Learning Gentle Grasping from Human-Free Force Control Demonstration

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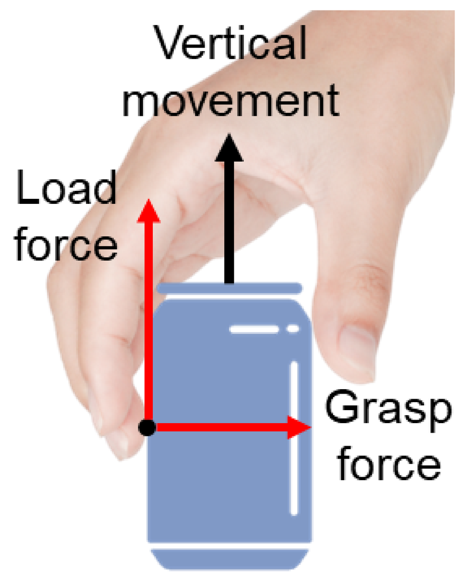
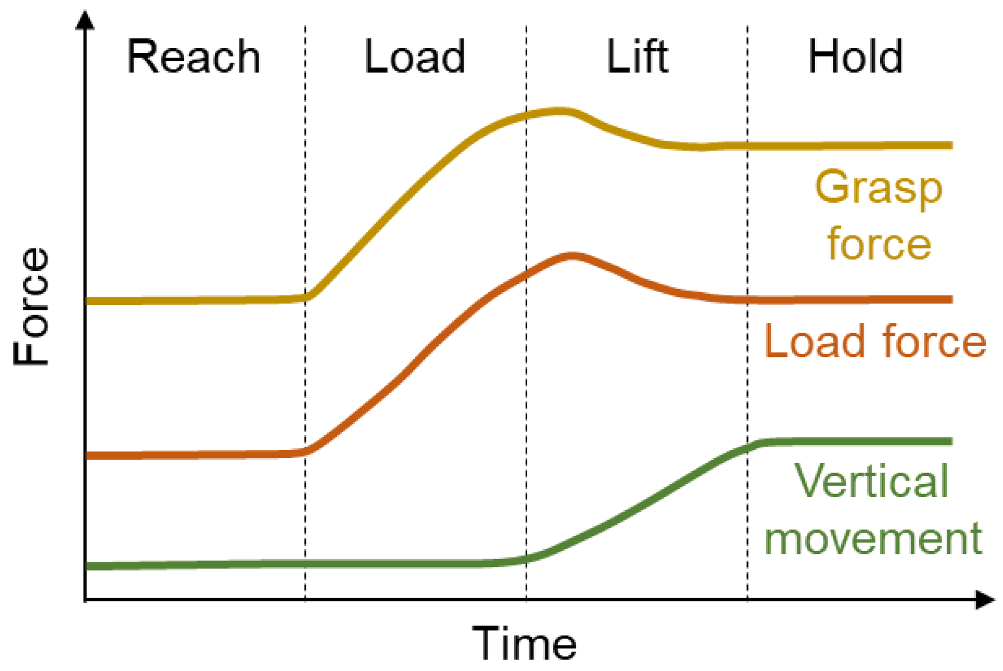
Motivations

Human gentle grasping: Humans can **stably and safely grasp unfamiliar objects** based on tactile perception.

- ✓ **Stability boundary**: The force should **not be too small** to avoid object slip (above the minimum force)
- ✓ **Safety boundary**: The force should **not be too large** to prevent damage (typically no more than 60%).

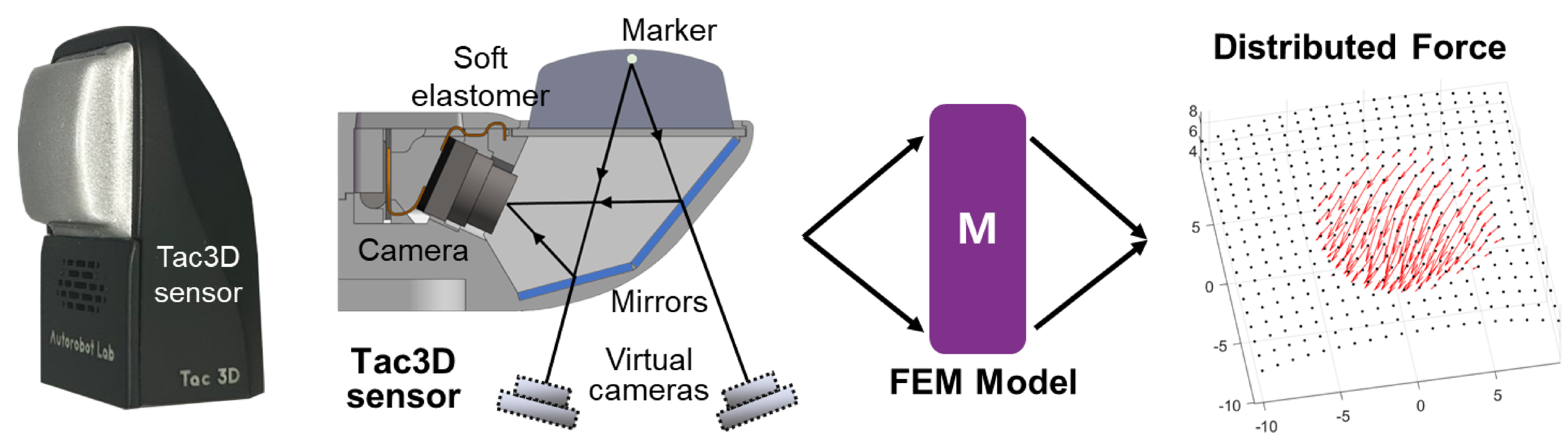
Challenges for robots: Learning accurate grasp-force predictions and control strategies that **can be generalized from limited data**.





Methodology

Tactile Sensing and Force Reconstruction:



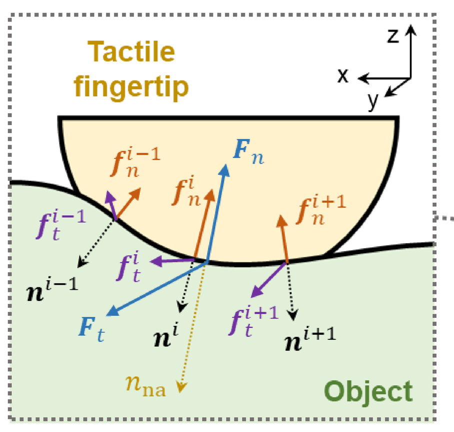
Generation of Force Control Demonstrations:

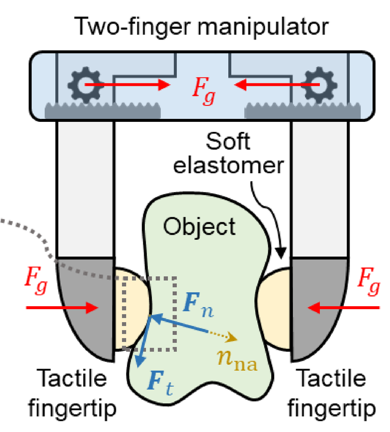
• Micro-element resultant forces

$$F_{MER,n} = \int_S \|\boldsymbol{f}_n^i\| \cdot dA = \int_S \|(\boldsymbol{f}^i \cdot \boldsymbol{n}^i) \cdot \boldsymbol{n}^i\| \cdot dA$$

$$F_{MER,t} = \int_S \|\boldsymbol{f}_t^i\| \cdot dA = \int_S \|\boldsymbol{f}^i - (\boldsymbol{f}^i \cdot \boldsymbol{n}^i) \cdot \boldsymbol{n}^i\| \cdot dA$$

$$F_g = \int_S (\boldsymbol{f}^i \cdot \hat{\boldsymbol{z}}) \cdot dA = (\boldsymbol{F}_n + \boldsymbol{F}_t) \cdot \hat{\boldsymbol{z}}$$





• Estimation with historical information

$$\beta = \begin{cases} \beta_{\max}, & \text{if } t \geq t_m \\ \beta_{\min} + \dfrac{\beta_{\max} - \beta_{\min}}{1 + \exp\left(-k \cdot (t - t_{\text{bias}})\right)}, & \text{if } t < t_m \end{cases}$$

$$F_{\text{Target},n}^{k+1} = \beta \mu^{-1} \cdot \max\left(F_{MRE,t}^k, F_m^{k-1}\right)$$

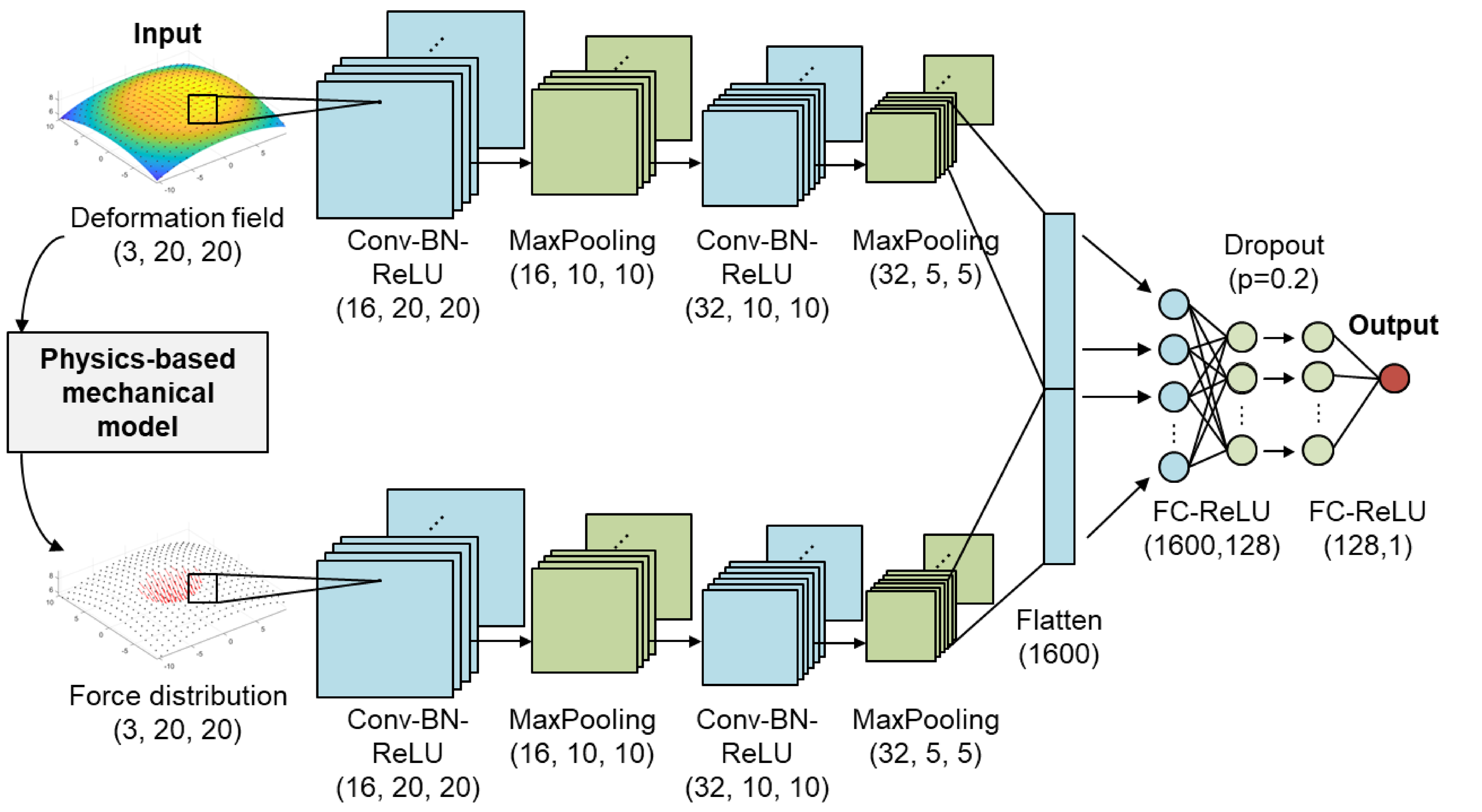
$$F_g^{k+1} = \begin{cases} F_g^k, & \text{if } F_{MER,n}^{k-1} = F_{MER,n}^k \\ F_g^k + \left(F_g^k - F_g^{k-1}\right) \cdot \dfrac{F_{\text{Target},n}^{k+1} - F_{MER,n}^k}{F_{MER,n}^k - F_{MER,n}^{k-1}} & \text{if } F_{MER,n}^{k-1} \neq F_{MER,n}^k \end{cases}$$

• Time-dependent function of safety margin

- ✓ Initially, the grasping force is relatively small, and the tangential force increases rapidly, requiring a **larger safety margin**;
- ✓ As the grasping force gradually approaches the final target value and the tangential force increase rate decreases, a **smaller safety margin** is needed to prevent overshooting.

Target Force Prediction and Online Force Control:

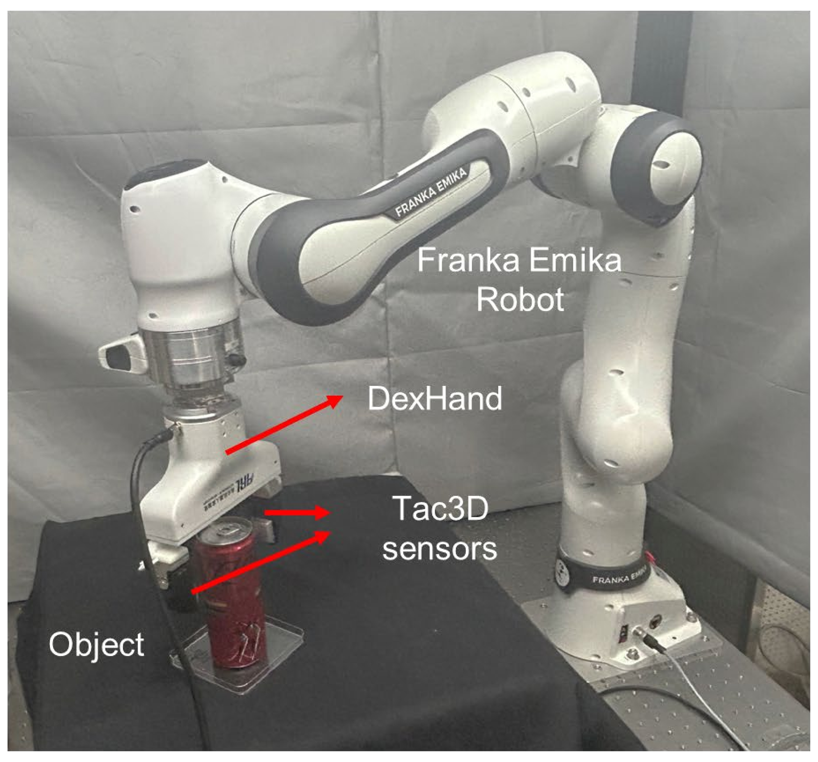
- ✓ Implicitly encode temporal dependencies → enables focused **spatial feature learning**
- ✓ Focus on key contact states and reference strategy → **less data and lightweight network**



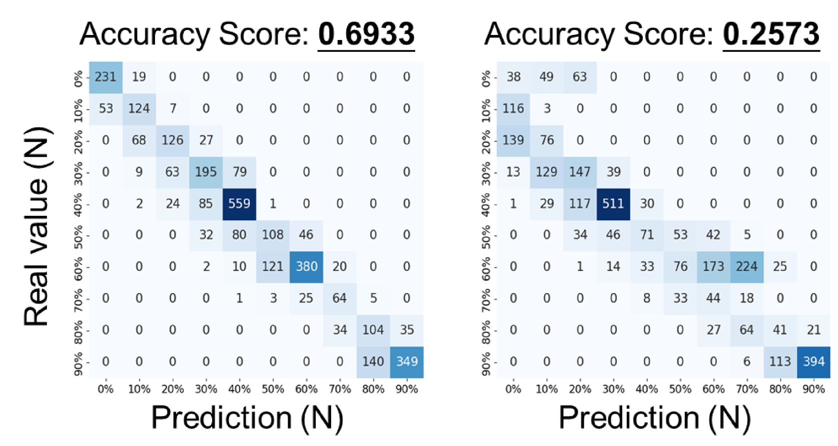
Experimental Results

Offline Evaluation:

Experiment platform:

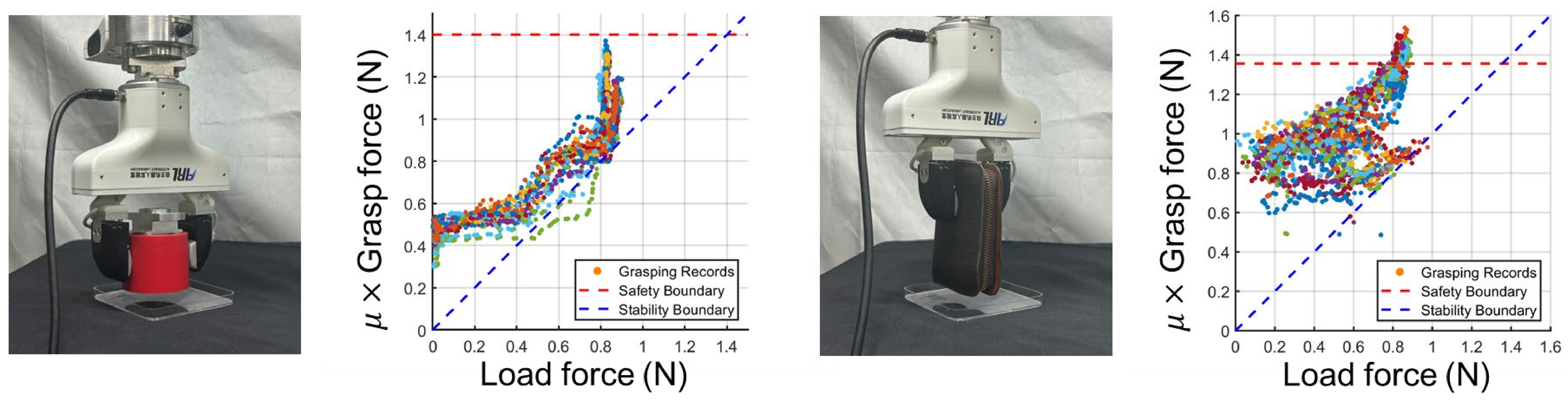


Test object and friction coefficient:



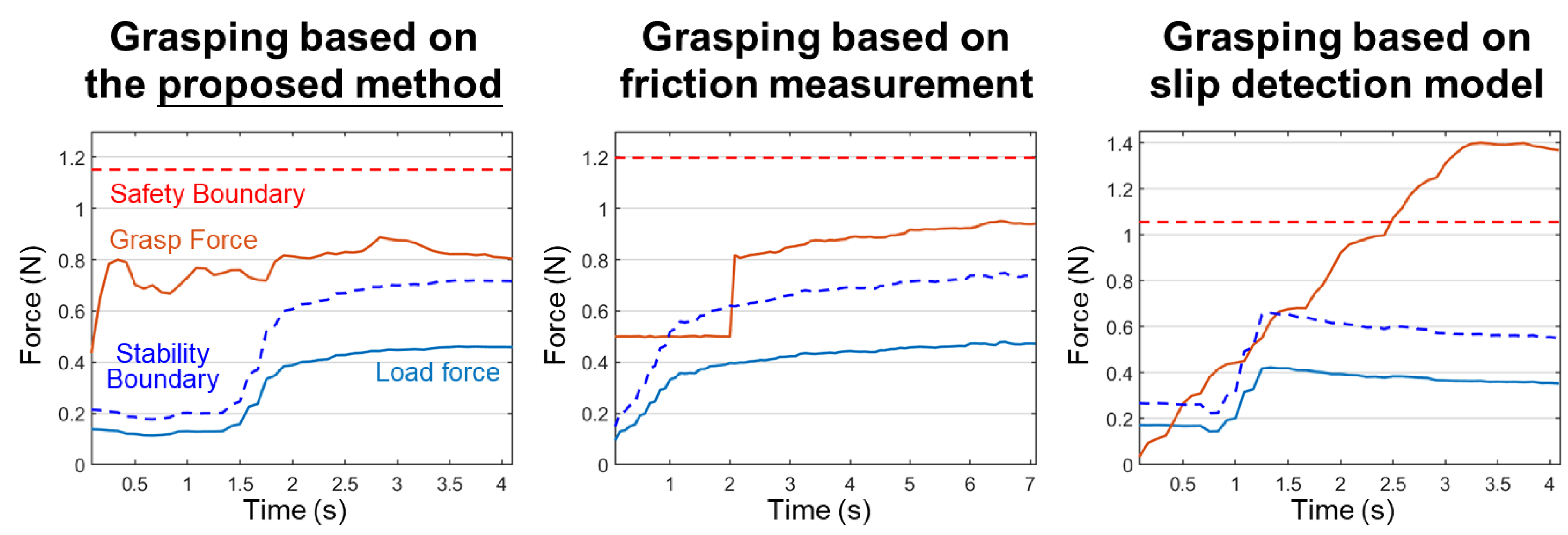
✓ **Force reconstruction module** can improve the accuracy of target force prediction

Online Evaluation:



✓ Control the grasping force between the **safety boundary** and **stability boundary**

Comparative Experiment:



✓ Eliminate the need of **object's characteristics** and shorten **the loading phase duration**

Conclusion

Results: This work utilizes objects with known contact characteristics to **automatically generate reference force curves without human demonstrations**. The described method can be applied in vision-based tactile sensors and teaches robots to gently and stably grasp objects.

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