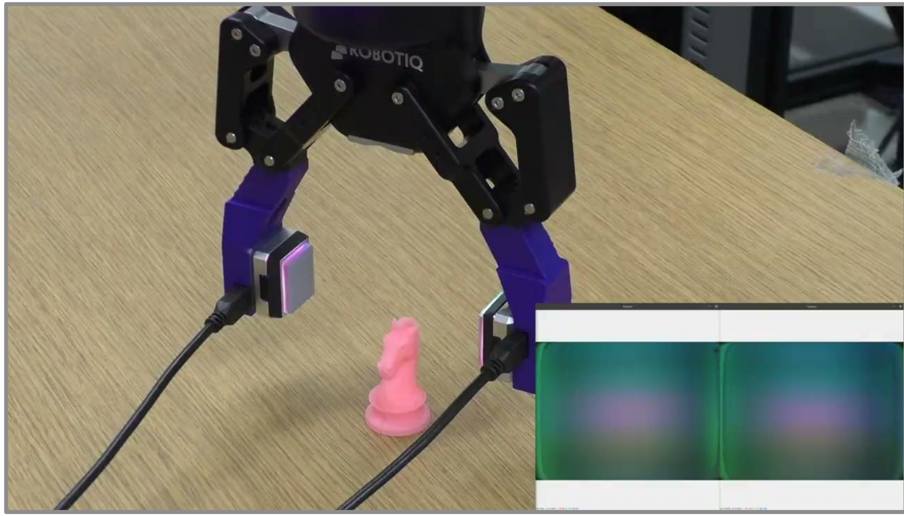
# DeepRob

[Student] Lecture 21

By Miles Priebe, Nirmal Raj, and Adam Imdieke

**Tactile Perception for Robot Grasping and Manipulation**

University of Michigan and University of Minnesota

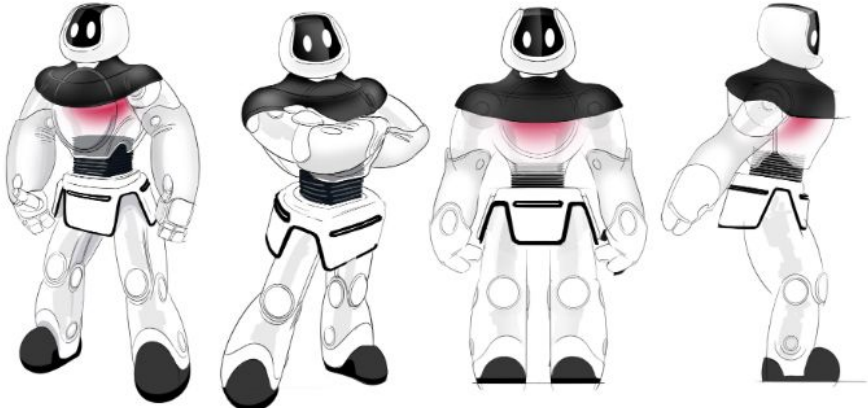



Gelsight grasp demo

# Agenda

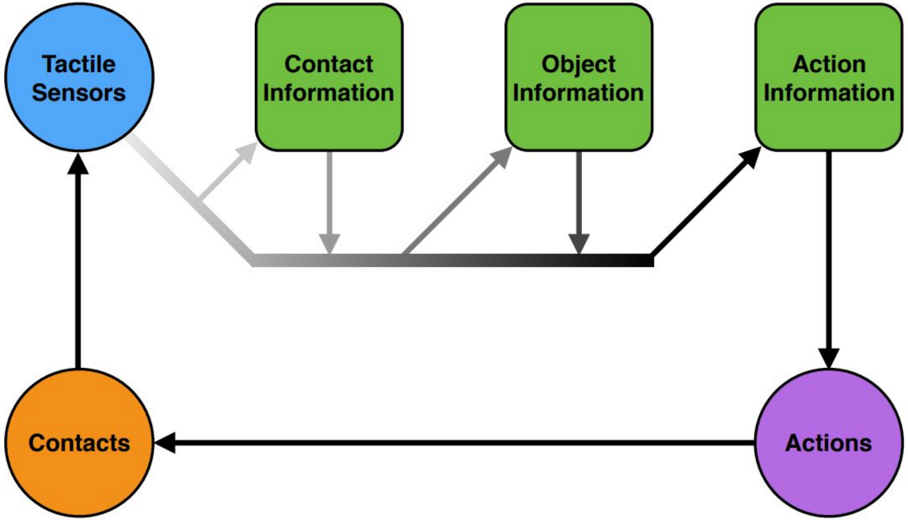
- Tactile perception
- Signal categories
- Types of sensors
- Haptic vs Tactile sensing
- Gelsight
- Tac2Pose
- Tacto
- Tactile sensing for Deep Learning

Punyo



# What is Tactile Perception?

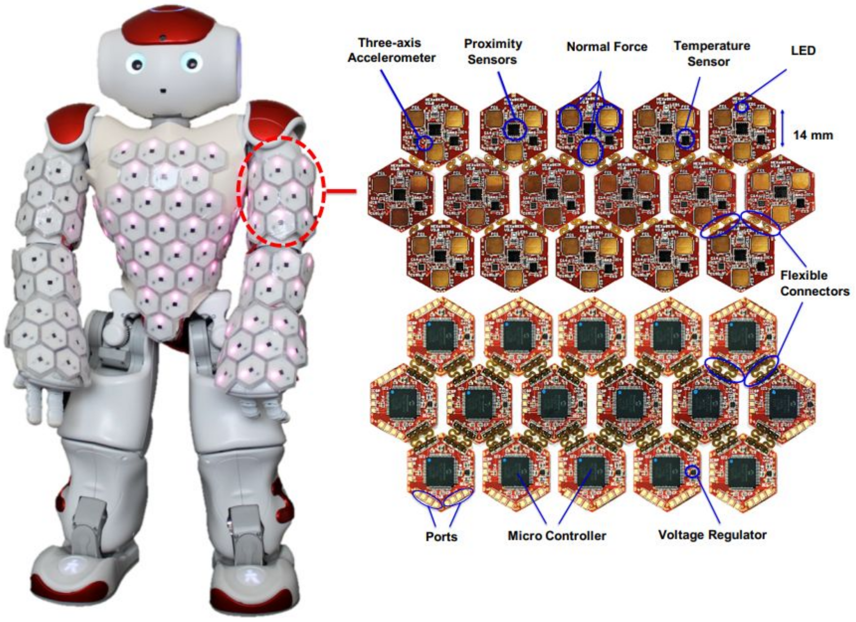
- Key sensor modality for robots
- Provide a rich and diverse set of data signals about...
  - Contact
  - Objects
  - Actions




A Review of Tactile Information: Perception and Action Through Touch, Li et al. , 2020

# Sensor-Level Signals

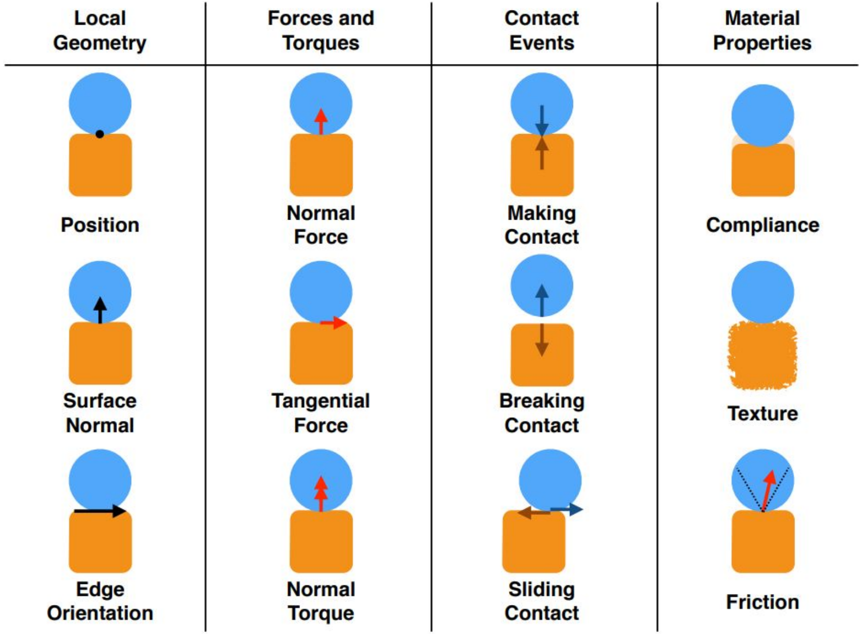
- Normal and tangential force
- Vibration
- Thermal
- Pretouch proximity
- Sensor coverage




A Review of Tactile Information: Perception and Action Through Touch, Li et al. , 2020

# Contact-Level Signals

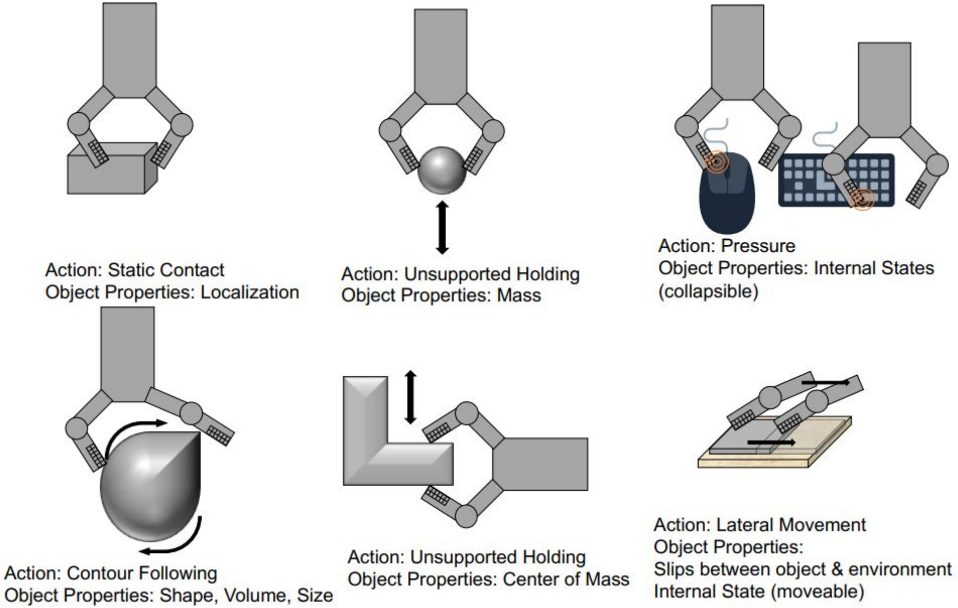
- Contact geometry
- Force and torque
- Contact events
- Material properties




A Review of Tactile Information: Perception and Action Through Touch, Li et al. , 2020

# Object-Level Signals

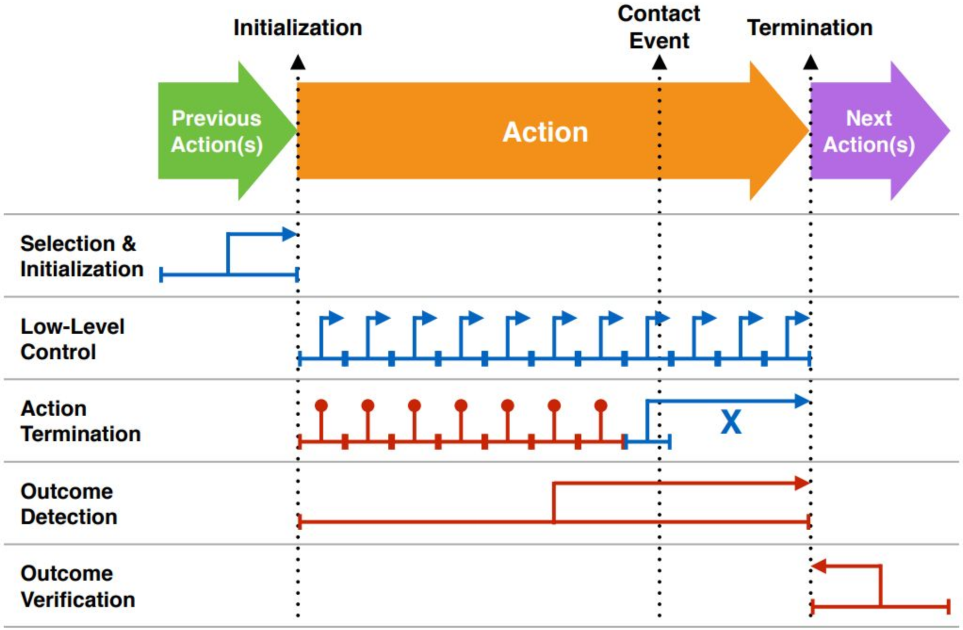
- Object localization
- Shape
- Mass and dynamics
- Contents of containers




A Review of Tactile Information: Perception and Action Through Touch, Li et al. , 2020

# Action-Level Signals

- Action selection and initialization
- Tactile feedback for low-level control
- Action termination
- Action outcome detection
- Action outcome verification

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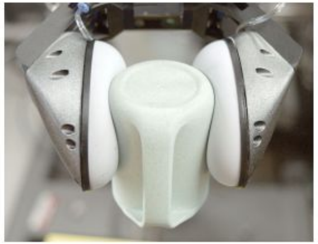
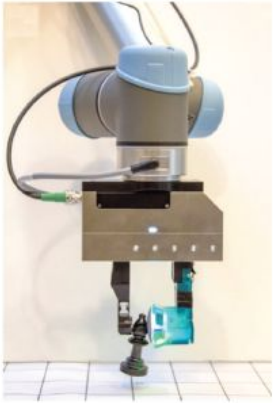
# Sensors

Facebook AI Digit

**Visuotactile**



TRI Punyo SoftBubble

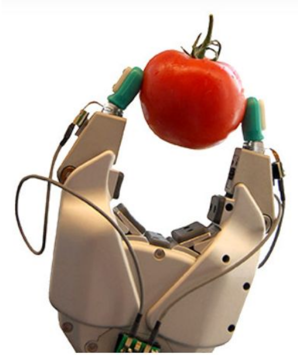


GelSight Mini

**Tactile**

Xela Robotics uSkin

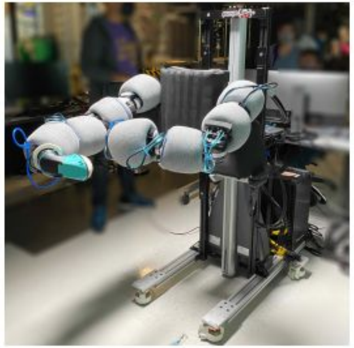
SynTouch BioTac

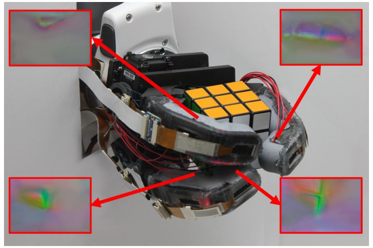



https://digit.ml/
https://arxiv.org/abs/2004.03691
https://xelarobotics.com/en/integrations
https://syntouchinc.com/robotics/#:~:text=core%2C%20enhancing%20durability.-,The%20sensor%20that%20paved%20the%20way%20to%20machine%20touch,capabilities%20of%20the%20human%20fingertip.
https://www.mdpi.com/1424-8220/17/12/2762#

# Tactile Sensing Timeline

- 2008 — BioTac
- 2016 — uSkin
- 2017 — GelSight Mini
- 2020 — SoftBubble
- 2020 — Digit
- 2021 — GelSlim 3.0
- 2022 — 3-Finger Gelsight
- 2023 — Punyo-1





https://arxiv.org/abs/2111.09354
https://arxiv.org/abs/2103.12269
https://news.mit.edu/2023/robotic-hand-can-identify-objects-just-one-grasp-0403

# Haptic vs. Tactile Sensing

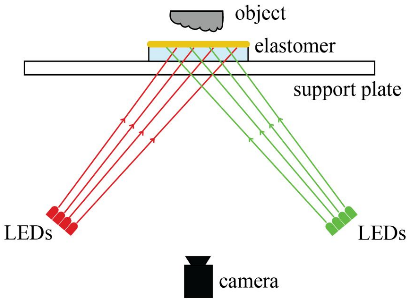
## Haptic

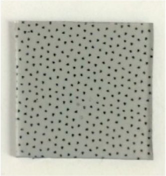
- Overall sensory experiences:
  - Tactile
  - Proprioception
  - Kinesthesia

## Tactile

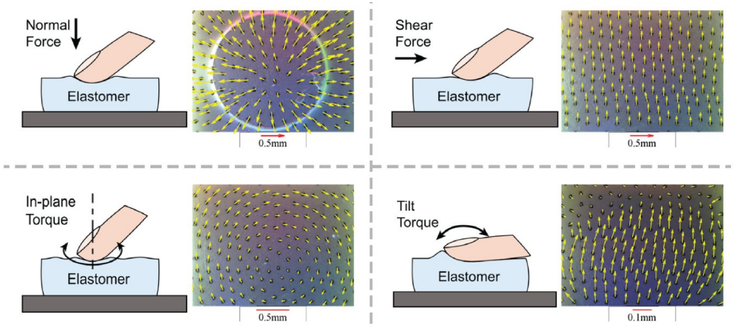
- Detection of physical sensations:
  - Pressure
  - Temperature
  - Texture

# What is Visuotactile Sensing?

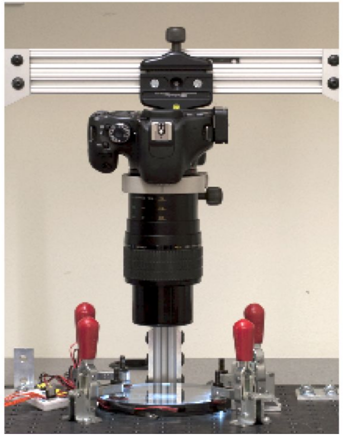
(a)

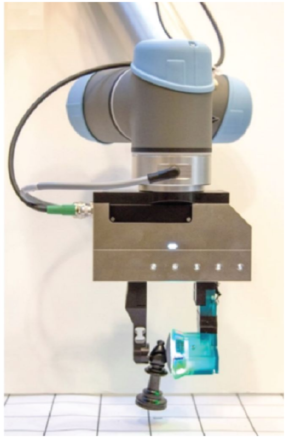


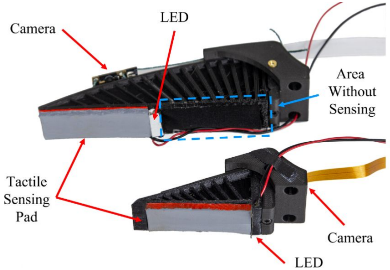

(b)

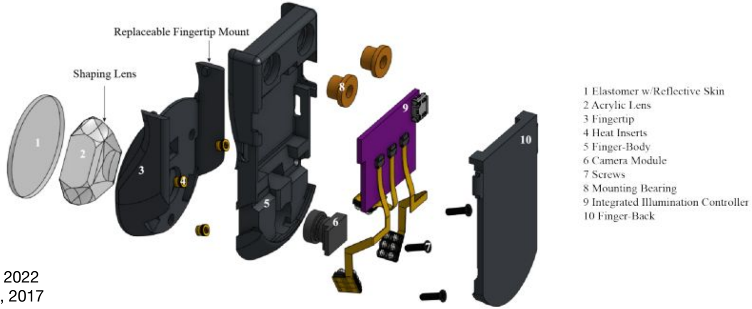
GelSight Fin Ray: Incorporating Tactile Sensing into a Soft Compliant Robotic Gripper, Liu et al. , 2022
GelSight: High-Resolution Robot Tactile Sensors for Estimating Geometry and Force,  Yuan et al. , 2017

# Exploring Gelsight Evolution





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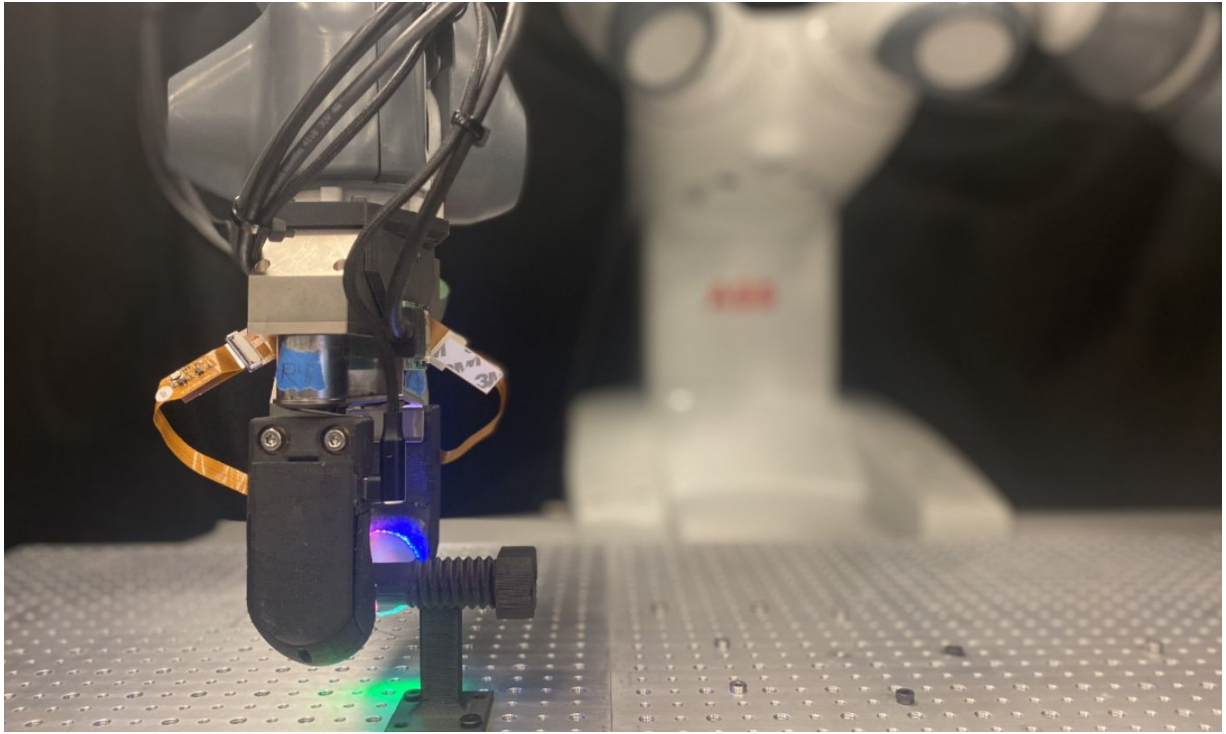
# Tac2Pose: Tactile Object Pose Estimation from the First Touch.

Maria Bauza,
Antonia Bronars, and
Alberto Rodriguez

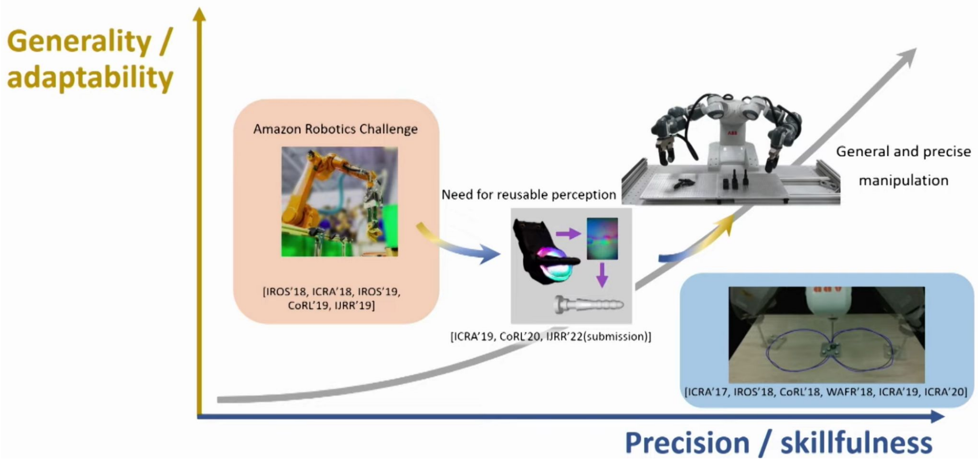
*CORL 2022*

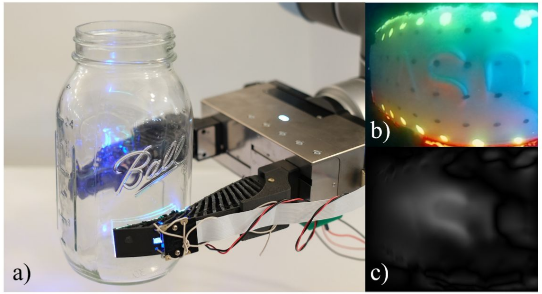


Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Motivation

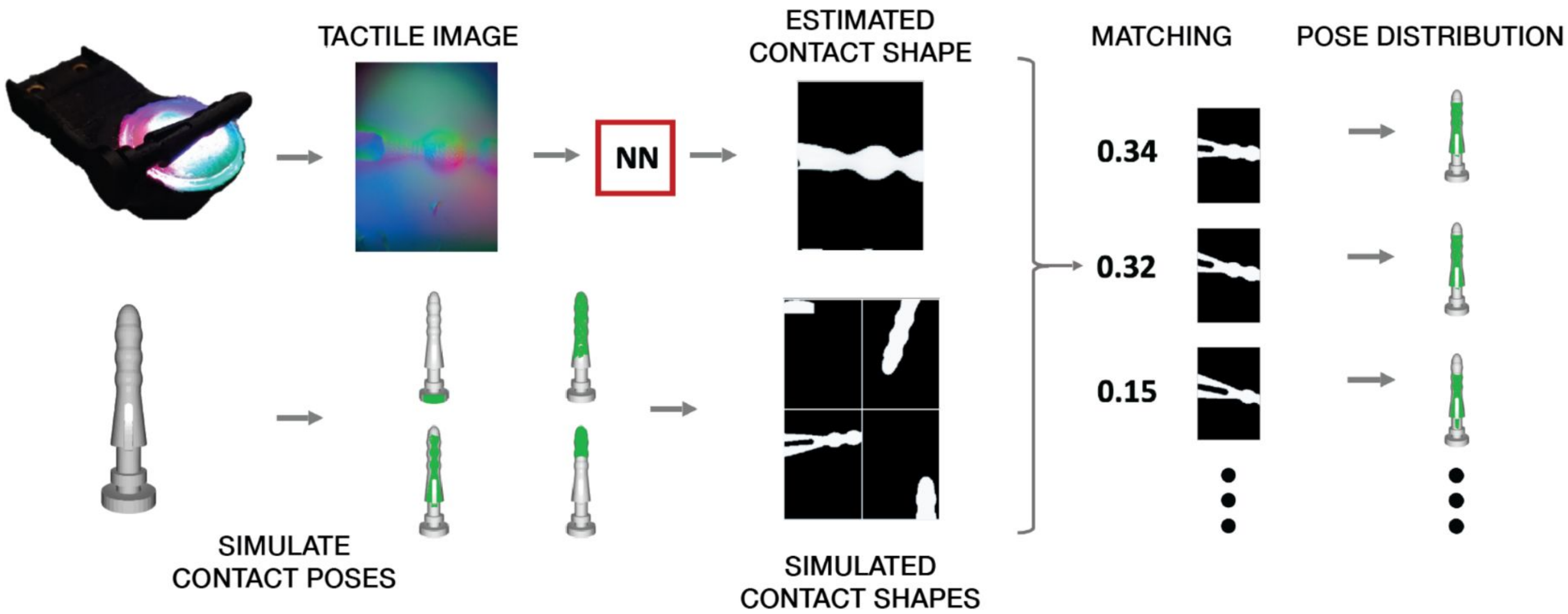
- Close the loop
  - Know the pose of the object
  - React to uncertainty
- Industry needs Precision
  - Often Specialized Solutions
- General solutions often lack Precision




GelSight Fin Ray: Incorporating Tactile Sensing into a Soft Compliant Robotic Gripper, Liu et al. , 2022
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022
[PhD Thesis Defense - Maria Bauza - Visuo-Tactile Perception for Dexterous Manipulation]

# Methods




Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

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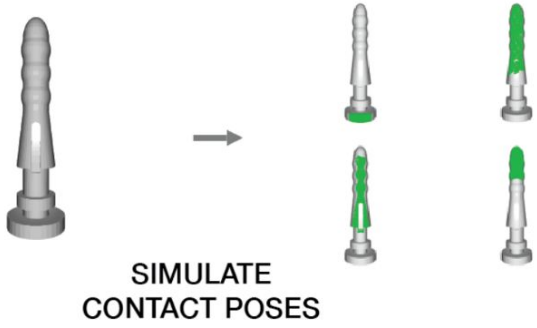


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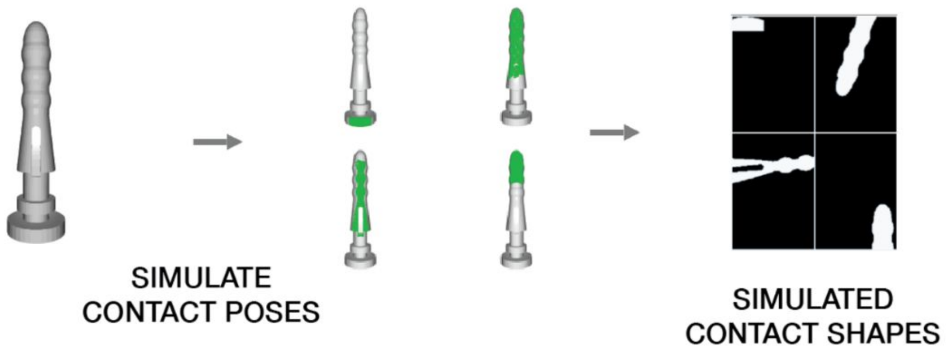


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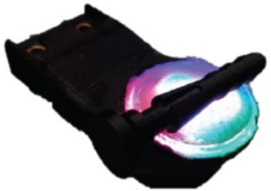

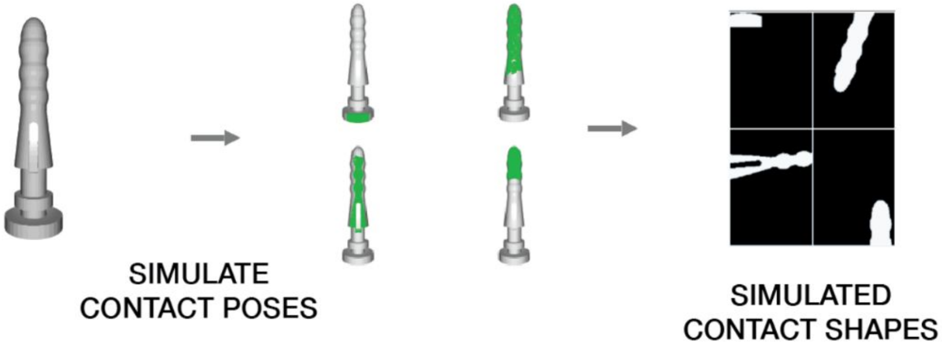


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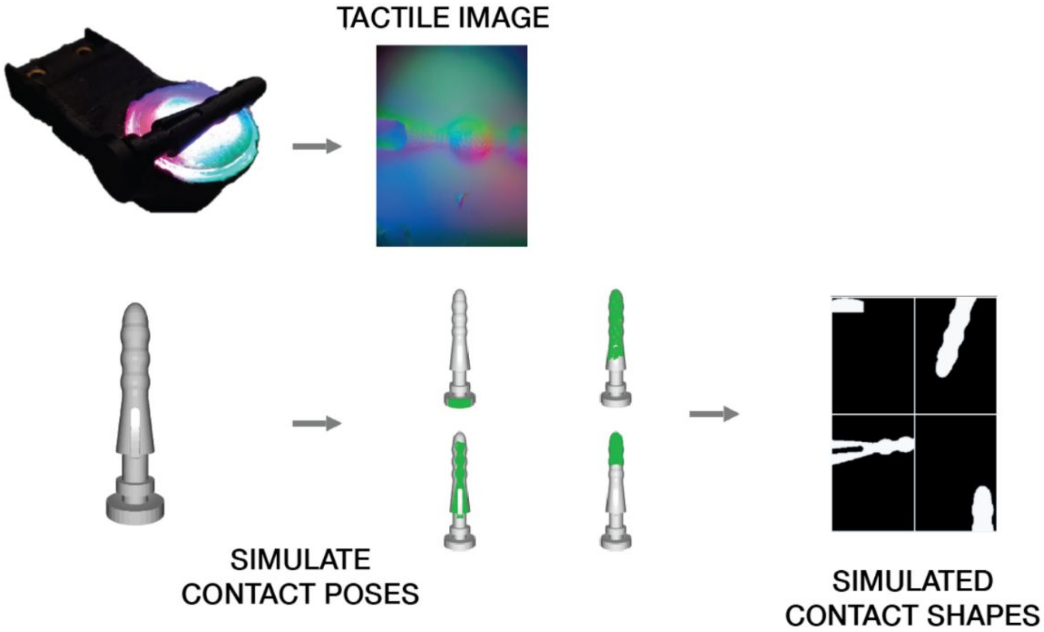


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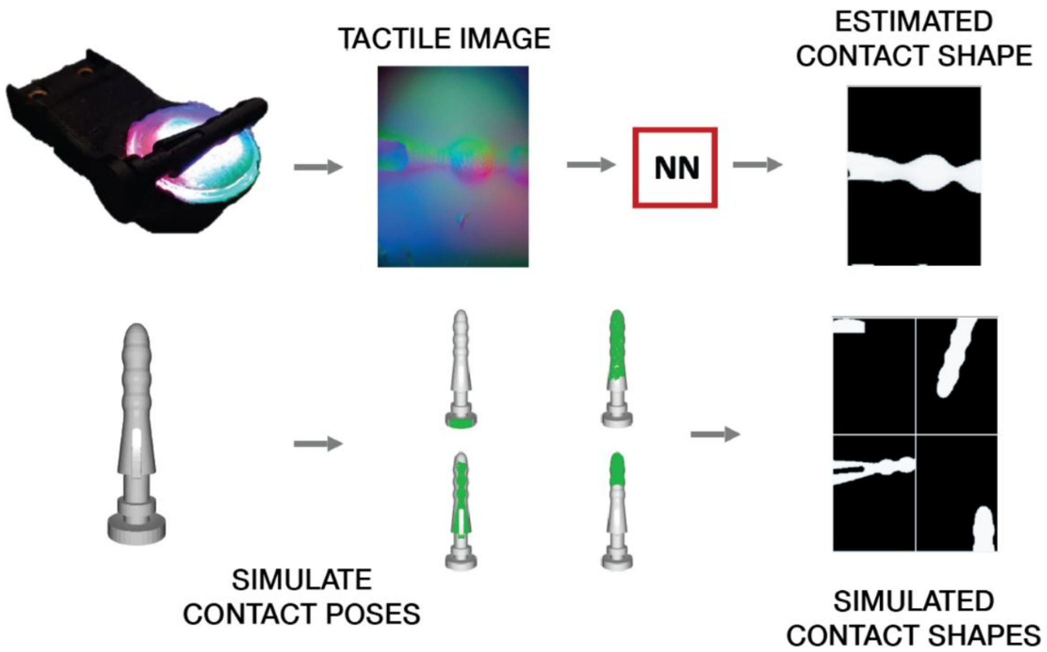


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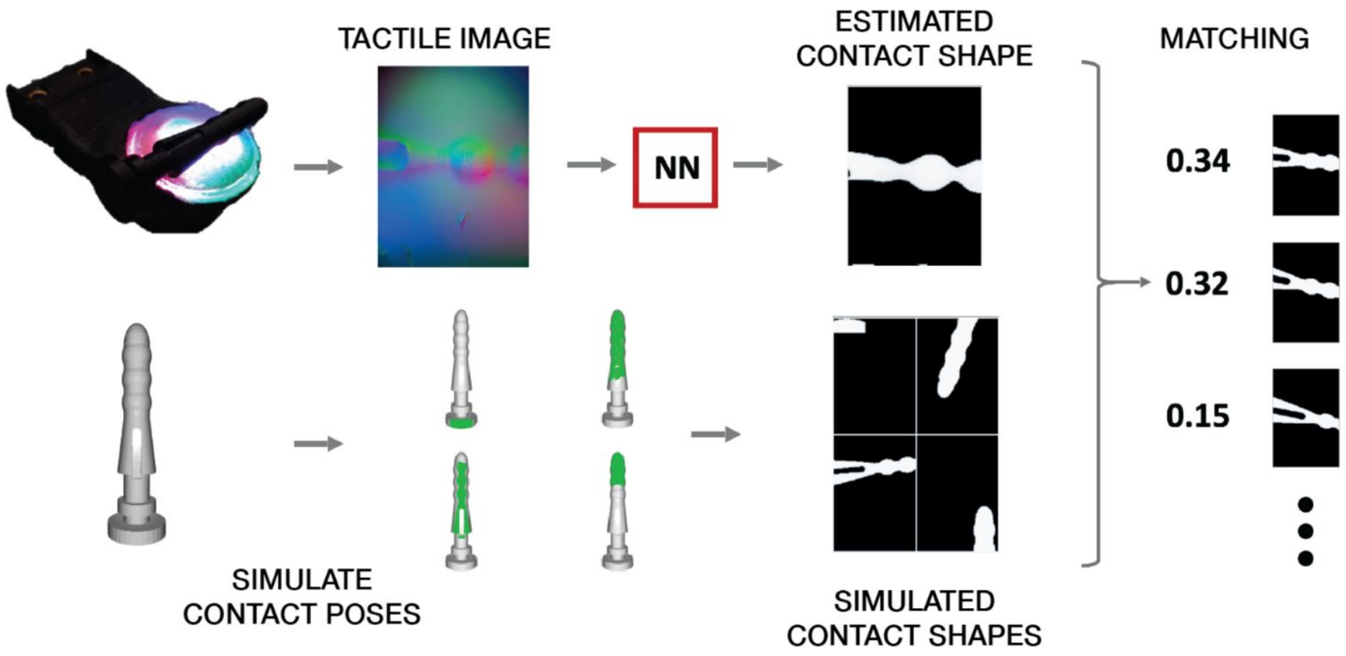


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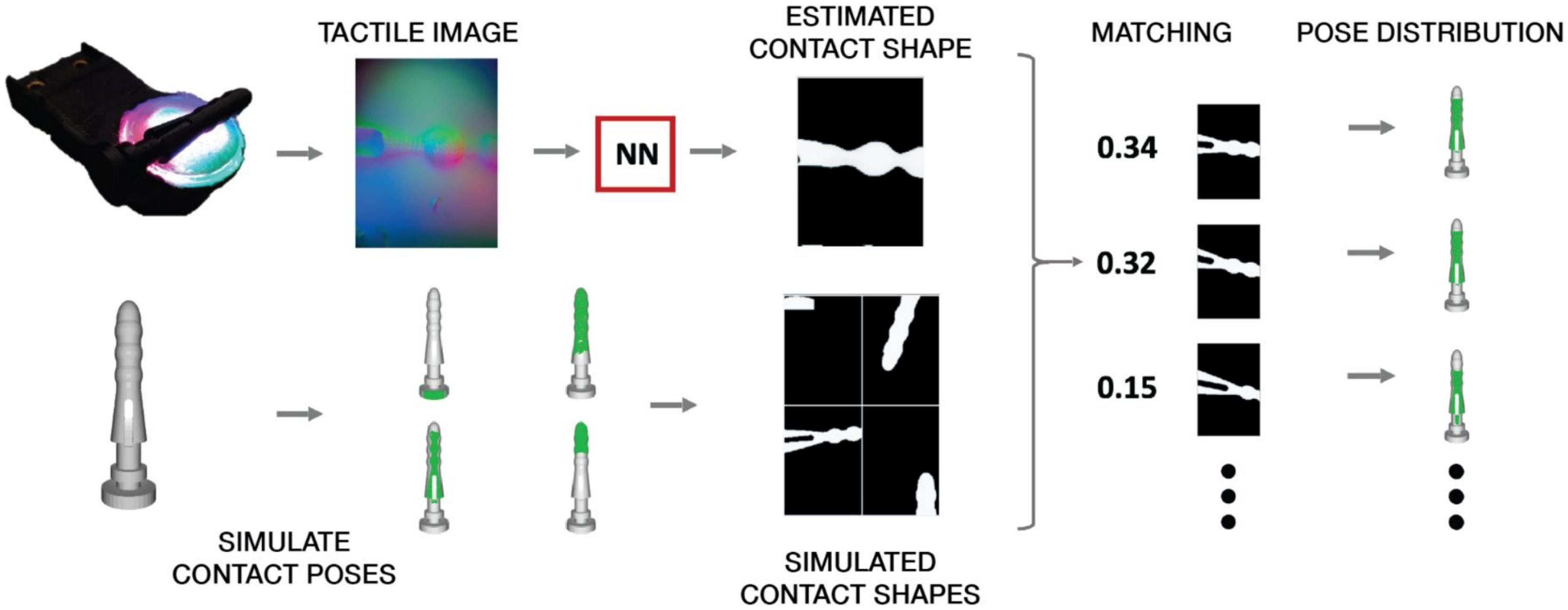


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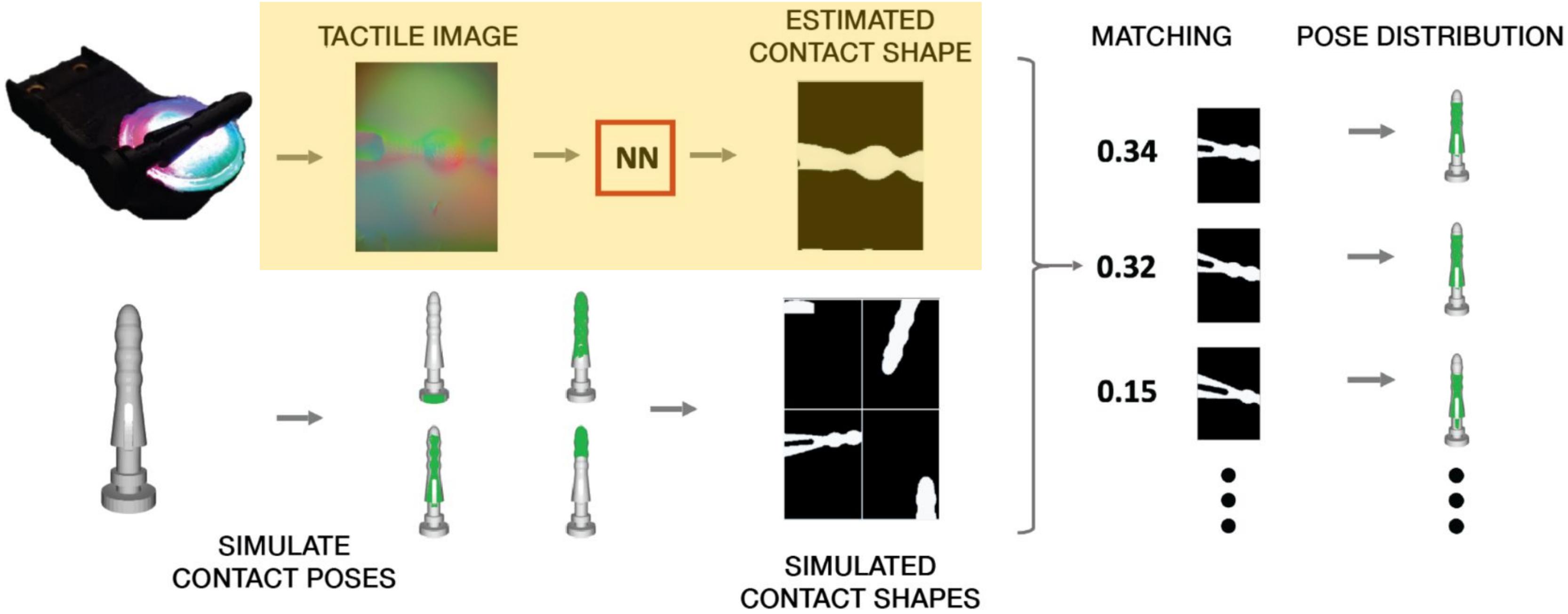
# Contact Shape Network




Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Contact Shape Network

Known GelSight Pose

- Real image
- Simulated Binary Contact Shape

General Enough to work across sensors

Based on: [Image-to-Image Translation with Conditional Adversarial Networks]

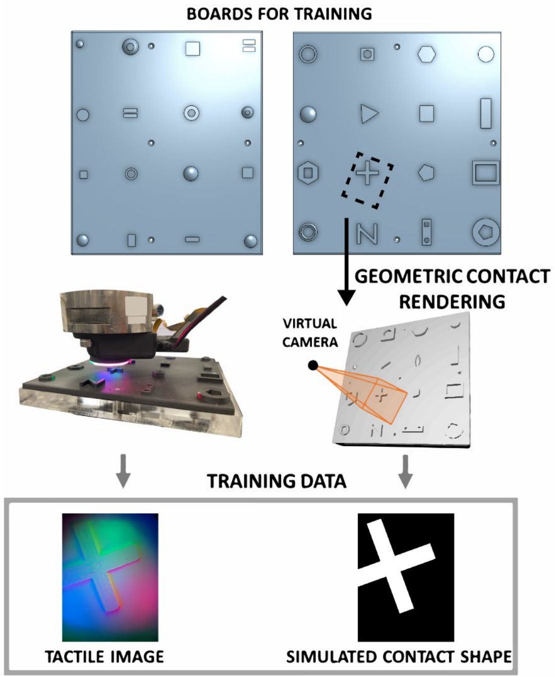
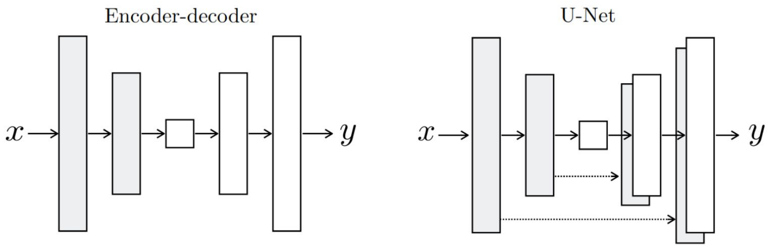



Image-to-Image Translation with Conditional Adversarial Networks, Isola et at. , 2018
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Image-to-Image Translation

- Input: Real image
- Output: Estimated Contact Shape

Trained with ground truth data.




Example: Satellite to Map


Example: Fake shoe to convincing fake shoe

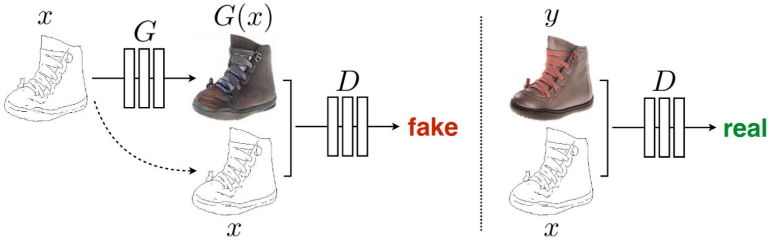


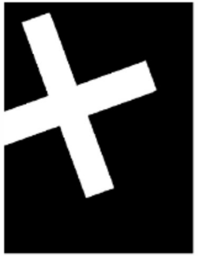


Image-to-Image Translation with Conditional Adversarial Networks, Isola et at. , 2018
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

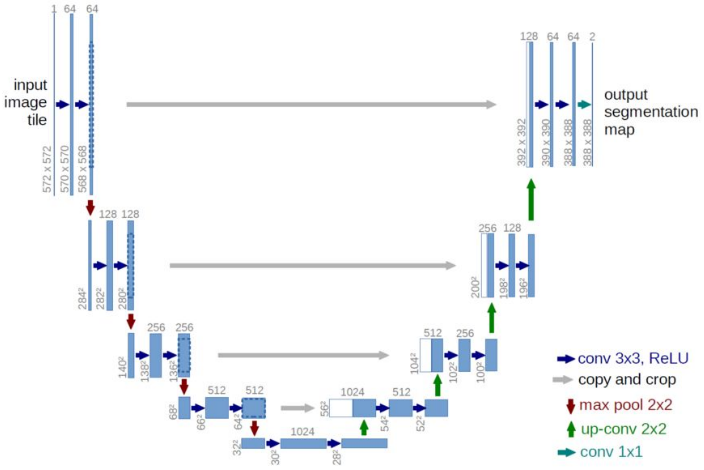
# Image-to-Image Translation

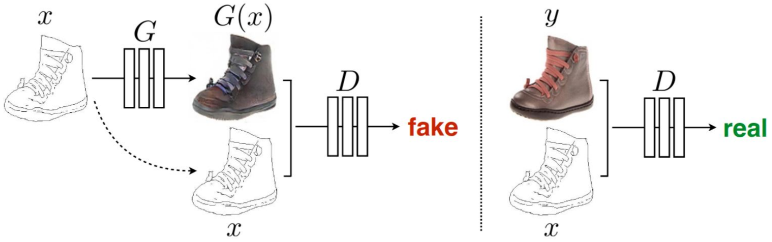
Generator: Creates contact mask
Discriminator: Identifies fake images

TACTILE IMAGE



SIMULATED CONTACT SHAPE

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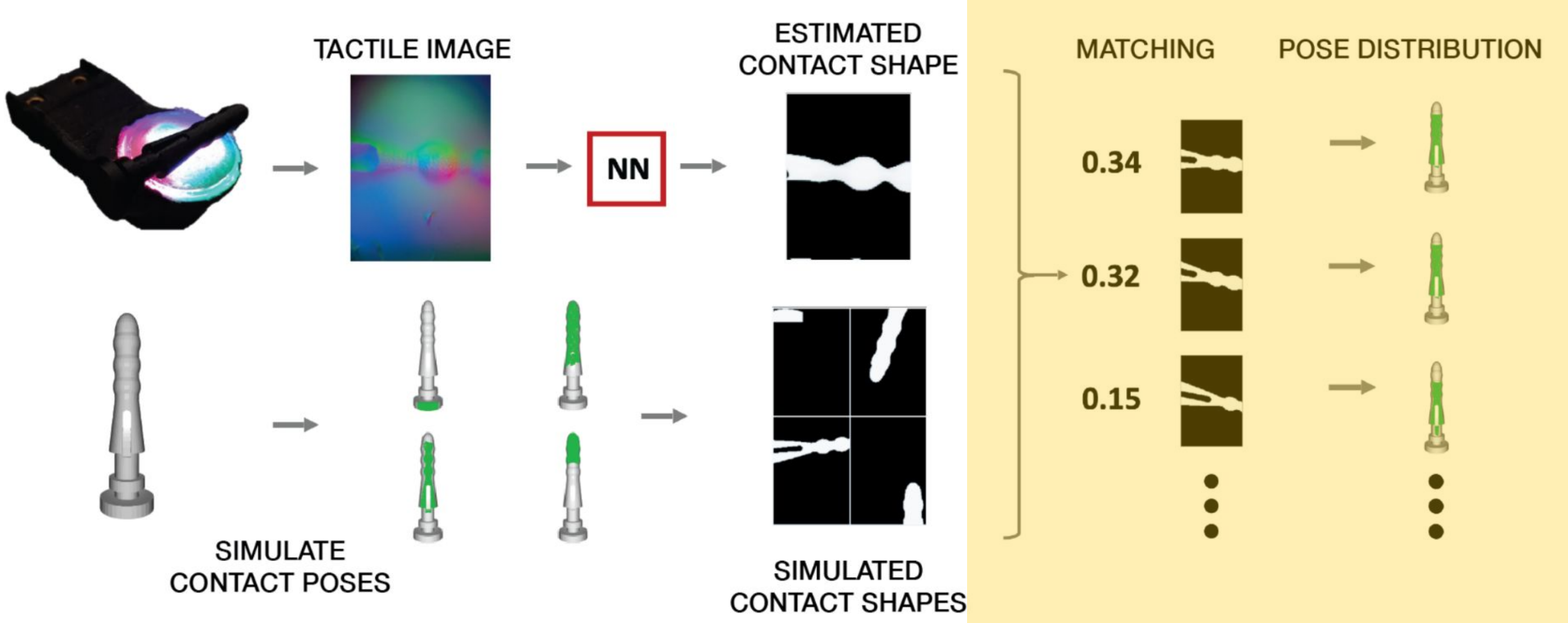
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Pose Matching

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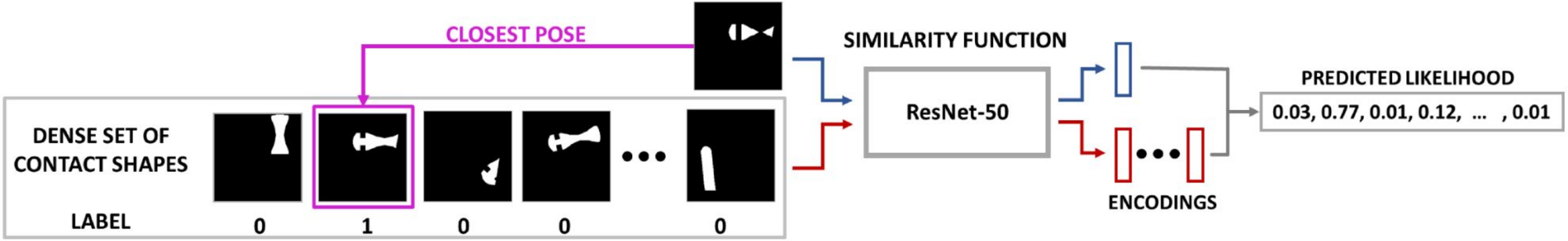
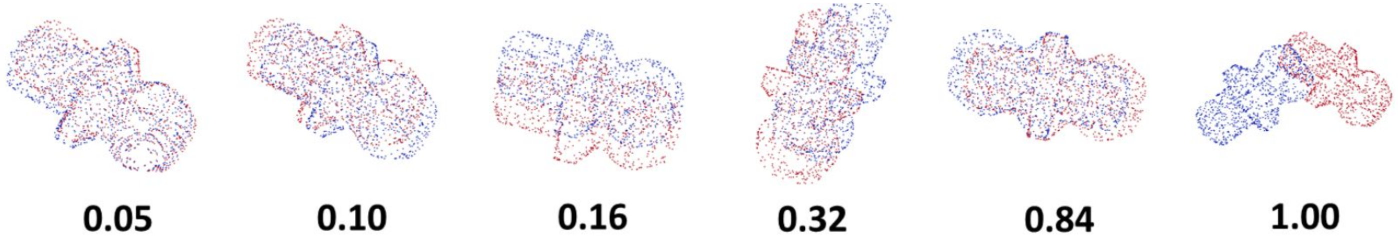



Normalized Pose Errors:




Normalized Pose Error: Original pose error divided by the average error obtained from predicting a random contact pose.

Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

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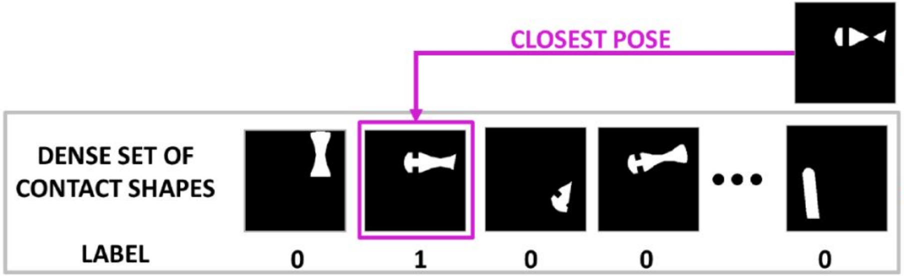
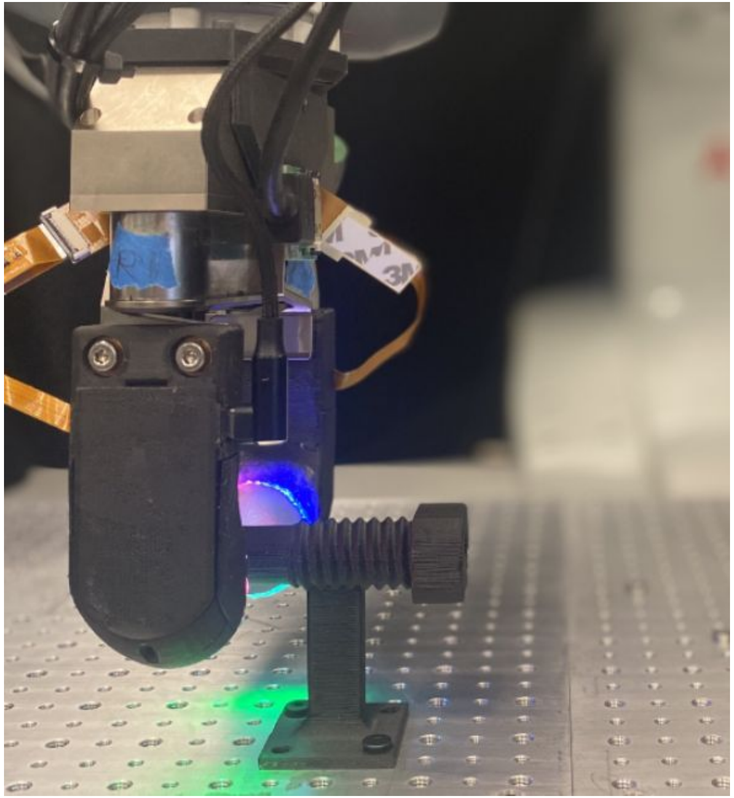


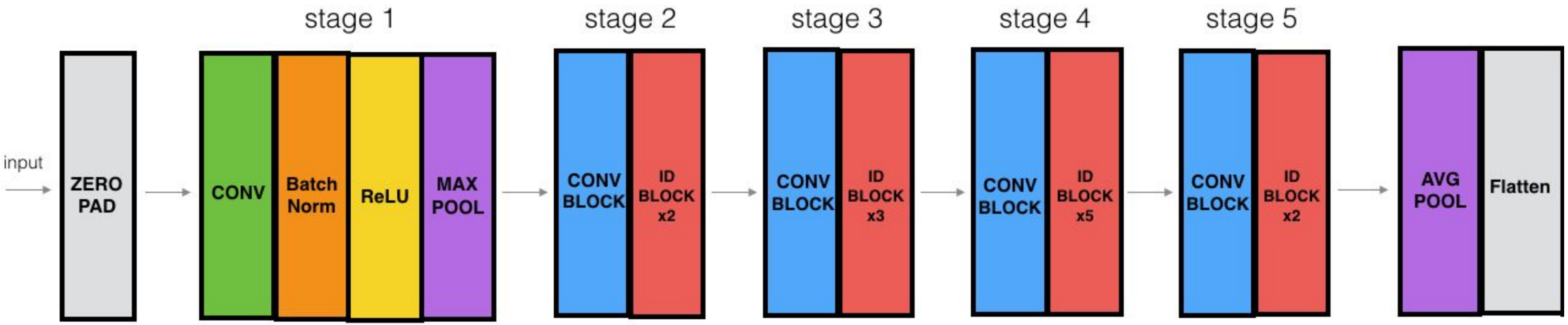
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Pose Matching


Encoder Network:
Pre-Trained ResNet 50

*Removed Linear Layers*

Trained with: [MoCo]



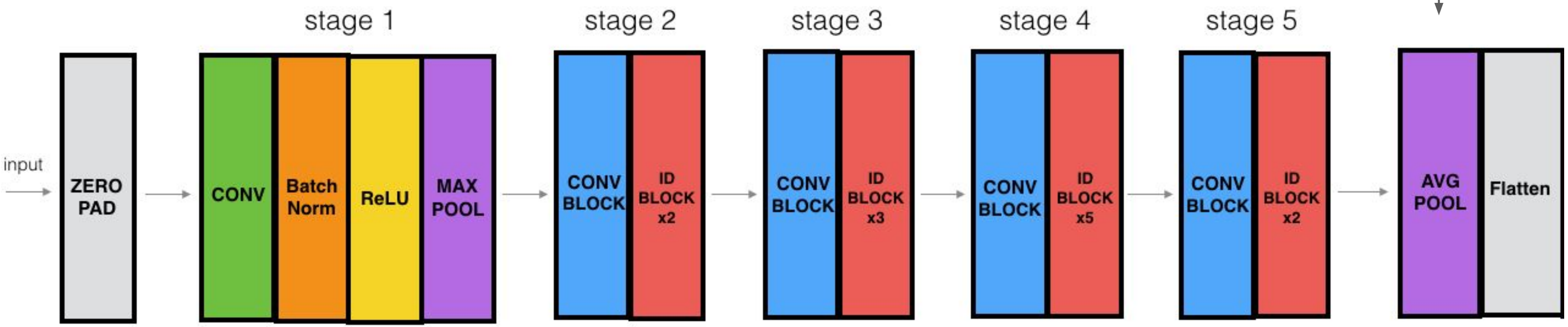

Deep Residual Learning for Image Recognition, He et al. , 2015
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Pose Matching


**It could never be that easy.**

**The designers this put in an AveragePool!**

**The AveragePool is removing critical spatial information.**

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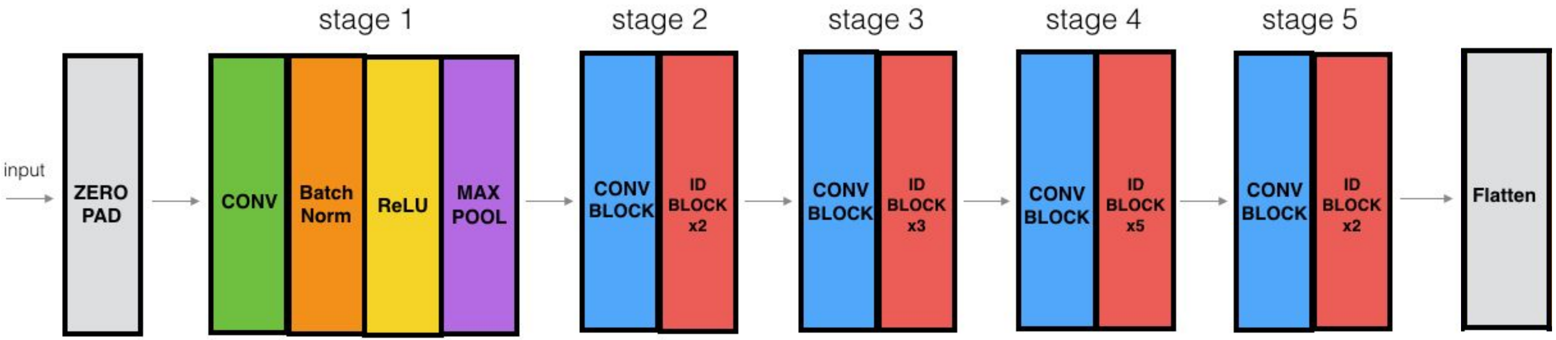
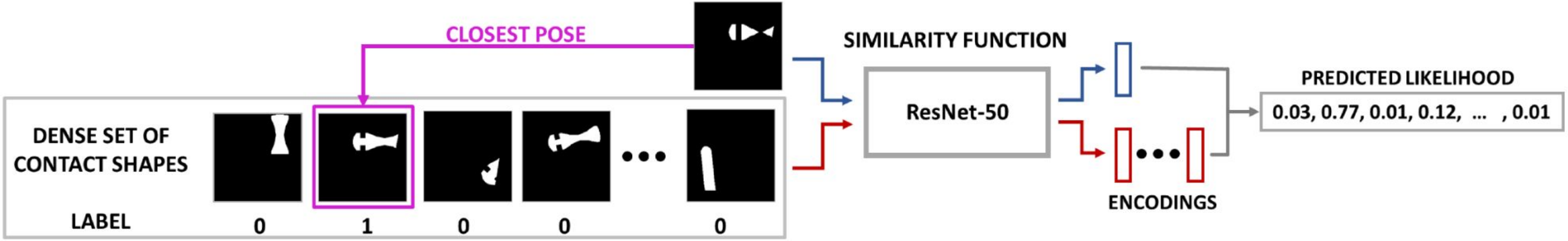



Much Better

Deep Residual Learning for Image Recognition, He et al. , 2015
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Pose Matching




Take Largest Probability from SoftMax to get the inferred pose!

Number of Contact Shapes: N
Encoding Size: S
Encoded GelSight mask: 1xS
Encoded simulation mask: NxS
Dot product distances: 1xN

Probability = SoftMax(Dot product distances)

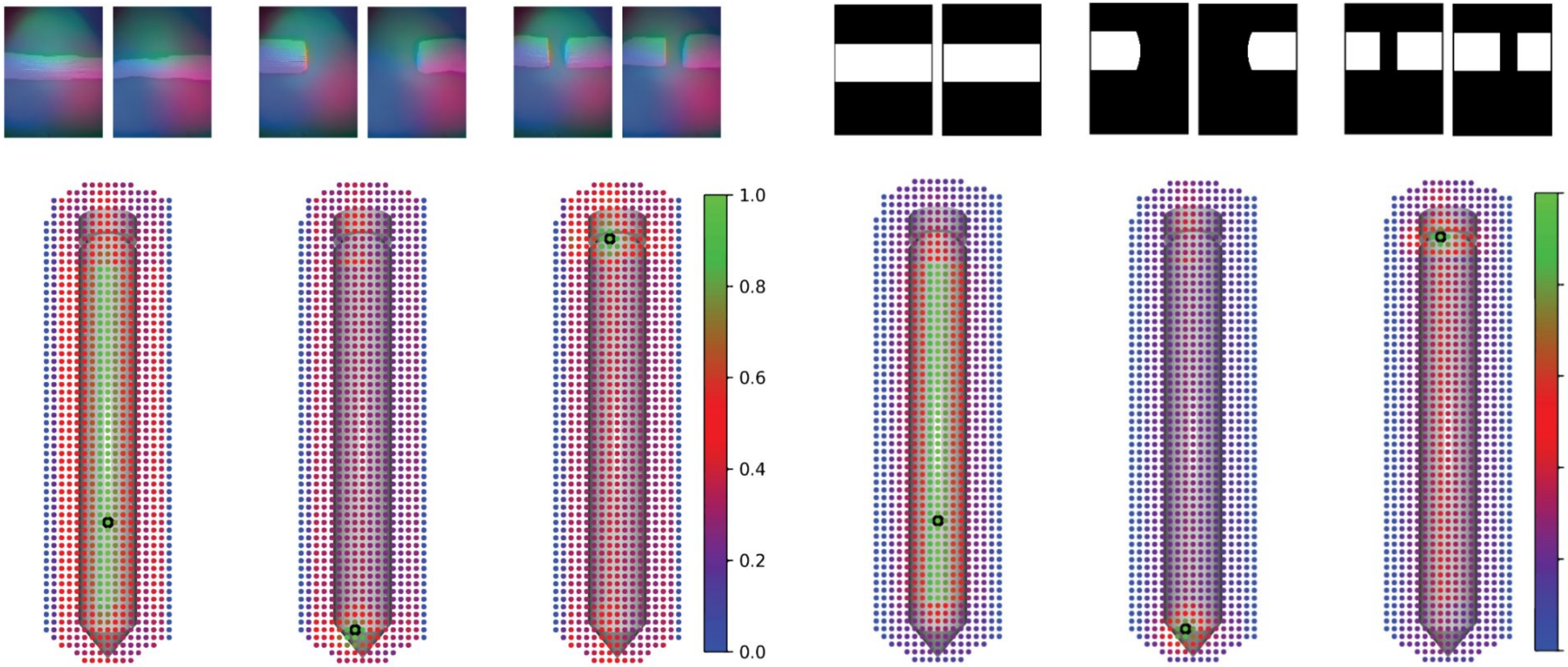
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Look! A pencil, how Fun!

Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

It is the best image I could find, give me some slack.

# Fun is not allowed

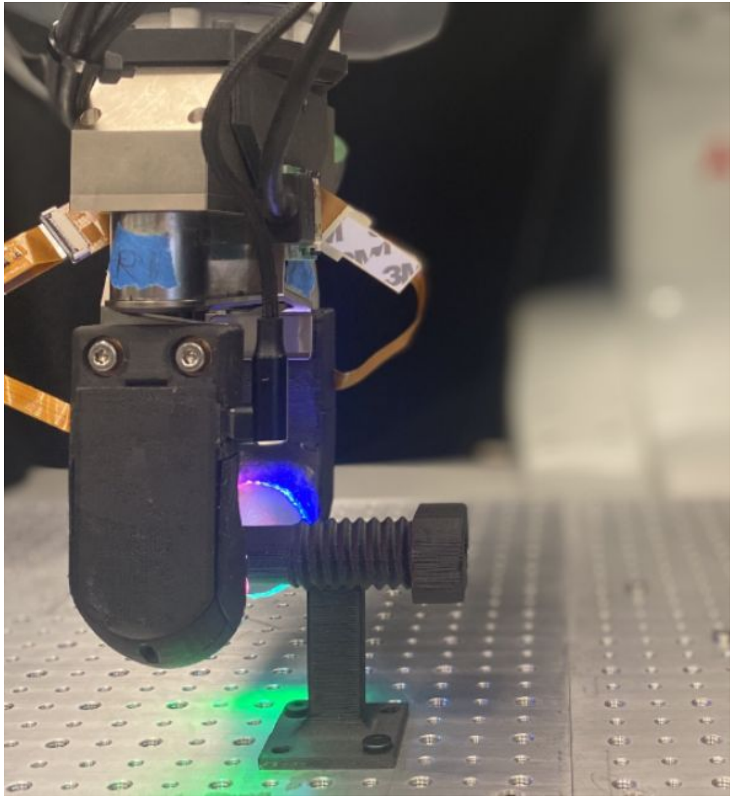



Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Pose Distributions


These sensors can be small!
Only a few $cm^2$ of perception per sensor.

- Unique contact patterns are needed to disambiguate non-unique contact mappings.
- Better to know that you don't know, than to know nothing at all.
    - Regrasp on ambiguous pose distributions.
    - Combine with other modes of sensing (Eg, Visual, Sound, Smell?).



Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Comparisons to Other Methods

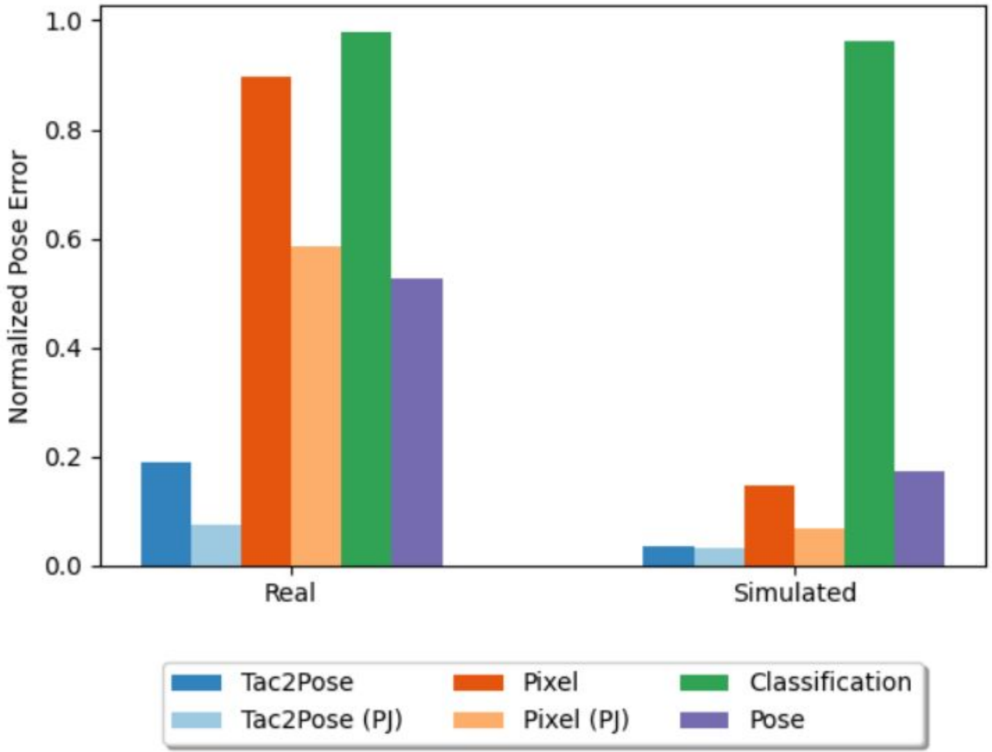
**Tac2Pose**: Method Described above.

**Pixel**: No encoder, direct pixel to pixel matching between input contact mask and all simulated contact masks.

**Classification**: Resnet-50, trained to One-Hot classify each discrete pose.

**Pose**: Resnet-50, trained to regress each pose.

***(PJ)**: Parallel Jaws, two images.*



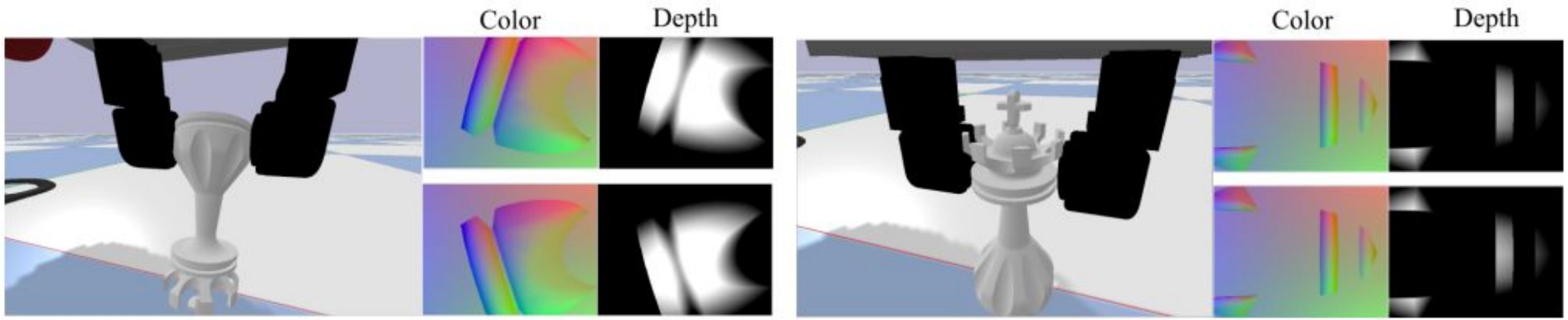

Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# Comparisons to Other Methods

| | | Tac2Pose SC mm (norm) | Tac2Pose PJ mm (norm) | Pixel SC mm (norm) | Pixel PJ mm (norm) | Classification SC mm (norm) | Pose SC mm (norm) |
|---|---|---|---|---|---|---|---|
| Long Grease |  | 26.6 (0.76) | 3.3 (0.09) | 32.8 (0.93) | 6.0 (0.17) | 33.3 (0.95) | 25.3 (0.72) |
| Snap Ring |  | 1.5 (0.10) | 1.4 (0.10) | 5.6 (0.39) | 2.2 (0.15) | 6.0 (0.42) | 5.9 (0.41) |
| Big Head |  | 7.8 (0.20) | 6.1 (0.16) | 27.6 (0.70) | 11.7 (0.30) | 35.0 (0.89) | 33.8 (0.86) |
| Cotter |  | 19.0 (0.49) | 19.6 (0.51) | 31.5 (0.81) | 36.7 (0.95) | 35.8 (0.93) | 38.1 (0.99) |
| Hanger |  | 6.6 (0.19) | 2.6 (0.07) | 31.3 (0.90) | 20.5 (0.59) | 34.2 (0.98) | 18.3 (0.53) |

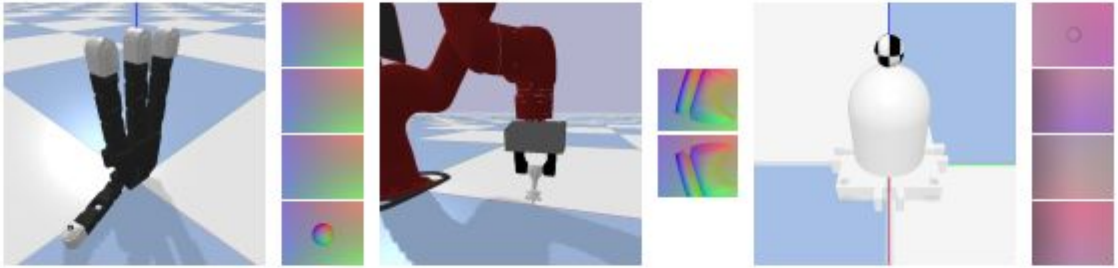
Tac2Pose: Tactile Object Pose Estimation from the First Touch, Bauza et al. , 2022

# TACTO: A Fast, Flexible, and Open-source Simulator for High-Resolution Vision-based Tactile Sensors



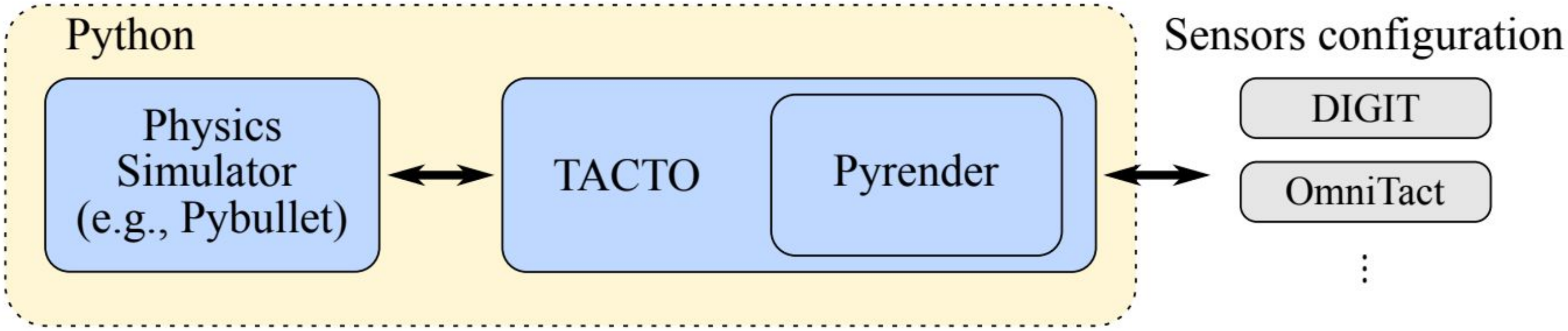

Wang, Shaoxiong, Mike Lambeta, Po-Wei Chou, and Roberto Calandra. *IEEE Robotics and Automation Letters* 7, 2022

# Motivation



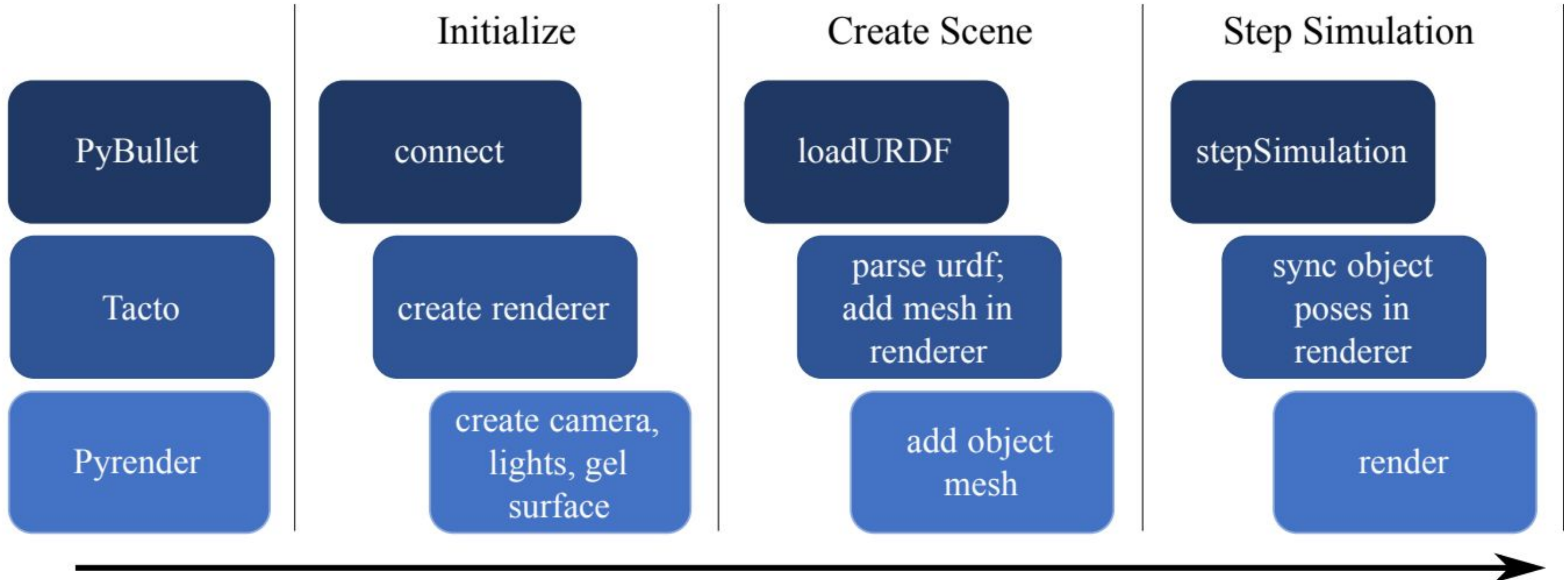
- Simulator for vision based tactile sensors
- Small Sim2Real gap
- Implements OmniTact and DIGIT sensors
- Value for different communities:
  - Hardware designers
  - Robotics
  - Machine learning

# Methods




Wang, Shaoxiong, et al. *TACTO: A Fast, Flexible, and Open-Source Simulator for High-Resolution Vision-Based Tactile Sensors*. 2020.

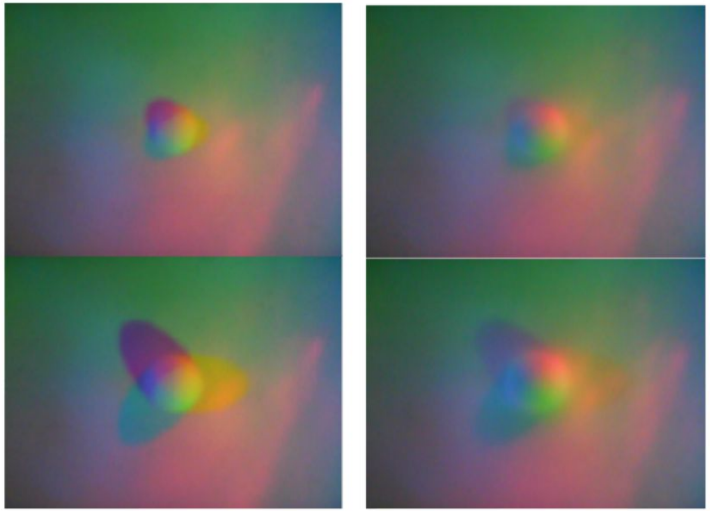
# Software Architecture



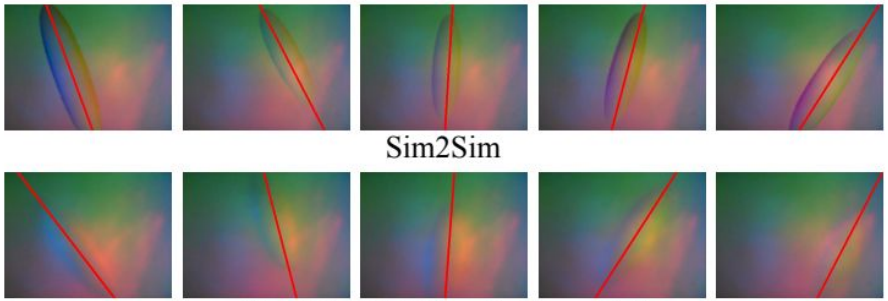

Wang, Shaoxiong, et al. *TACTO: A Fast, Flexible, and Open-Source Simulator for High-Resolution Vision-Based Tactile Sensors*. 2020.

# Sim vs Real

Sim Real



Pose estimation results

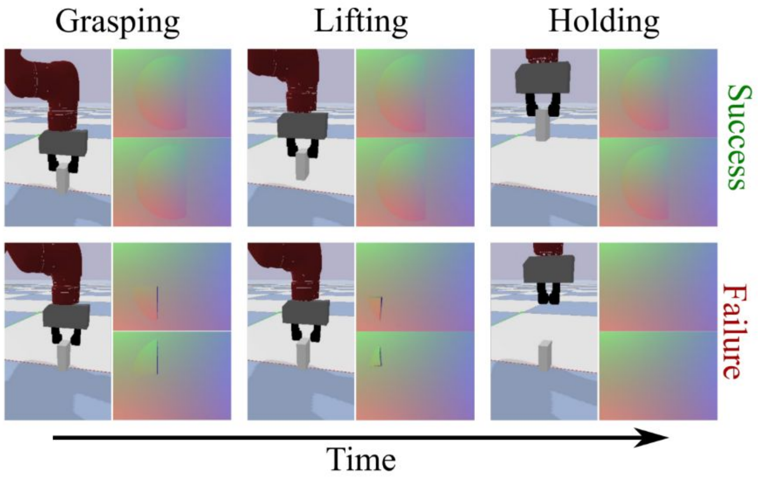


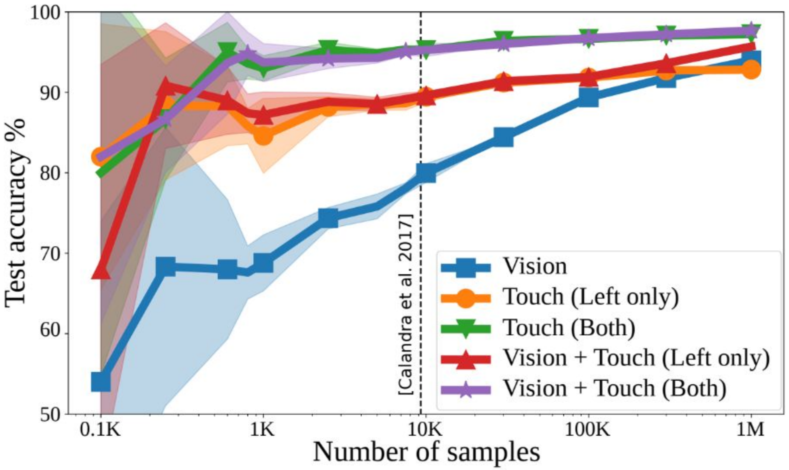
Sim2Sim

Sim + Real (128 real datapoints)

Wang, Shaoxiong, et al. *TACTO: A Fast, Flexible, and Open-Source Simulator for High-Resolution Vision-Based Tactile Sensors*. 2020.

# Results



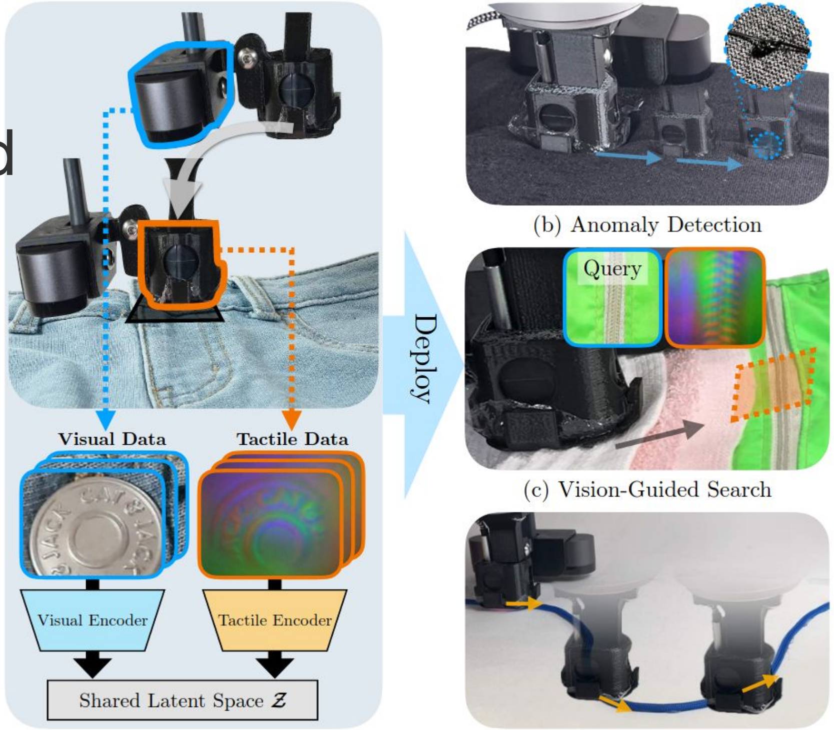




Wang, Shaoxiong, et al. *TACTO: A Fast, Flexible, and Open-Source Simulator for High-Resolution Vision-Based Tactile Sensors*. 2020.

Questions?

# Learning Self-Supervised Representations from Vision and Touch for Active Sliding Perception of Deformable Surfaces

- Align visual and tactile data
  - Train encoders to embed into a shared latent feature space.
  - Uses cross-modal contrastive loss
  - Object agnostic representation.




(a) Self-Supervised Learning

(b) Anomaly Detection

(c) Vision-Guided Search

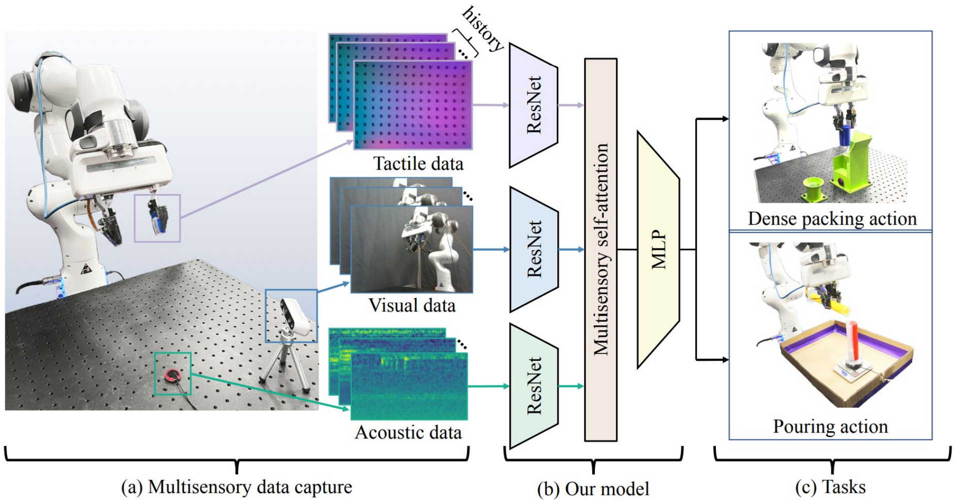
(d) Tactile Servoing

Kerr et al. (*ICRA 2023*)

Learning Self-Supervised Representations from Vision and Touch for Active Sliding Perception of Deformable Surfaces, Kerr et al. , 2022

# See, Hear, and Feel: Smart Sensory Fusion for Robotic Manipulation

- Explore using multi sensory data for performing Tasks
- Combines vision, tactile, and audio data

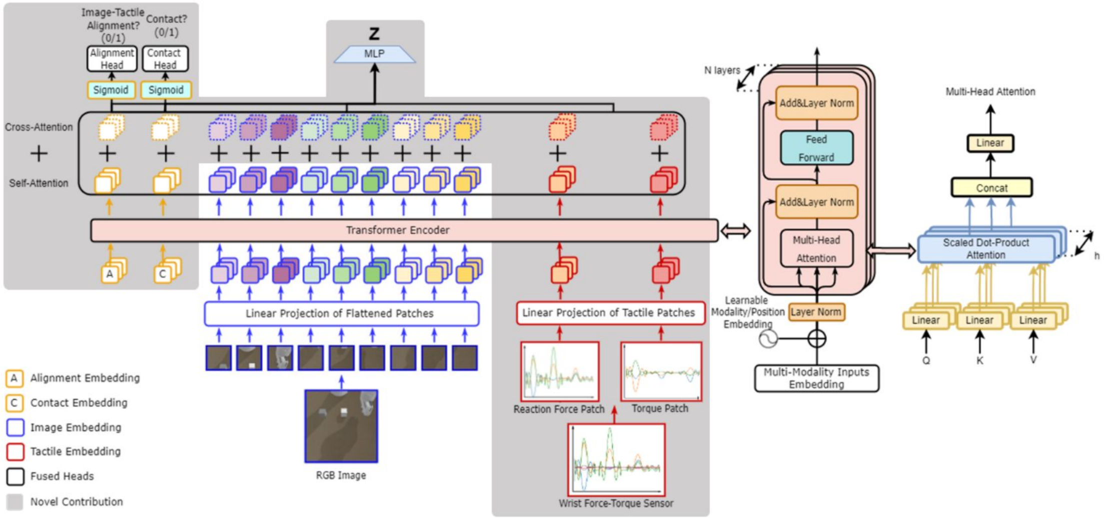



Li, Hao, et al. *See, Hear, and Feel: Smart Sensory Fusion for Robotic Manipulation*.. *DOI.org (Datacite)*, https://doi.org/10.48550/ARXIV.2212.03858.

Li et al. (*Corl 2022*)

# Visuo-Tactile Transformers for Manipulation (VTT)

- Modality Patches
- Self and Cross-Modal Attention
- Learned embeddings:
  - Contact
  - Alignment
  - Position/Modality
- Compressed Representation Head
- Combined Reinforcement Learning



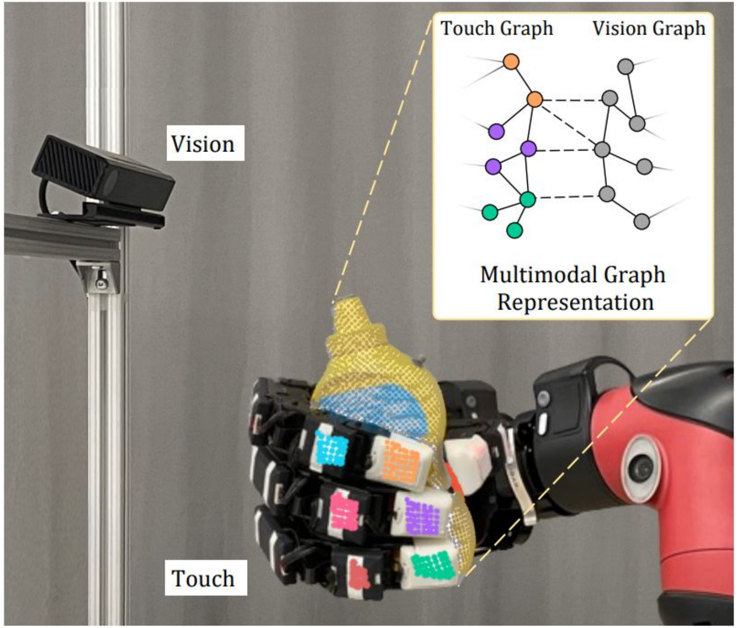

https://arxiv.org/abs/2210.00121

$$\ell_{VTT} = BCE_{logits}(MLP(Al_{head})), Al_{gt}) + BCE_{logits}(MLP(C_{head}), C_{gt})$$

Chen et al., CoRL 2022

# Hierarchical Graph Neural Networks for Proprioceptive 6D Pose Estimation of In-hand objects

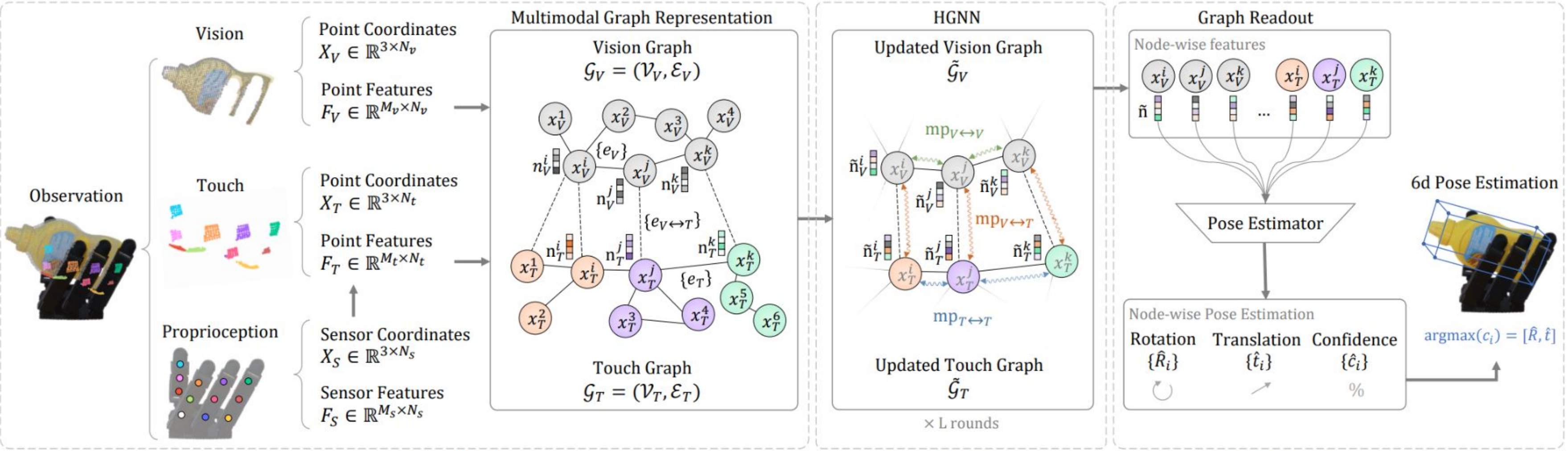
- HGNN combines vision and touch
- Geometrically informed 6D object pose estimation
- Multimodal graph message passing
- Proprioceptive information for in-hand object representation




https://drive.google.com/file/d/1UoOAbM37O4ylzQxXaQae2rK8-ijnWz4n/view

Rezazadeh et al. ICRA 2023

# Architecture




(a) Graph Encoder (b) Graph Processor (c) Pose Decoder

**Node-wise pose estimation loss**

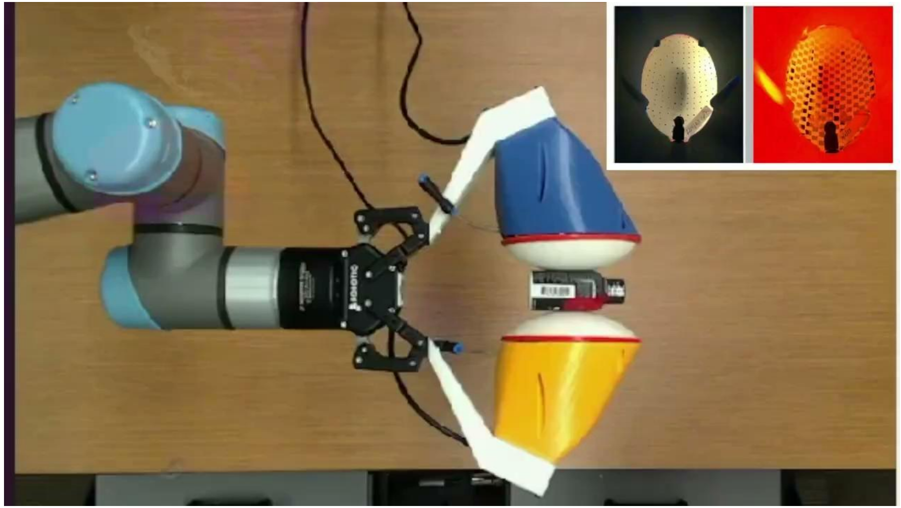
$$L_i^{\mathbf{n}} = \frac{1}{P} \sum_{p=1\ldots P} ||(R_{gt}x_p + t_{gt}) - (\hat{R}_i x_p + \hat{t}_i)||$$

**Total loss**

$$L = \frac{1}{K} \sum_{i=1\ldots K} (L_i^{\mathbf{n}} \hat{c}_i - \lambda \log(\hat{c}_i))$$

# Recap

- Tactile perception
- Signal categories
- Types of sensors
- Haptic vs Tactile sensing
- Gelsight
- Tac2Pose
- Tacto
- Tactile sensing for Deep Learning



# Questions?