In-Hand Manipulation in Power Grasp: Design of an Adaptive Robot Hand with Active Surfaces

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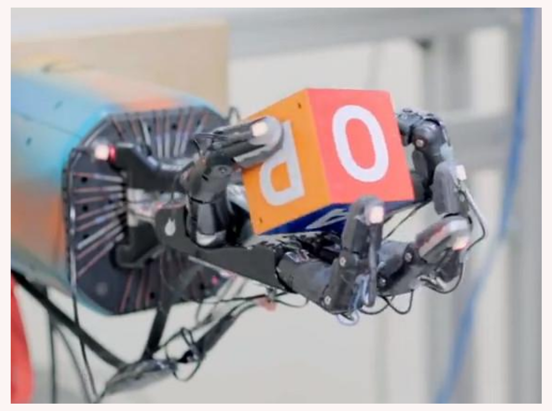
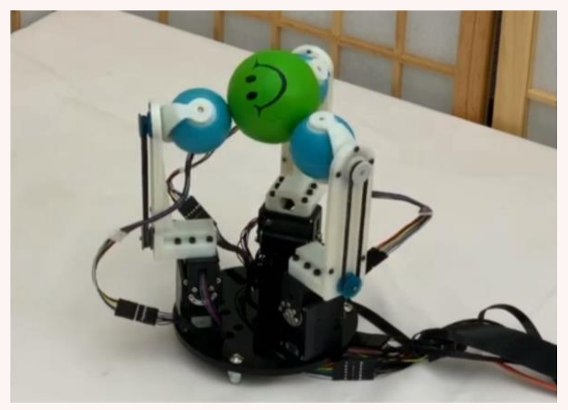
Background

In most common in-hand manipulation scenarios, the object being manipulated needs to be grasped in the hand during hand movement, which leads to a trade-off between grasp stability and manipulation dexterity.

Articulated robot hands using finger gaiting or active surfaces relies on precision grasp, which cannot provide sufficient grasp stability for robust in-hand manipulation. Underactuated hands can conform to different objects but has limited dexterity to perform in-hand manipulation.

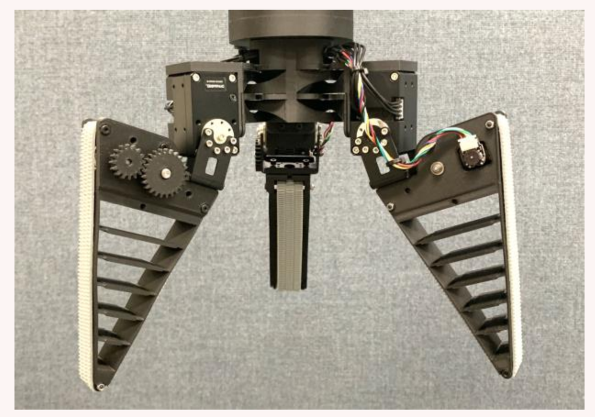


- Finger gaiting
- Low stability



- Active surfaces
- Low stability

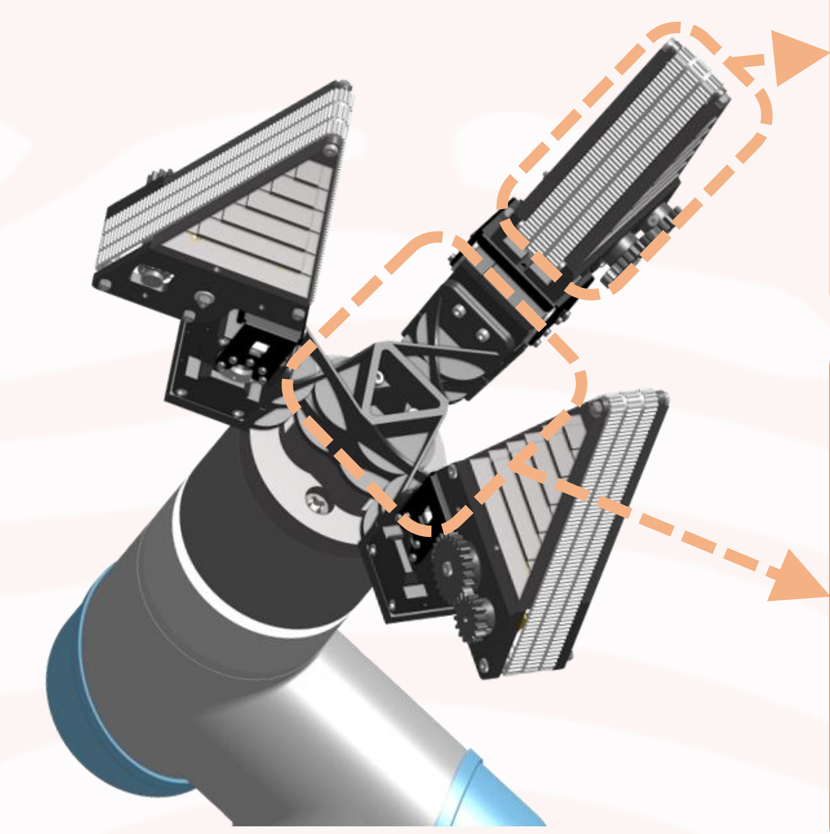
- Compliant grasp
- Limited dexterity



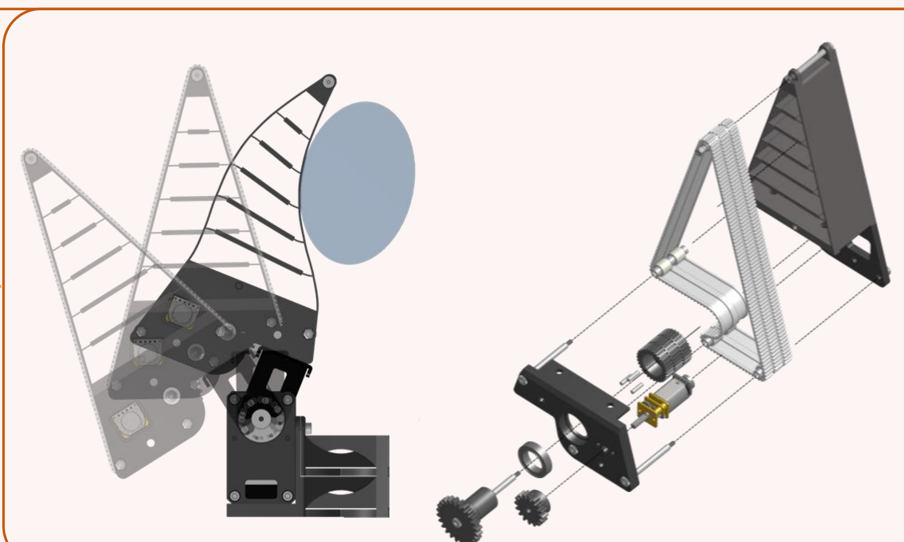
- High stability
- High dexterity

Design

BACH: Belt–Augmented Compliant Hand

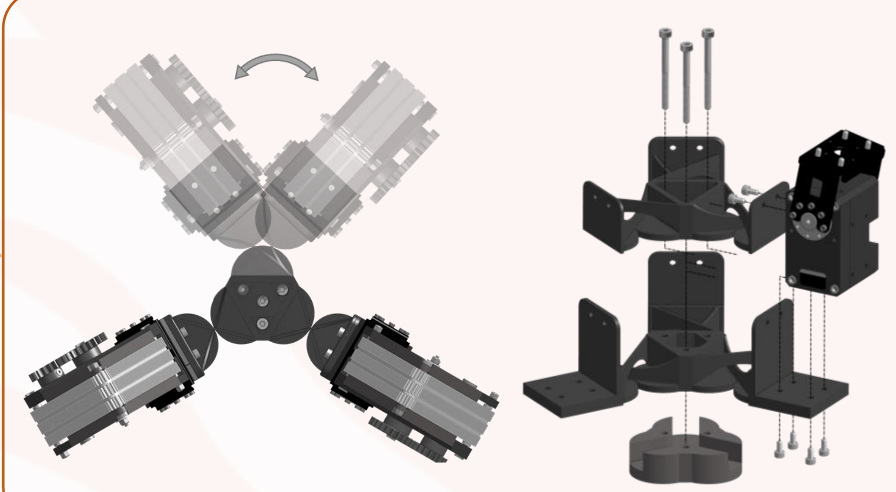


Compliant Finger Design



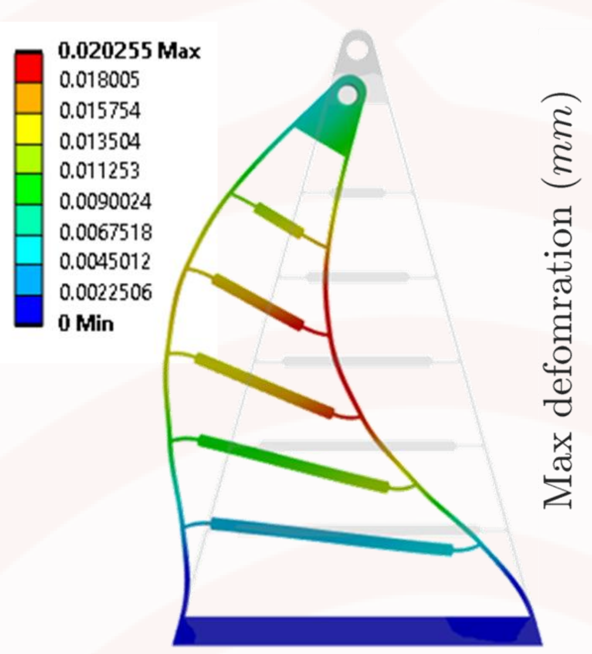
- Fin Ray mechanism that is 3D-printed using micro carbon-filled nylon
- Actuated timing belt that is 3D-printed using TPU

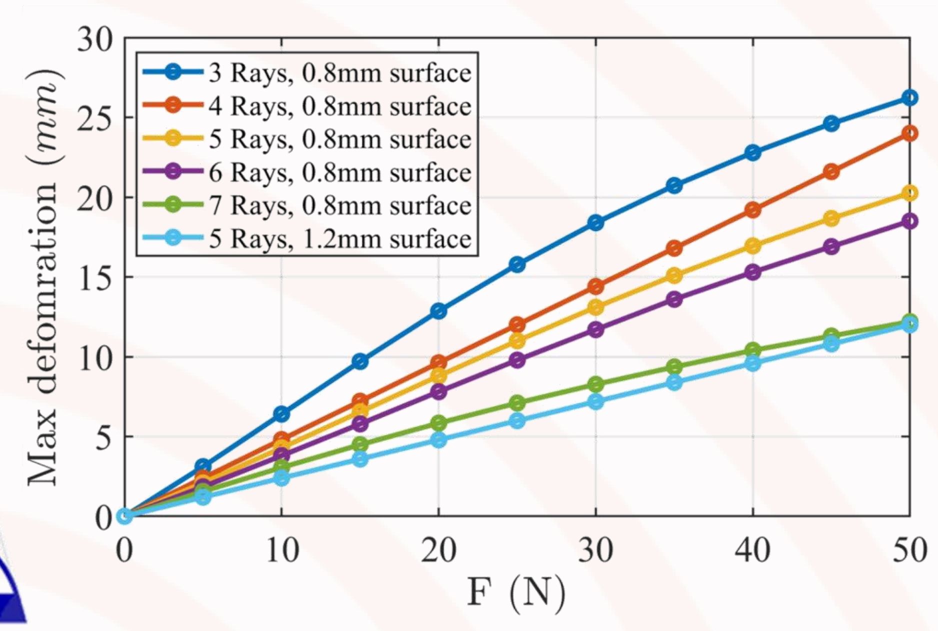
Adaptive Palm Design



- Two levels of cross-axis flexural pivots (CAFPs)
- Contact-aided members to compensate for twisting
- Allow finger to pivot to 90°

Analysis

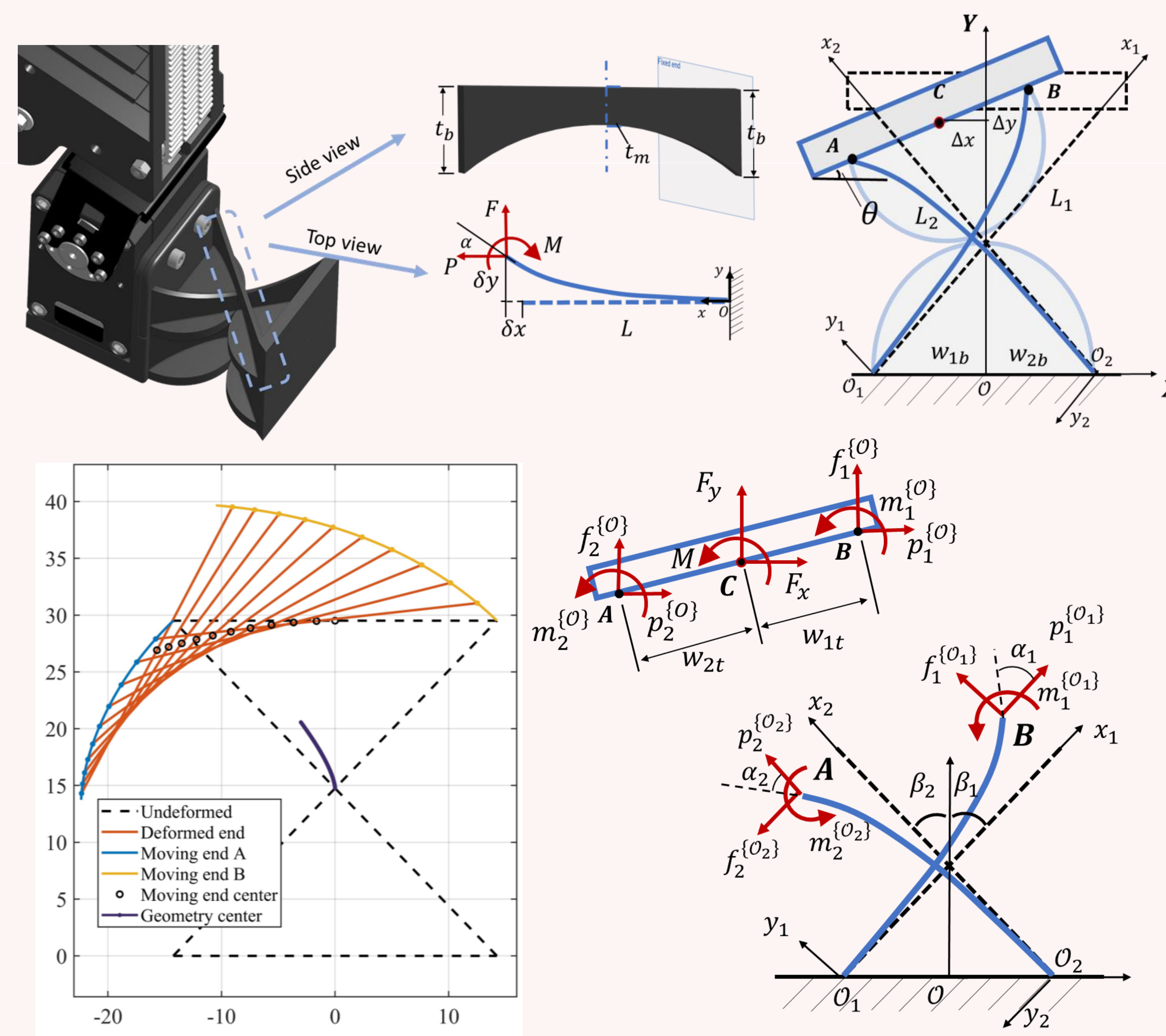




Analysis of finger compliance

- FEA informs design decision
- Selected 5-ray and 0.8mm-thick sides to balance the compliance and strength
- Verifying that the friction between the active surface and the backbone has minimal influence on finger compliance

Analysis of pivot joints



Modeling the cross-axis flexural pivots

- Input: external load $[F_x \quad F_y \quad M]$
- Output: pivot deflection $[\Delta x \quad \Delta y \quad \theta]$

1. Beam-Constraint Model for single flexural beam

$$\begin{bmatrix} f_i \\ m_i \end{bmatrix} = \boldsymbol{G_c} \begin{bmatrix} \delta y_i \\ \alpha_i \end{bmatrix} + p_i \boldsymbol{P_c} \begin{bmatrix} \delta y_i \\ \alpha_i \end{bmatrix} + p_i^2 \boldsymbol{Q_c} \begin{bmatrix} \delta y_i \\ \alpha_i \end{bmatrix}$$

$$\delta x_i = \frac{t_i^2 p_i}{12 L_i^2} - \frac{1}{2} [\delta y_i \ \ \alpha_i] \boldsymbol{U_c} \begin{bmatrix} \delta y_i \\ \alpha_i \end{bmatrix} - p_i [\delta y_i \ \ \alpha_i] \boldsymbol{V_c} \begin{bmatrix} \delta y_i \\ \alpha_i \end{bmatrix}$$

2. Geometric Constraint for pivot joint's deflection

$$0 = \alpha_1 = \alpha_2 \quad \mathbf{R}(\beta) = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}$$

$$\begin{bmatrix} w_b + w_t c\theta \\ w_b s\theta \end{bmatrix} = \mathbf{R}\left(\beta_2 - \frac{\pi}{2}\right) \begin{bmatrix} x_A \\ y_A \end{bmatrix} + \mathbf{R}\left(\frac{\pi}{2} - \beta_1\right) \begin{bmatrix} x_B \\ y_B \end{bmatrix}$$

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = -\mathbf{R}\left(\beta_2 - \frac{\pi}{2}\right) \begin{bmatrix} x_A \\ y_A \end{bmatrix} + \begin{bmatrix} w_{2b} + w_{2t} c\theta \\ w_{2t} s\theta - L_2 c\beta_2 \end{bmatrix}$$

3. Static equilibrium for single pivot joint

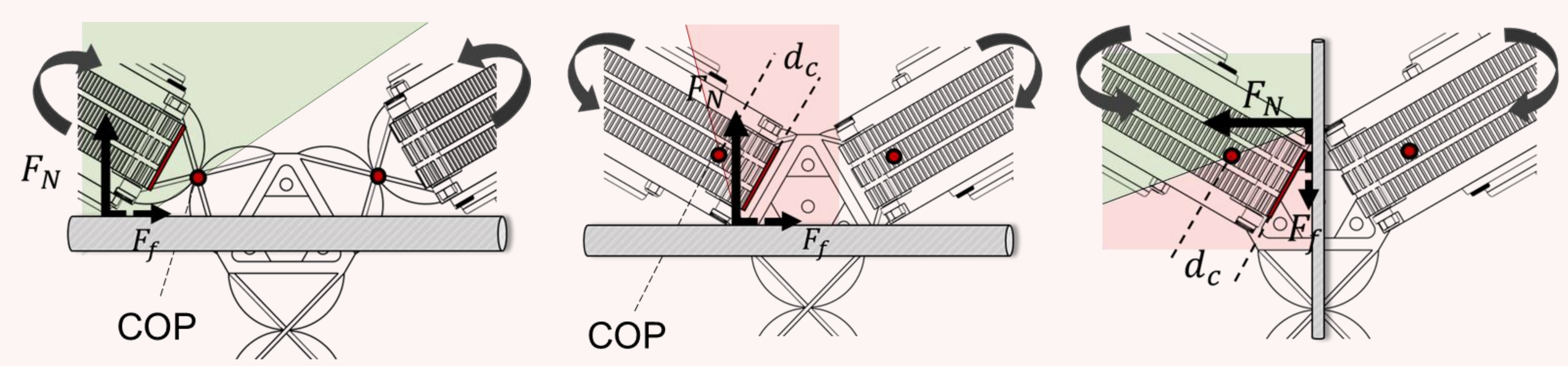
- Force $$M + (w_{1t} + w_{2t}) \frac{EI_2}{L_2^2} [\sin\theta \ \ -\cos\theta] \begin{bmatrix} p_2^{\{O\}} \\ f_2^{\{O\}} \end{bmatrix} + w_{1t} [\sin\theta \ \ -\cos\theta] \begin{bmatrix} F_x \\ F_y \end{bmatrix} - \frac{EI_1}{L_1} m_1 - \frac{EI_2}{L_2} m_2 = \mathbf{0}$$
- Moment $$\begin{bmatrix} F_x \\ F_y \end{bmatrix} - \frac{EI_1}{L_1^2} \mathbf{R}\left(\frac{\pi}{2} - \beta_1\right) \begin{bmatrix} p_1 \\ f_1 \end{bmatrix} - \mathbf{R}\left(\beta_2 - \frac{\pi}{2}\right) \begin{bmatrix} p_2 \\ f_2 \end{bmatrix} = \mathbf{0}$$

Design decision and verification:

- Force to achieve the max pivoting angle of each joint can be safely undertaken by the Fin Ray mechanism

Analysis of the center of pivot (COP)

- Contact force should be in the green region for successful pivoting
- Arrangement of the COP to ensure the desired pivoting direction



Experiments

- Secure grasp with dexterous in-hand manipulation
- 5-DoF spatial in-hand manipulation
- Adapt to various cross-section shapes of the grasped object
- Reorientate the objects around any horizontal axes
- Manipulation in the directions not aligned with objects' extreme axes