Beyond Rigid Worlds: Representing and Interacting with Non-Rigid Objects (RINO) @ CoRL2025

Real-Time Tracking of Origami with Physics Simulator Considering Fold Lines

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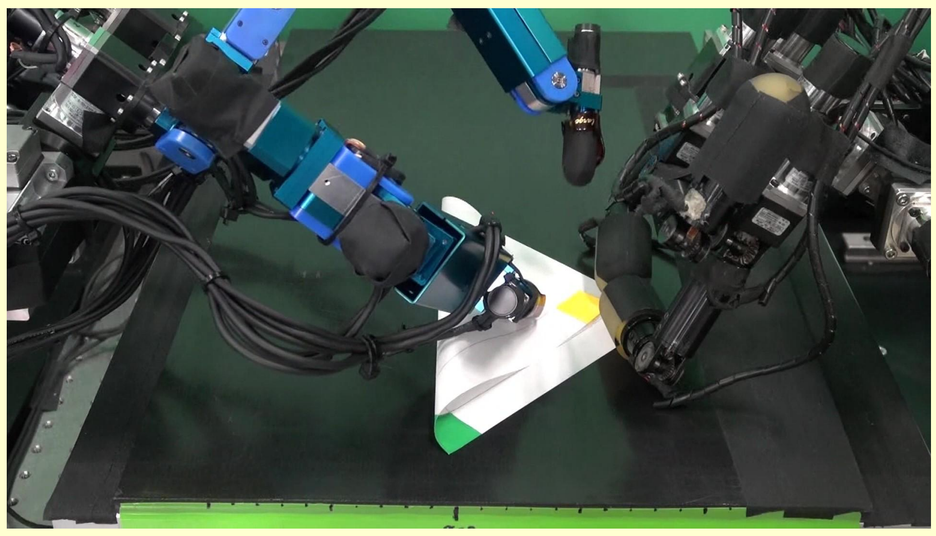
Robotic Origami Folding

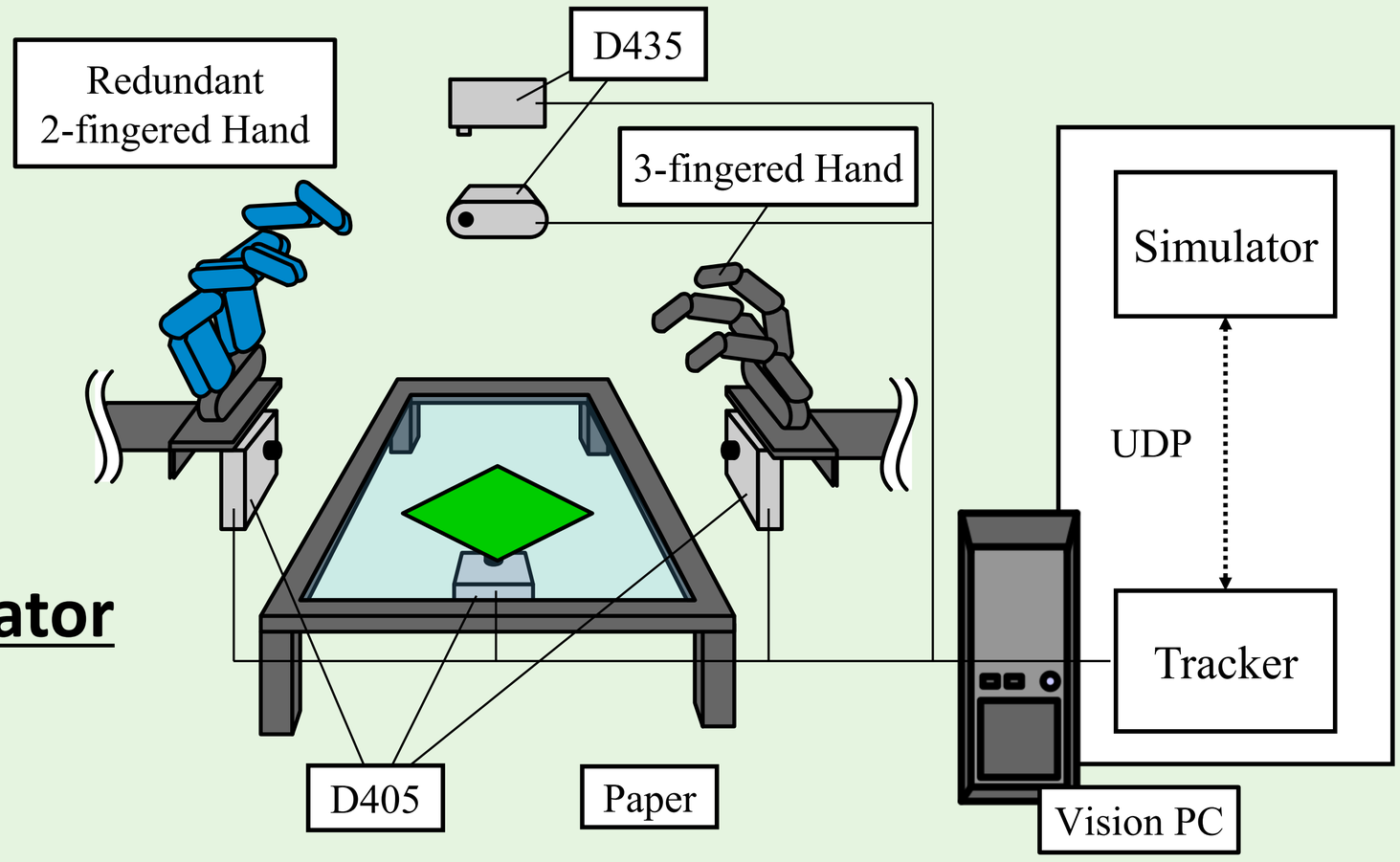
- **Difference from cloth or rope:**
  - Bending elasticity
  - Plastic Deformation (Fold line)
- **Succeeded in twice valley triangular folds**



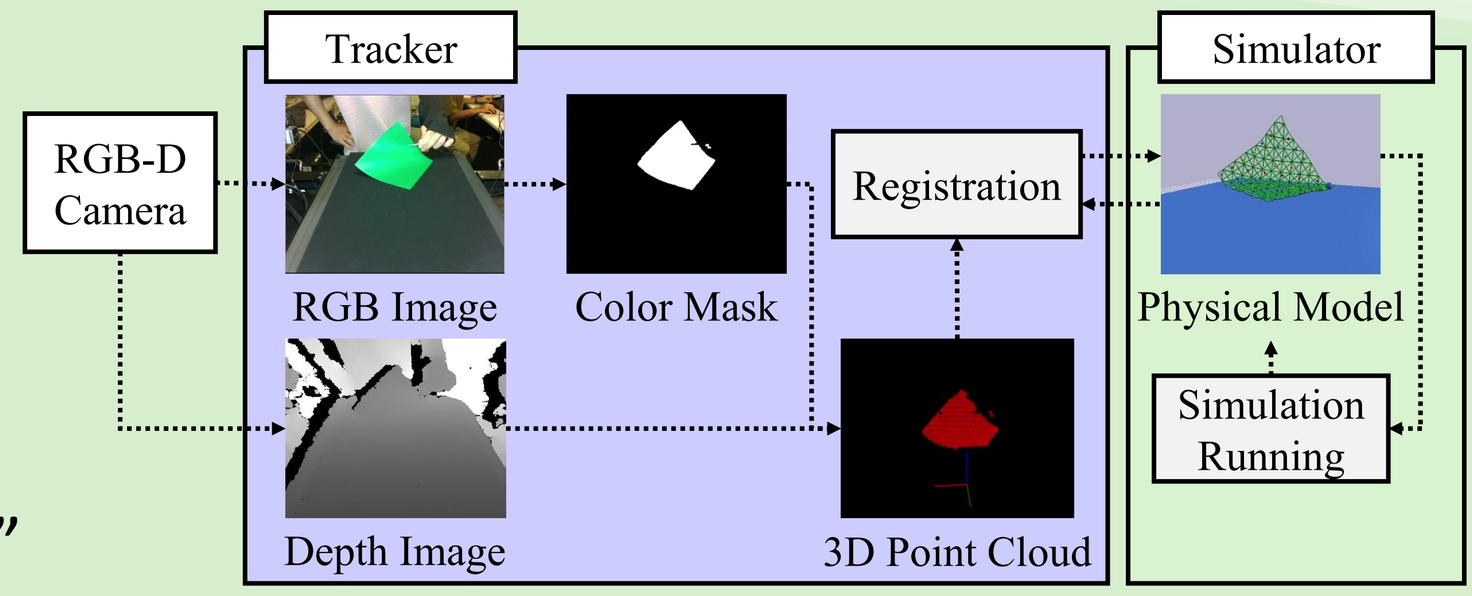
- **Paper Shape Recognition**
  - Difficulty with complex

Paper-Shape Tracking System

- **RGB-D Sensor**
  - Intel RealSense D435 (overhead, rear)
  - Intel RealSense D405 (left, right, below)
- **Real-time Digital Twin Simulator**
- **Paper Detection**
  - mask from RGB image
  - obtain 3D Point Cloud Data
- **Simulation**
  - Predict paper's 3D deformation
- **Point Cloud Registration**
  - Match the "model PCD" to "observed PCD"
  - Coherent Point Drift (CPD)



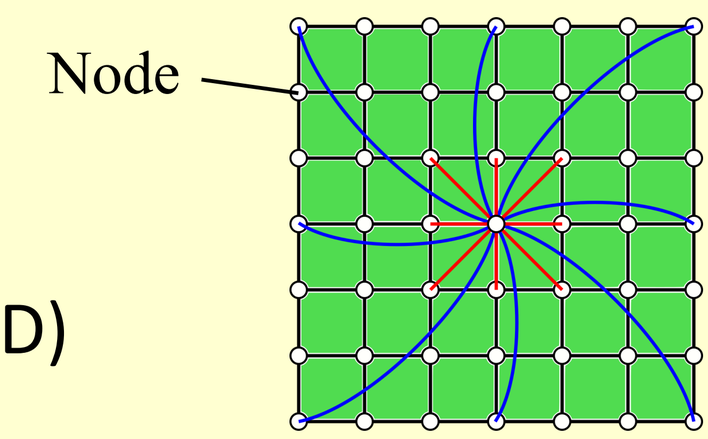
System Overview

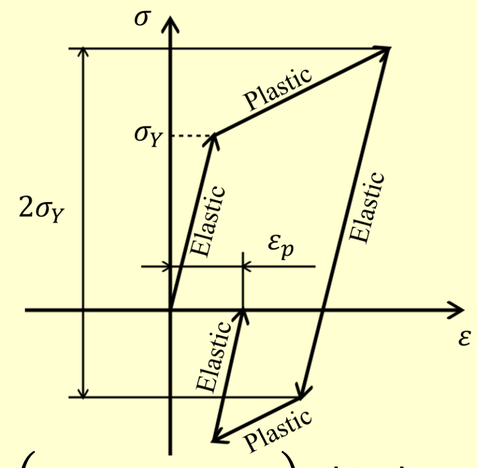


Processing Pipeline

Simulator

- **Realtime Simulation**
  - Substep Extended
    Position Based Dynamics (XPBD)
- **Physical Model**
  - Mass-link array model (spring, damper)
  - Elastoplastic spring (α, Δl_p)





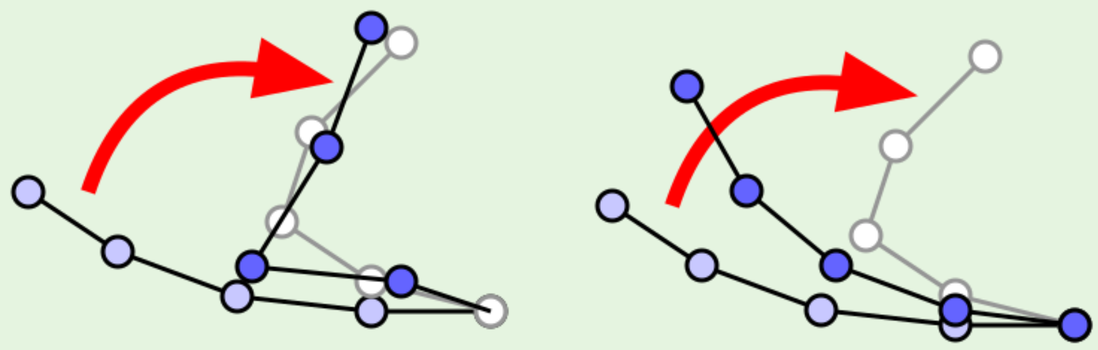
$$\Delta \boldsymbol{x}_j = \frac{|\Delta \boldsymbol{p}| - (l + \Delta l_p) - \gamma \Delta \boldsymbol{p} \cdot \left(\boldsymbol{x}_{j_{\text{new}}} - \boldsymbol{x}_{j_{\text{old}}}\right)/|\Delta \boldsymbol{p}|}{m_j \left(m_1^{-1} + m_2^{-1} + \frac{\alpha}{\Delta t_s^2}\right)} \frac{\Delta \boldsymbol{p}}{|\Delta \boldsymbol{p}|}$$

Position update by link constraints ($\Delta \boldsymbol{p} = \boldsymbol{x}_i - \boldsymbol{x}_j$)

Damper β:
$\gamma = \alpha\beta/\Delta t_s^2$

Plasticity Localization

- **Trade-off in plasticity**
  - Deformability - Robustness

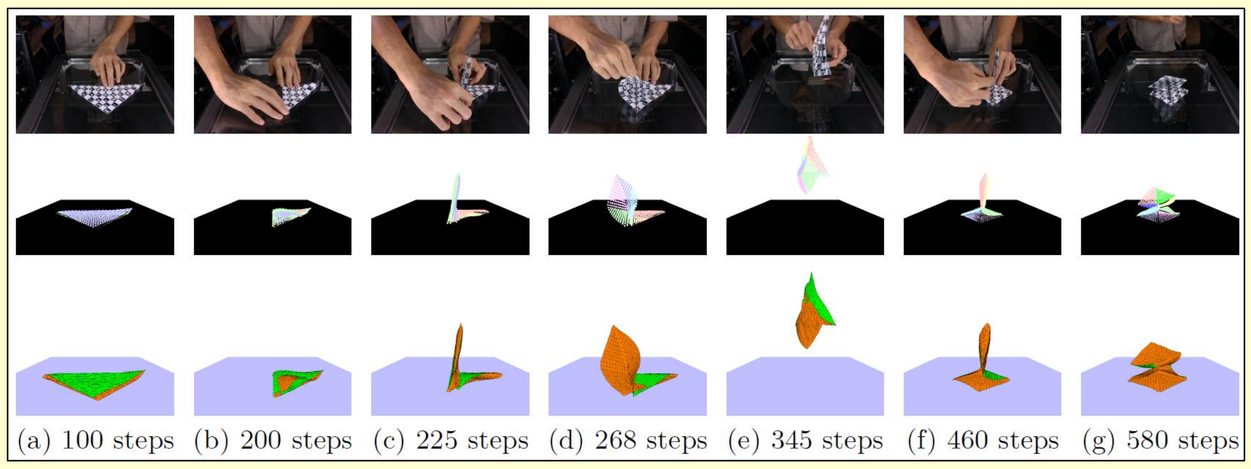


High plasticity Low plasticity

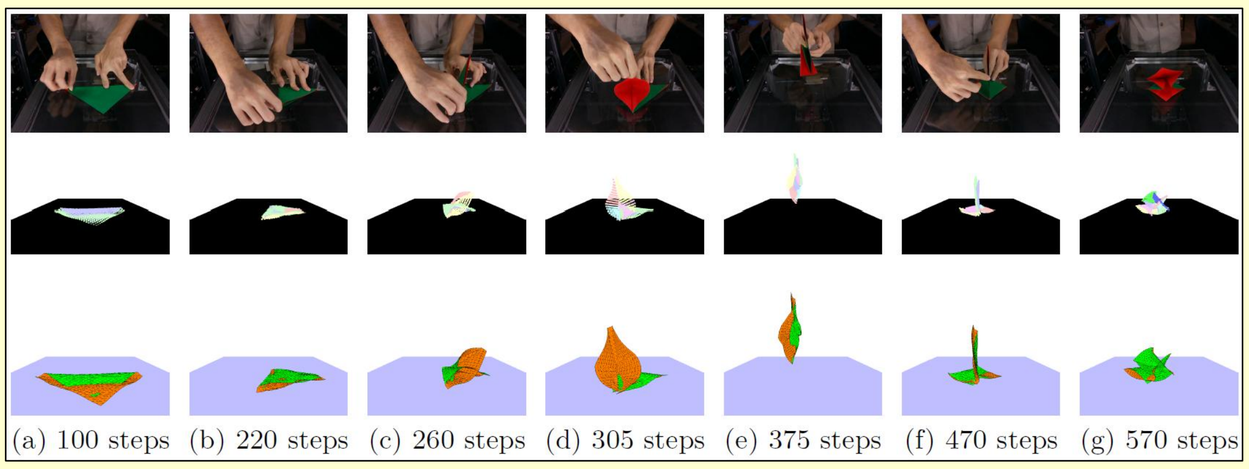
- **Detect fold line as cluster boundaries**
  - Mahalanobis k-means clustering
  - Cluster constraint: Planer distributions
- **Plasticity applied only fold lines**
  - Link has **different** cluster endpoints
    = Fold line. Apply plasticity
  - Link has **same** cluster endpoints
    = Plane. Reset plasticity

- Node Position Data (3D + 2D)
  $\boldsymbol{x} = (x, y, z, u, v)$ parametric
- Mahalanobis Distance
  $d_M(\boldsymbol{x}, \boldsymbol{\mu}) = \sqrt{(\boldsymbol{x} - \boldsymbol{\mu})^{\mathrm{T}} \boldsymbol{\Sigma} (\boldsymbol{x} - \boldsymbol{\mu})}$
- Principal Component Analysis
  $\boldsymbol{\Sigma} = \mathbf{W}^{\mathrm{T}} \boldsymbol{\Lambda} \mathbf{W}$
  $\boldsymbol{\Lambda} = \mathrm{diag}(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5)$
  → replace with small constant

Experiment



ArUco Tracking



CPD Tracking

- **Results & Contributions**
  - **Success in square-base folding** (more complex than valley triangular folds)
- **Limitations**
  - **Model tunneling has occurred**
  - Heuristic parameter tuning
  - Low speed (approximately 5 Hz)
- **Future Work**
  - Address model tunneling problem
  - Optimizing system parameters
  - Accelerating processing