Learning Robotic Manipulation for Human-Robot Interaction and Tactile Exploration

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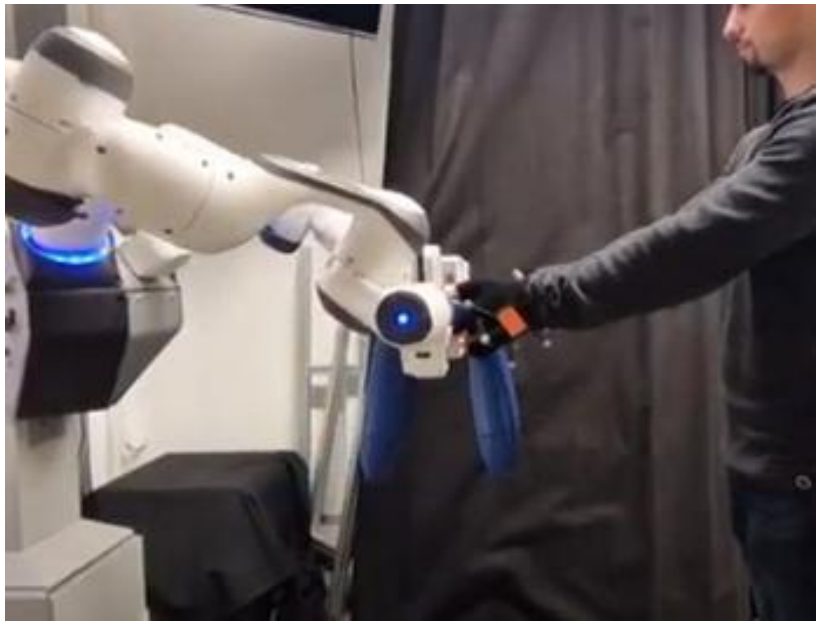
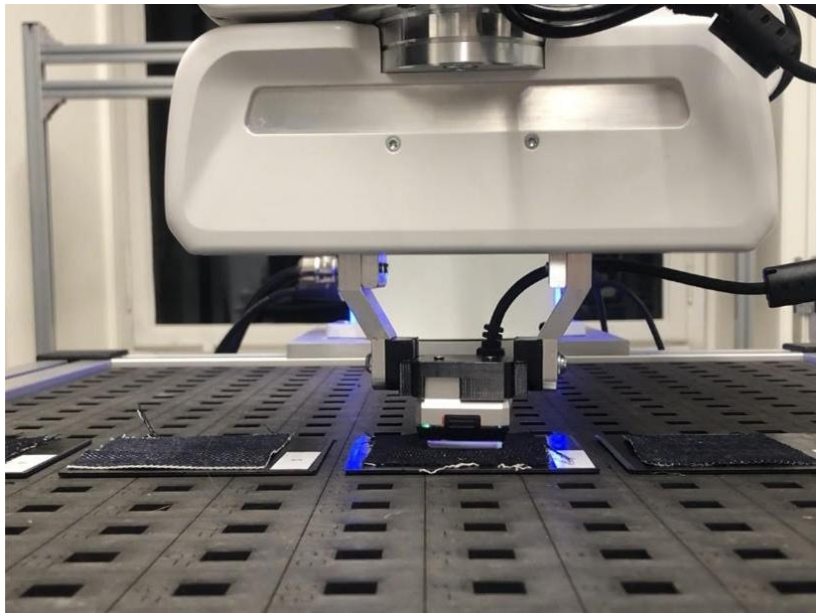
Intelligent Autonomous Systems
Technische Universität Darmstadt

Robotic Manipulation

Robotic Manipulation



Human-Robot Interaction



Tactile Exploration

Collaborators

BSc/MSc Students

Alina Boehm, Antonio De Almeida-Correia, Duc Huy Nguyen, Fabian Hahne, Felix Nonnengießer, Frederik Heller, Mario Gomez, Raphael Fortuna, Yasemin Goeksu, Zhiming Xie

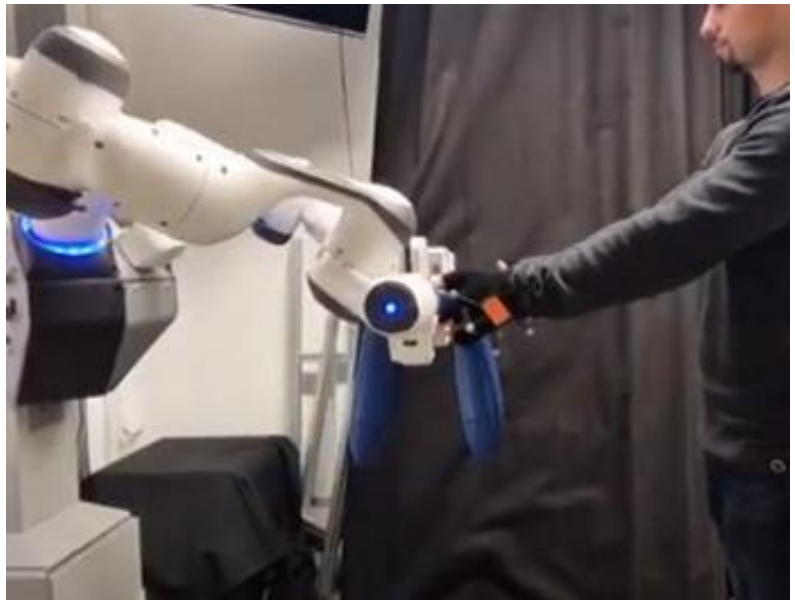
PhD Students/Postdocs

Boris Belousov, Dorothea Koert, Lisa Lin, Tim Schneider, Vignesh Prasad

Professors

Constantin Rothkopf, Georgia Chalvatzaki, Guy Hoffman, Jan Peters, Katja Doerschner, Knut Drewing, Ruth Stock-Homburg

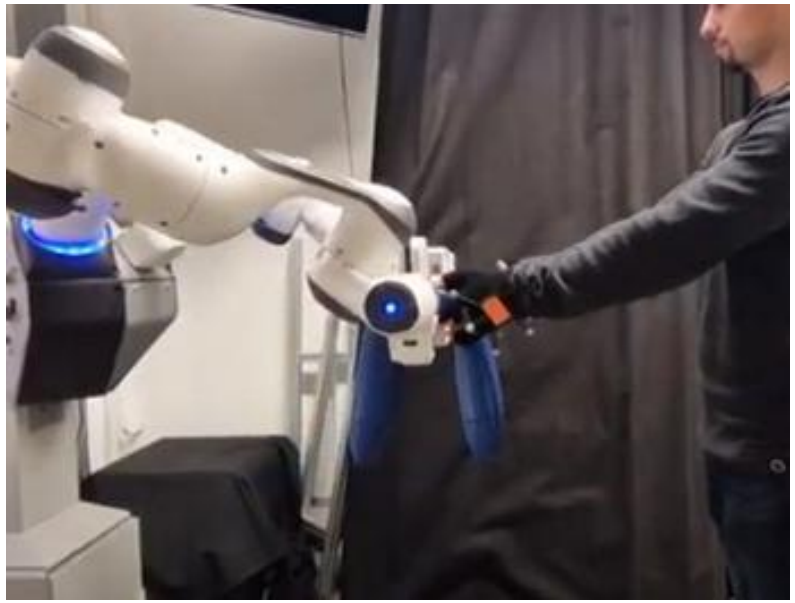
Robotic Manipulation

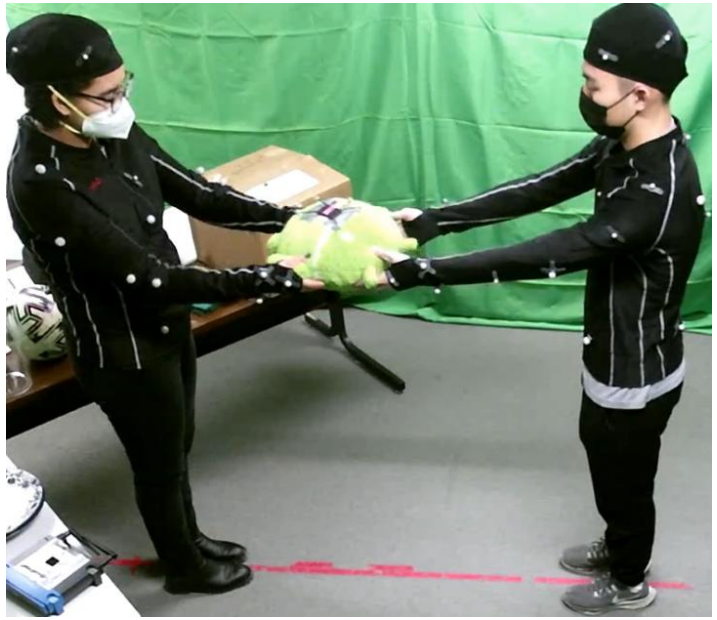


Human-Robot Interaction

Tactile Exploration

Learning Human-Robot Interaction from Human-Human Interaction





Handovers – Essential Skill for Collaborative Robots

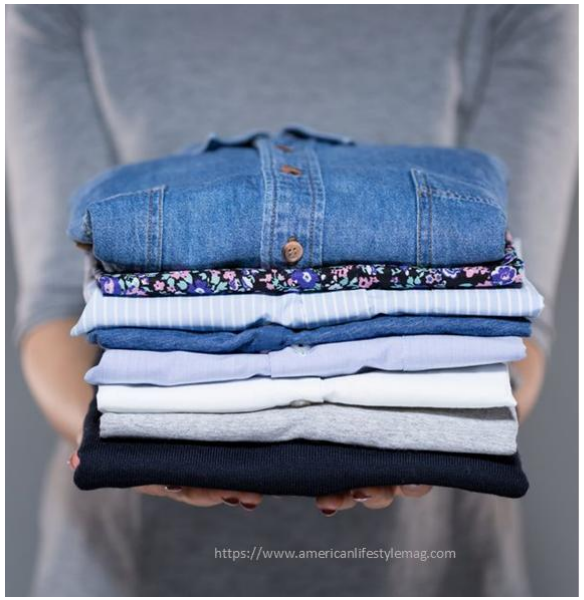
https://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/Collaborative-Robotics-Puts-People-First/content_id/7021

Source: https://www.zdnet.com/pictures/photo-robot-in-

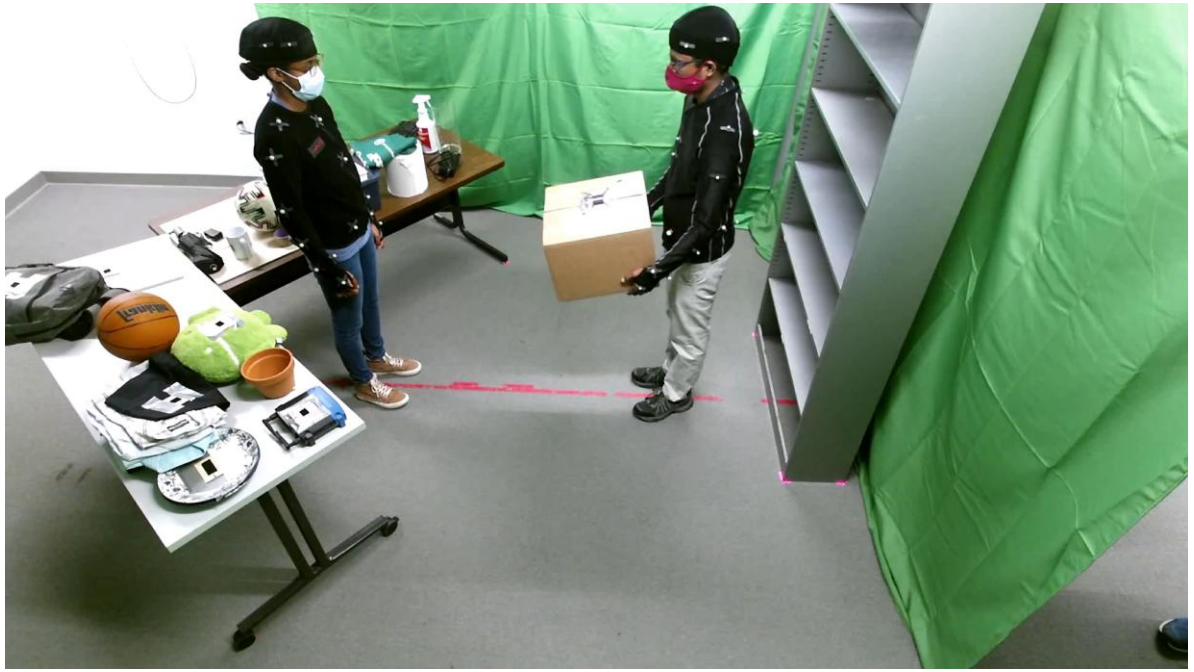
Source: https://www.engineering.com/PLMERP/ArticleID/10519/Can-a-Robot-Help-with-the-

Source: https://sites.google.com/nvidia.com/handovers-of-arbitrary-objects/reactive-human-to-robot-handovers-of-arbitrary-objects

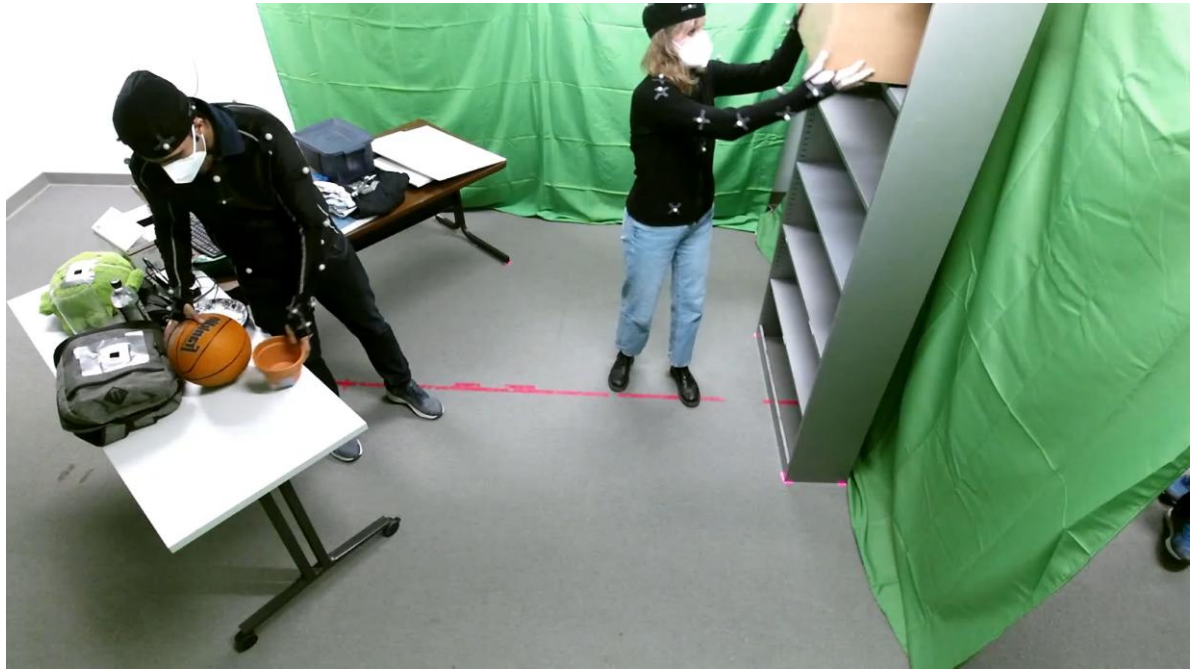
Bimanual Handovers



Multi-Sensor Datasets of Bimanual Human-Human Handovers



Dataset 1: 24 participants, 10 objects, 360 handovers



Dataset 2: 24 participants, 30 objects, 1440 handovers (shelving / un-shelving tasks)

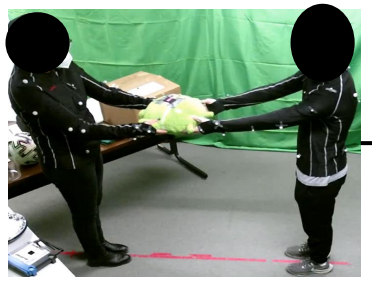
Kshirsagar et al. "Dataset of bimanual human-to-human object handovers." Data in Brief (2023)

Kshirsagar et al. "Multi-sensor Dataset of Multiple Sequential Human-to-Human Object Handovers in Shelving and Un-shelving Tasks.“ Zenodo (2023)

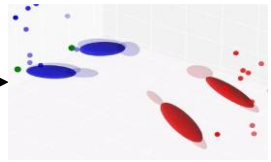
Learning Bimanual Robot-to-Human Handovers

Offline

Human Demonstration



Train Hidden Semi-Markov Model (HSMM)

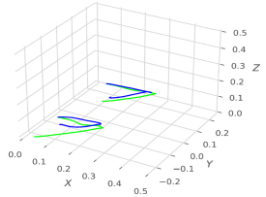


Trained HSMM

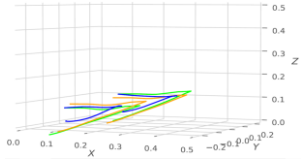
Online

Observe Human's Trajectory upto Current Time

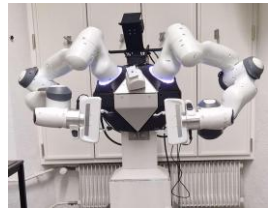
Compute Robot's Position with HSMM conditioning



Optimize Robot's Position with Grip-width Constraint



Apply Inverse Kinematics and Send Joint Angles



Goeksu et al. "Kinematically Constrained Human-like Bimanual Robot-to-Human Handovers" *Late Breaking Report, ACM/IEEE International Conference on Human Robot Interaction (HRI)* (2024)

Learning Bimanual Robot-to-Human Handovers

Preliminary Study (4 participants, 3 objects)

Metric Scale 1-5	Baseline Median	Proposed Median
Humanlike	1	**2**
Sensible	2	**3**

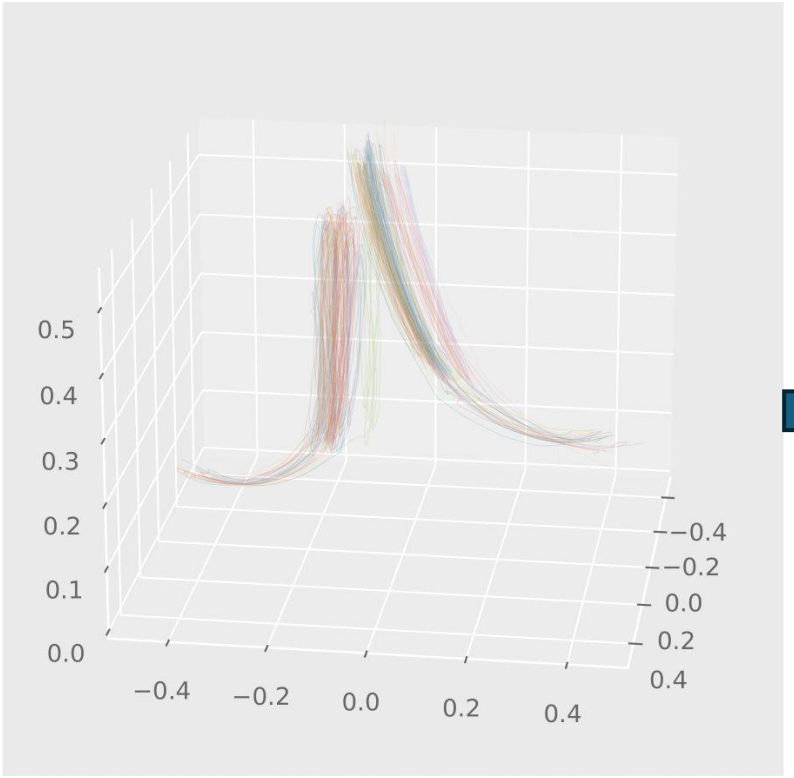
p-value < 0.05

Limitation: Inaccurate transitions between segments

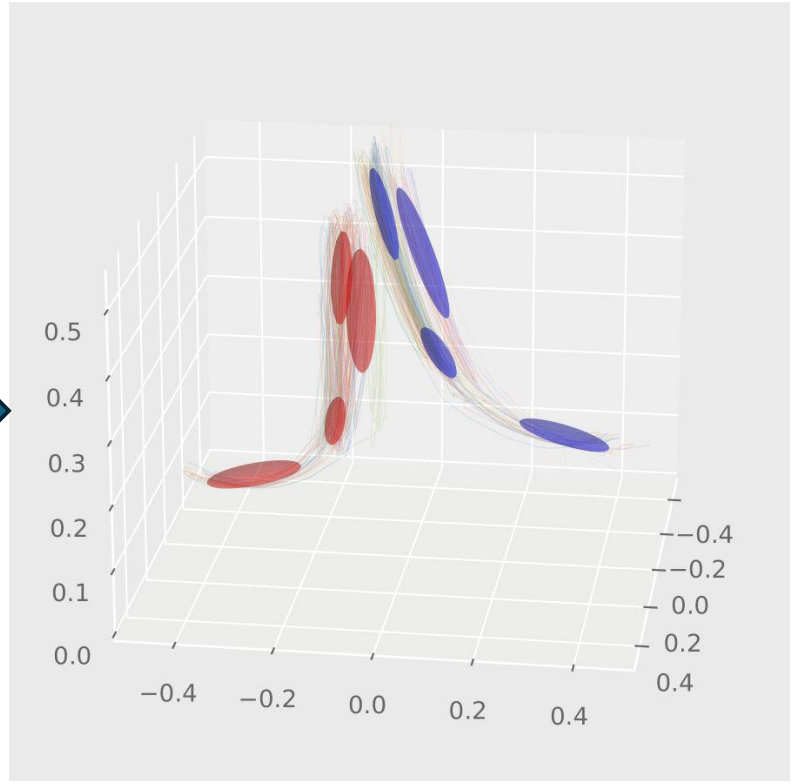
Goeksu et al. “Kinematically Constrained Human-like Bimanual Robot-to-Human Handovers“ *Late Breaking Report, ACM/IEEE International Conference on Human Robot Interaction (HRI)* (2024)

Other Interactions

Learning Interactions with HMMs



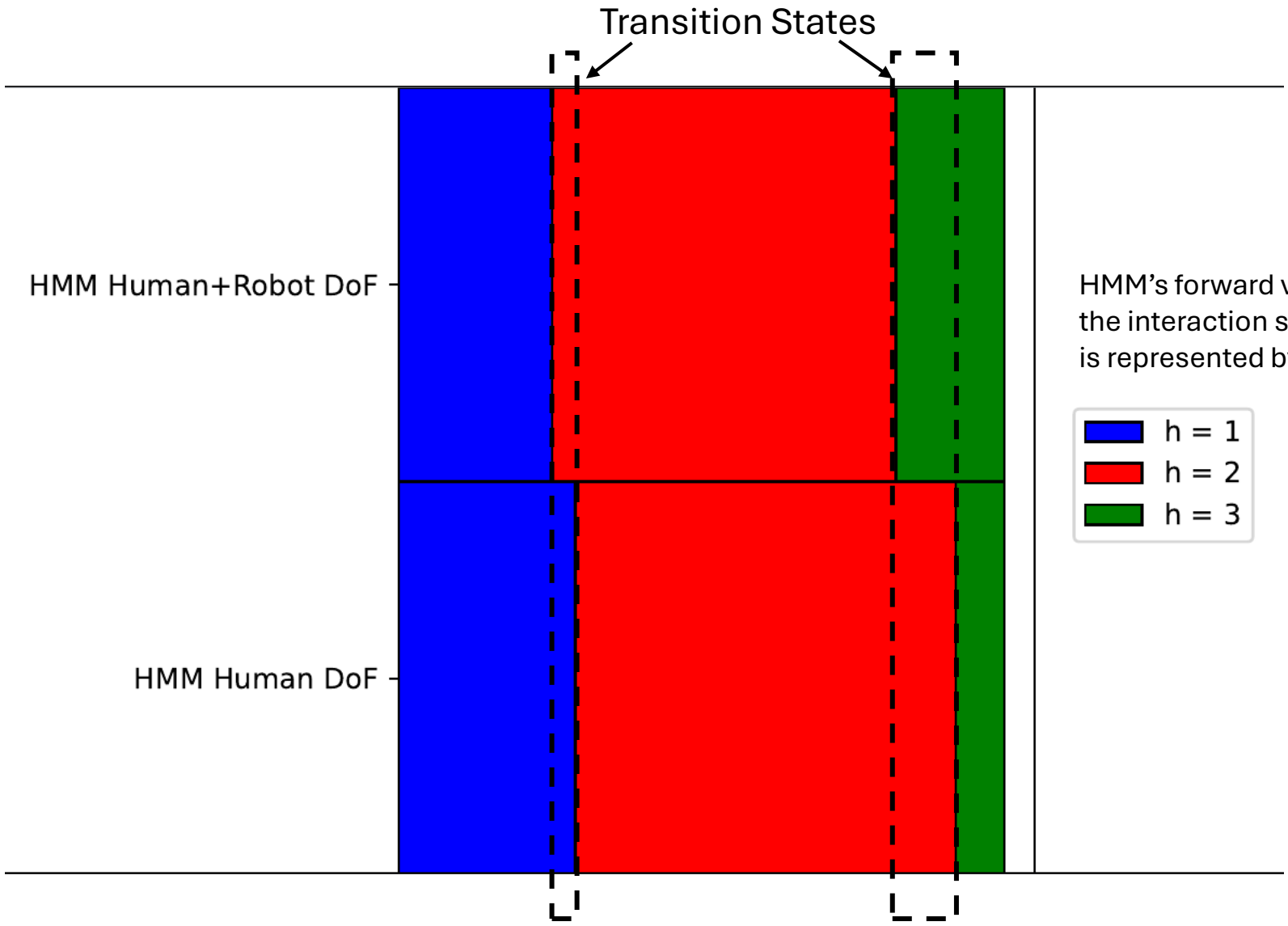
Interaction Demonstrations



Learned HMM Components

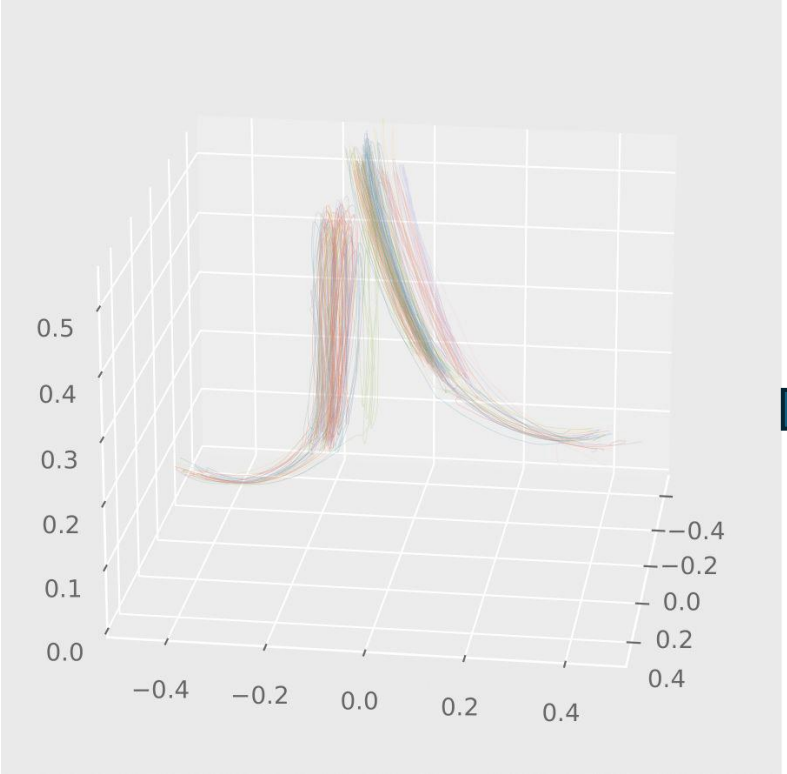
Hahne et al. “Transition State Clustering for Interaction Segmentation and Learning“ *Late Breaking Report, ACM/IEEE International Conference on Human Robot Interaction (HRI)* (2024)

Inaccurate HMM Predictions in Transition States

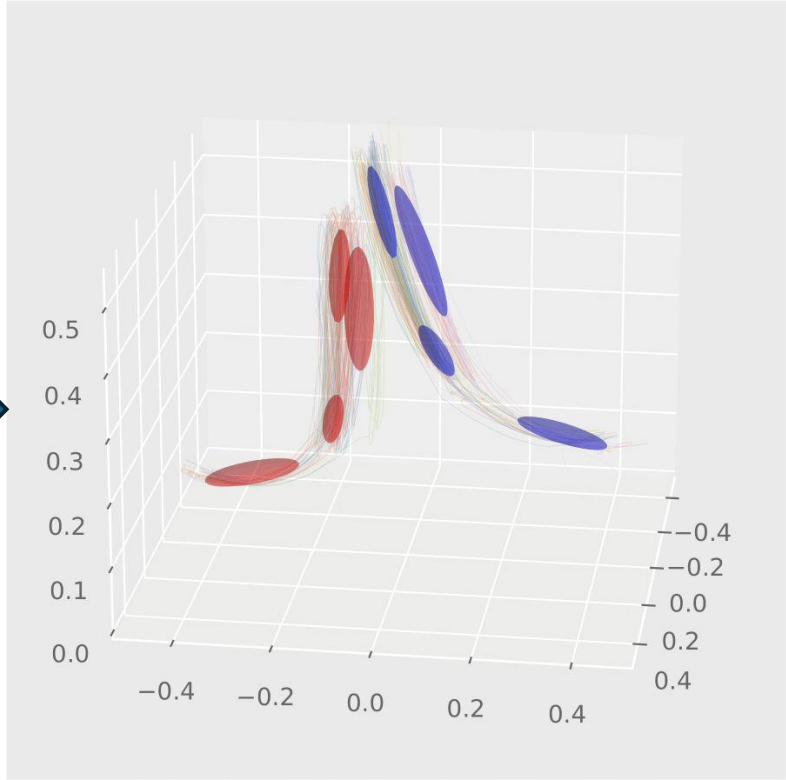


Hahne et al. "Transition State Clustering for Interaction Segmentation and Learning" *Late Breaking Report, ACM/IEEE International Conference on Human Robot Interaction (HRI)* (2024)

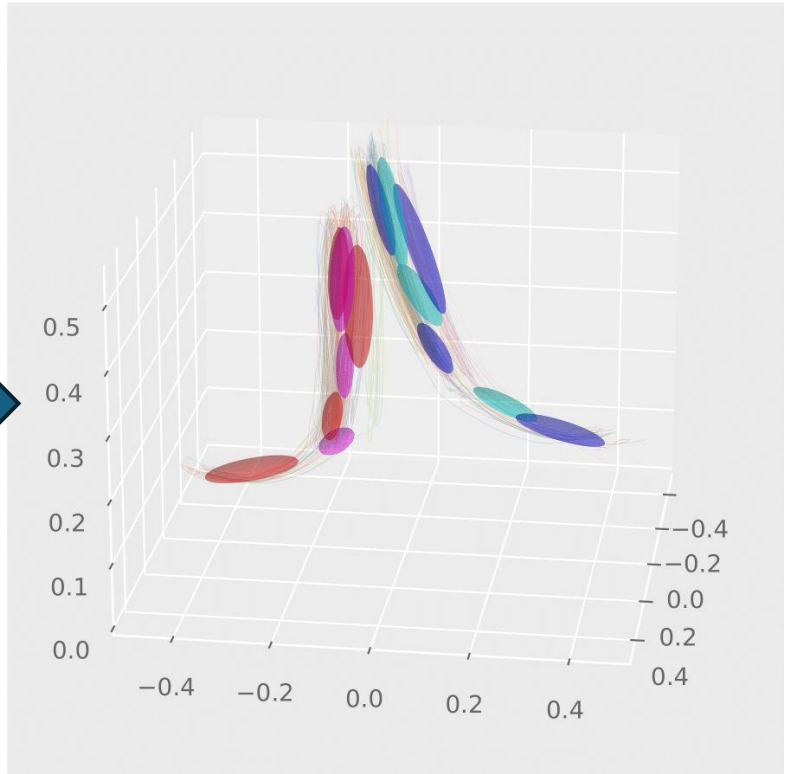
Transition State Clustering + HMM



Interaction Demonstrations



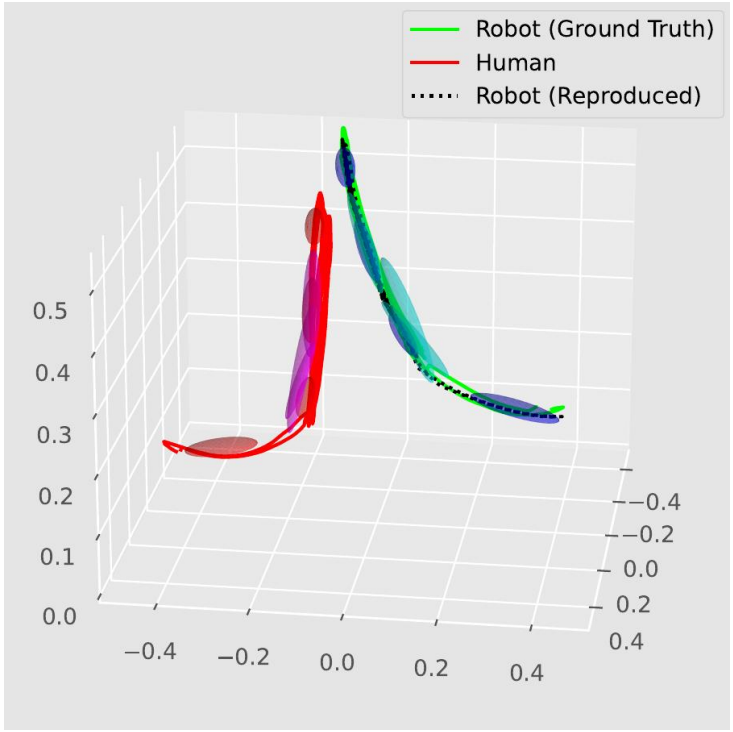
Learned HMM Components



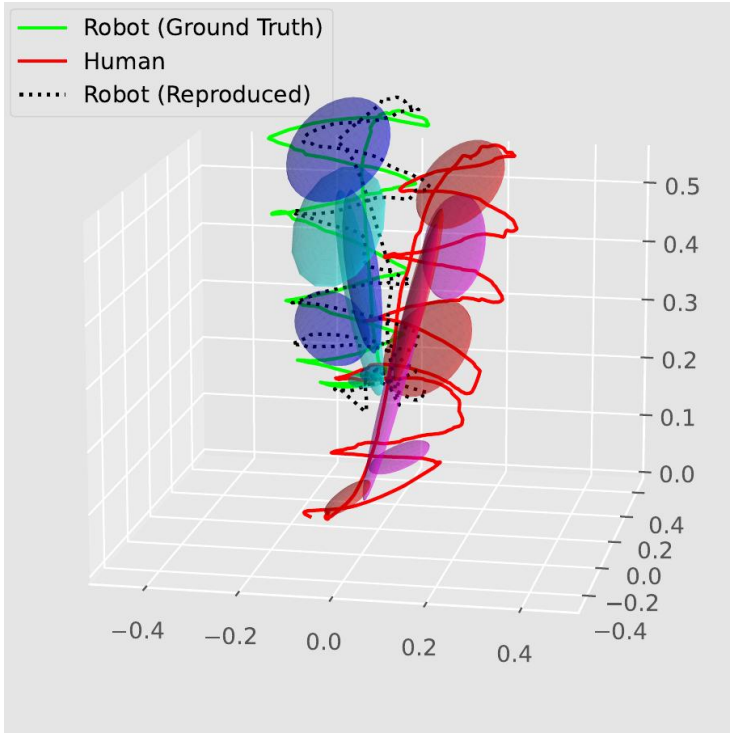
Transition State Clusters based on learned HMM Components

Hahne et al. “Transition State Clustering for Interaction Segmentation and Learning“ *Late Breaking Report, ACM/IEEE International Conference on Human Robot Interaction (HRI)* (2024)

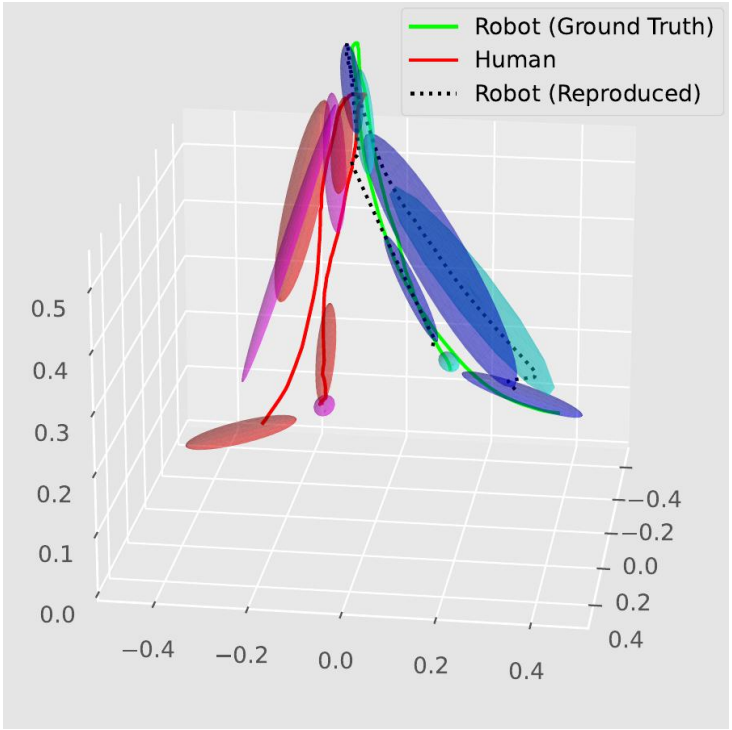
Generated Robot Trajectories



Handshake



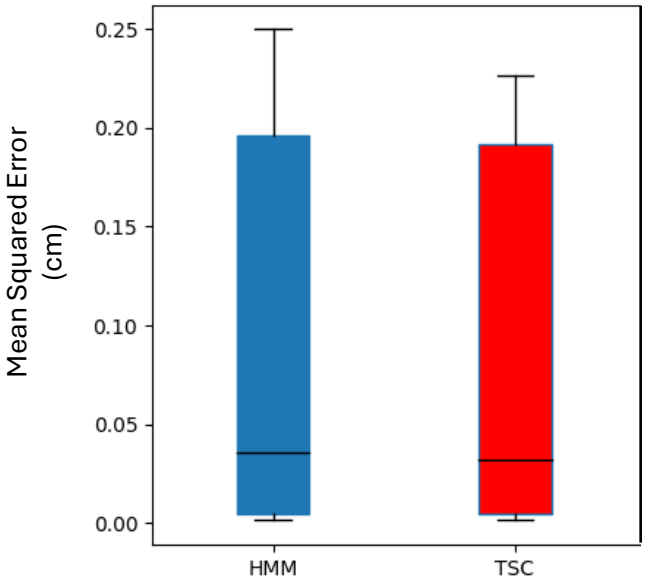
Parachute Fistbump



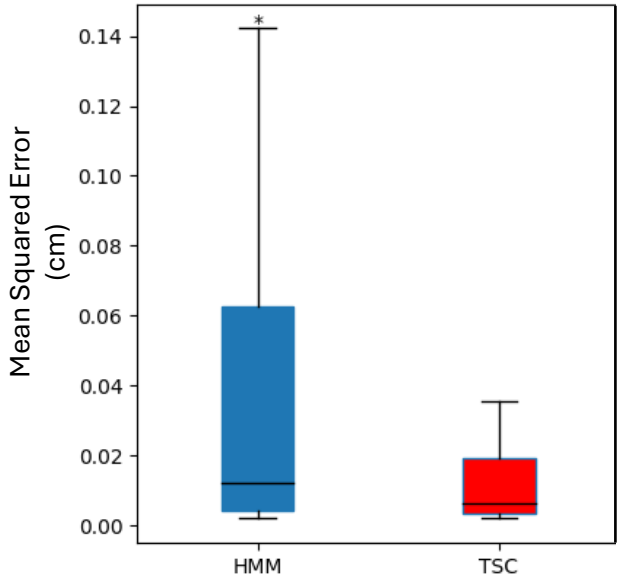
Rocket Fistbump

Hahne et al. “Transition State Clustering for Interaction Segmentation and Learning“ *Late Breaking Report, ACM/IEEE International Conference on Human Robot Interaction (HRI)* (2024)

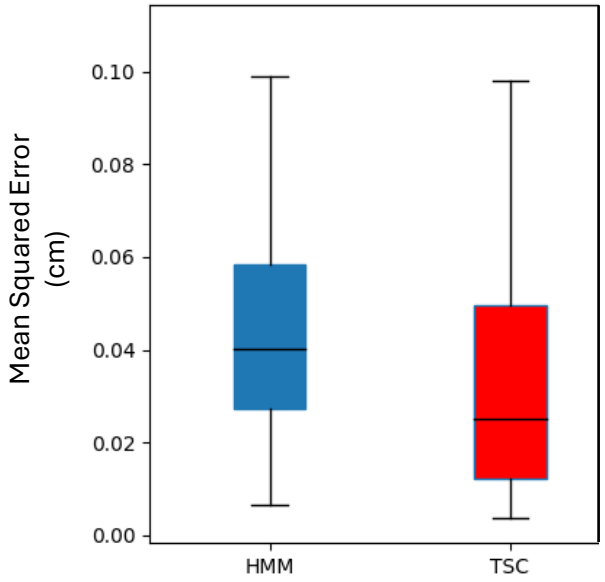
Mean Squared Error in Reconstructed Robot Trajectories



Handshake



Parachute Fistbump



Rocket Fistbump

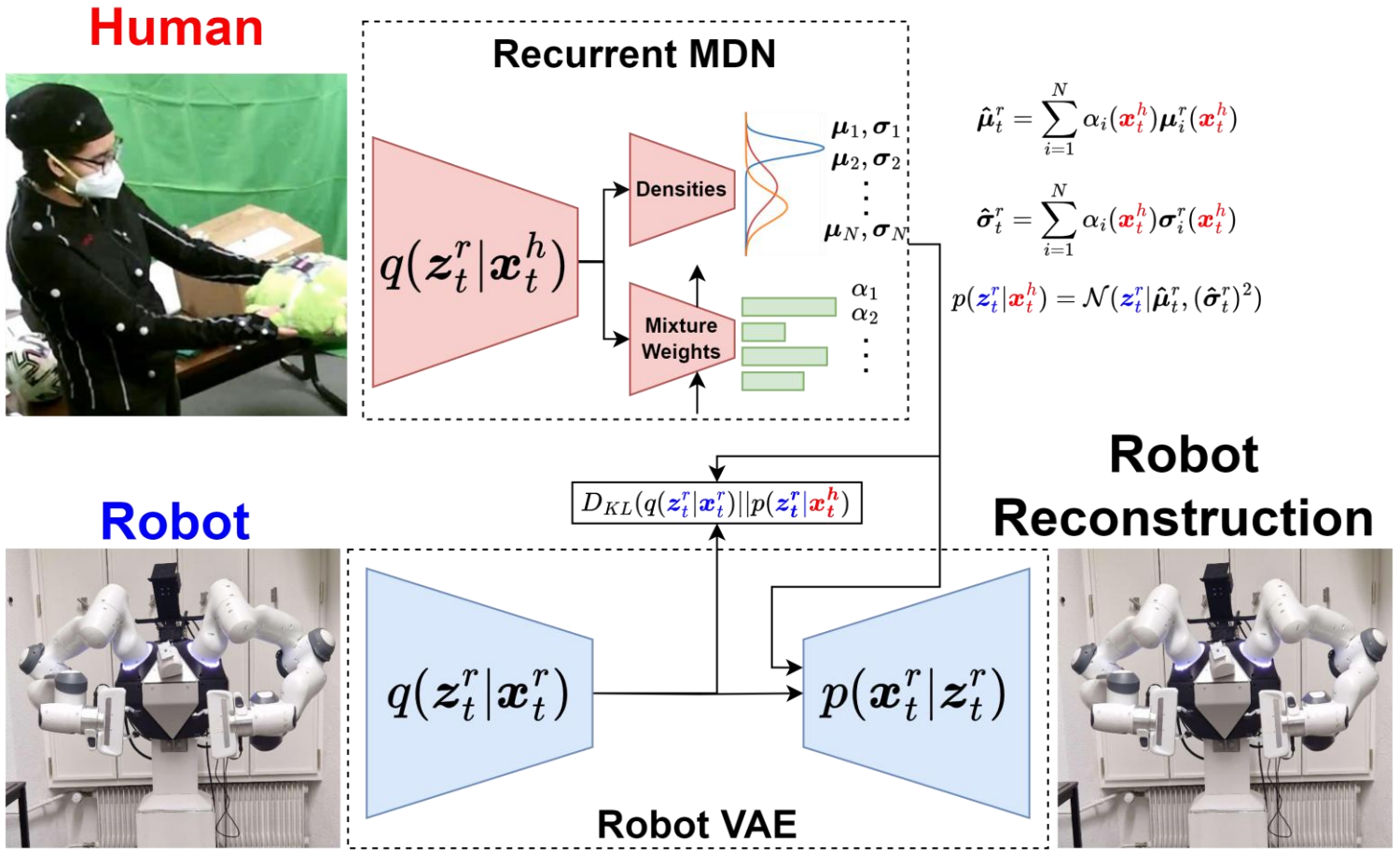
Hahne et al. “Transition State Clustering for Interaction Segmentation and Learning“ *Late Breaking Report, ACM/IEEE International Conference on Human Robot Interaction (HRI)* (2024)

Limitations

Separate model for each interaction

Limited representation capabilities of GMMs

Mixture **o**f **V**ariational **E**xperts for **Int**eractions (MoVEInt)

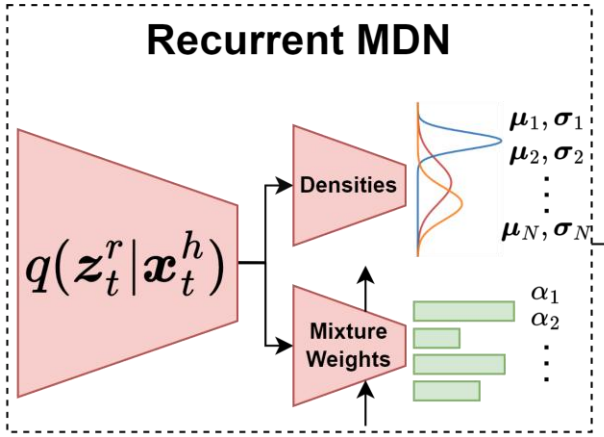


(Human - 2, Training)

Prasad et al. “MoVEInt: Mixture of Variational Experts for Learning Human-Robot Interactions from Demonstrations”, IEEE Robotics and Automation Letters (RA-L), submitted

Mixture **o**f **V**ariational **E**xperts for **Int**eractions (MoVEInt)

Human

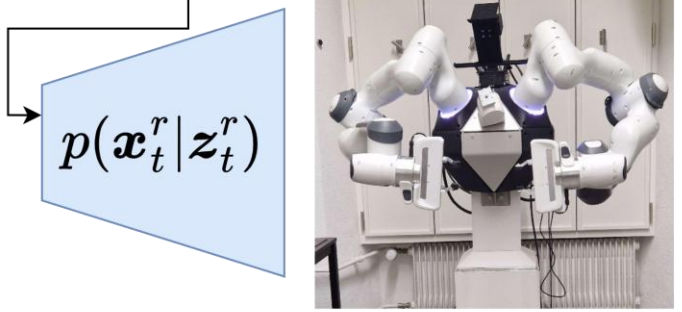


$$\hat{\mu}_t^r = \sum_{i=1}^{N} \alpha_i(x_t^h)\mu_i^r(x_t^h)$$

$$\hat{\sigma}_t^r = \sum_{i=1}^{N} \alpha_i(x_t^h)\sigma_i^r(x_t^h)$$

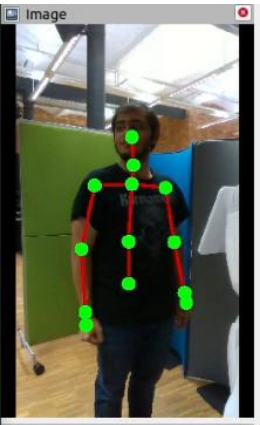
$$p(z_t^r|x_t^h) = \mathcal{N}(z_t^r|\hat{\mu}_t^r, (\hat{\sigma}_t^r)^2)$$

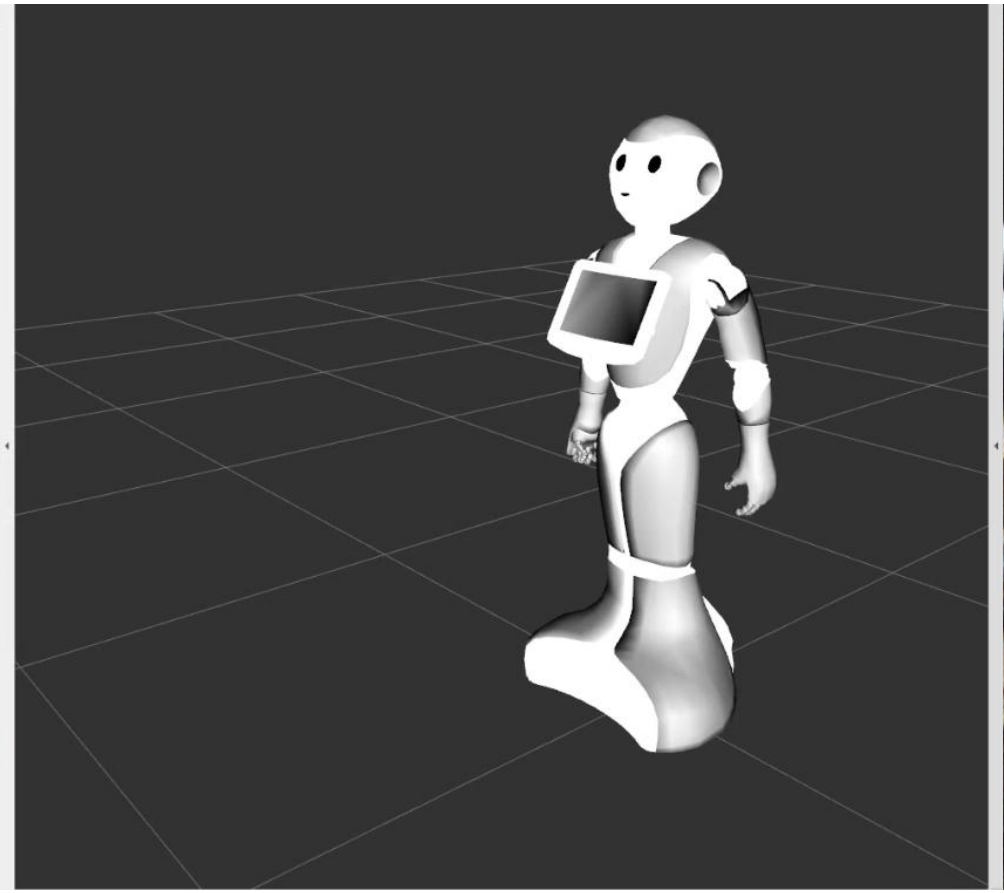
Reactive Robot Motion (Test)

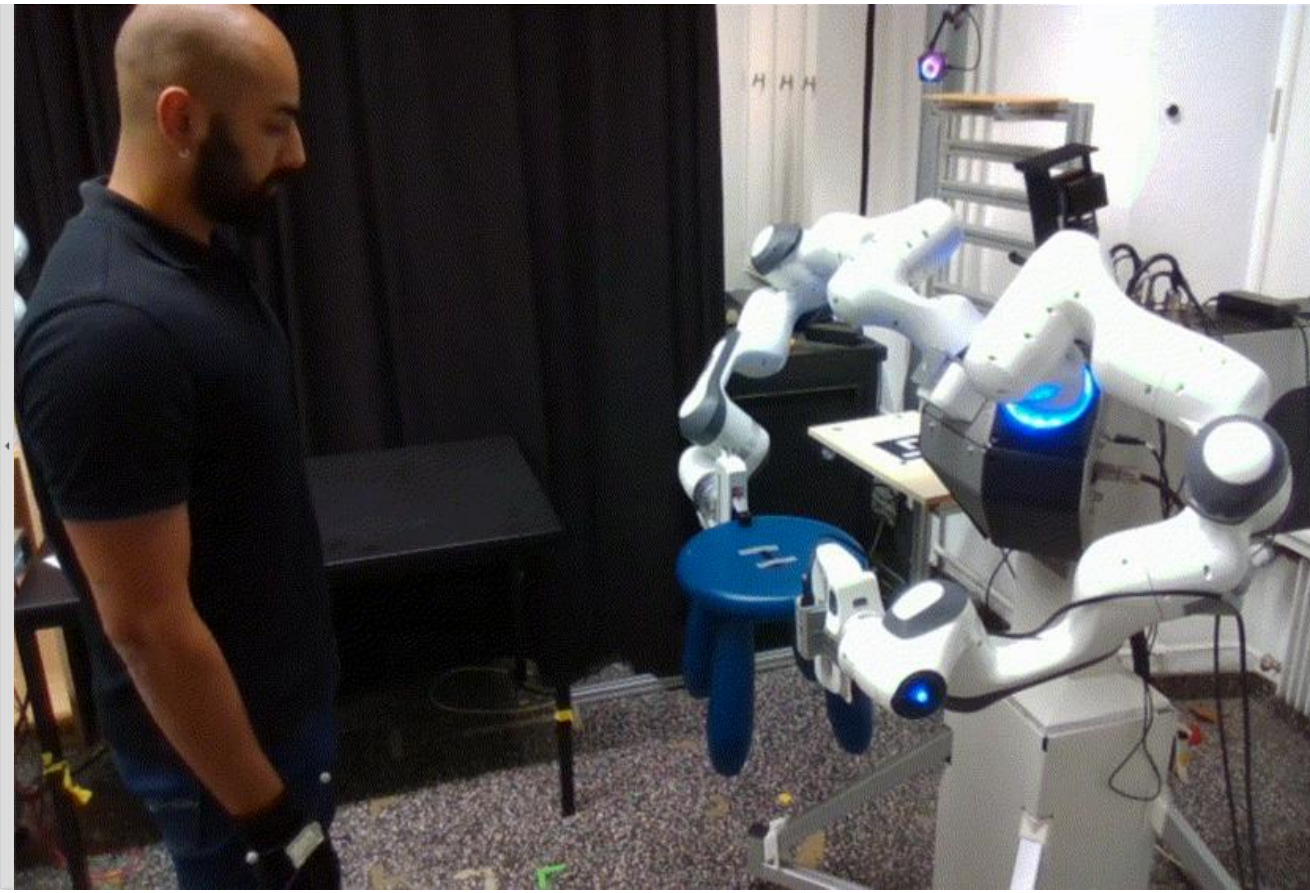


Prasad et al. “MoVEInt: Mixture of Variational Experts for Learning Human-Robot Interactions from Demonstrations”, IEEE Robotics and Automation Letters (RA-L), submitted

Mixture **o**f **V**ariational **E**xperts for **Int**eractions (MoVEInt)

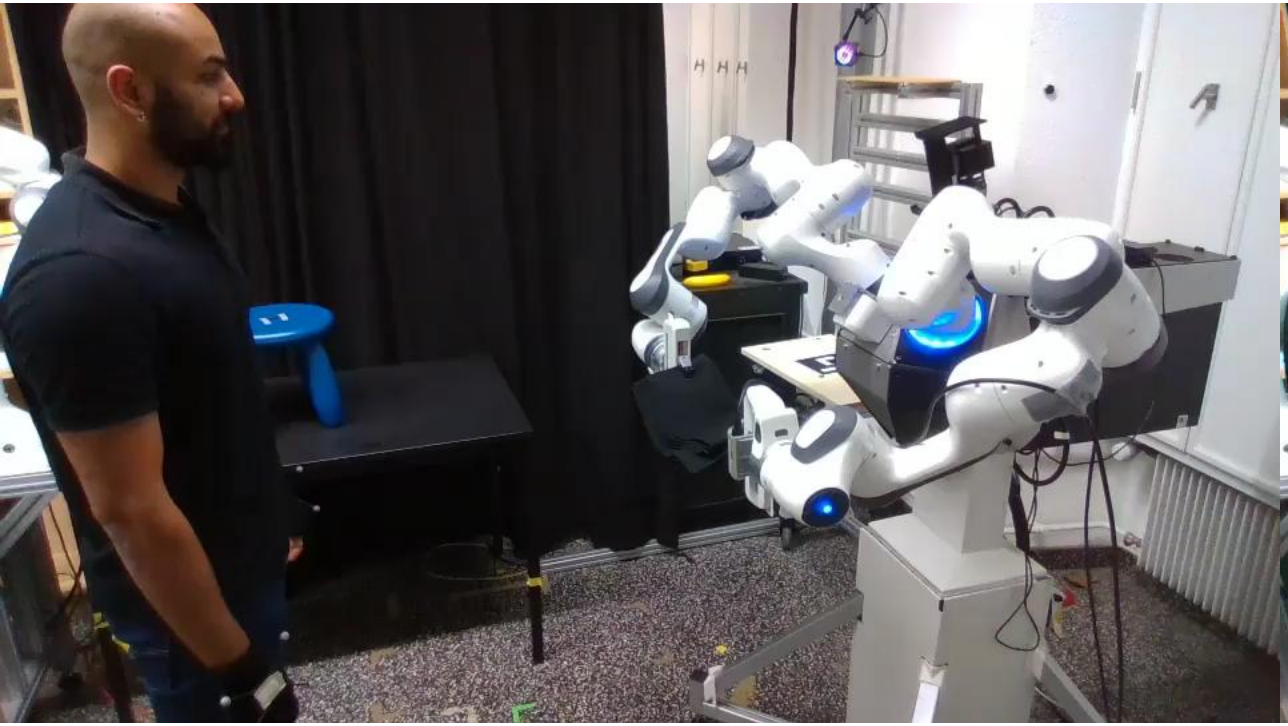


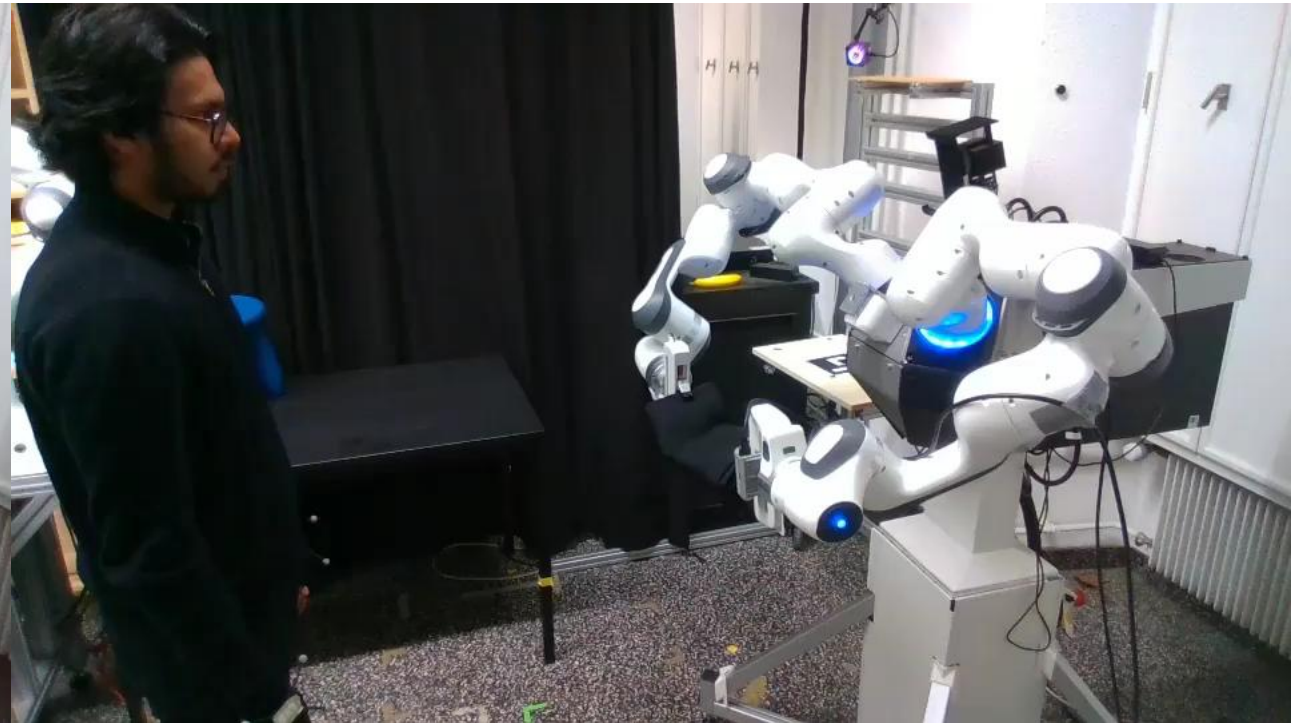




Prasad et al. “MoVEInt: Mixture of Variational Experts for Learning Human-Robot Interactions from Demonstrations”, IEEE Robotics and Automation Letters (RA-L), submitted

Failure Cases

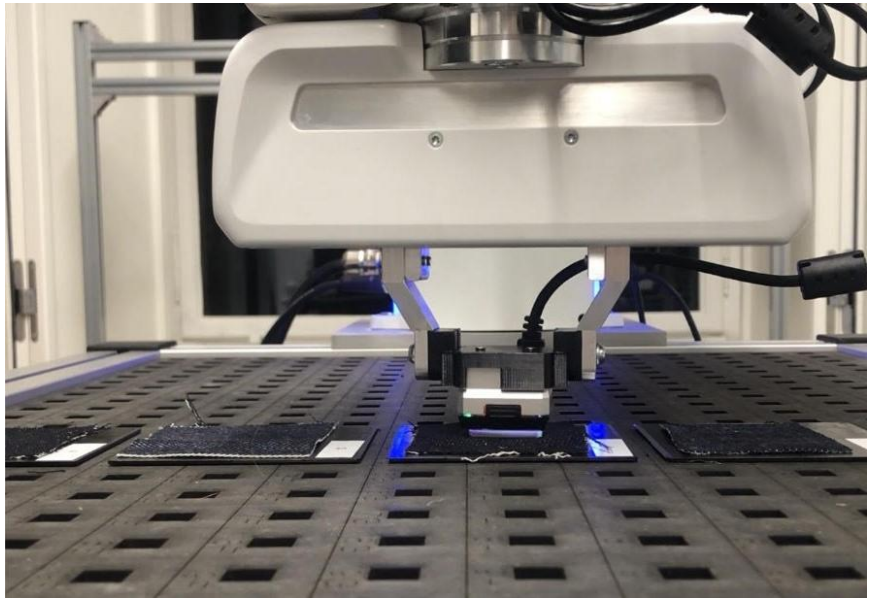




Prasad et al. “MoVEInt: Mixture of Variational Experts for Learning Human-Robot Interactions from Demonstrations”, IEEE Robotics and Automation Letters (RA-L), submitted

Robotic Manipulation

Human-Robot Interaction



Tactile Exploration

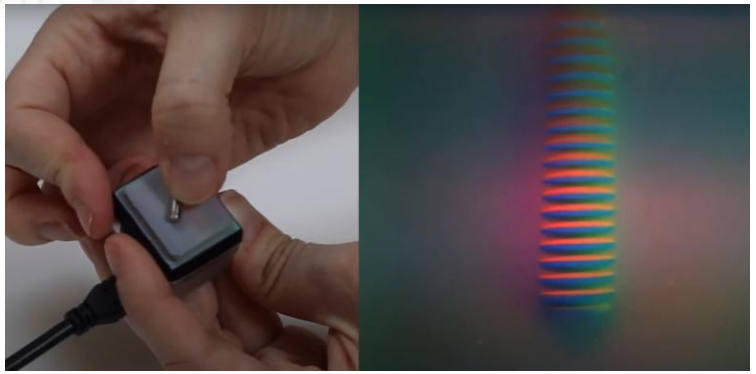
Vision-Based Tactile Sensors

Digit

Source: https://digit.ml/

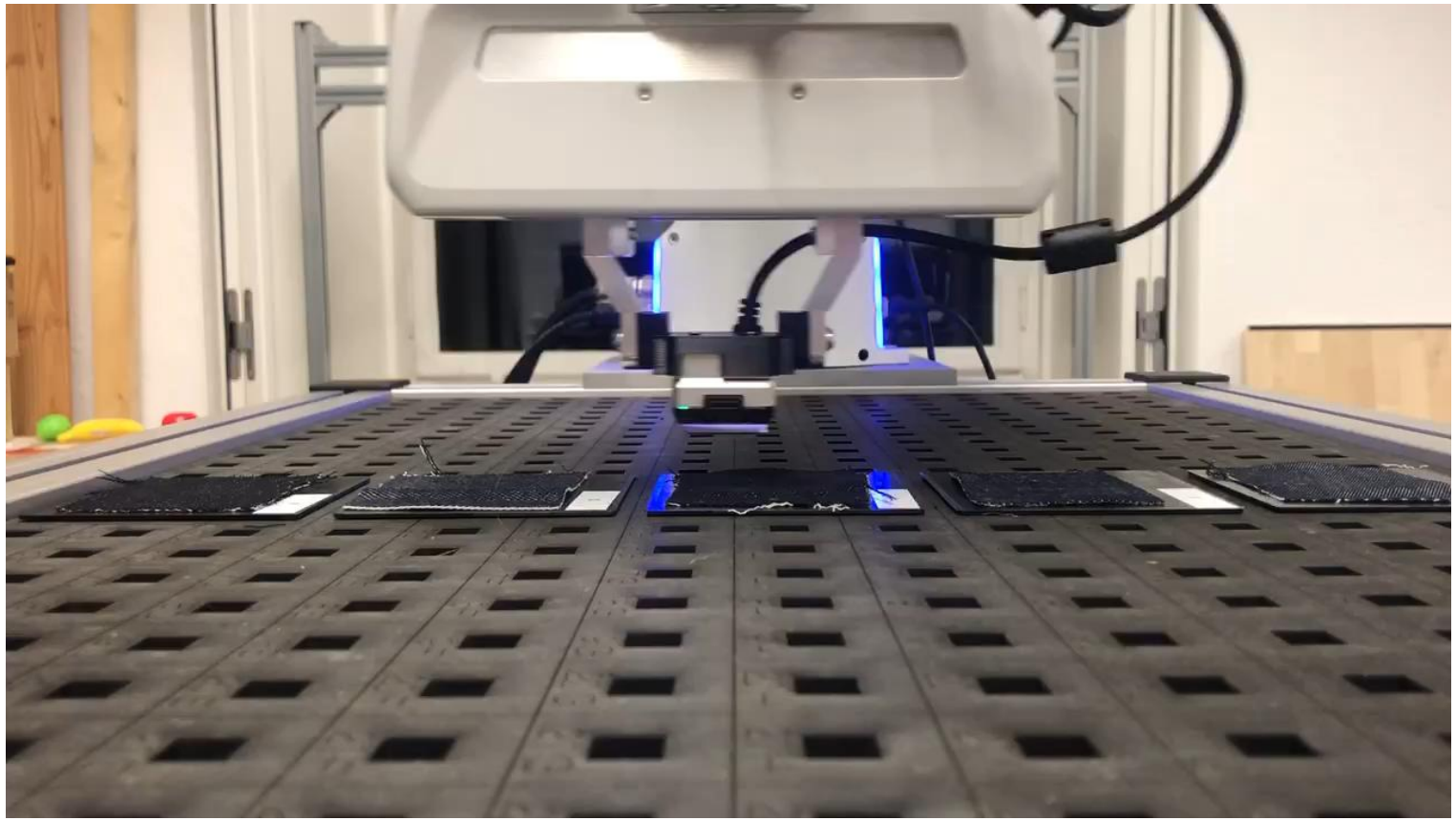
Gelsight Mini

Source: https://www.gelsight.com



Texture Recognition With Vision-Based Tactile Sensors

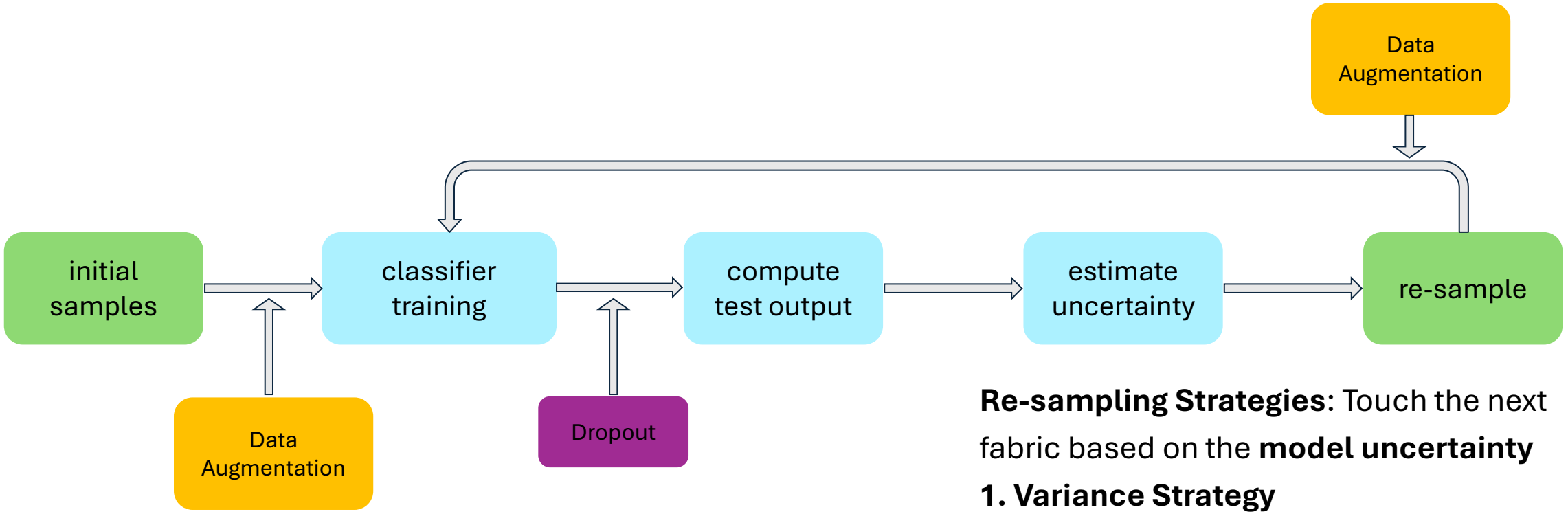
Task: Find reference fabric among comparison fabrics in **as few touches as possible**



Boehm et al. “What Matters for Active Texture Recognition with Vision-Based Tactile Sensors”, IEEE International Conference on Robotics and Automation (ICRA), 2024 (accepted)

Proposed method: **T**actile **A**ctive **R**ecognition of **T**extures (TART)

Idea: Perform **multiple rounds of exploration** and **continual model fine-tuning**

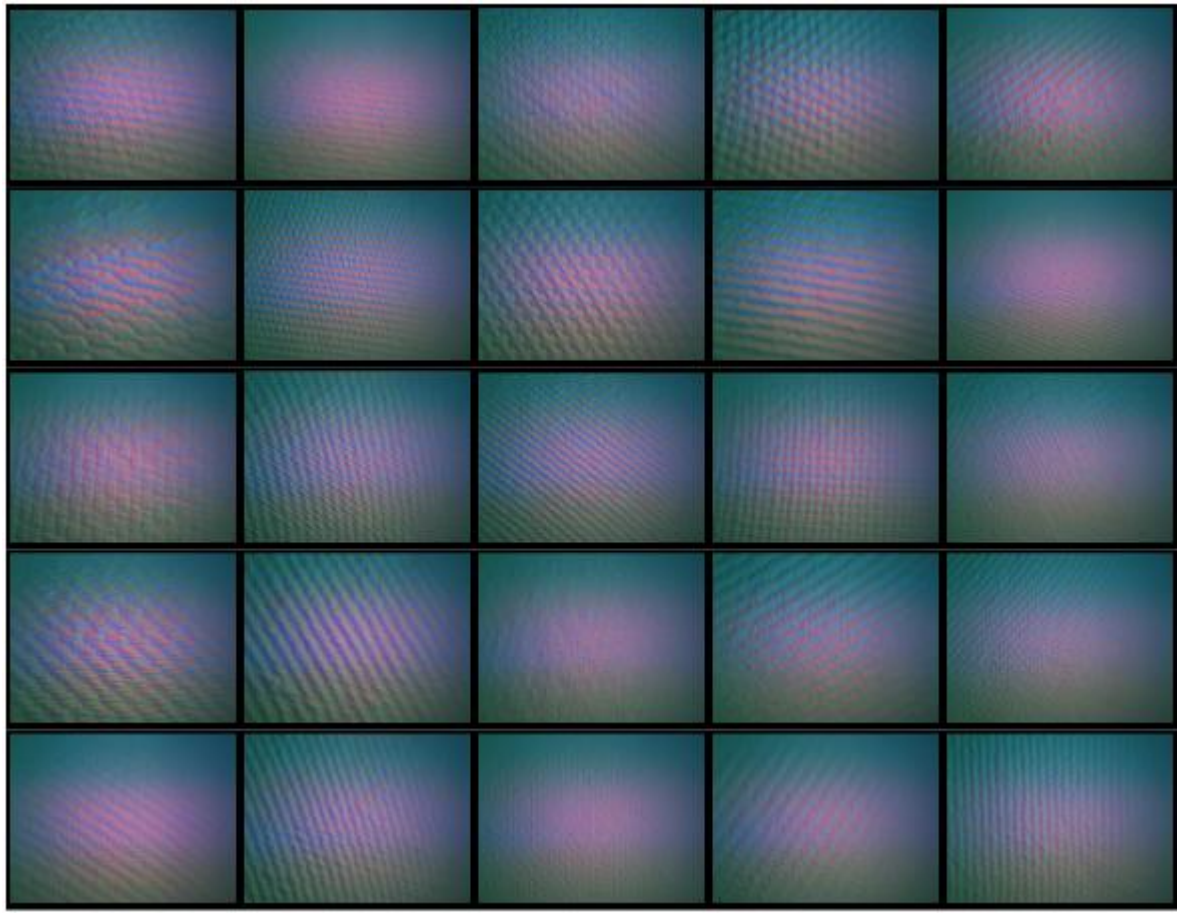


Re-sampling Strategies: Touch the next fabric based on the **model uncertainty**

1. **Variance Strategy**
2. **Entropy Strategy**
3. **Random Strategy**
4. **You Only Touch Once (YOTO) Strategy**

Boehm et al. “What Matters for Active Texture Recognition with Vision-Based Tactile Sensors”, IEEE International Conference on Robotics and Automation (ICRA), 2024 (accepted)

Texture Dataset



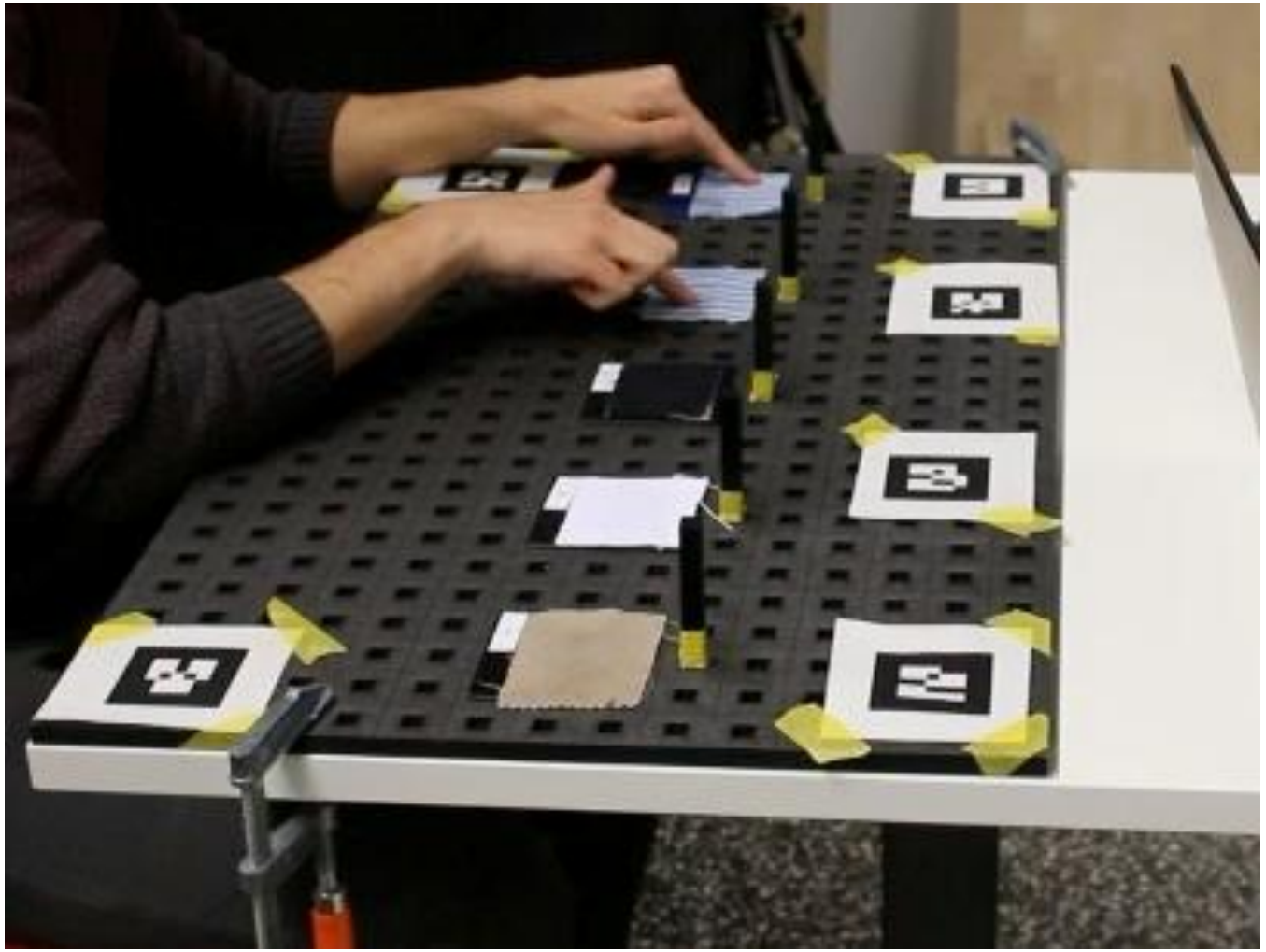
200 texture images each for 25 denim and cotton fabrics

(hard to distinguish by touch)

Boehm et al. “What Matters for Active Texture Recognition with Vision-Based Tactile Sensors”, IEEE International Conference on Robotics and Automation (ICRA), 2024 (accepted)

Human Study Setup

Blindfolded participants (n=10) explore the fabrics by touch



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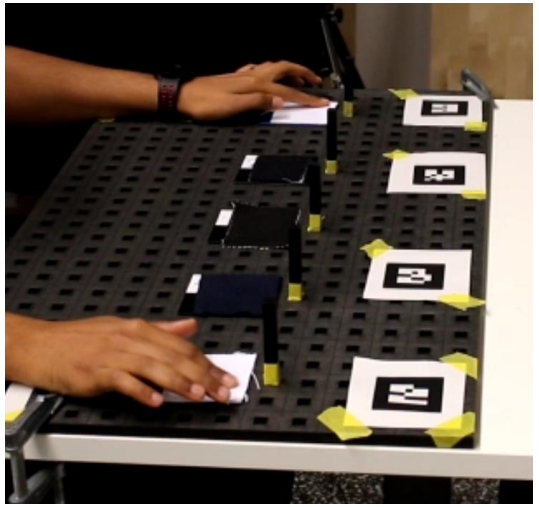
Results

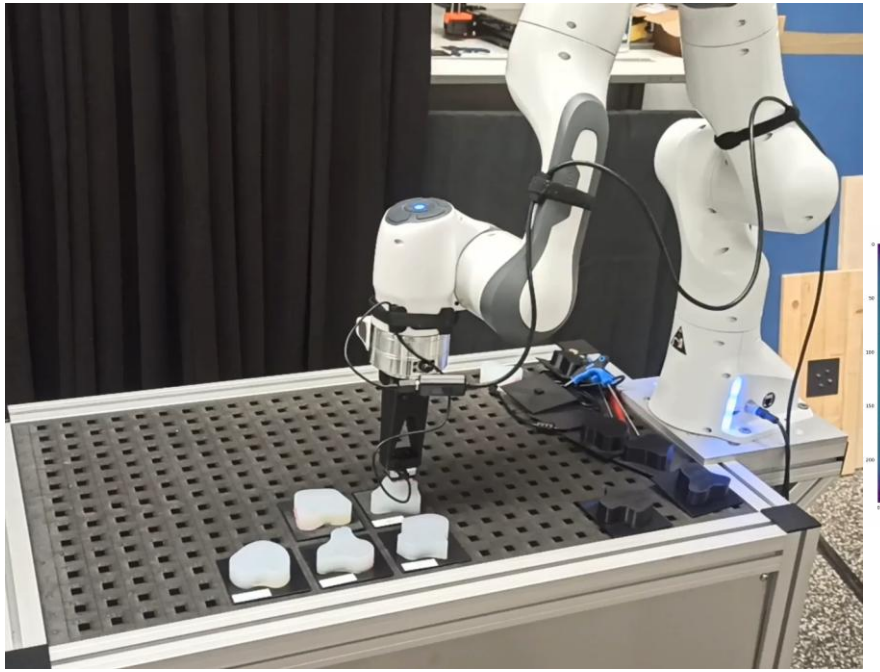


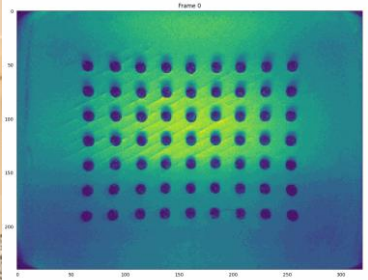
Humans	*Variance*	*Entropy*	*Random*	*YOTO*
66.88% ±16.93%	**90.00**% ±15.24%	88.13% ±14.24%	89.38% ±14.35%	80.63% ±22.42%

Boehm et al. “What Matters for Active Texture Recognition with Vision-Based Tactile Sensors”, IEEE International Conference on Robotics and Automation (ICRA), 2024 (accepted)

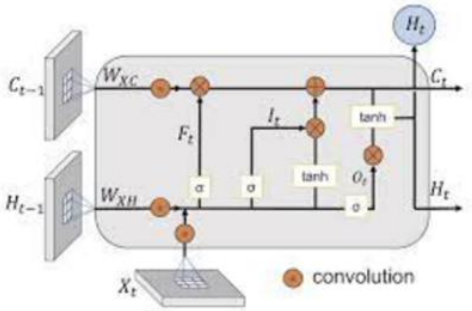
Hardness Classification

Task: Find the comparison object **closest in hardness** to the reference object





5 frames of 320x240 selected per push



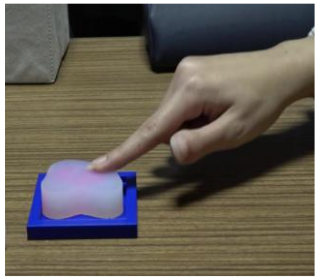
Convolutional LSTM

Classification

Hardness Classification

Hardness Similarity Judgements

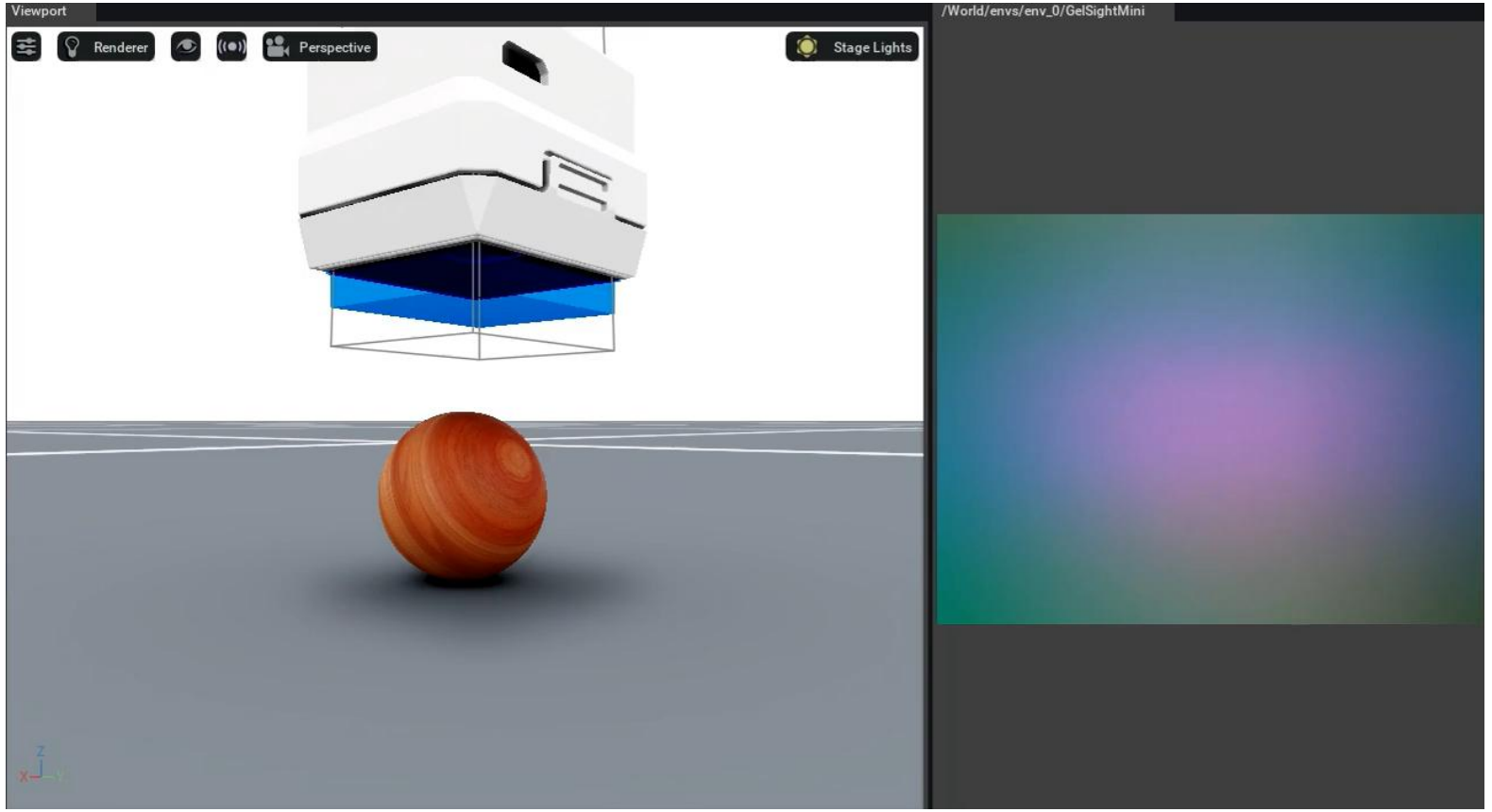
Robot (1 touch)	Robot (20 touches)	Humans (1-20 touches)
$50.00\% \pm 9.18\%$	$76.33\% \pm 4.33\%$	$80.25\% \pm 9.14\%$



Lin et al. “Task-Adapted Single Finger Explorations of Complex Objects”, Eurohaptics, 2024 (submitted)

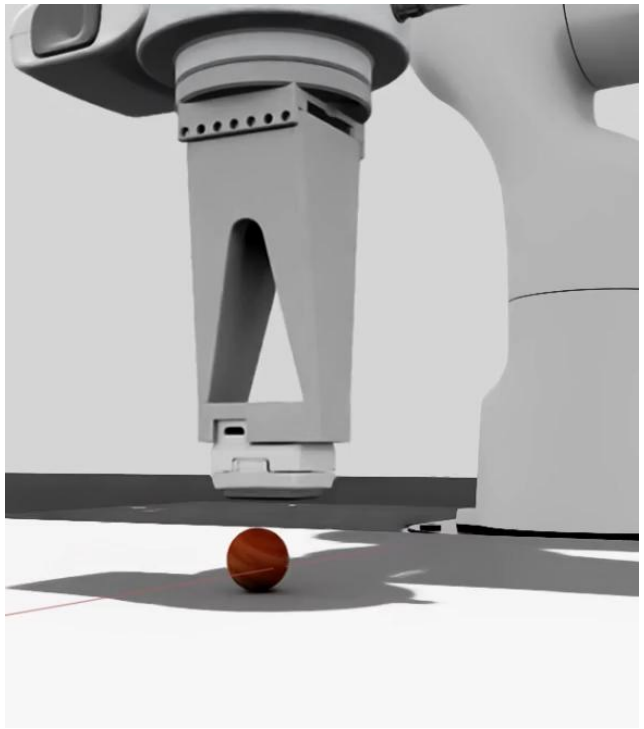
Ongoing Work: Simulation of Vision-based Tactile Sensors

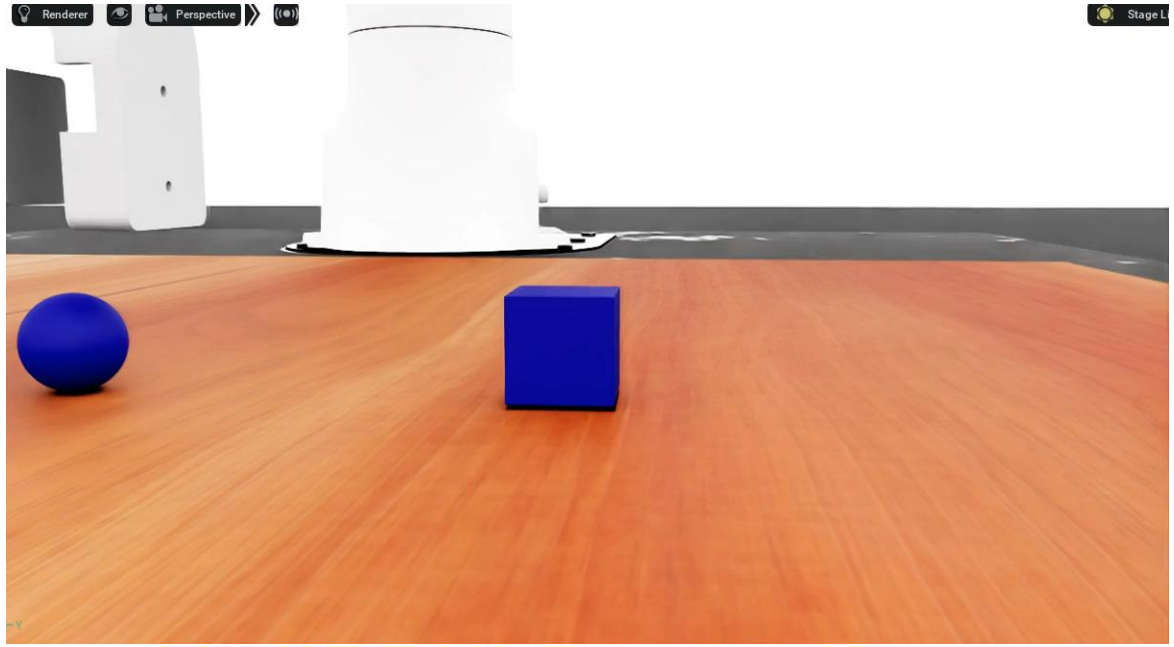
Integration of Taxim [Si and Yuan 2022] in Isaac Sim for GelSight Mini sensor (rigid bodies and compliant-contact)



Ongoing Work: Simulation of Vision-based Tactile Sensors

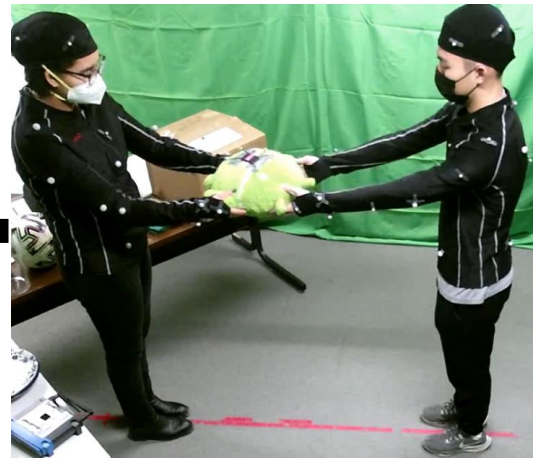
Soft-body Gelpad Simulation in Isaac Sim





Summary

Learning Manipulation for Human-Robot Interaction

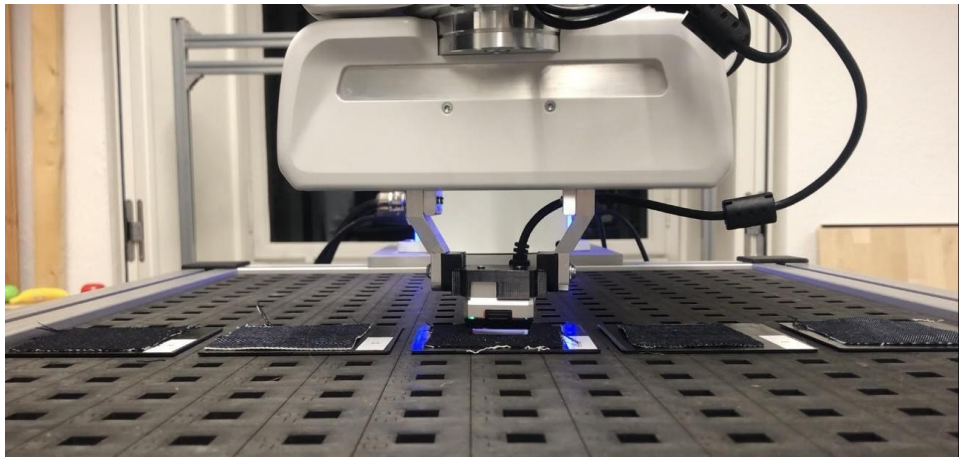


HSMM + Constrained Optimization

HMM/HSMM + Transition State Clustering

Mixture of Variational Experts

Learning Manipulation for Tactile Exploration



Active Texture Recognition

Hardness Similarity Judgement

Tactile Sensor Simulation

Thank You

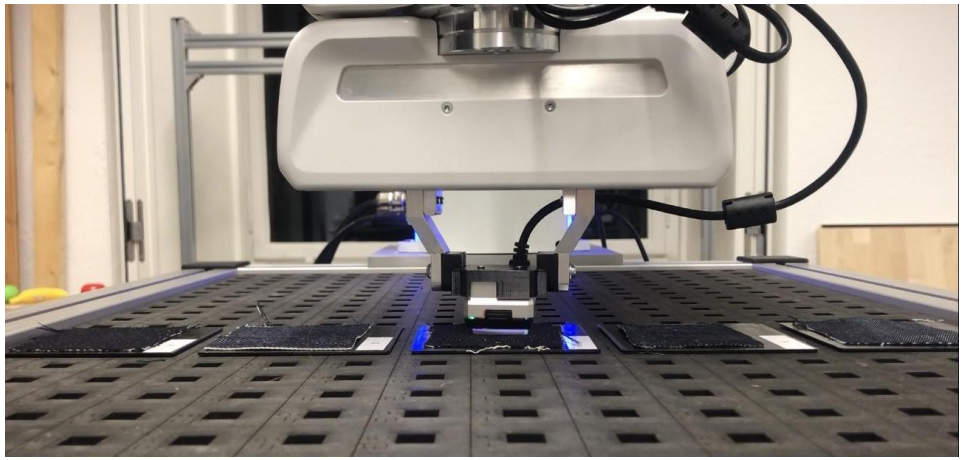
Learning Manipulation for Human-Robot Interaction

HSMM + Constrained Optimization

HMM/HSMM + Transition State Clustering

Mixture of Variational Experts

Learning Manipulation for Tactile Exploration



Active Texture Recognition

Hardness Similarity Judgement

Tactile Sensor Simulation

Collaborators

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