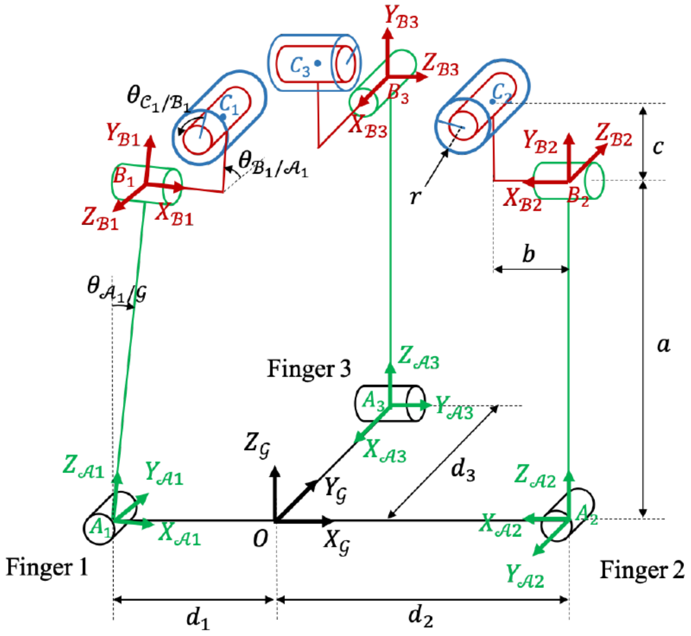
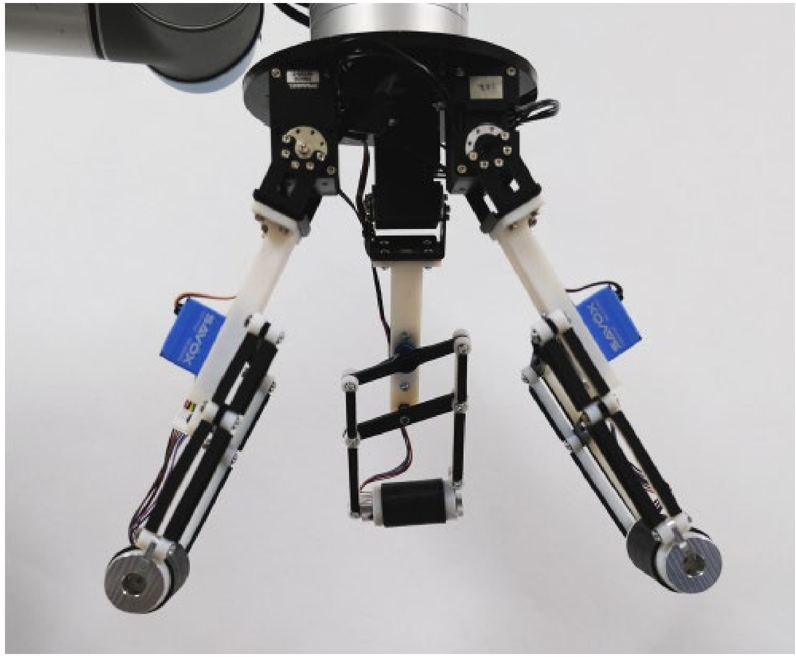
Roller Grasper V1

Re-production

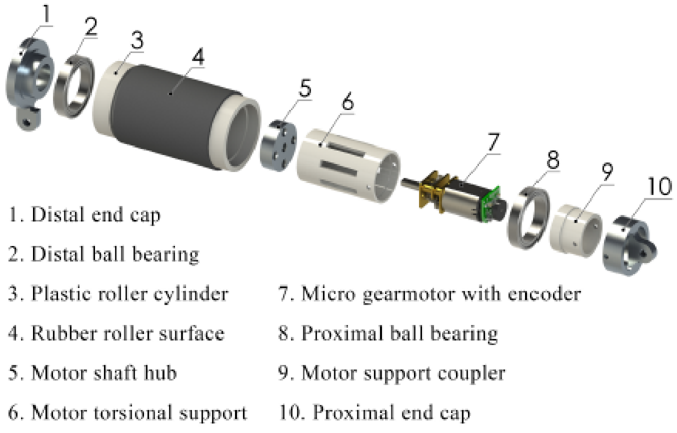
Introduction

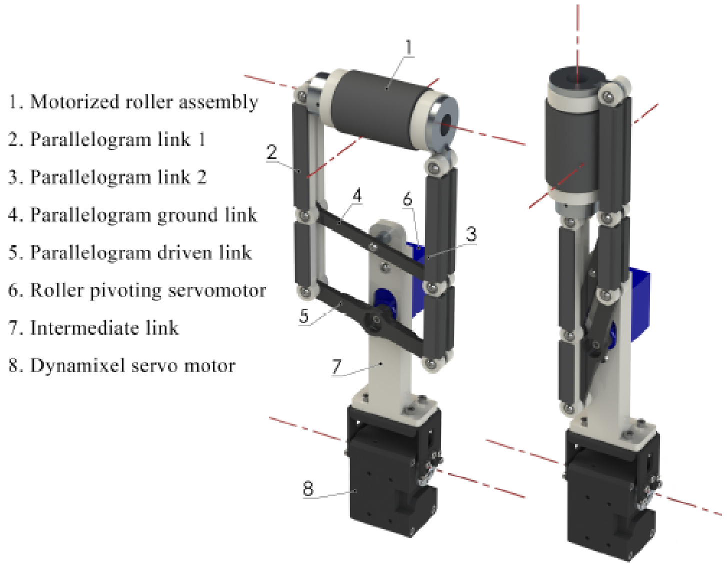
- Full six degree of freedom nonholonomic spatial motion capability.
- Unlike conventional approaches to within-hand manipulation using legacy robotic hands, the continuous rotation capability of the rolling fingertips (active surfaces) allows for unbounded rotation of a grasped object without the need for finger gaiting.





Design





- The grasper assembly consists of three kinematically similar fingers (Fig. 2), each consisting of three actuated DoF.
- The proximal DoF is a revolute joint directly driven by a Robotis Dynamixel XM430-W350 smart actuator.
- The intermediate DoF is orthogonal to the proximal DoF and is based on a parallelogram mechanism similar to with the input and ground links anchored on the centerline of the parallelogram. The intermediate DoF controls the orientation of the fingertip roller, and is actuated by a micro digital servomotor (Savox SW0250MG).
- Structural parts are made of machined aluminium, 3D printed resin and laser cut acrylic. Silicon strips are adhered to the faces of the two vertical links of the parallelogram mechanism so that they may be used as secondary grasping surfaces. The parallelogram configuration was selected in order to place the actuator further from the roller so as to maximize the area of the roller’s surface that is available for grasping and within hand manipulation.
- The fingertip roller is actuated by a micro DC gearmotor equipped with a quadrature encoder, and is capable of continuous rotation. The roller is fitted with a stack of square cross-section Silicon O-rings to provide a high-friction surface for grasping and manipulation. The complete grasper weighs 800 g, and each finger can provide 20 N of normal force at the roller center.

Analysis

- The hand's multiple degrees of freedom and contact surfaces result in a wide range of manipulation and grasping capabilities.

A. Sphere Manipulation Configurations

- For simplicity, constraining each roller i to a vertical or horizontal position, results in eight possible three-finger sphere manipulation configurations, and twelve possible two-finger ones.
- Considering the symmetrical combinations to be the same, this leaves six distinct three finger and seven two-finger combinations. Of the thirteen combinations, five were deemed particularly useful for their versatility and/or ease of use.
- Sequentially combining those six configurations enables full 6-DoF spatial motion of a sphere.
- V V X is potentially unstable, as the sphere could roll out due to gravity, VVV is more stable.

TABLE III

SPHERE MANIPULATION DOF VS. ROLLER PIVOT ANGLE

Roller Config.			Translation			Rotation		
1	2	3	T_X	T_Y	T_Z	R_X	R_Y	R_Z
H	H	×	✓		✓		✓	
V	V	×	✓R_Y	✓			✓T_X	✓
P	P	×				✓		
V	V	H		✓	✓R_X	✓T_Z		
V	V	V		✓				✓
H	H	H			✓			

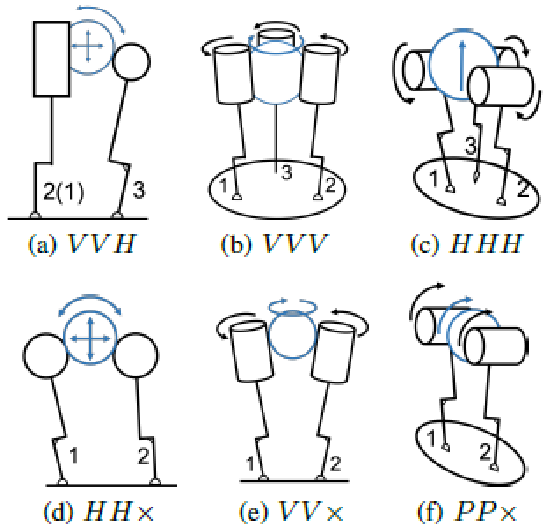


Fig. 5. Roller configurations for spherical object manipulation

As a demonstration of how one would control a sphere, we present an in-depth analysis of three-finger V V H manipulation and two-finger HHX manipulation.

B. Example Three-Finger Manipulation VVH

Geometry constraints: The distance between the center of the ball and axis of rollers

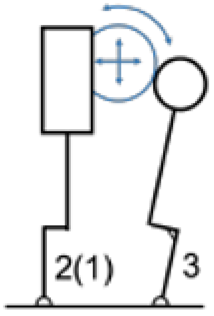
$$\|Z_{\mathcal{B}_i} \times (C_i - D)\| = r + R \tag{1}$$

where

$$\begin{bmatrix} C_i \\ 1 \end{bmatrix} = {}^{\mathcal{G}}_{\mathcal{A}_i}M\,{}^{\mathcal{A}_i}_{\mathcal{B}_i}M\,{}^{\mathcal{B}_i}_{\mathcal{C}_i}M \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^T \tag{2}$$

Angles of roller and object using no-slip conditions

$$\frac{d}{dt}\boldsymbol{I}_{\mathcal{D}\in\mathcal{C}_i} - \frac{d}{dt}\boldsymbol{I}_{\mathcal{C}_i\in\mathcal{D}} = \boldsymbol{0} \tag{3}$$



(a) VVH

TABLE IV

REFERENCE FRAME TRANSFORMATIONS

From frame	To frame	Homogeneous transformation matrix
$\mathcal{G}$	$\mathcal{A}_1$	${}^{\mathcal{G}}_{\mathcal{A}_1}M = \begin{bmatrix} R_{Y_\mathcal{G}}(\theta_{\mathcal{A}_1/\mathcal{G}}) & -d_1\,{}^{\mathcal{G}}\boldsymbol{X}_\mathcal{G} \\ 0\quad 0\quad 0 & 1 \end{bmatrix}$
$\mathcal{G}$	$\mathcal{A}_2$	${}^{\mathcal{G}}_{\mathcal{A}_2}M = \begin{bmatrix} R_{Z_\mathcal{G}}(\pi)R_{Y_\mathcal{G}}(\theta_{\mathcal{A}_2/\mathcal{G}}) & d_2\,{}^{\mathcal{G}}\boldsymbol{X}_\mathcal{G} \\ 0\quad 0\quad 0 & 1 \end{bmatrix}$
$\mathcal{G}$	$\mathcal{A}_3$	${}^{\mathcal{G}}_{\mathcal{A}_3}M = \begin{bmatrix} R_{Z_\mathcal{G}}(-\pi/2)R_{Y_\mathcal{G}}(\theta_{\mathcal{A}_3/\mathcal{G}}) & d_3\,{}^{\mathcal{G}}\boldsymbol{Y}_\mathcal{G} \\ 0\quad 0\quad 0 & 1 \end{bmatrix}$
$\mathcal{A}_i$	$\mathcal{B}_i$	${}^{\mathcal{A}_i}_{\mathcal{B}_i}M = \begin{bmatrix} R_{X_{\mathcal{A}_i}}(\theta_{\mathcal{B}_i/\mathcal{A}_i}) & a\,{}^{\mathcal{A}_i}\boldsymbol{Z}_{\mathcal{A}_i} \\ 0\quad 0\quad 0 & 1 \end{bmatrix}$
$\mathcal{B}_i$	$\mathcal{C}_i$	${}^{\mathcal{B}_i}_{\mathcal{C}_i}M = \begin{bmatrix} R_{Z_{\mathcal{B}_i}}(\theta_{\mathcal{C}_i/\mathcal{B}_i}) & b\,{}^{\mathcal{B}_i}\boldsymbol{X}_{\mathcal{B}_i} + c\,{}^{\mathcal{B}_i}\boldsymbol{Y}_{\mathcal{B}_i} \\ 0\quad 0\quad 0 & 1 \end{bmatrix}$

When $\dot{\theta}_{\mathrm{Ai}/G}$ and $\dot{\theta}_{\mathrm{Bi}/A\,i}$ are known, (1) gives a 2D solution space of possible ball positions for each finger, and in nondegenerate cases the intersection of all three spaces gives a unique ball position for that configuration. When D is known, (1) gives a 1D inverse kinematic solution space for $\dot{\theta}_{\mathrm{Ai}/G}$ and $\dot{\theta}_{\mathrm{Bi}/A\,i}$, which can be reduced to one or two discrete joint positions by e.g. imposing $\dot{\theta}_{\mathrm{Bi}/A\,i}$.

C. Example Two-Finger Manipulation

- In the HHX configuration, 3-DoF manipulation of a convex object in the X-Z plane is possible using the joints at A1, A2, C1 and C2. This can be described using (1) and (3), though the case of a spherical or cylindrical object D can be regarded as a 5-bar linkage, whose forward and inverse kinematics have been explicitly solved

Forward kinematics:

$$\boldsymbol{D} = \frac{1}{2}(\boldsymbol{C}_1 + \boldsymbol{C}_2) \pm (\boldsymbol{C}_2 - \boldsymbol{C}_1) \times \boldsymbol{Y}_{\mathcal{G}} \sqrt{\frac{(r+R)^2}{\|\boldsymbol{C}_2 - \boldsymbol{C}_1\|^2} - \frac{1}{4}} \tag{4}$$

Inverse kinematics:

$$\theta_{\mathcal{A}_i/\mathcal{G}} = \frac{\pi}{2} \pm \alpha_i(\boldsymbol{D}) - \beta_i(\boldsymbol{D}) - \gamma \tag{5}$$

Where,

$$\alpha_i(\boldsymbol{D}) = \arccos\left(\frac{\|\boldsymbol{C}_i - \boldsymbol{A}_i\|^2 - (r+R)^2 + \|\boldsymbol{D} - \boldsymbol{A}_i\|^2}{2\|\boldsymbol{C}_i - \boldsymbol{A}_i\|\|\boldsymbol{D} - \boldsymbol{A}_i\|}\right) \tag{6}$$

$$\beta_i(\boldsymbol{D}) = |\operatorname{atan2}((\boldsymbol{D} - \boldsymbol{A}_i) \cdot \boldsymbol{Z}_{\mathcal{G}}, (\boldsymbol{D} - \boldsymbol{A}_i) \cdot \boldsymbol{X}_{\mathcal{G}})| \tag{7}$$

$$\gamma = \operatorname{atan2}(b, a+c) \tag{8}$$

$$\|\boldsymbol{C}_i - \boldsymbol{A}_i\| = \sqrt{(a+c)^2 + b^2} \tag{9}$$

No-slip conditions:

$$R\dot{\theta}_{\mathcal{D}/\mathcal{G}} = r(\dot{\theta}_{\mathcal{C}_1/\mathcal{B}_1} - \dot{\theta}_{\mathcal{A}_1/\mathcal{G}}) + (r+R)\dot{\theta}_{DC_1} \tag{10}$$

$$R\dot{\theta}_{\mathcal{D}/\mathcal{G}} = r(-\dot{\theta}_{\mathcal{C}_2/\mathcal{B}_2} + \dot{\theta}_{\mathcal{A}_2/\mathcal{G}}) + (r+R)\dot{\theta}_{DC_2} \tag{11}$$

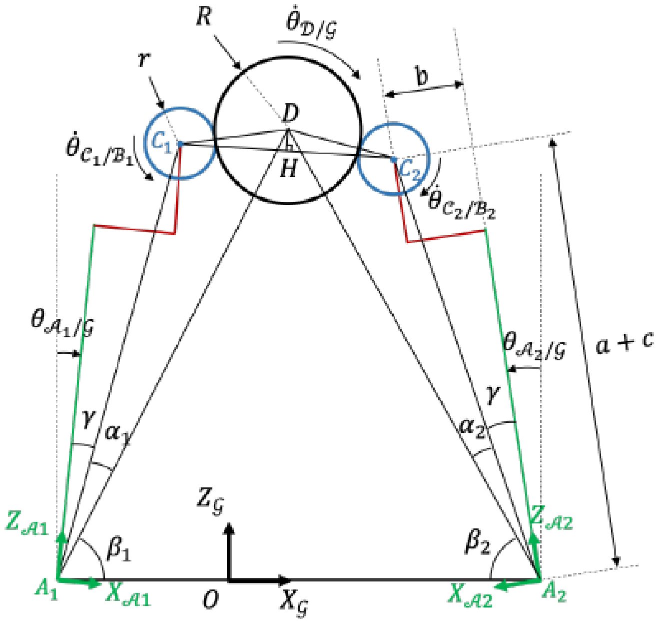
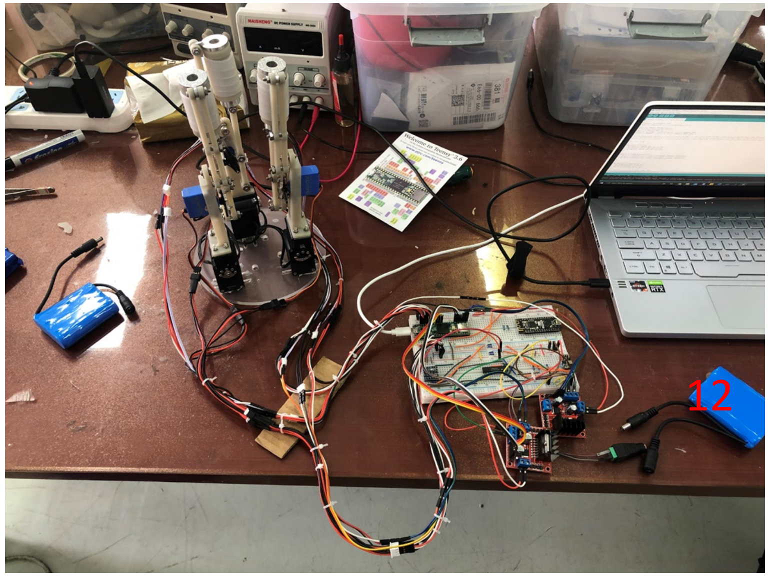
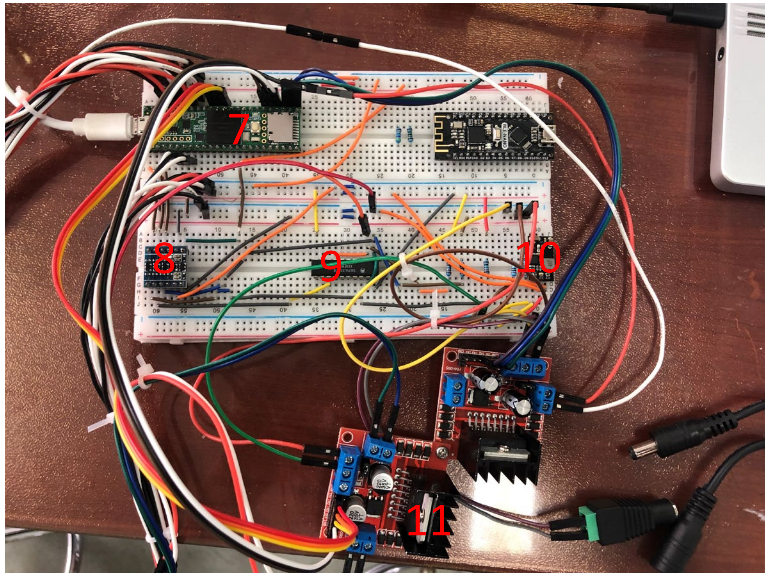


Fig. 7. 2D Kinematics

Implementation



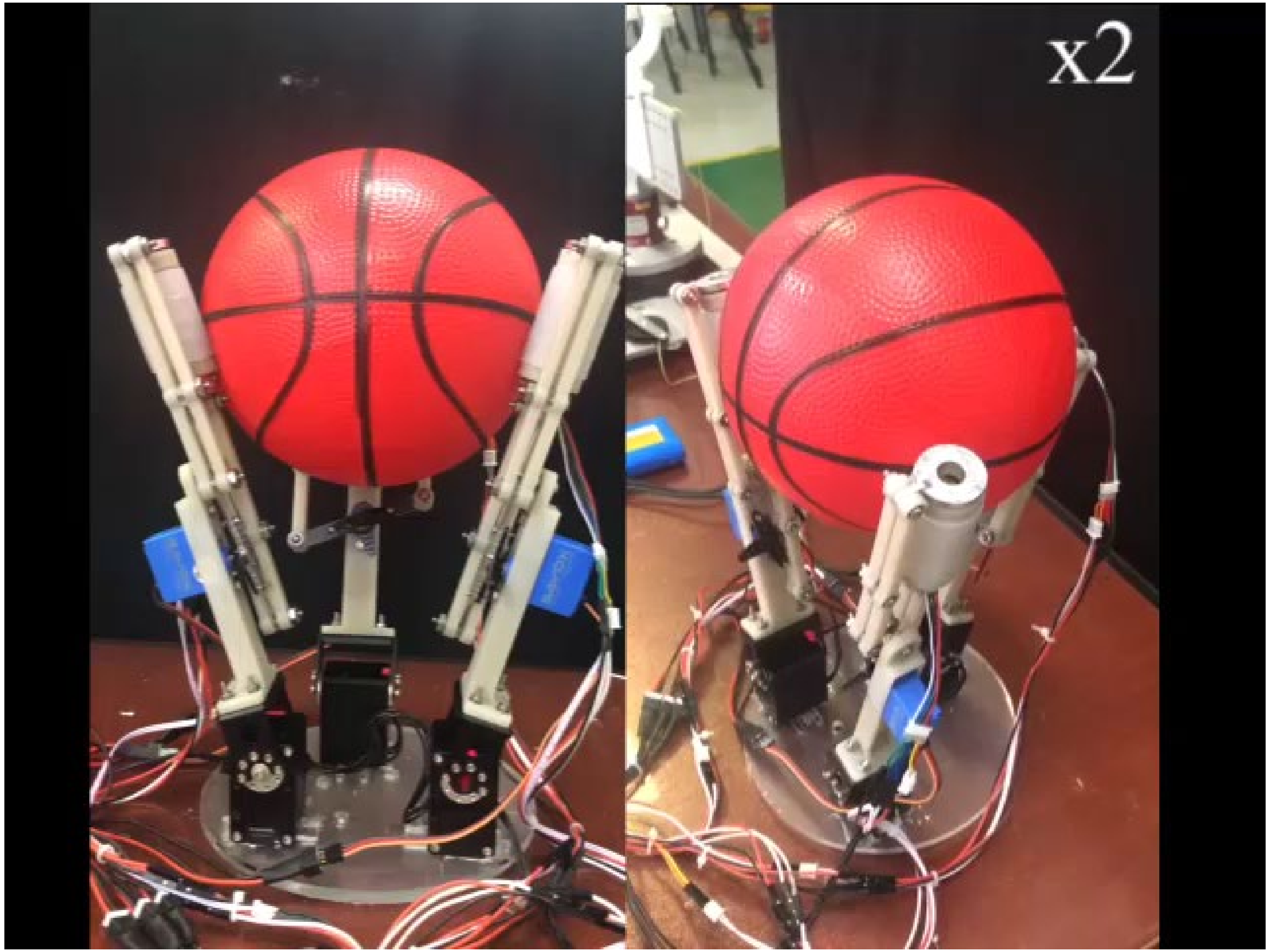


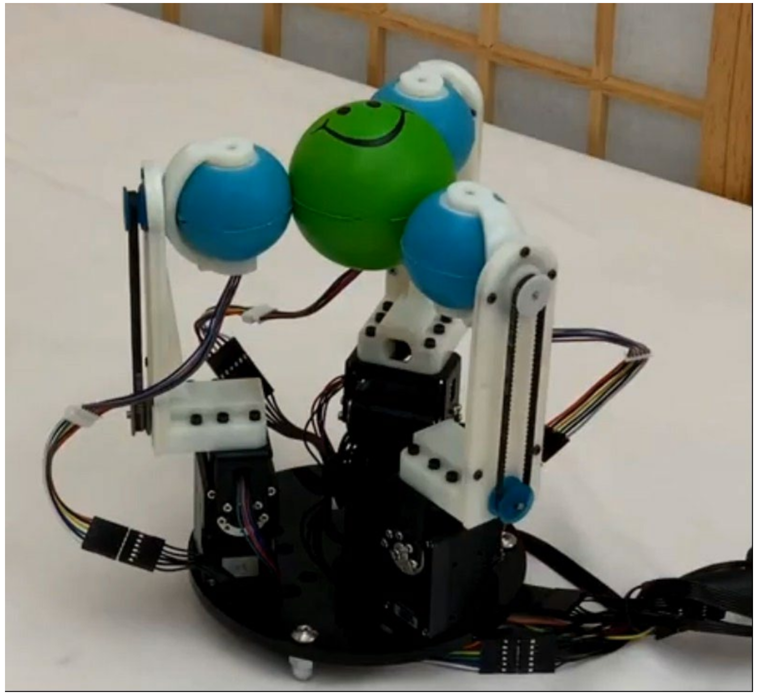
1. Dynamixel XM430-W350 smart actuator
2. Savox SW0250MG digital servomotor
3. Machined aluminum
4. 3D printed resin
5. Laser cut acrylic
6. Silicon O-rings
7. Teensy 3.6 MCU
8. 3.3V-5V logic level convertor
9. SN74LS241N Buffer
10. 5V voltage convertor
11. L298N motor driver
12. 12V Battery

Limitations

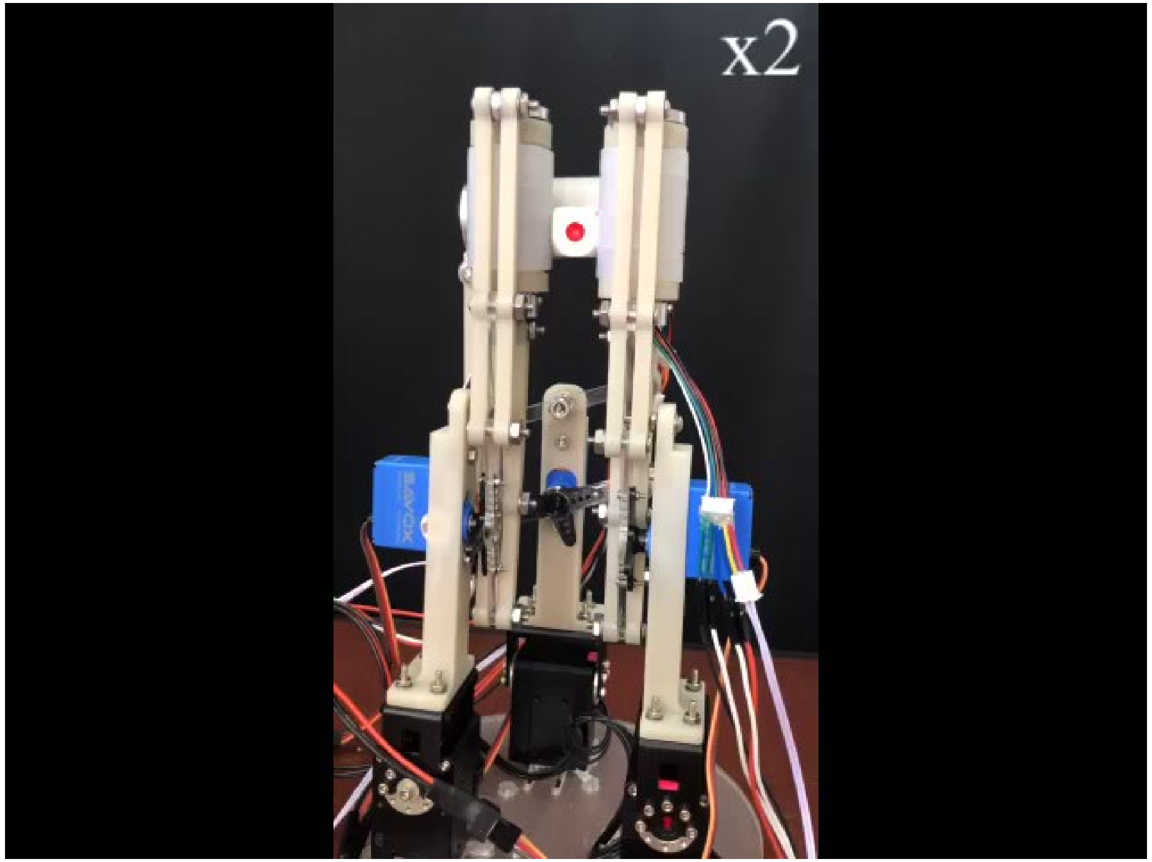
1) Nonholonomic Nature: The system is nonholonomic, as the grasped object cannot be moved in an arbitrary direction instantaneously. (coupled DoF) (See experiment-sphere)
2) Slipping: The object might slip when there is not enough contact area or contact points with the rollers, causing inaccuracy in the manipulation.
3) Power Grasping: Although each finger has three DoF, two of them are dedicated to controlling roller motions, and only one controls general finger pose.

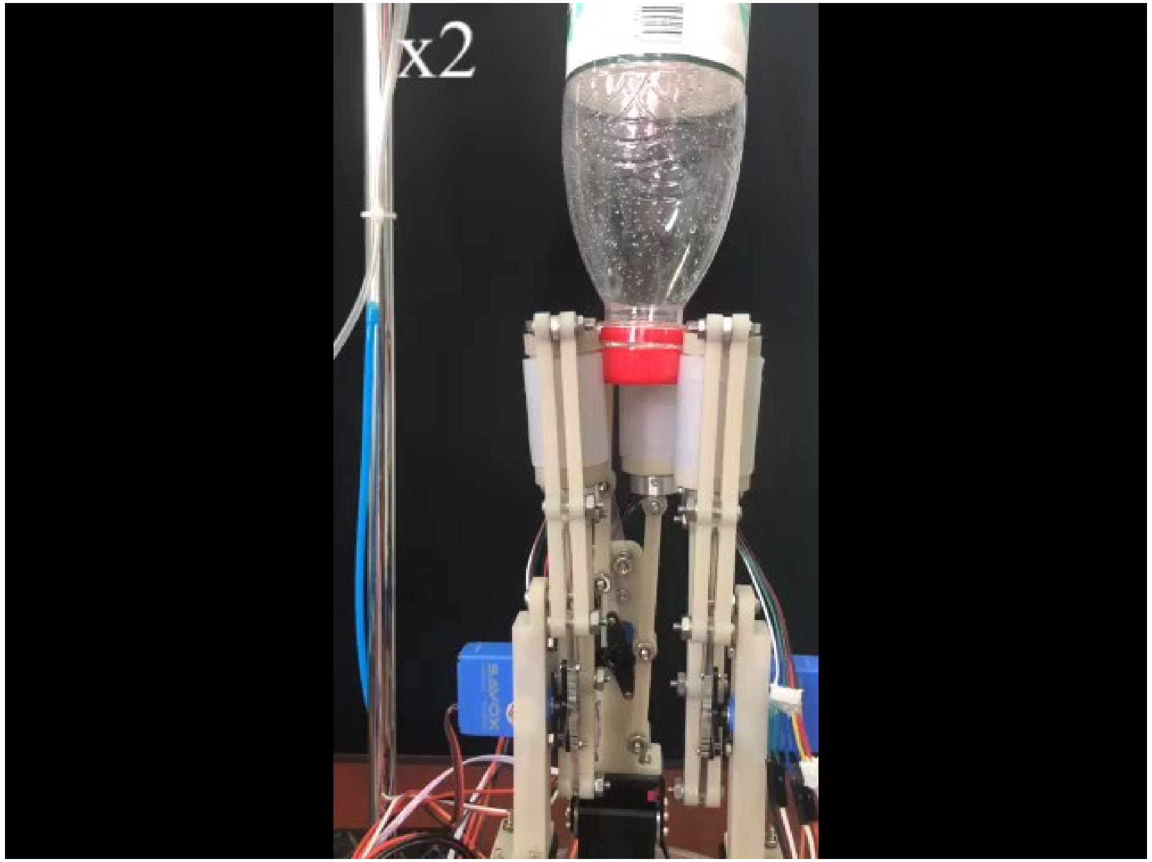
Experiments-Sphere





Experiments - Die, Bottle Cap





Experiments – Paper Board, Box