Folding Deformable Objects using Predictive Simulation and Trajectory Optimization

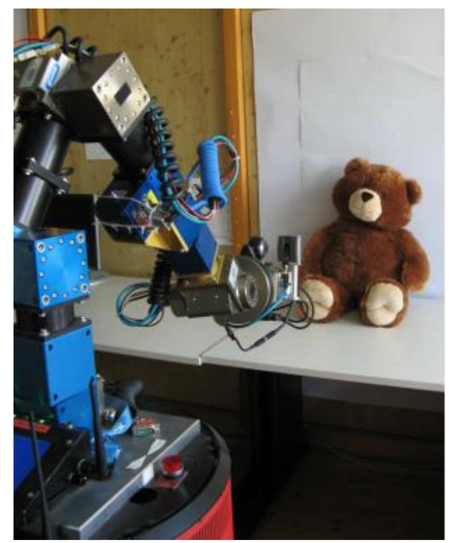
Columbia University

Yinxiao Li, Yonghao Yue, Danfei Xu

Eitan Grinspun, Peter Allen

Columbia University Robotics Group

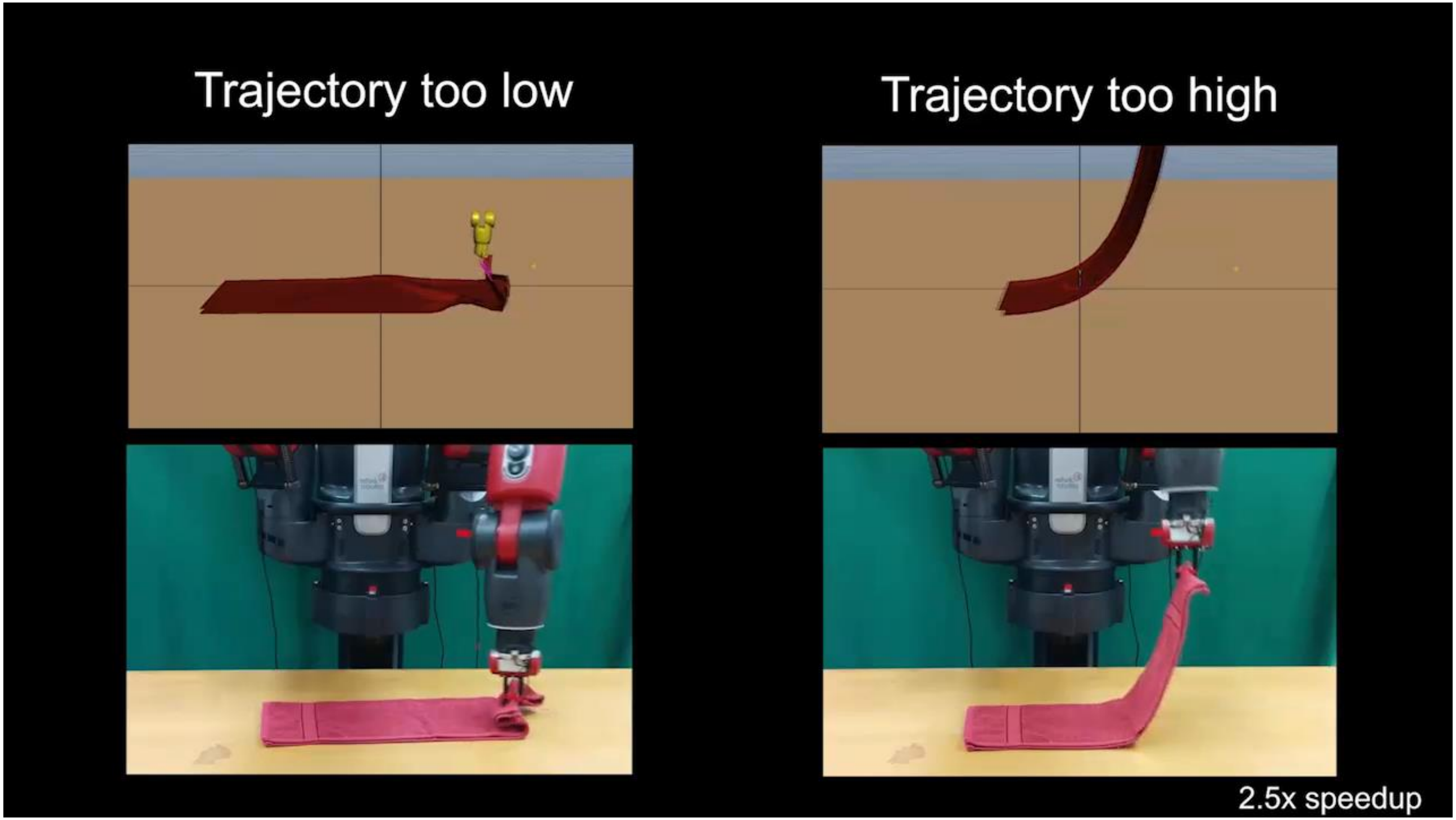
Why do robots need to recognize and manipulate deformable objects?



http://mynorthwest.com/920/2312665/Why-robots-could-soon-replace-fast-food-workers-demanding-higher-minimum-wage
http://www.cs.berkeley.edu/~pabbeel/
http://mynorthwest.com/920/2312665/Why-robots-could-soon-replace-fast-food-workers-demanding-higher-minimum-wage
http://www2.informatik.uni-freiburg.de/~stachnis/pdf/frank10rssws.pdf

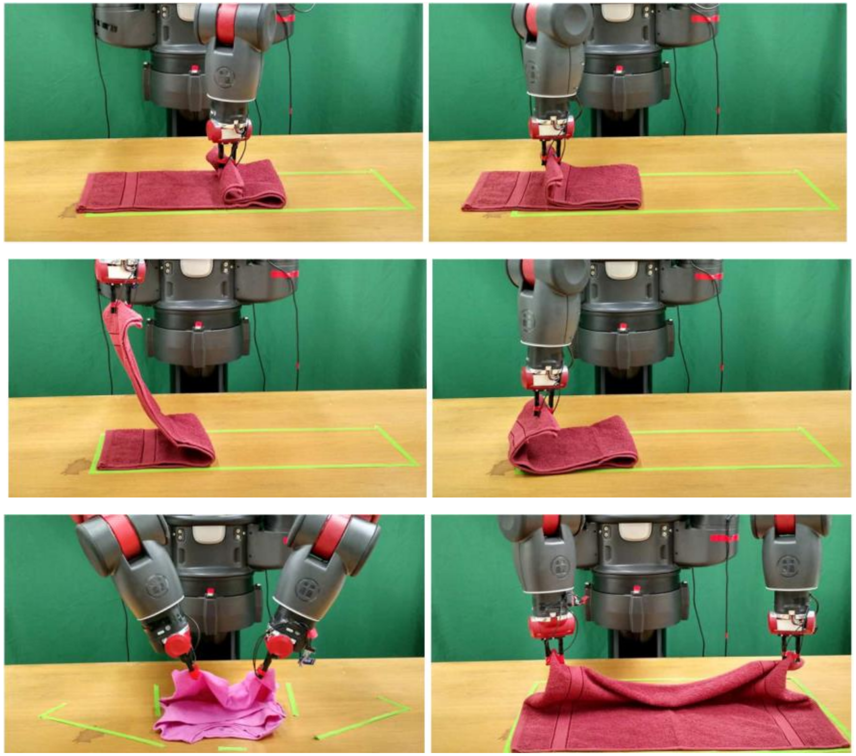
Pipeline

Why trajectory is important?

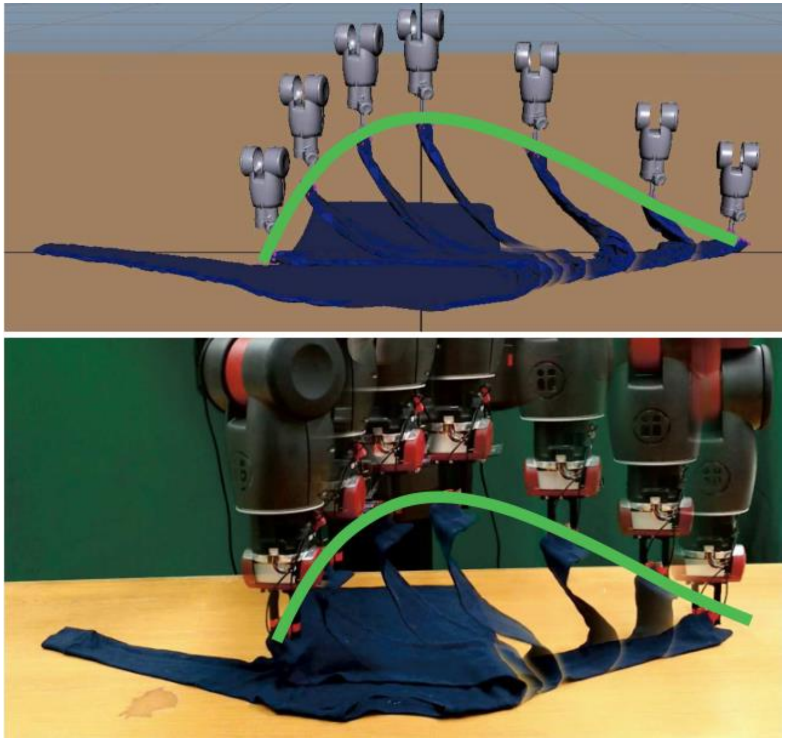


Why trajectory is important?

Problematic scenarios:



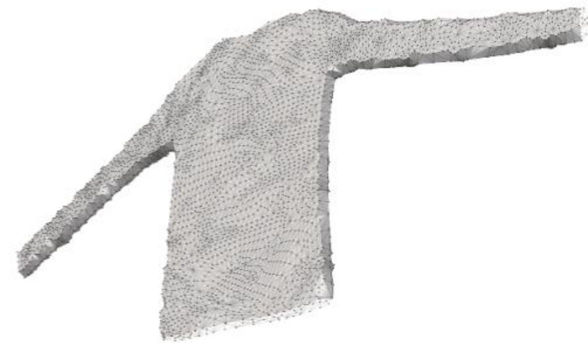
Solution:



Offline Simulation → Trajectory Optimization → Transfer to Robot

Simulation

- **Build the garment model**

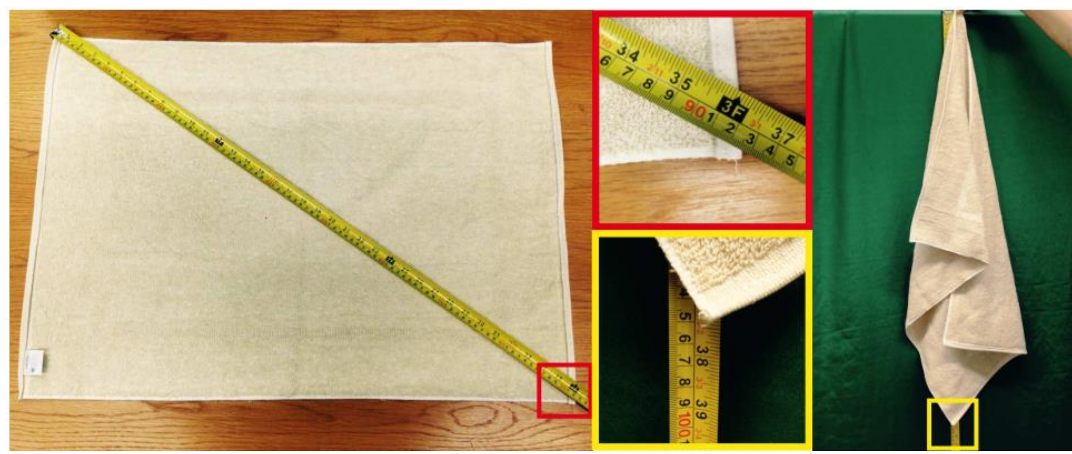


- **Parameter adaptation**
  - **Shear friction**

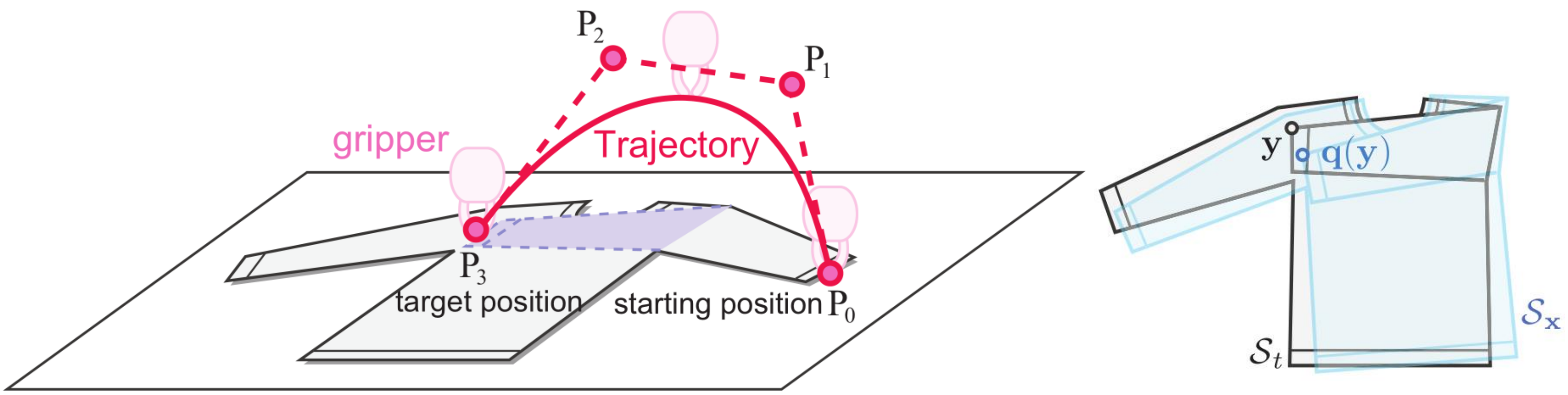
$$shear\_frac = (L_1 - L_2)/L_2$$

  - **Friction force on the able**

$$\angle_{Friction} = \sin^{-1}(H_s/L_t)$$



Trajectory Optimization

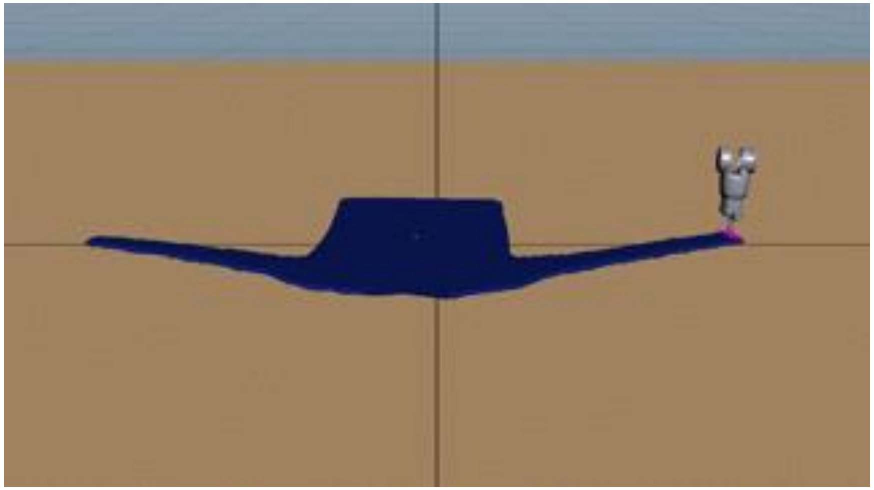


- Initial trajectory --- Bézier curve:

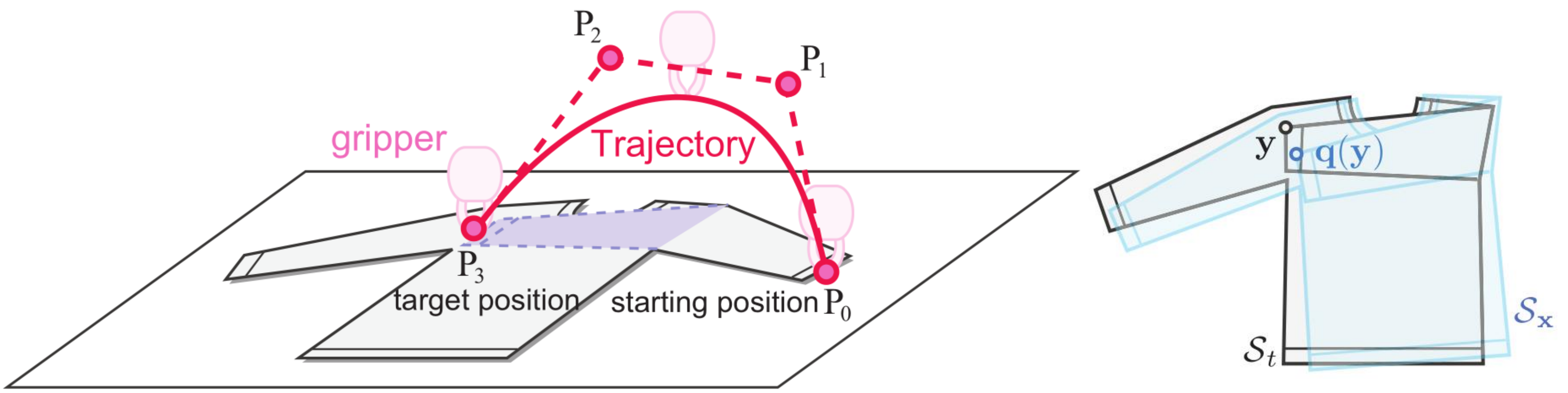
$$\mathbf{T}(u) = \sum_{k=0}^{n} B_k^n(u)\mathbf{P}_k$$

$$\mathbf{P}_1 = \frac{2}{3}\mathbf{P}_0 + \frac{1}{3}\mathbf{P}_3 + h\|\mathbf{P}_0 - \mathbf{P}_3\|\mathbf{e}_v$$

$$\mathbf{P}_2 = \frac{1}{3}\mathbf{P}_0 + \frac{2}{3}\mathbf{P}_3 + h\|\mathbf{P}_0 - \mathbf{P}_3\|\mathbf{e}_v$$



Trajectory Optimization (cont.)



- Initial trajectory --- Bézier curve: $\mathbf{T}(u) = \sum_{k=0}^{n} B_k^n(u)\mathbf{P}_k$
- Optimization Objective:

$$\mathbf{x}_{opt} = \underset{\mathbf{x}}{\operatorname{argmin}} \underbrace{\{l_{\mathbf{x}} + \alpha D(\mathcal{S}_t, \mathcal{S}_{\mathbf{x}})\}^2}_{C(\mathbf{x})}$$

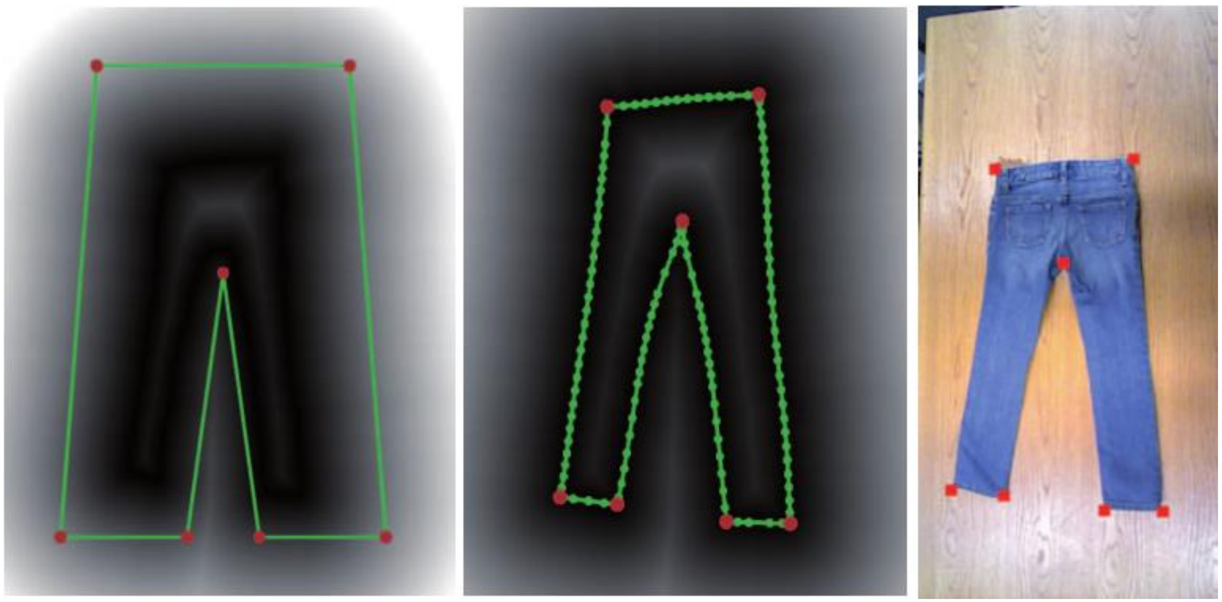
$$\tilde{D}(\mathcal{S}_t, \mathcal{S}_{\mathbf{x}}) = \frac{1}{|\mathcal{S}_t|} \sum_i \|\mathbf{q}_i - \mathbf{y}_i\| A_i$$

Application to garment folding

- Key point localization

$$E_T(S,\bar{S}) = E_{\text{fit}}(S,T) + \boxed{E_{\text{def}}(S,\bar{S})}$$

$$\boxed{E_{\text{def}}(S,\bar{S})} = \kappa E_{\text{stretch}}(\bar{S},\mathbf{x}) + \beta E_{\text{bend}}(\bar{S},\mathbf{x})$$



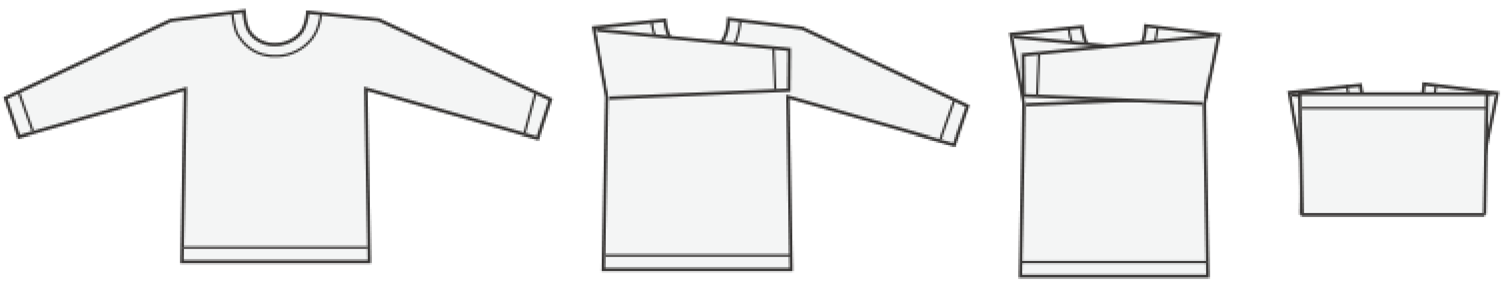
Experimental Results

- Robot setup

- Garment folding candidates

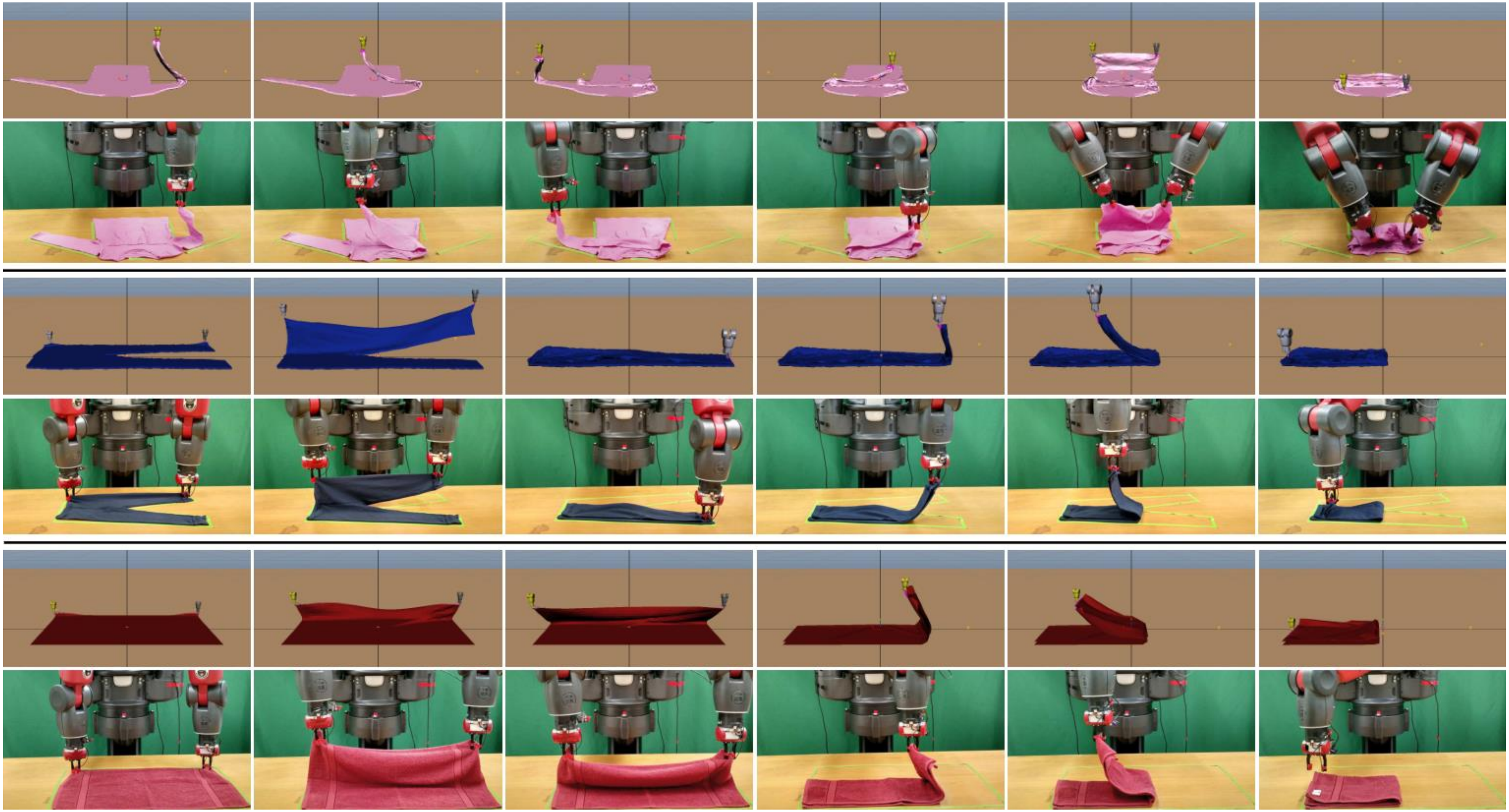
Garment Type
Long-Sleeve T-Shirt (large)
Long-Sleeve T-Shirt (small)
Jeans
Pants
Large Towel
Medium Towel
Small Towel

Experimental Results (cont.)

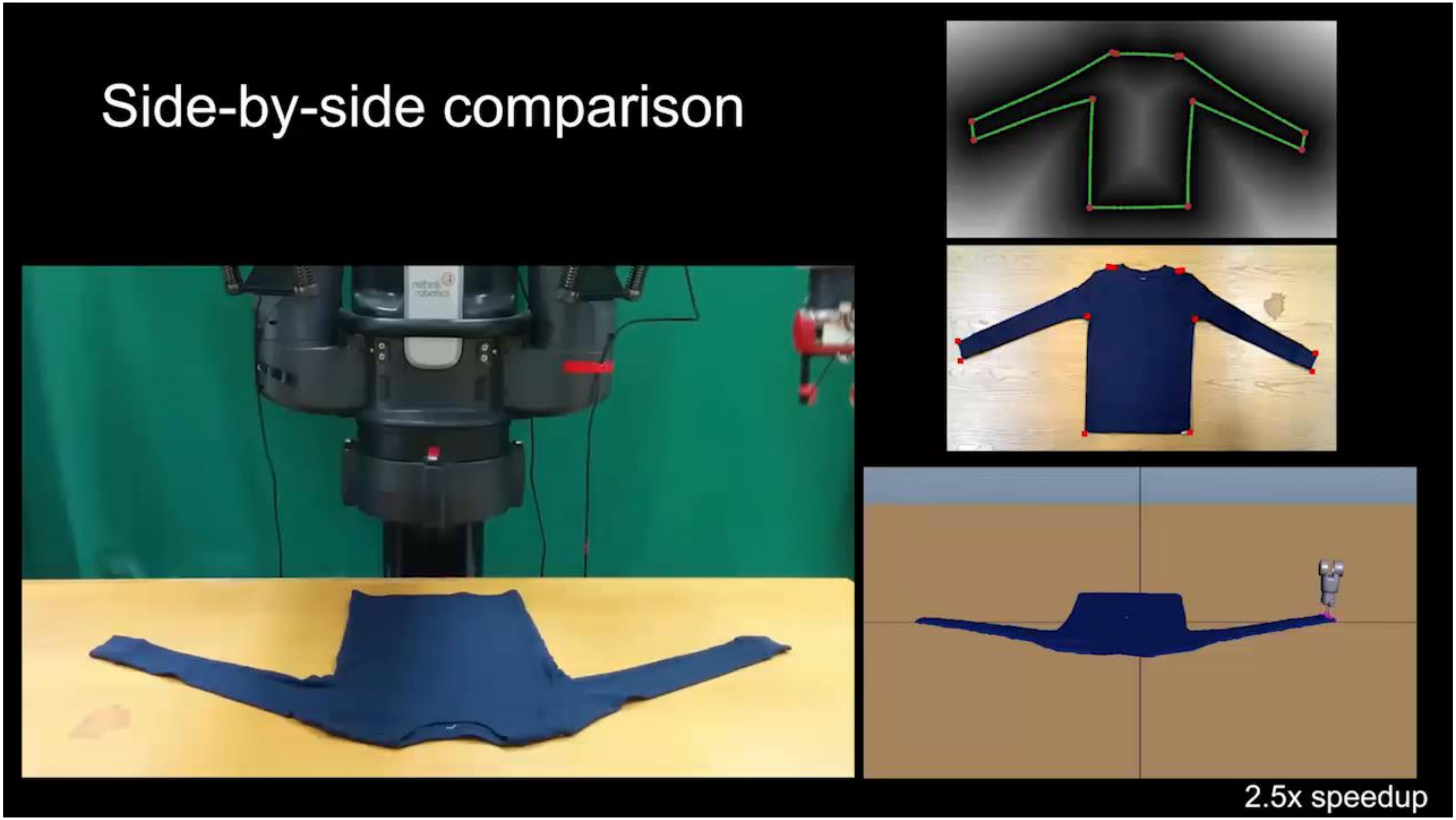


Garment Type	# of folds	Success Rate	Avg. Time (sec)
L-S T-Shirt (large)	3	10/10	121
L-S T-Shirt (small)	3	10/10	118
Jeans	2	7/10	88
Pants	2	8/10	88
Large Towel	2	10/10	90
Medium Towel	2	10/10	88
Small Towel	2	10/10	83
Average	**2.3**	**9.3/10**	**97**

Experimental Results (cont.)

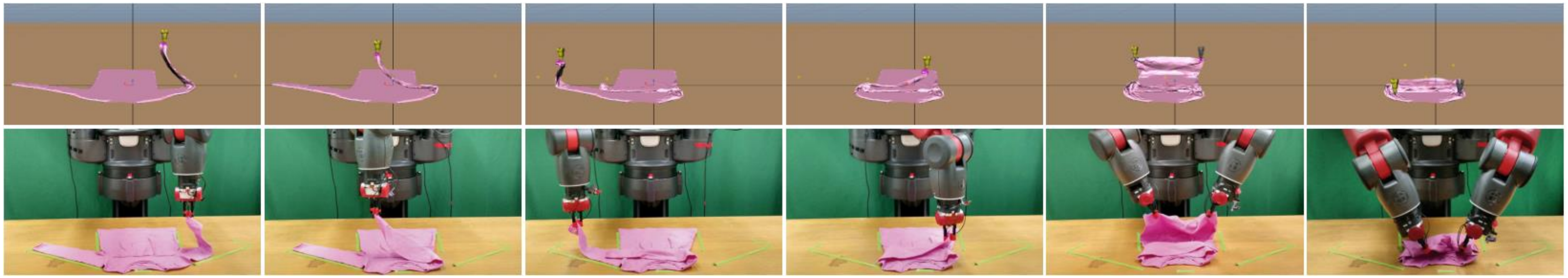


Experimental Results (cont.)

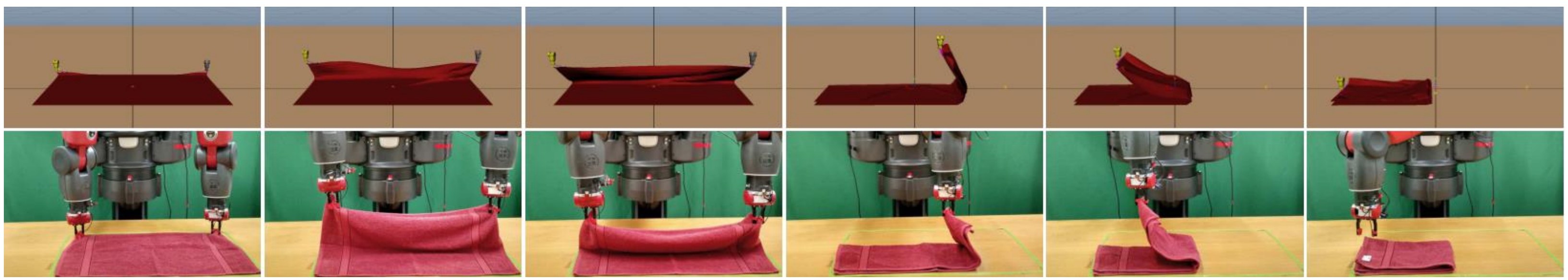


Experimental Results (cont.)

3-folds



2-folds



Garment Type	# of folds	Success Rate	Avg. Time (sec)
L-S T-Shirt (large)	3	10/10	121
L-S T-Shirt (small)	3	10/10	118
Jeans	2	7/10	88
Pants	2	8/10	88
Large Towel	2	10/10	90
Medium Towel	2	10/10	88
Small Towel	2	10/10	83
Average	**2.3**	**9.3/10**	**97**