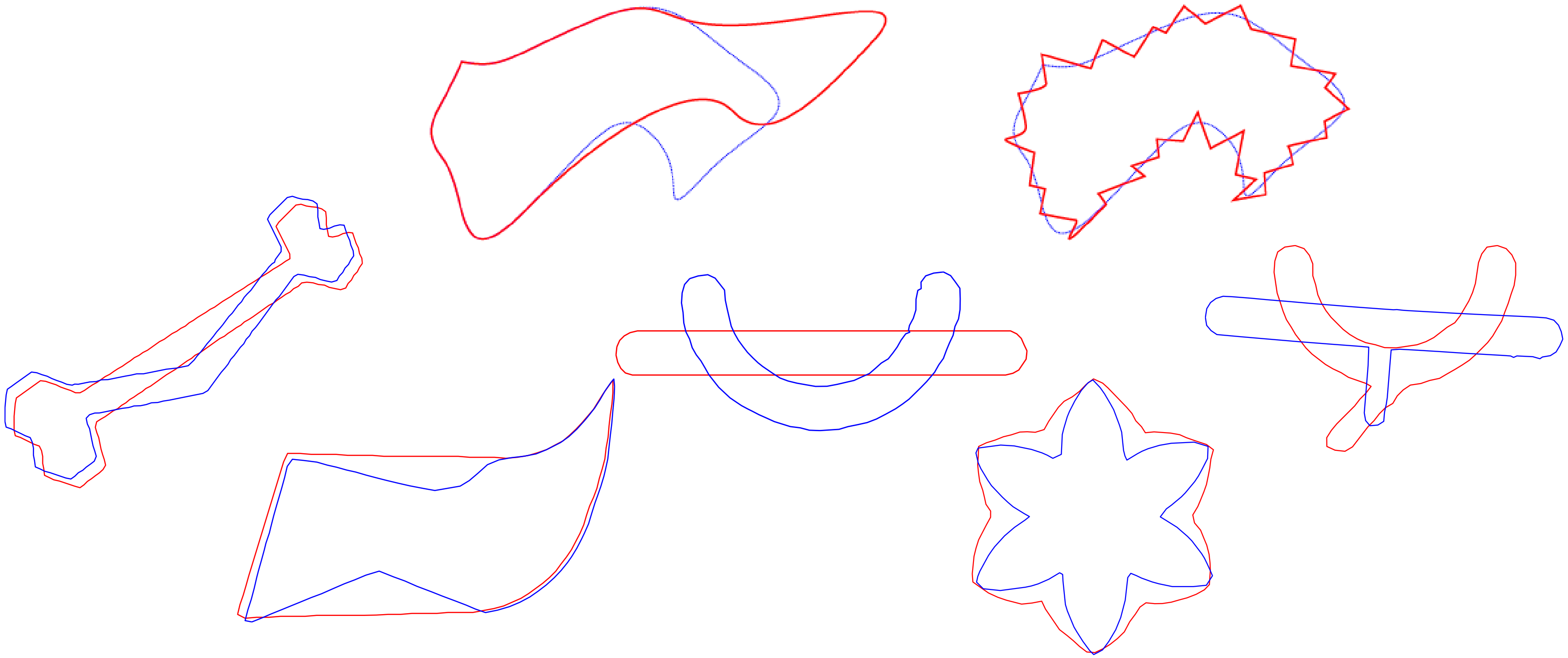


blue contour



Comparing shapes in an automatic, general, and measurable way is tricky

Comparing shapes (mapping domains) ≈ deformation process estimation



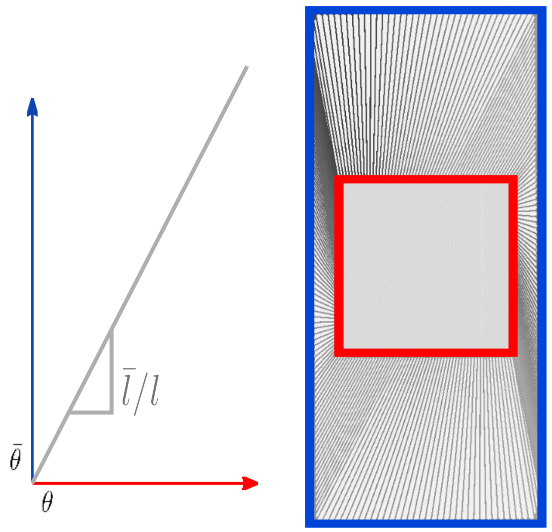
Elastic contour mapping

Challenges

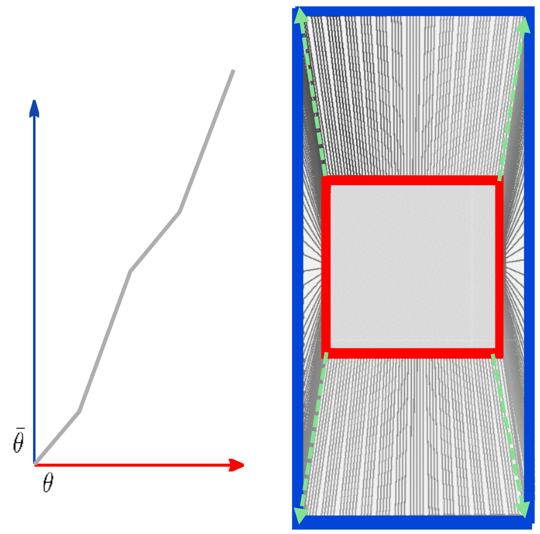
- No reference/landmark points
- Large and non-isometric deformation

Our elastic mapping:

- Favours geometry-preserving maps
- Proposed Multi-scale Laplacian descriptors
- Fast Marching Method (FMM) optimisation



homogeneous map (conventional approach)



elastic map (ours)

Elastic contour mapping

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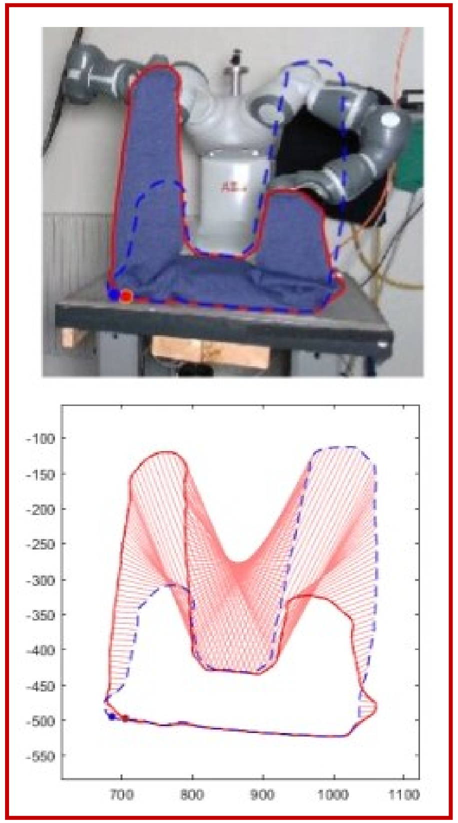
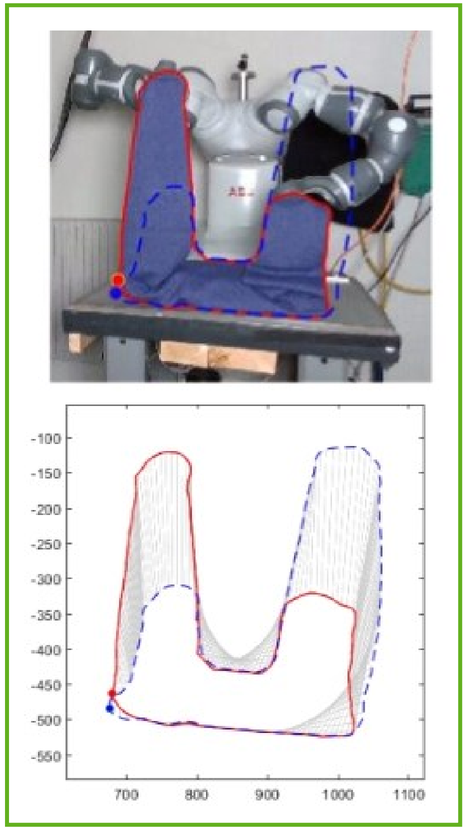


homogeneous map (conventional approach)



elastic map (ours)

Control: Fourier-based deformation Jacobian estimation

Cuiral-Zueco, I., et al., *IEEE ICRA*, 2022.
Cuiral-Zueco, I., et al., Workshop, *IEEE ICRA*, 2023.
Cuiral-Zueco, I., et al., *IEEE Robotics and Automation Letters*, 2023.
Cuiral-Zueco, I., et al., *Lecture Notes in Networks and Systems, Springer*, 2024.
Cuiral-Zueco, I., et al., *Robotics and Autonomous Systems, Springer*, 2025.

Objectives and structure

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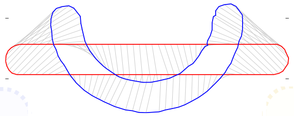
elastically mapped contours



current contour

target contour

elastic curve mapping → object compliant shape control → control actions for low deformation paths

Object-compliant shape control

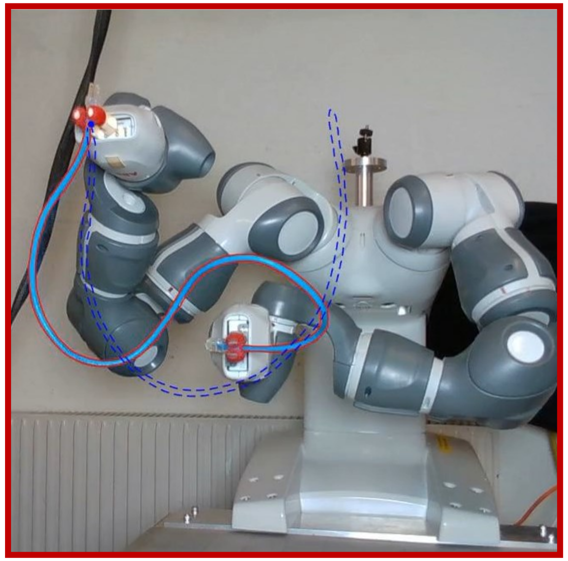
Challenges

- Object's have physical deformation limits
- We only have visual information

Our object-compliant control solution:

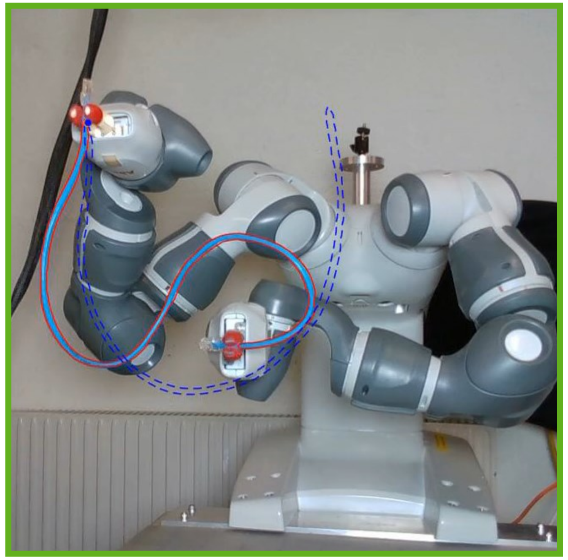
- Offline Jacobian estimation + online updates
- Exploits our elastic mapping
- Minimises joint intrinsic-extrinsic shape energy
- SE(2) invariant

Conventional shape control



high stress = risk to object ✗

Object-Compliant Shape Control



low deformation path ✓

Object: ethernet cable
Task: reach U-like shape

Cuiral-Zueco, I., et al., *IEEE ICRA*, 2022.
Cuiral-Zueco, I., et al., Workshop, *IEEE ICRA*, 2023.
Cuiral-Zueco, I., et al., *IEEE Robotics and Automation Letters*, 2023.
Cuiral-Zueco, I., et al., *Lecture Notes in Networks and Systems, Springer*, 2024.
Cuiral-Zueco, I., et al., *Robotics and Autonomous Systems, Springer*, 2025.

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II. Deformable object perception

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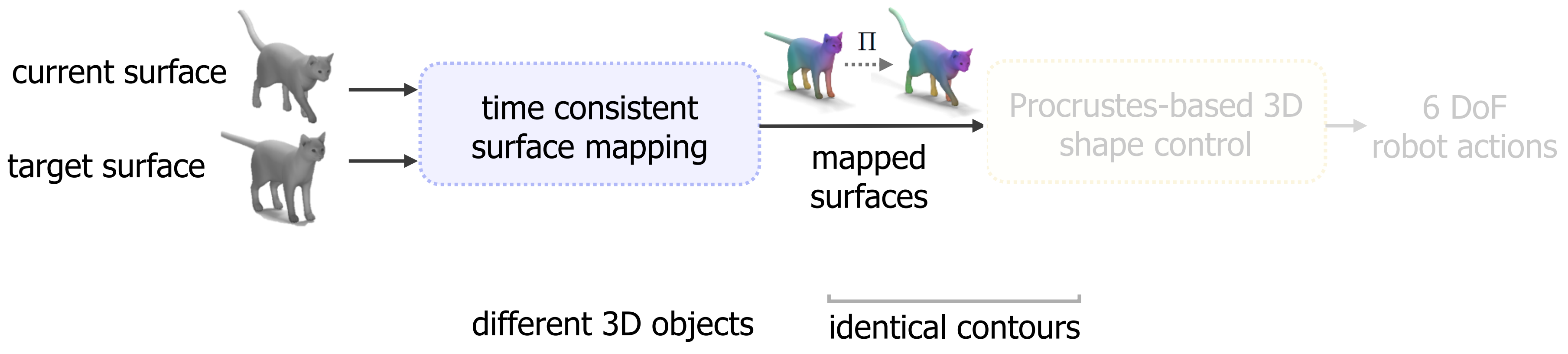
- Map surfaces to infer realistic deformations
- Ensure consistent mapping through deformation process

- Control 3D shapes without offline object exploration
- Maintain robustness to singularities and disturbances

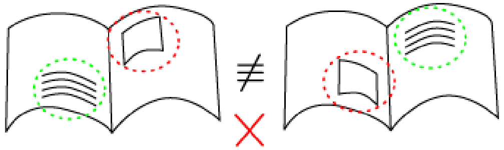


Shape as surface: shape comparison

Existing shape control methods compare surfaces through:

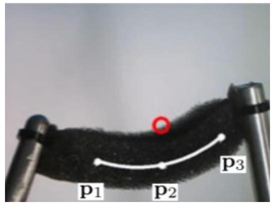
Visual features

[M. Shetab-Bushehri et al., 2022]

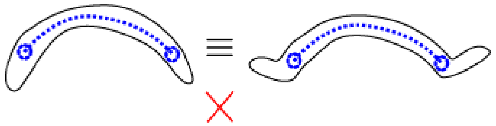


a) Not all objects have rich visual texture,
+ visual texture does not *mean* shape

Object-specific geometric features



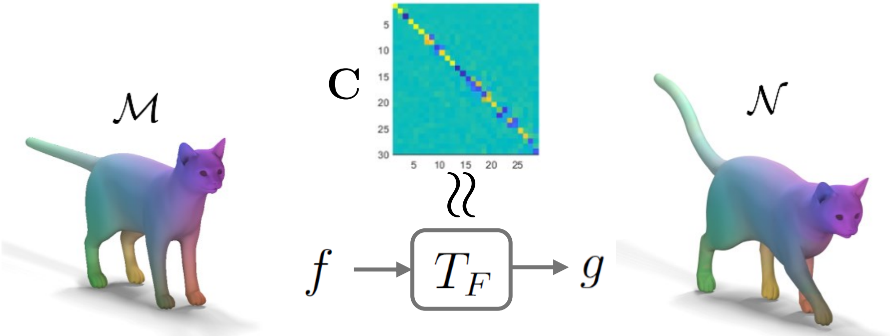
[D. Navarro-Alarcón et al., 2013]



b) poor generalization + parts of the object are left out

Functional maps (computer graphics literature):

- Holistic static surface comparison
- No visual texture, pure shape analysis ✓
- Can I just apply these methods to **non-ideal, time-evolving** meshes with **weak geometric features**, generated from **real, noisy sensor data**?



f : real-valued function defined over a domain $\mathcal{M}$

g : *equivalent* function, defined over another domain $\mathcal{N}$

[Ovsjanikov, M. et al, 2012]

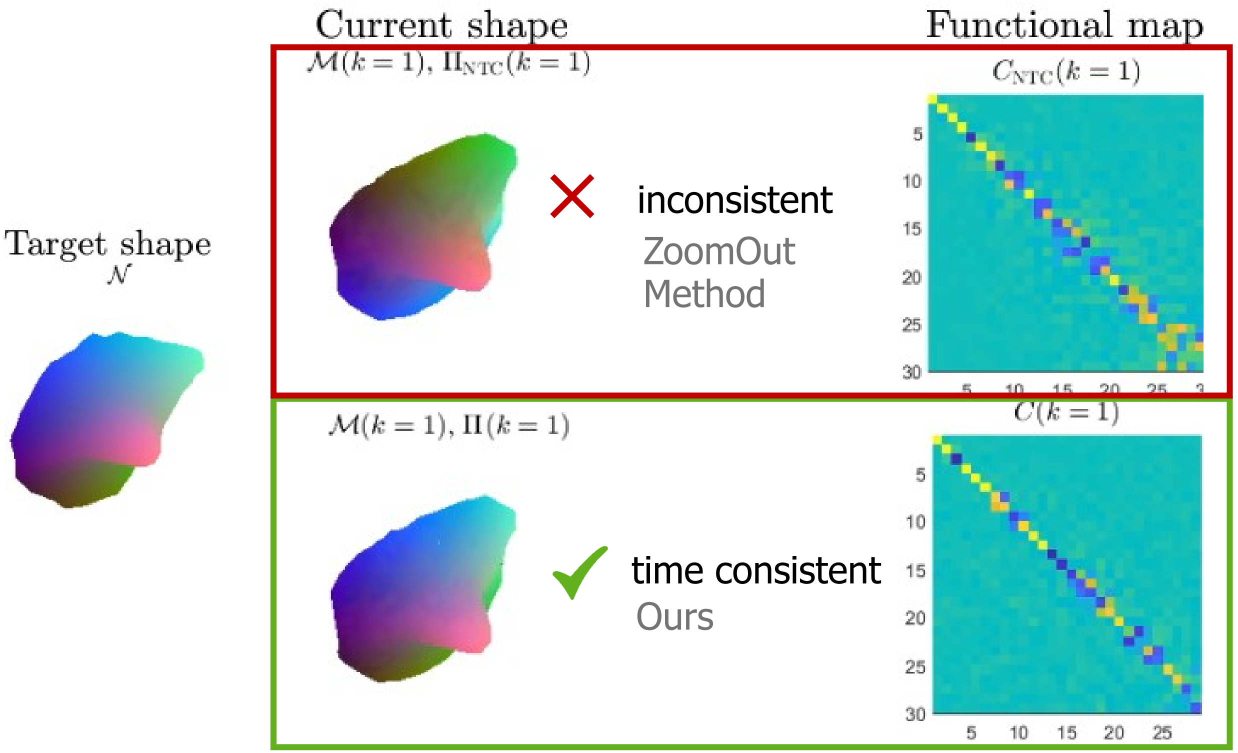
Time consistent surface mapping with functional maps

Challenges

- Noisy, texture-less point clouds
- Symmetries, deformations, *poor* geometry

Our time consistent surface mapping:

- Re-uses of low freq. Laplace eigenfunctions
- Keeps Eigen-basis sign consistent
- Robust to non-isometries



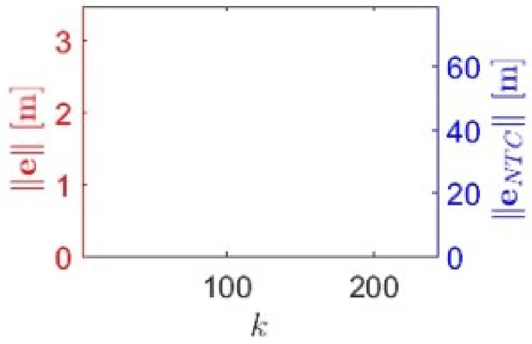
Object: hat

Cuiral-Zueco, I. et al., *IEEE Transactions on Automation Science and Engineering*, 2025.

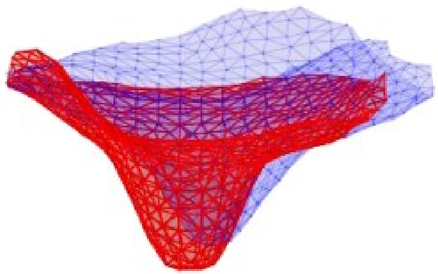
Time consistent surface mapping: shape control

General camera view

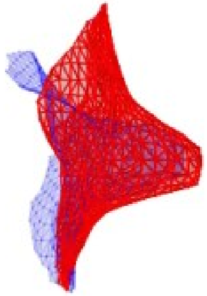
Our error /inconsistent error



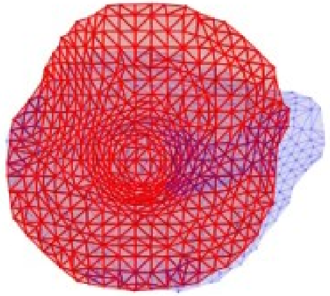
Top view



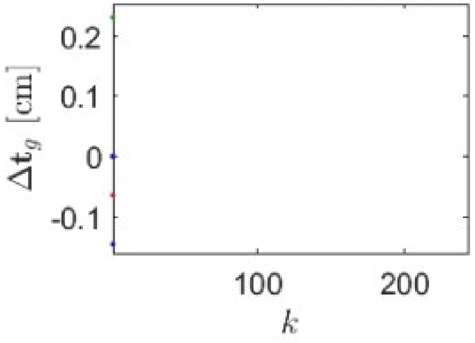
Side view



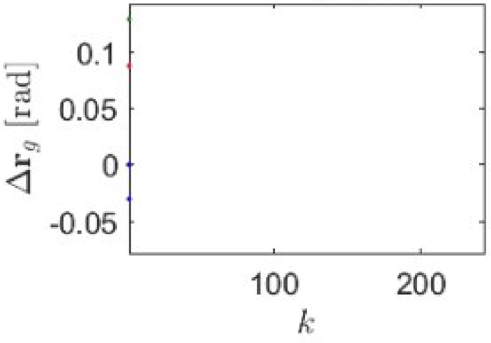
Front view



Translation (x, y, z)



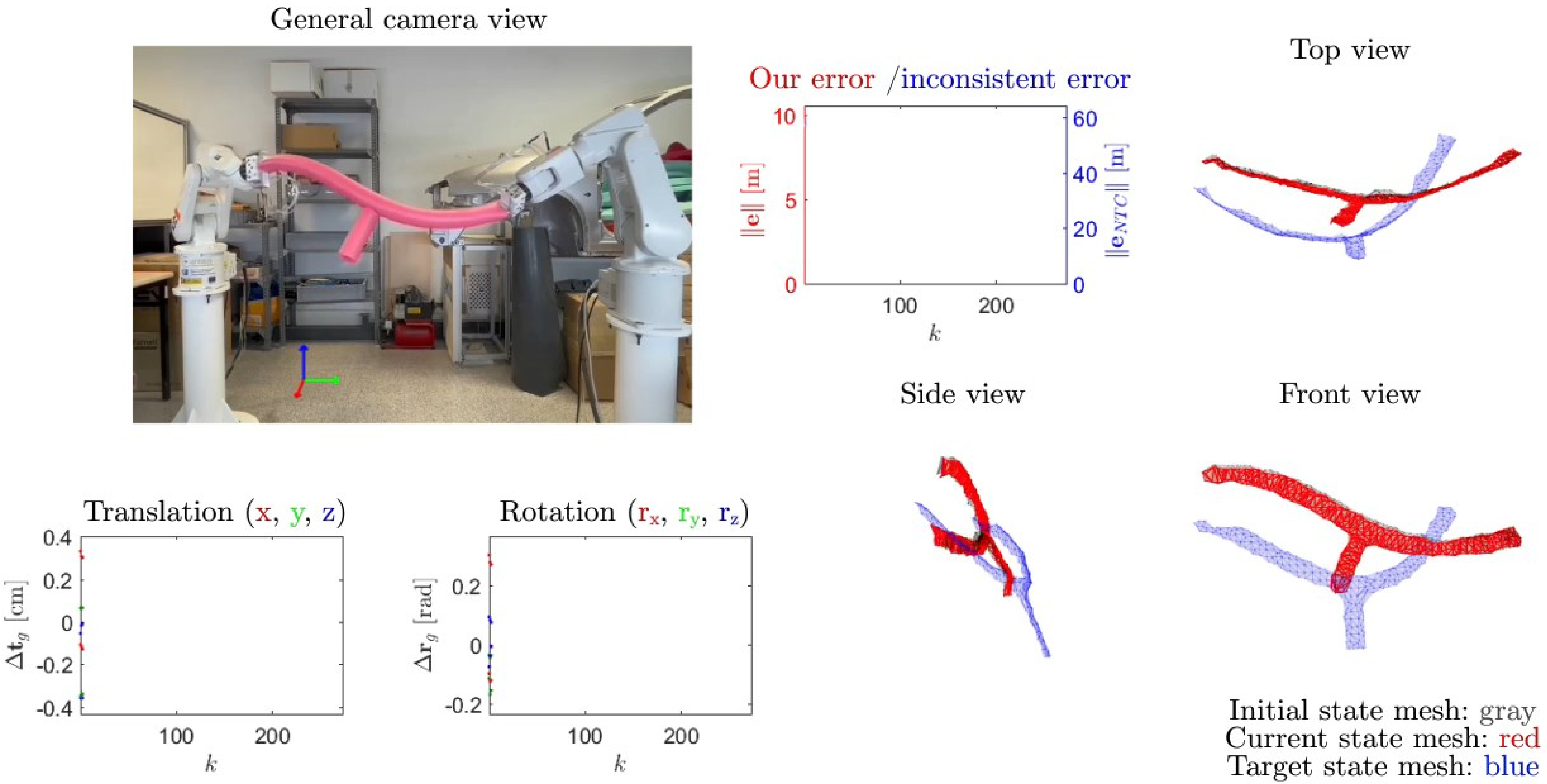
Rotation (r_x, r_y, r_z)



Initial state mesh: gray
Current state mesh: red
Target state mesh: blue

Cuiral-Zueco, I. et al., *IEEE Transactions on Automation Science and Engineering*, 2025.

Time consistent surface mapping: shape control



Deformation Jacobian: offline estimated and online updated

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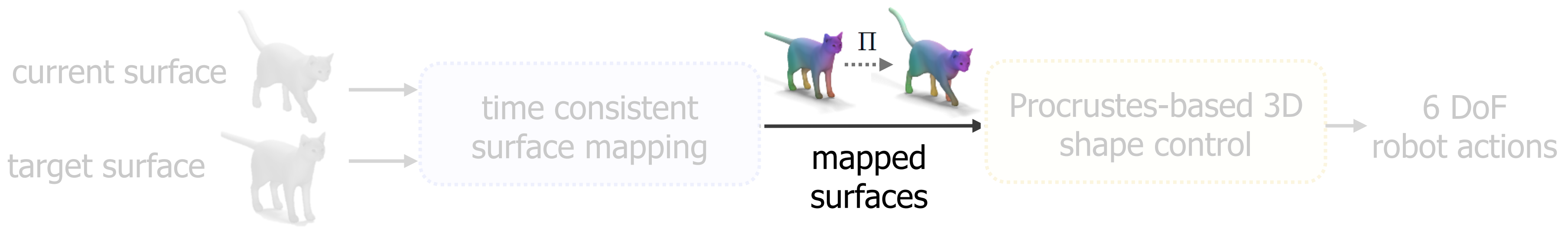
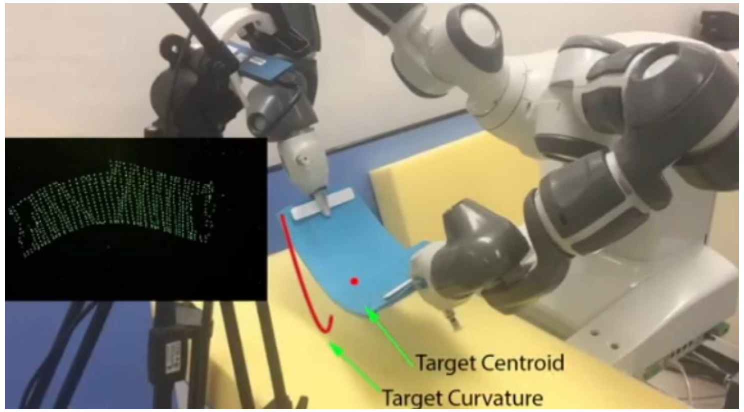


3D shape control of surfaces

Existing surface control approaches

- Few analysed features ⇒ incomplete shape control
  [Hu et al., 2018 , M Shetab-Bushehri et al., 2022]
- Offline object exploration ⇒ impractical for industrial processes
  [Navarro-Alarcon et al., 2016; Hu et al., 2018]



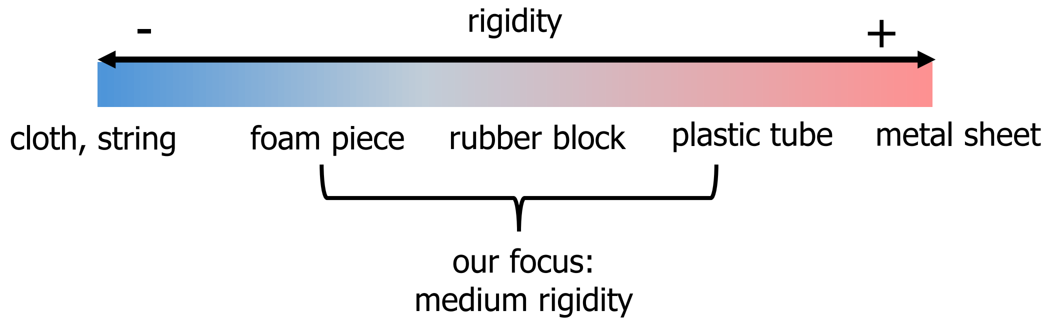
[Hu et al., 2018]

Our goals

- Control entire object geometry
- Online process: no offline object exploration
- Robust against singularities and disturbances

However

- Achieving these goals for all object types is unrealistic



Procrustes-based 3D shape control

Challenges

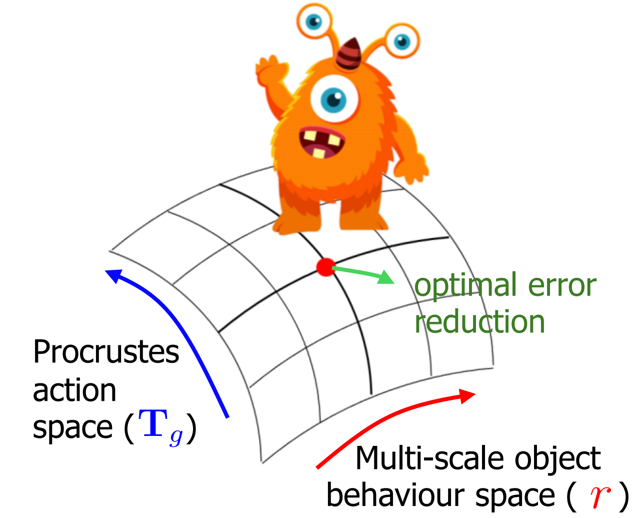
- Control entire object geometry
- Offline object behaviour exploration ⇒ impractical

Our 3D surface shape online control:

- Exploits time consistent surface mapping
- Optimisation in SE(3), Procrustes geodesics
- Lyapunov stability (local)

$$\frac{\mathrm{d}x}{\mathrm{d}t} = f(x(t), u(t))$$

infinitely dimensional, underactuated nonlinear system

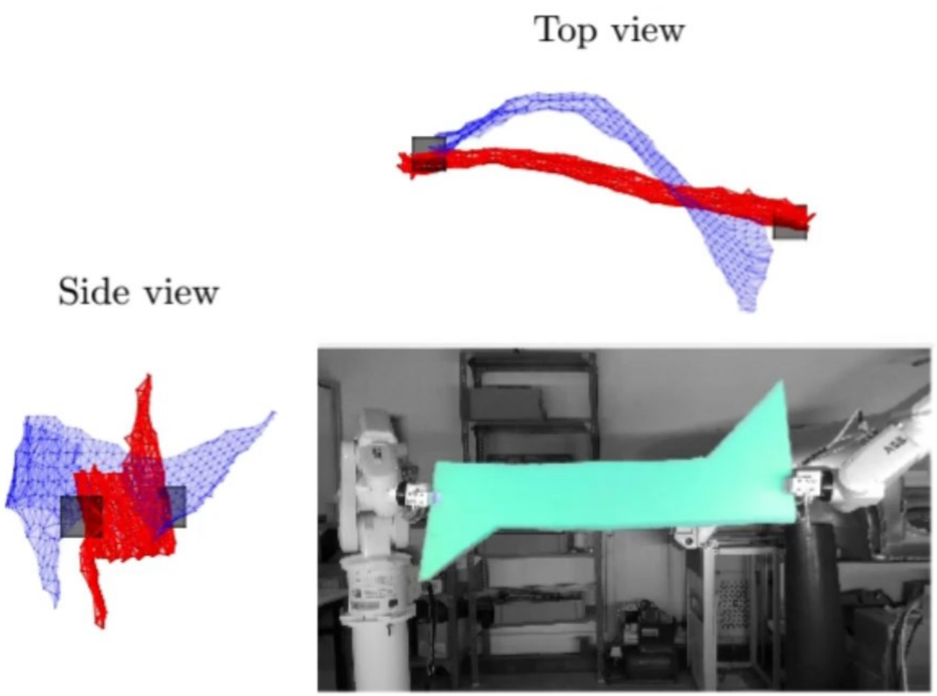


$$r^*(t) = -\int_{t_0}^{t} \frac{\partial q(t, r^*(t))}{\partial r} + r^*(t_0)$$

Reduced to the online estimation of a single parameter

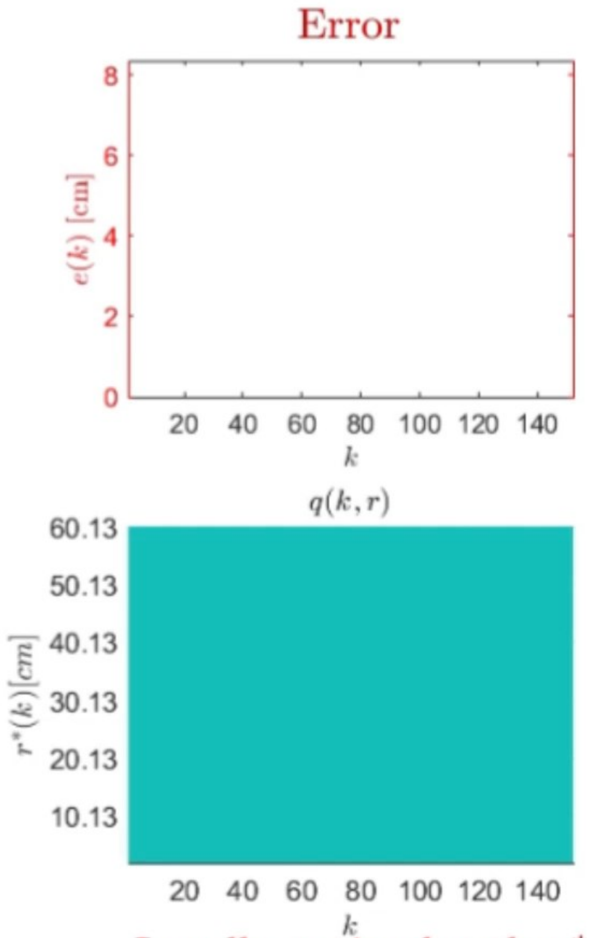
Cuiral-Zueco, I., et al., *IEEE/ASME Transactions on Mechatronics, 2023*.

Procrustes-based 3D shape control: results



Bending + twisting process (x4)

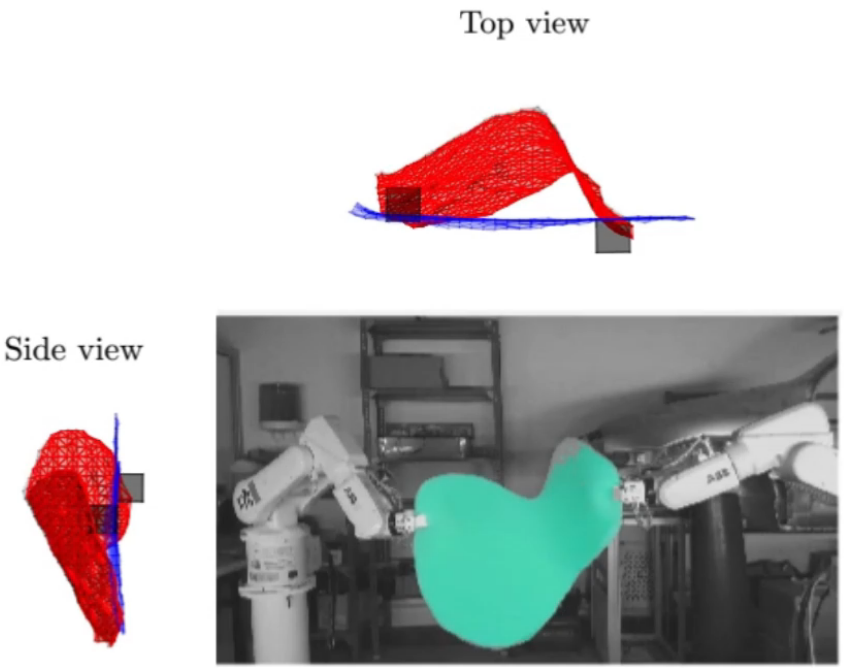
Target shape



Locally optimal scale r*

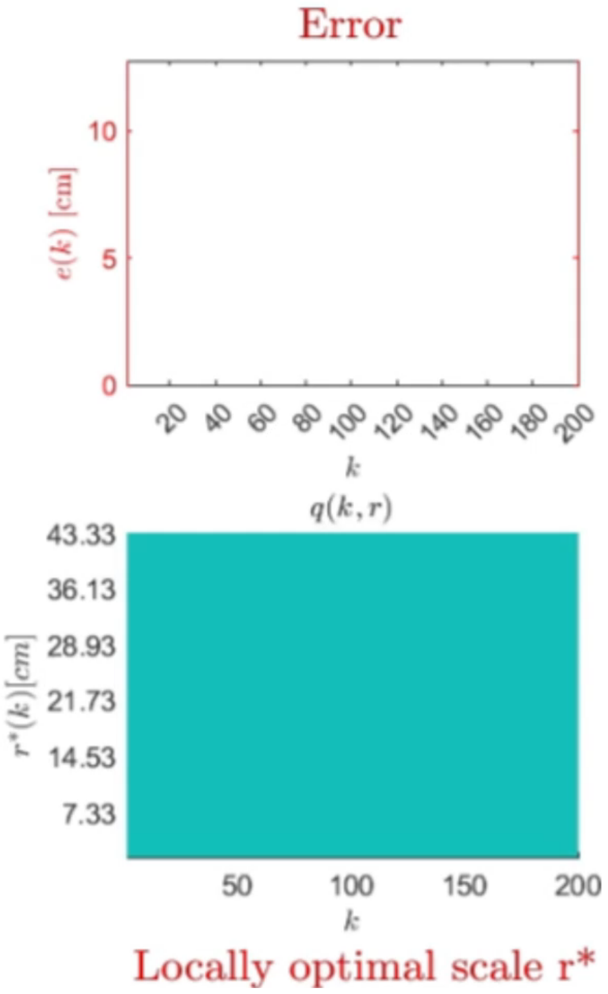
Cuiral-Zueco, I., et al., *IEEE/ASME Transactions on Mechatronics, 2023*.

Procrustes-based 3D shape control: results



Challenging case:

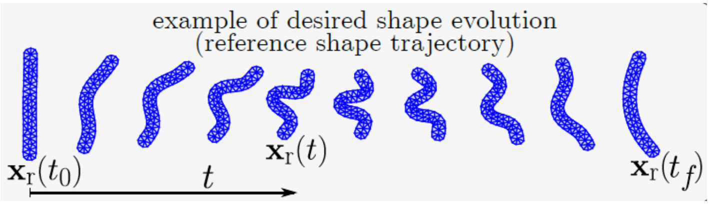
- Really high rigidity shape
- Un-modelled buckling process (treated as large disturbance)



Cuiral-Zueco, I., et al., *IEEE/ASME Transactions on Mechatronics, 2023*.

Objectives and structure

- Use time-varying shape evolution as control reference
- Predict and control non-quasistatic responses
- Stability and reachability analysis



desired target shape trajectory

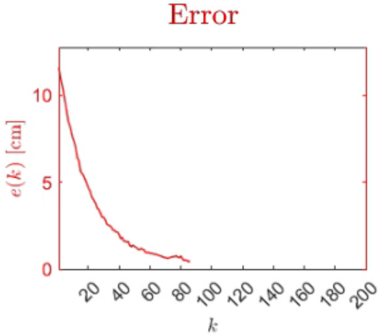
Controller:
- Koopman-based
- Bilinear model

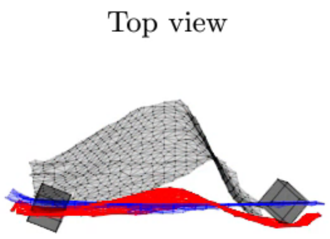
→ robot actions

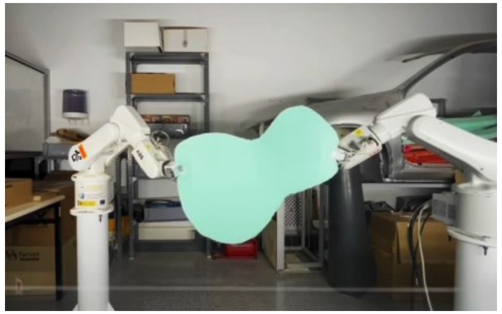
Shape trajectory control

Challenges

- Model and control non-quasistatic behaviour
- *Highly* non-linear





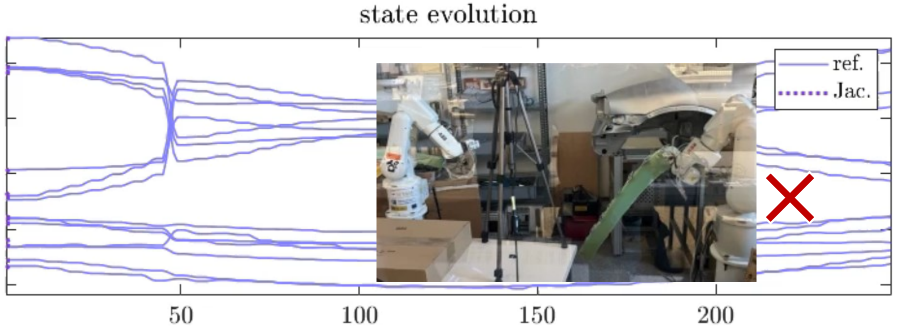


Our Procrustes control: rejected the buckling *disturbance* but did not predict it

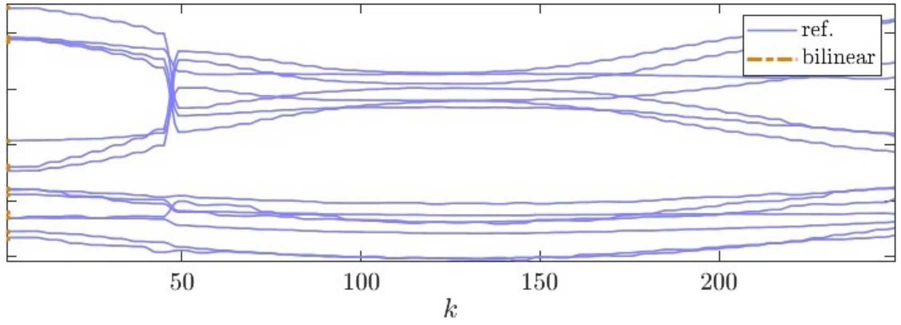
Our shape trajectory control system

- SINDY (Sparse Identification of Non-linear Dynamics)
- Koopman and Bilinear models
- Lie algebra transitivity analysis (reachable space) + Global uniform ultimate boundedness (GUUB)

Jacobian (conventional)



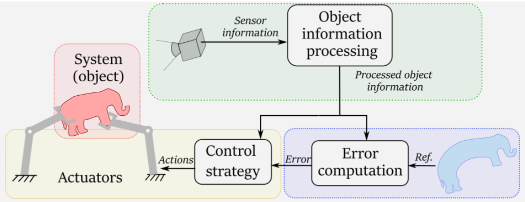
Bilinear (ours)



So far...

Taxonomy for deformable object shape control:

1. First taxonomy in the literature.



Optimal deformable object perception:

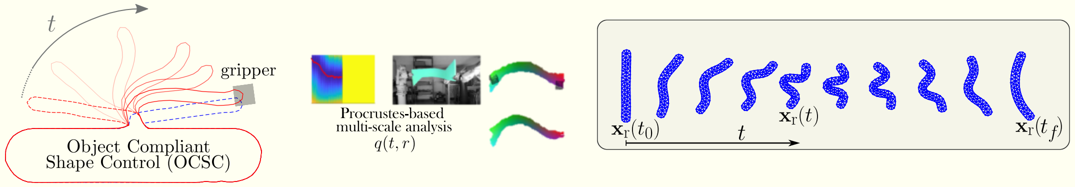
2. Active perception system with Next Best View and occlusion avoidance.

Holistic shape analysis and comparison from real data (contours and surfaces)

3. Multi-scale elastic contour mapping (FMM, Laplacian descriptors).
4. Time-consistent surface mapping (Functional Maps).

Novel shape control methods for deformable object

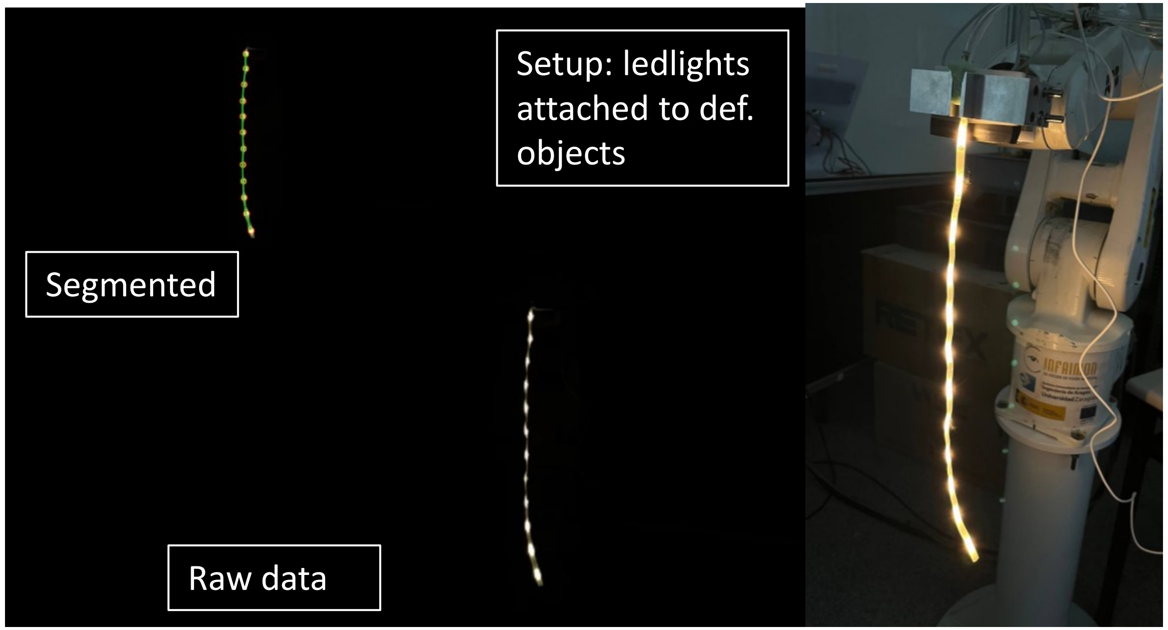
5. Contour-based Object-Compliant Shape Control (OCSC).
6. Pure-online Procrustes-based surface shape control.
7. Shape Trajectory Control: Koopman and Bilinear formulations.



\+ automatic gripper positioning method, and abrupt deformation estimation method

What's next? (1/3)

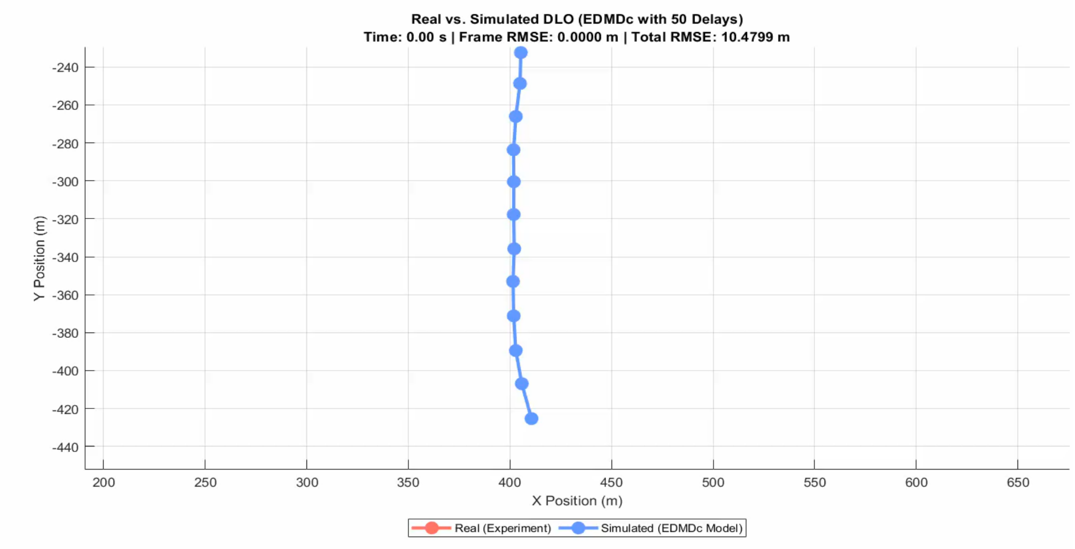
- Identification and control of highly dynamic systems (the *not-so-pleasantly* quasi-static kind)



Groundtruth data obtention of object material points
240 fps, otherwise, motion blur ruins segmentation

Promissing directions…

- Extended Dynamic Mode Decomposition + Control
- Order reduction to achieve real-time nonlinear MPC just from robot hand sensor data (not vision dependent)



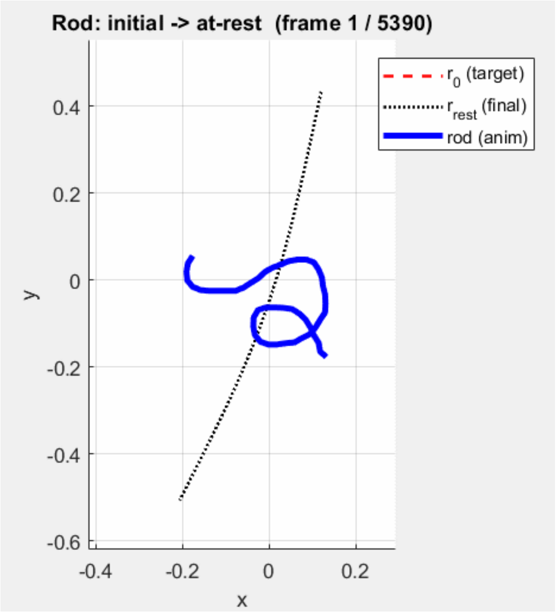
DMDc (with delays) open-loop estimation

What’s next? (2/3)

- Task-oriented feasible target shape definition
  - In all the experiments we saw, target shapes were defined by pre-acquiring the object state as a snapshot
  - Defining task-relevant target shapes (planning) that are compliant with the object AND the robot system… seems interesting

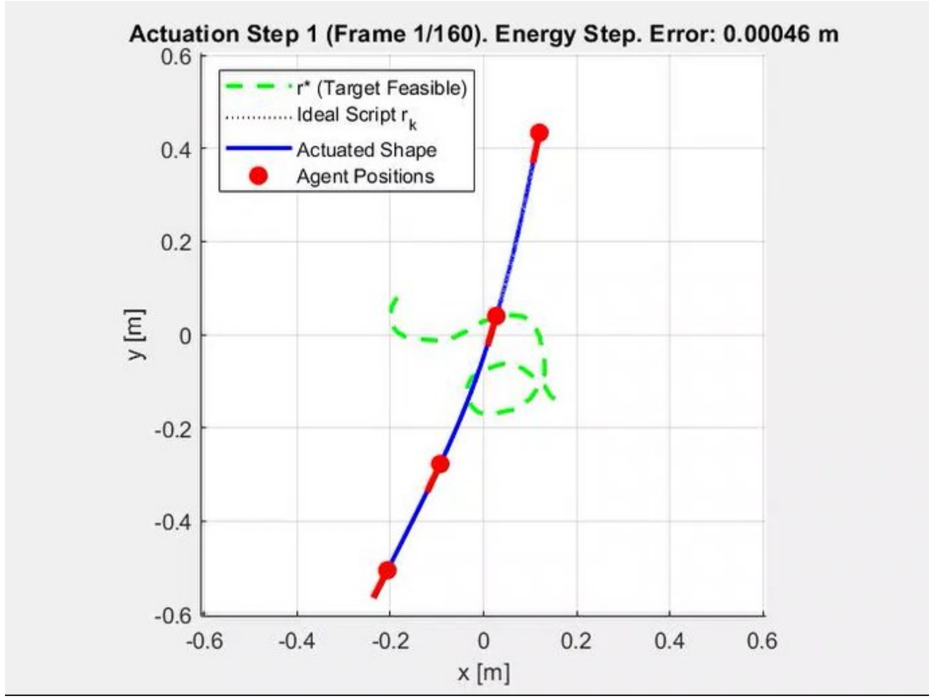
Promising directions…

- Cosserat rod model variational analysis + optimal grasping point definition
- Force-based control, impedance-based control



Free-rod relaxation from arbitrary target shape

Physical-feasibility analysis (strain limits) + agent-pose optimisation



Shape control with 4 agents

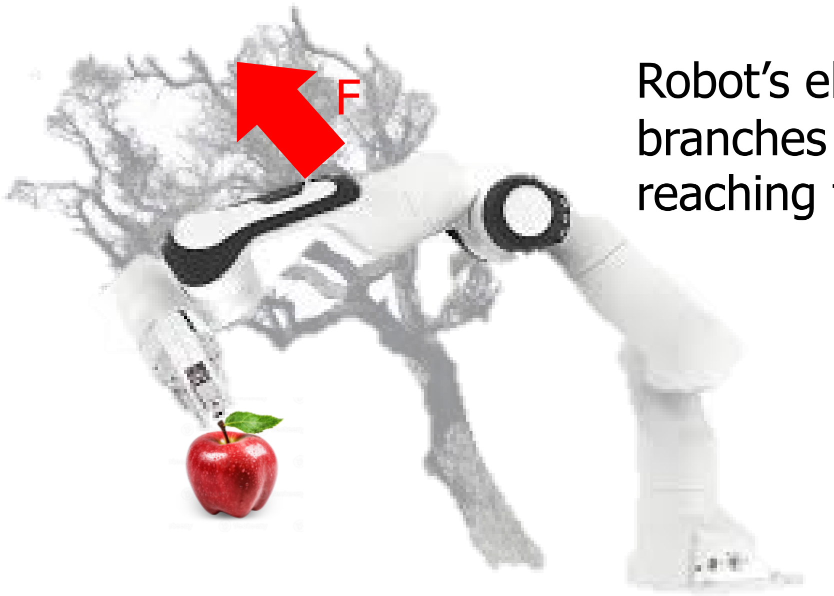
What’s next? (3/3)

- Non-prehensile multi-contact (whole-body) manipulation
  - Coordinating Prehensile and Non-Prehensile Contacts
  - With particular focus in agriculture (but generalizable to other manufacturing processes)
  - Basically pushing obstacles away while manipulating other objects

Promising directions…

- Impedance-based control, virtual force analysis
- Cosserat rod model + friction-cone definition and control (CBFs?) to avoid slippage

Occluded fruits
(branches = obstacles)



Robot’s elbow pushes branches away while reaching for the apple

Presentation based on these publications (first author):

Journals:
1. *RGB-D Tracking and Optimal Perception of Deformable Objects*, **IEEE Access**, 2020.
2. *Contour-Based Object-Compliant Shape Control*, **IEEE RA-L**, 2023.
3. *Taxonomy of Deformable Object Shape Control*, **IEEE RA-L**, 2024.
4. *Deformable Object Shape Trajectory Control with Data-Driven Models*, IEEE/ASME T-MECH (under review).
5. *Multiscale Procrustes-Based 3D Shape Control*, **IEEE/ASME T-MECH**, 2024.
6. *Time-Consistent Surface Mapping for Shape Control*, **IEEE T-ASE**, 2025.
7. *Multi-Scale Elastic Contour Mapping for Shape Control*, **ELSEVIER RAS**, 2025.

Conference Papers:
1. *Gripper Positioning for Object Deformation Tasks*, **ICRA**, 2022.
2. *Multi-Scale Laplacian-Based FMM for Shape Control*, **IROS**, 2021.
3. *Dynamic Occlusion Handling for Real-Time Object Perception*, **ICRAE**, 2020.
4. *Elastic Contour Mapping for Estimation of Abrupt Shape Deformations*, **ROBOT**, 2023.

Workshops:
1. *RGB-D Sensing of Challenging Deformable Objects*, Workshop on Managing Deformation, **IROS** 2020.
2. *Mesh Estimation for Abrupt Deformations of Texture-Less Objects*, Workshop on Representing and Manipulating Deformable Objects, **ICRA** 2023.

Data-driven manipulation and control of deformable objects

Thanks!

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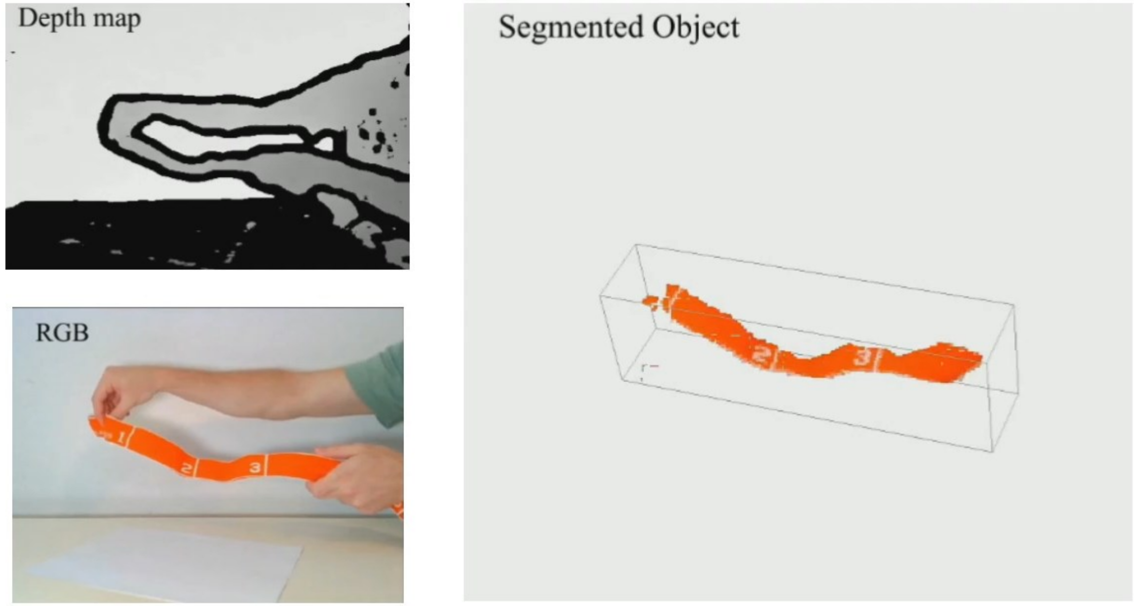

Experiment videos

General research interests: to develop novel techniques for the **perception, shape analysis, and control** of deformable objects.

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