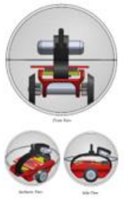
Electro-hydraulic Rolling Soft Robot

Khoi Ly

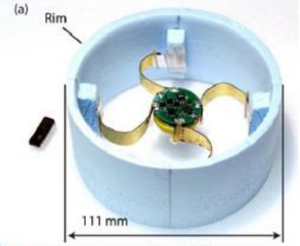
Comprehensive Exam

Shift of Center of Mass

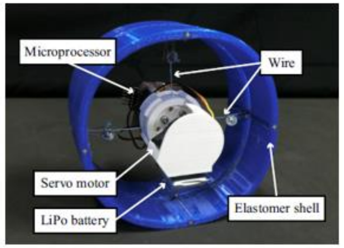


(Xuelei et. al., 2014)

(Nguyen et. al., 2017)

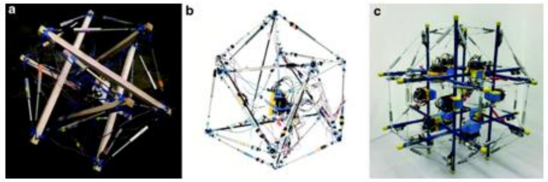


(Must, 2015)



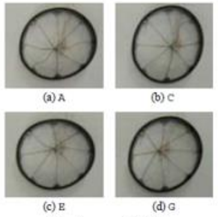
(Masuda, 2017)

Geometry Deformation



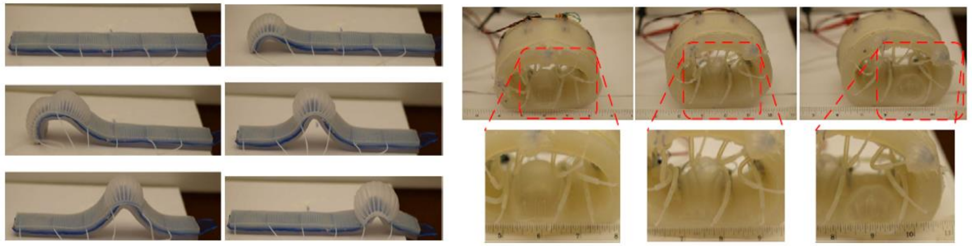
(Kim et. al., 2020

(Chiu et. al., 2018)

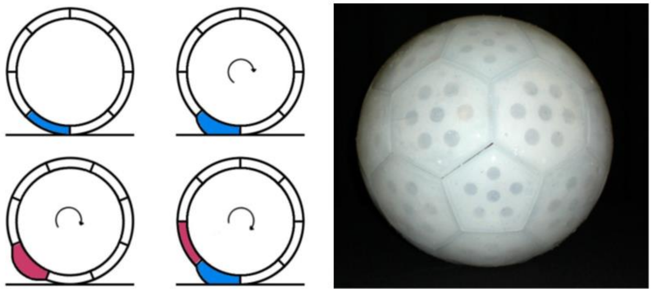


(Sugiyama, 2006)

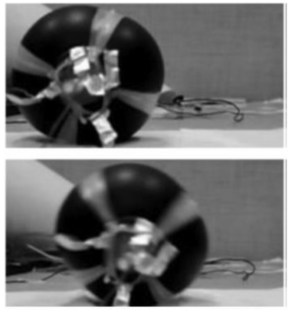
Shell Bulging



(Correll et. al., 2010)



(Wait et. al, 2010)



(Potz et. al., 2010)

- Lack system integration
- Lack modeling
- Lack speed regulator

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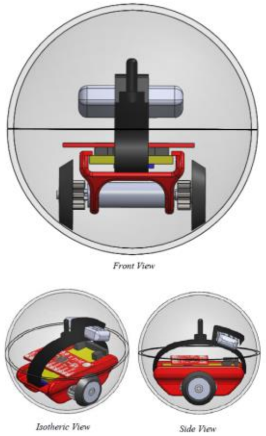
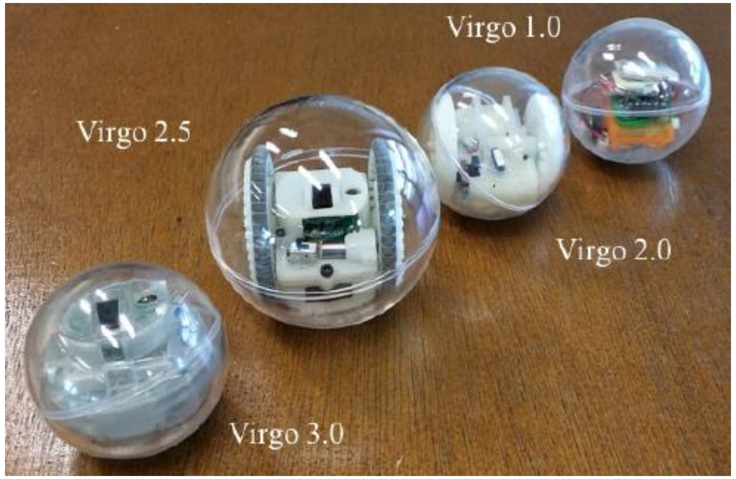
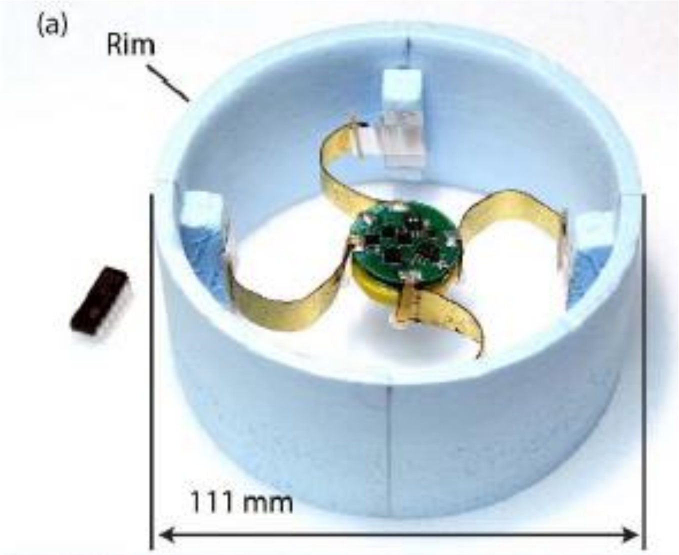
Shift of Center of Mass



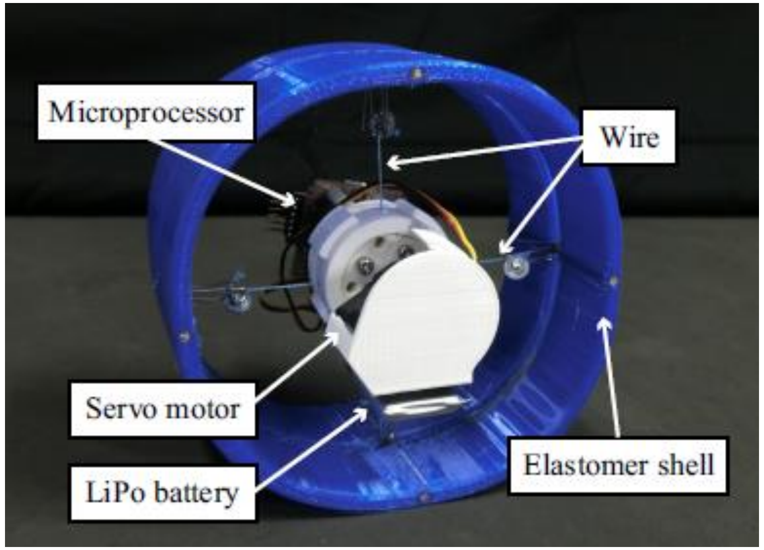
(Xuelei et. al., 2014)



(Nguyen et. al., 2017)

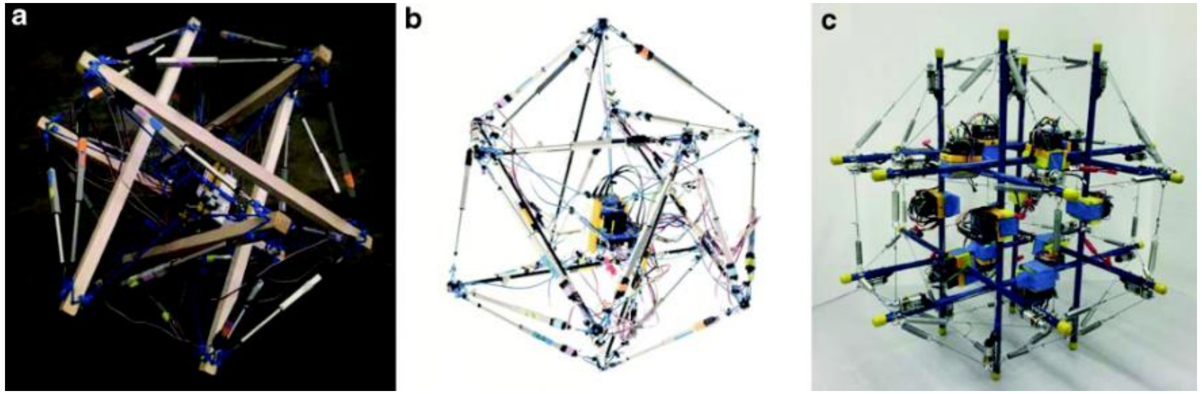


(Must, 2015)

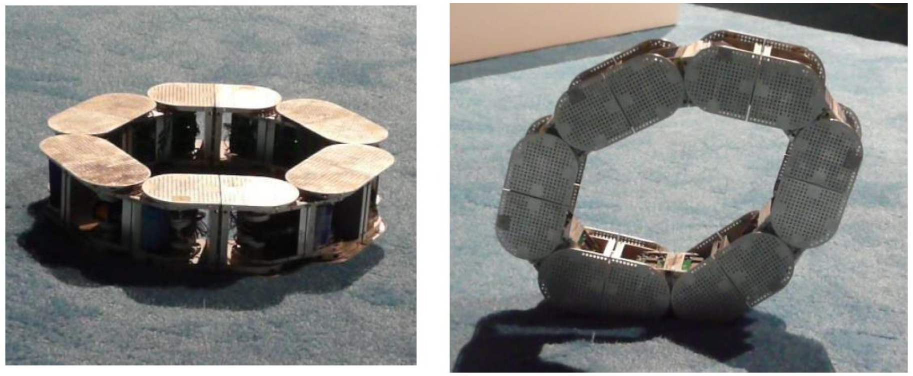


(Masuda, 2017)

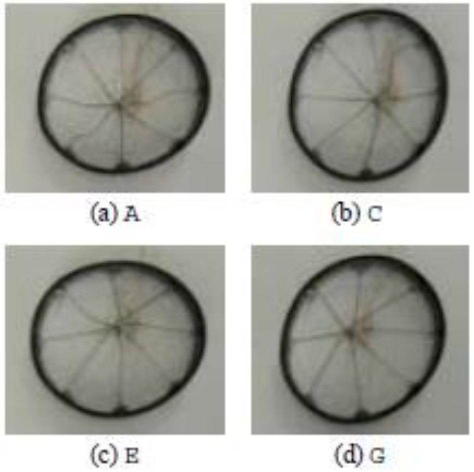
Geometry Deformation



(Kim et. al., 2020

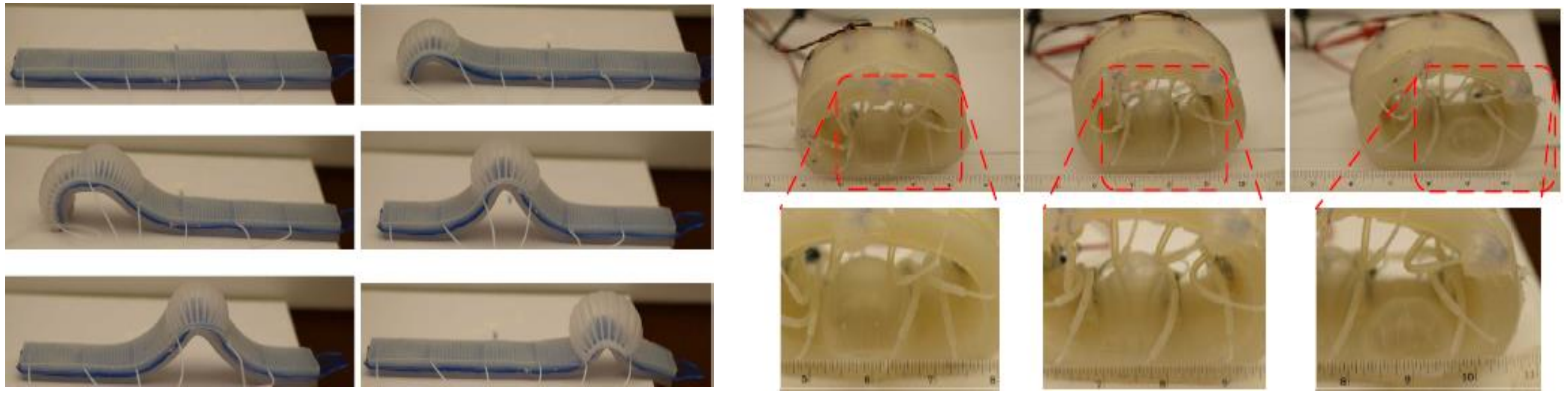


(Chiu et. al., 2018)

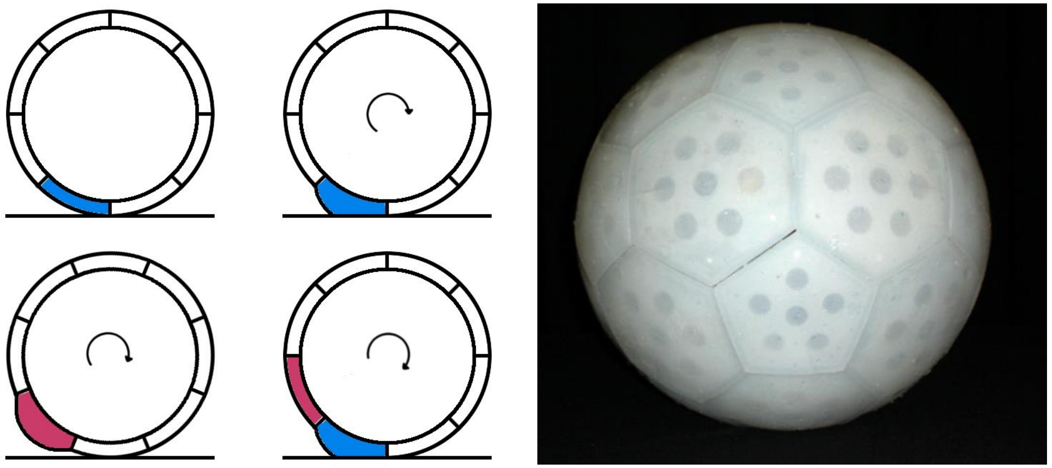


(Sugiyama, 2006)

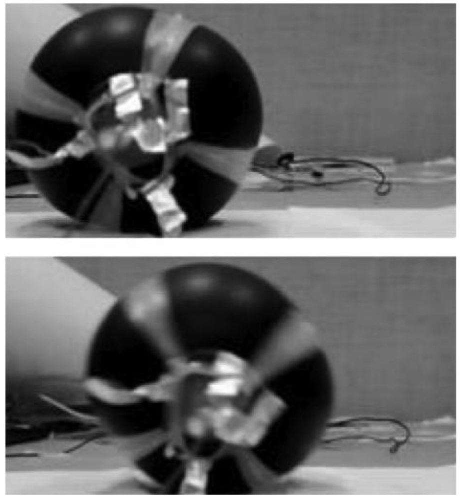
Shell Bulging



(Correll et. al., 2010)

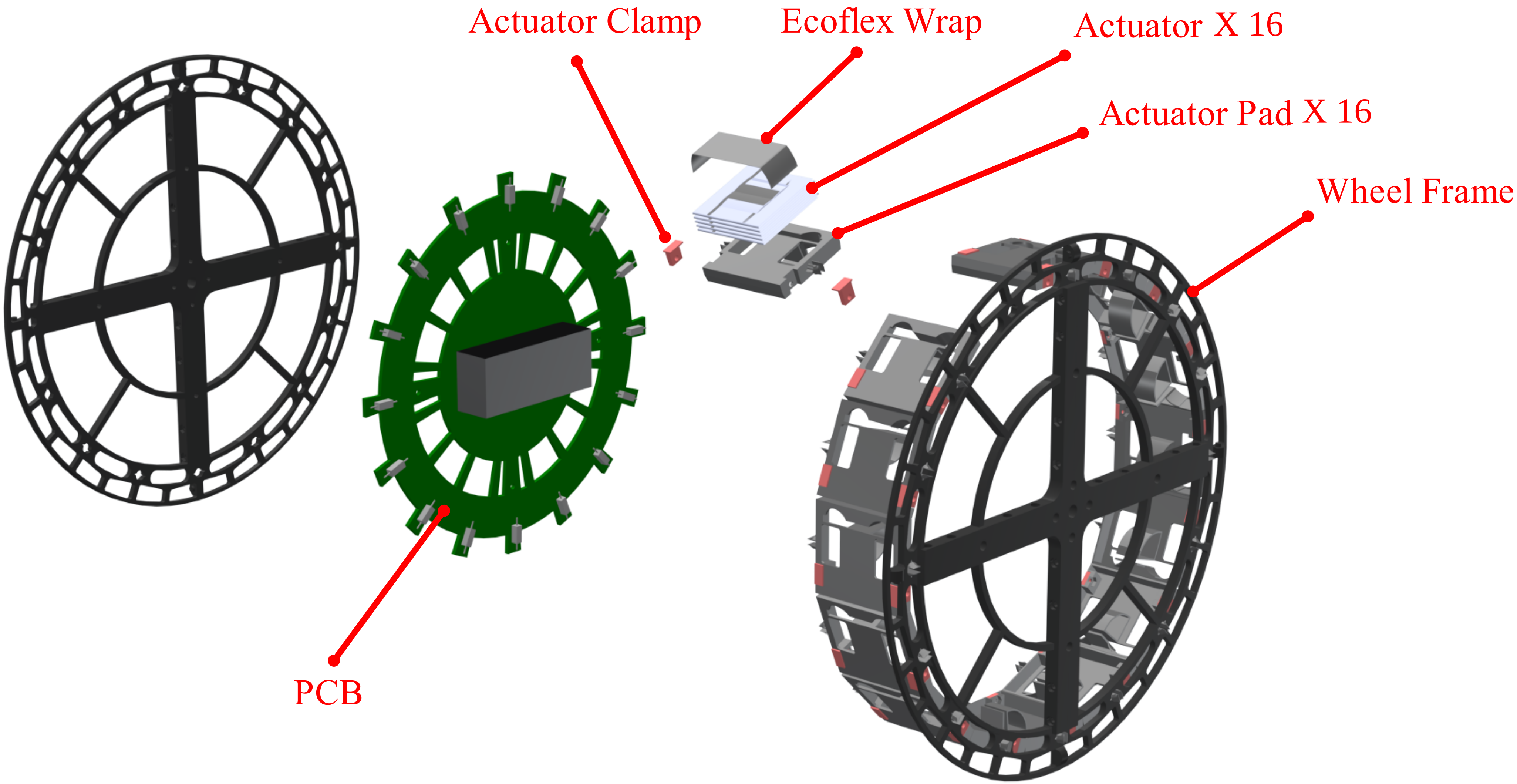


(Wait et. al, 2010)



(Potz et. al., 2010)

1. Mechanical Design



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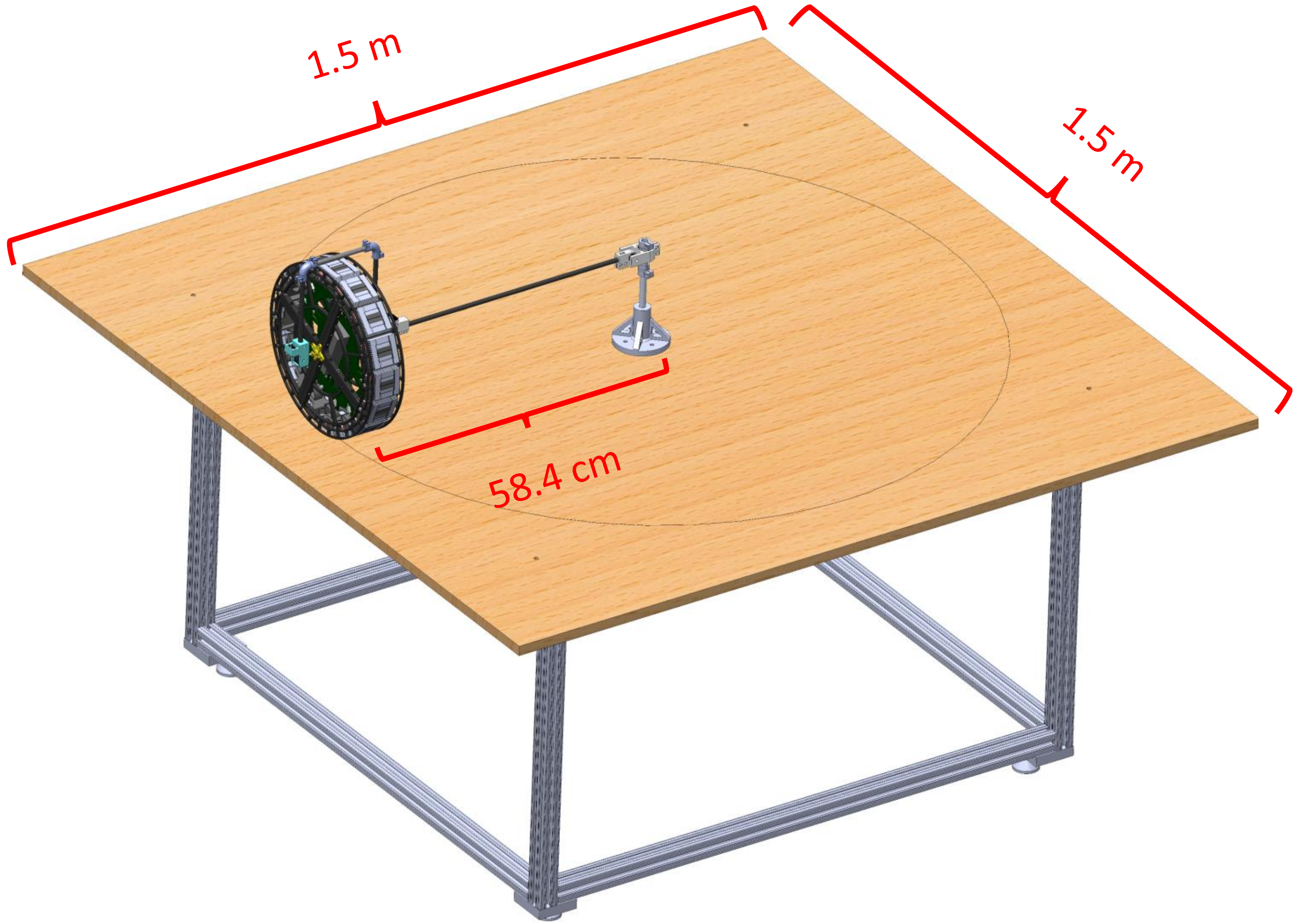
1. Mechanical Design



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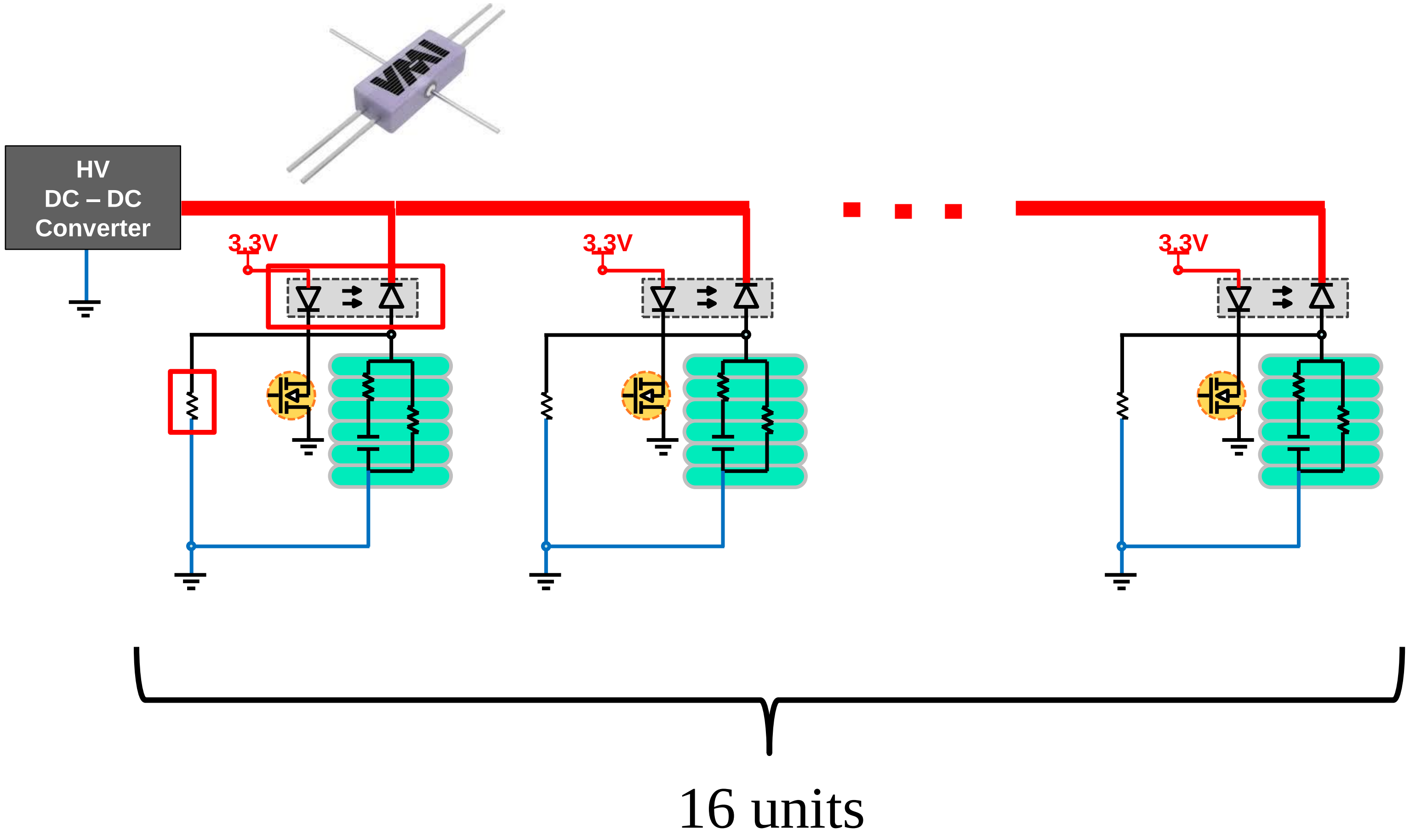
2. Electrical Design



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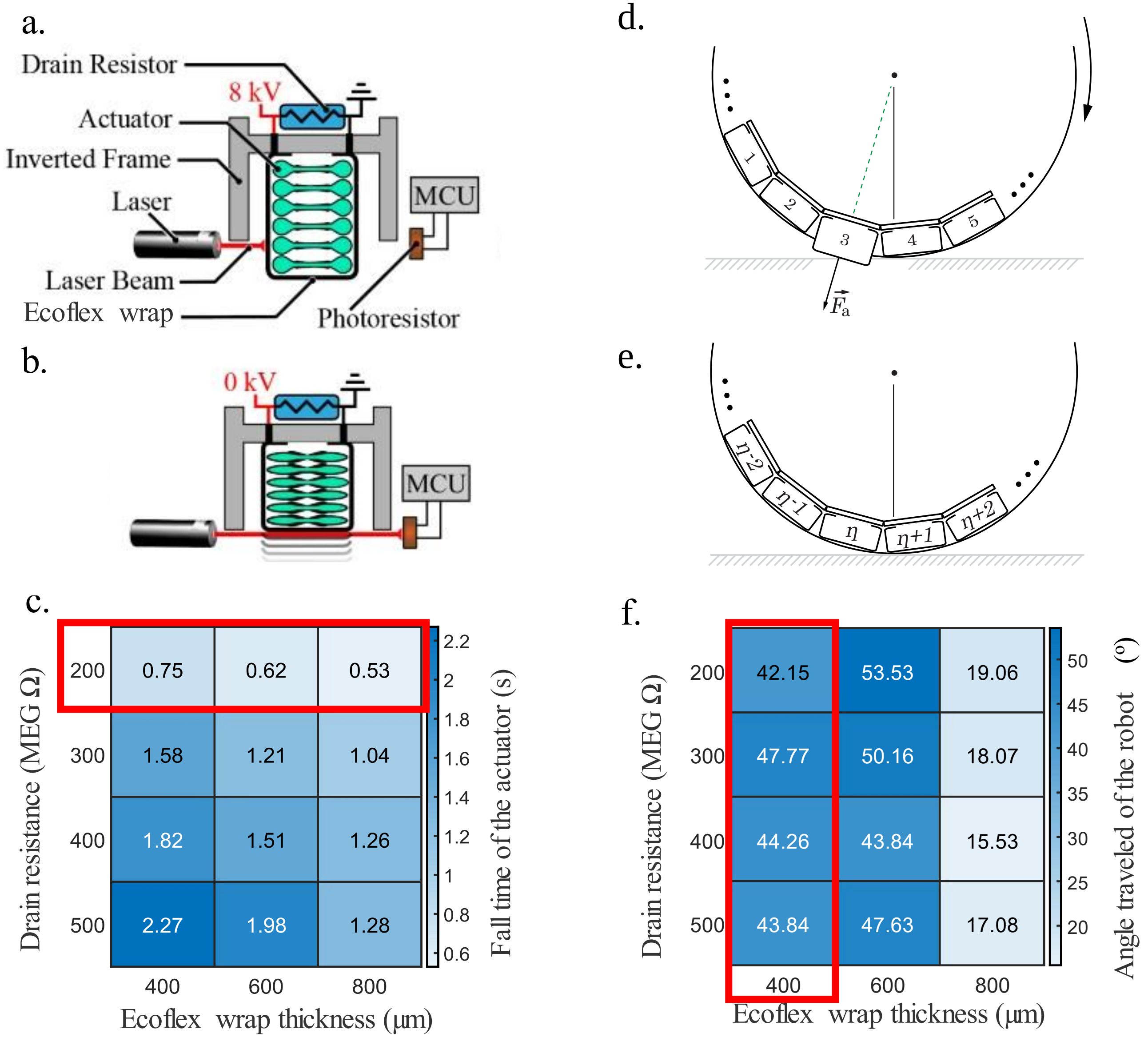

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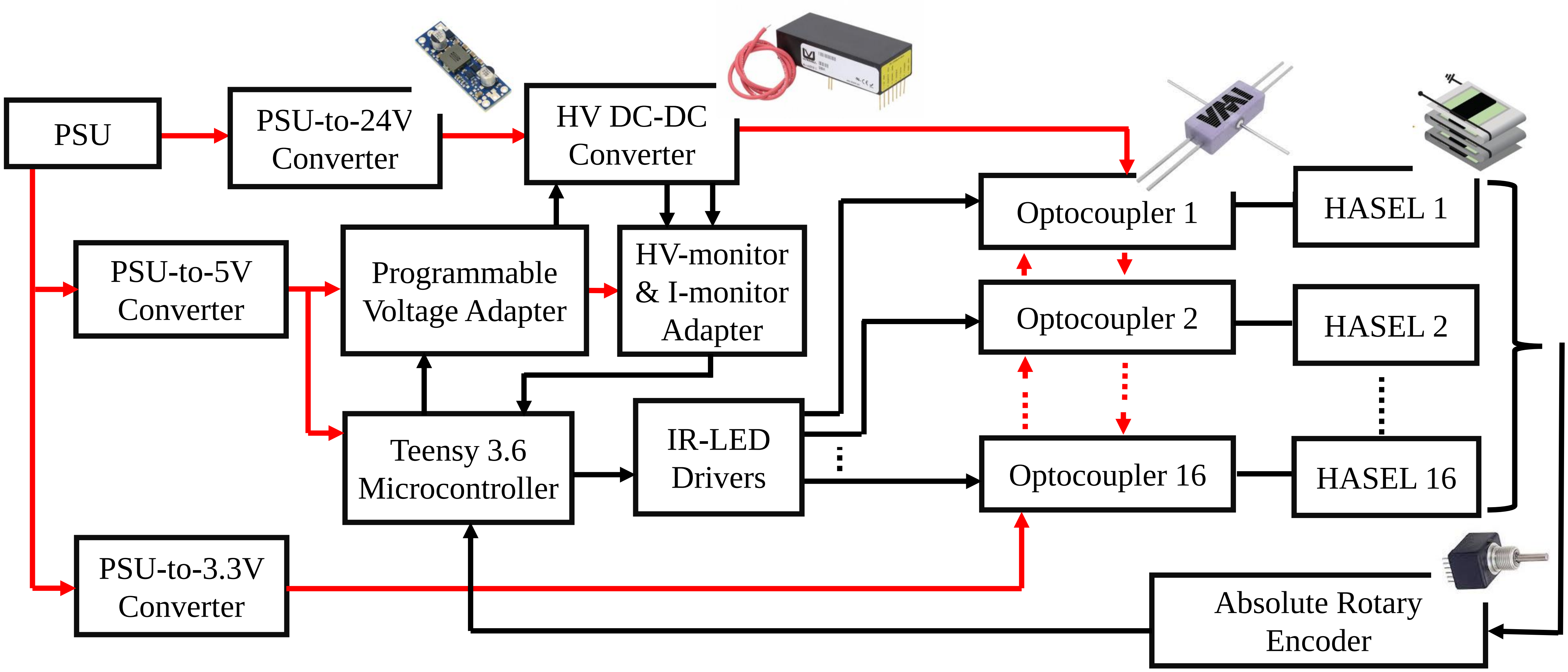

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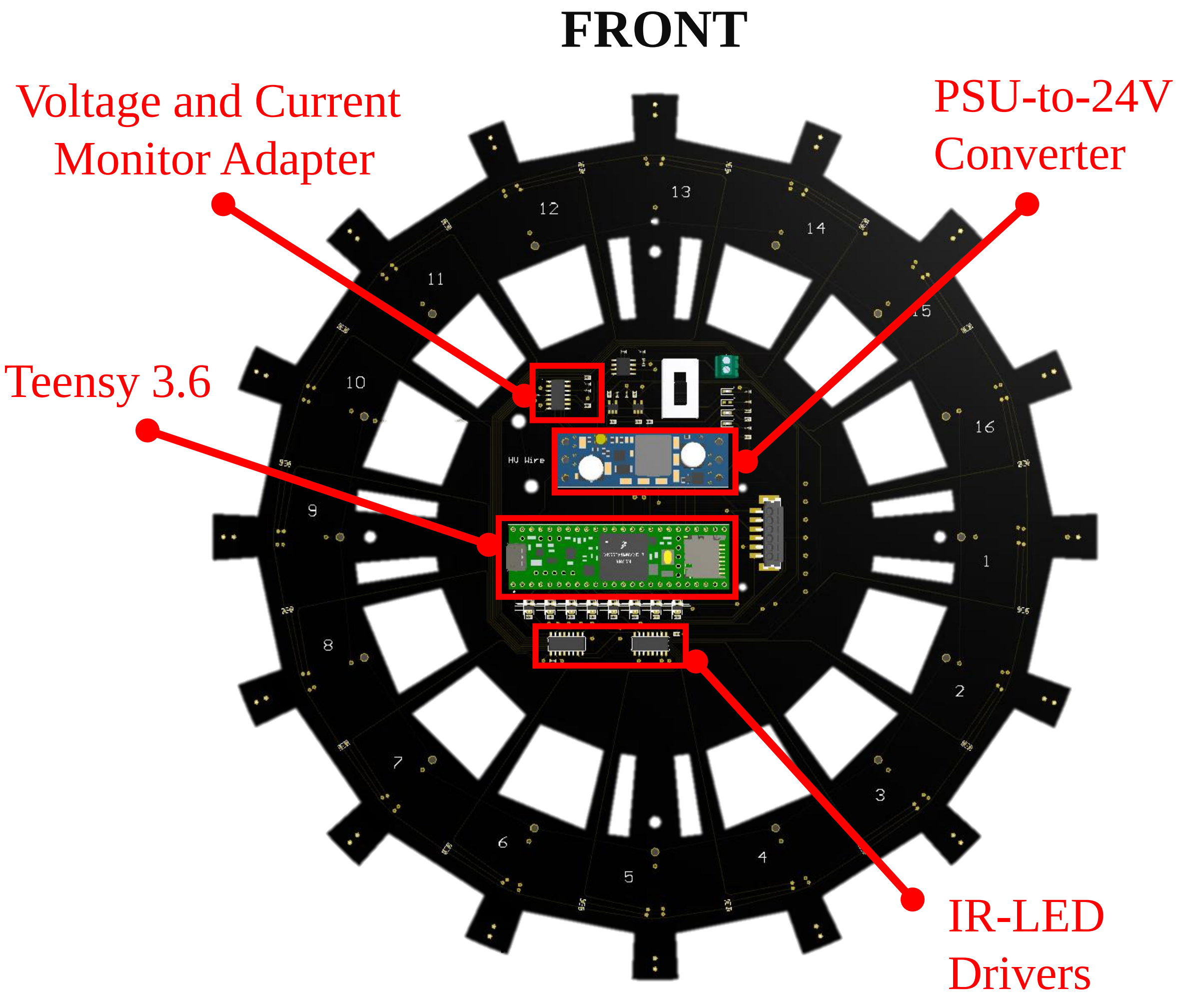

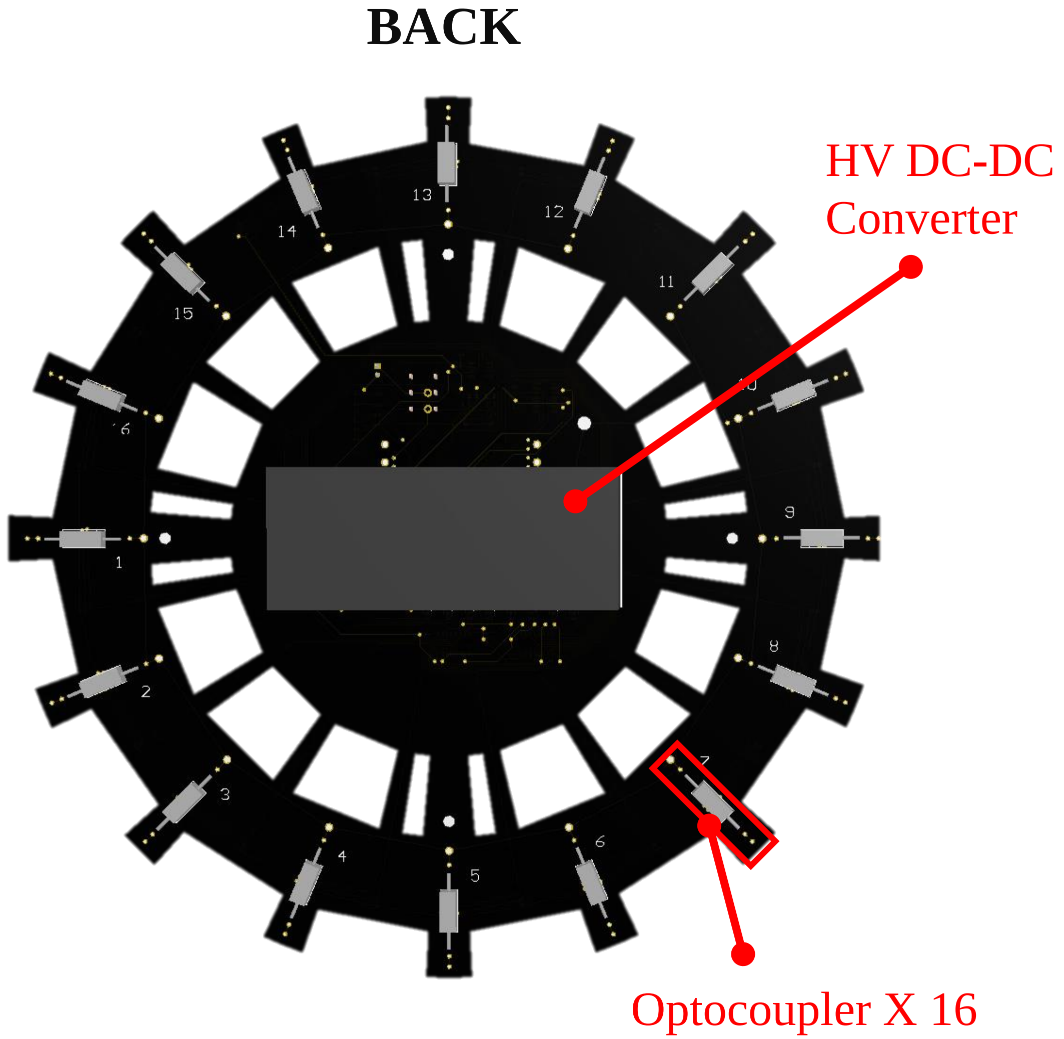

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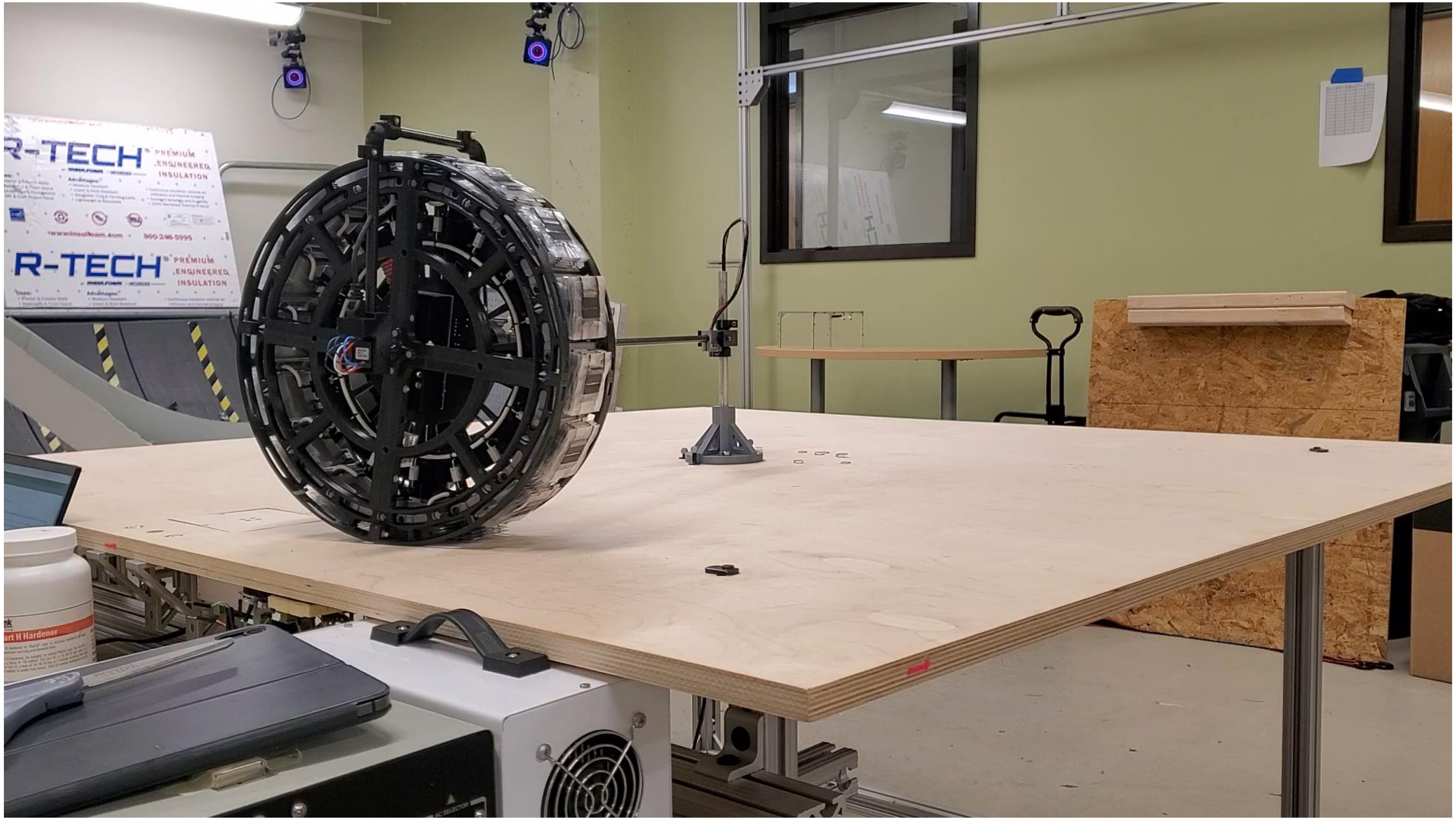

MARK 8

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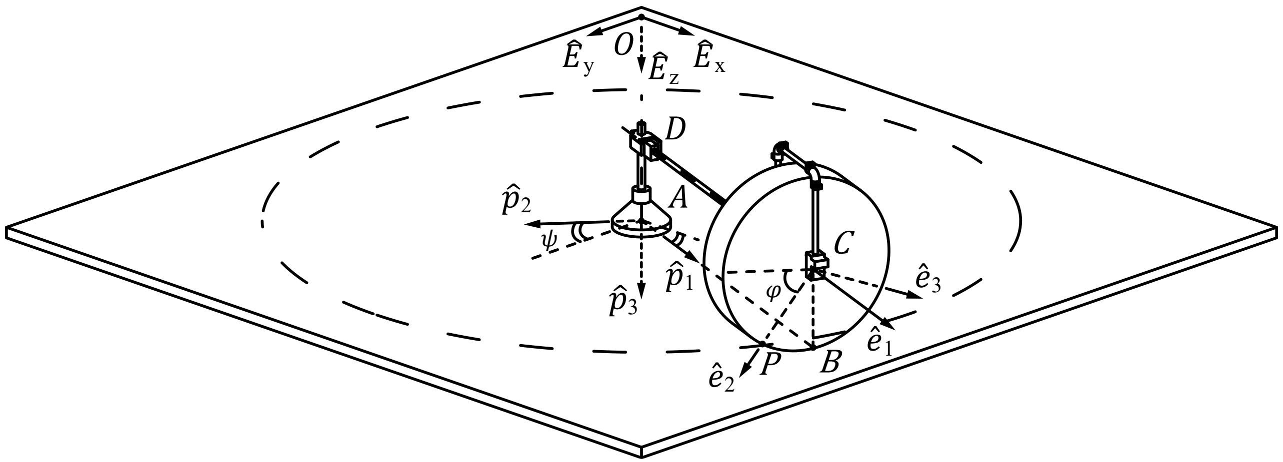
1. Dynamics modeling of the rolling robot



- Platform-fixed frame $\mathcal{F}$: $\{\hat{E}_\mathrm{x},\ \hat{E}_\mathrm{y},\ \hat{E}_\mathrm{z}\}$
- The refence frame $\mathcal{P}$: $\{\hat{p}_1,\ \hat{p}_2,\ \hat{p}_3\}$
- The reference frame $\mathcal{R}$: $\{\hat{e}_1,\ \hat{e}_2,\ \hat{e}_3\}$

Assumption $\quad {}^{\mathcal{F}}\vec{v}_B^{\mathcal{R}} = \vec{0}$

Velocity of the Robot's Center of Mass (point C)

$${}^{\mathcal{F}}\vec{v}_C = {}^{\mathcal{F}}\vec{v}_B^{\mathcal{R}} + {}^{\mathcal{F}}\vec{\omega}^{\mathcal{R}} \times (\vec{r}_C - \vec{r}_B)$$

$$\Rightarrow {}^{\mathcal{F}}\vec{v}_C = r\dot{\varphi}\hat{p}_2$$

$${}^{\mathcal{F}}\vec{v}_C = \frac{{}^{\mathcal{P}}d}{dt}(\vec{r}_C) + {}^{\mathcal{F}}\vec{\omega}^{\mathcal{P}} \times \vec{r}_C$$

$$\Rightarrow {}^{\mathcal{F}}\vec{v}_C = \dot{\psi}\, L \cdot \hat{p}_2$$

$$\boxed{\dot{\psi} = \frac{r}{L}\dot{\varphi}}$$

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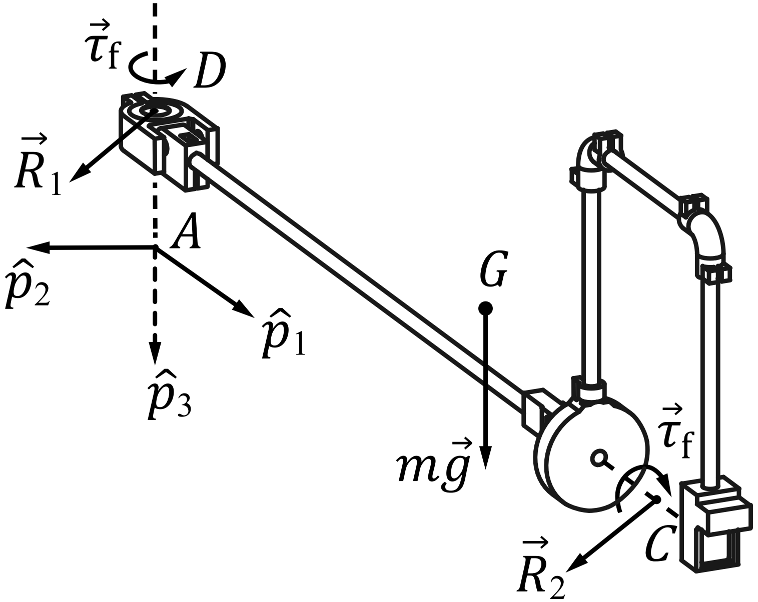
1. Dynamics modeling of the rolling robot



Only rotational motion

$$\vec{M}_D = \frac{^{\mathcal{F}}d}{dt}\left(^{\mathcal{F}}\vec{H}_D\right)$$

$$\begin{aligned} 0 &= I_{13}\,\ddot{\psi} - I_{23}\,\dot{\psi}^2 \\ -m\,g\,x_{GA} - L\,R_{23} &= I_{23}\,\ddot{\psi} + I_{13}\,\dot{\psi}^2 \\ L\,R_{22} - \tau_f &= I_{33}\,\ddot{\psi} \end{aligned}$$

$\begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{21} & I_{22} & I_{23} \\ I_{31} & I_{32} & I_{33} \end{bmatrix}$: Inertia Tensor matrix for the pivot arm and U-mount

L: Distance between the pivot center (A) and the robot's COM (C)

G: COM of the pivot arm and U-mount

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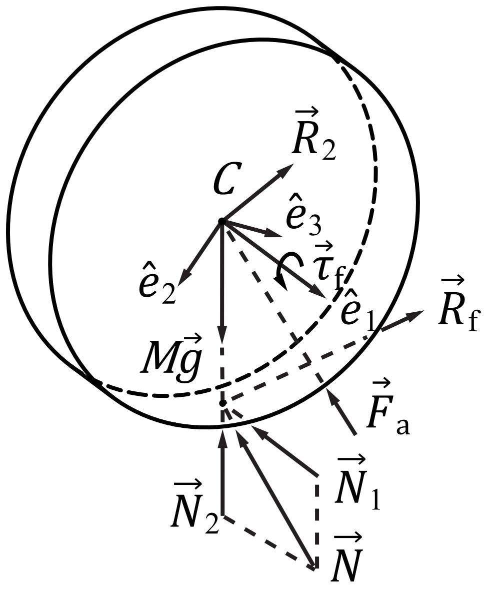
1. Dynamics modeling of the rolling robot



Translational motion

$$\sum \vec{F} = M \cdot {}^{\mathcal{F}}\vec{a}_C$$

$$-R_{21} + N_1 = M\, r\, \dot{\psi}\, \dot{\varphi}$$

$$-R_{22} - R_f + F_{a,2} = M\, r\, \ddot{\varphi}$$

$$Mg - R_{23} + N_3 + F_{a,3} = 0$$

Rotational motion

$$\vec{M}_C = \frac{{}^{\mathcal{F}}d}{dt}\left({}^{\mathcal{F}}\vec{H}_C\right)$$

$$r\, R_f - \tau_f = I_1\, \ddot{\varphi} + (I_3 - I_2)\, \psi^2 \sin(\varphi)\cos(\varphi)$$

$$r\, N_1 \cos(\varphi) = I_2\, (\ddot{\psi} \sin(\varphi) + \dot{\psi}\, \dot{\varphi} \cos(\varphi)) + (I_1 - I_3)\dot{\psi}\, \dot{\varphi}\, \cos(\varphi)$$

$$-r\, N_1 \sin(\varphi) = I_3\, (\ddot{\psi} \cos(\varphi) - \dot{\psi}\, \dot{\varphi} \sin(\varphi)) + (I_2 - I_1)\dot{\psi}\, \dot{\varphi}\, \sin(\varphi)$$

$\begin{bmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & I_3 \end{bmatrix}$: Inertia Tensor matrix for the rolling robot

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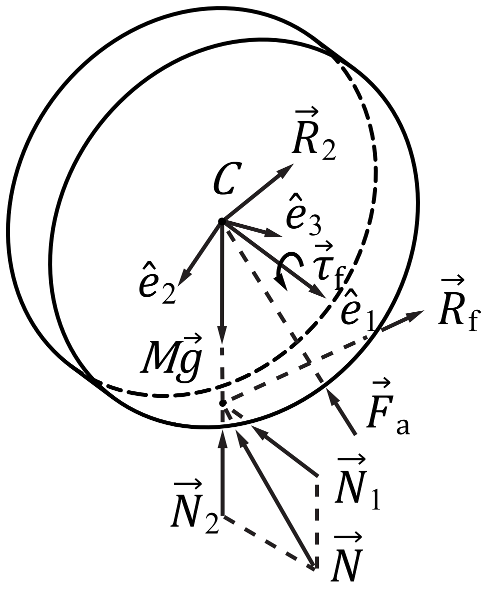
1. Dynamics modeling of the rolling robot



$$L\,r\,F_2 - r\,\tau_f - L\,\tau_f = L\,I_1\,\ddot{\varphi} + r\,(I_3 - I_2)\frac{I_{13}}{I_{23}}\,\ddot{\varphi}\sin(\varphi)\cos(\varphi) + \left(L\,M\,r^2 + I_{33}\frac{r^2}{L}\right)\ddot{\varphi}$$

$$\left(L\,I_1 + L\,M\,r^2 + I_{33}\frac{r^2}{L}\right)\ddot{\varphi} = L\,r\,F_{a,2} - (r\,\tau_f + L\,\tau_f)sign(\dot{\varphi})$$

$$\begin{bmatrix}\dot{\xi}_1\\ \dot{\xi}_2\end{bmatrix} = \begin{bmatrix} \xi_2 \\ \frac{1}{L\,I_1 + L\,M\,r^2 + I_{33}\frac{r^2}{L}}\left(L\,r\,F_{a,2} - (r\,\tau_f + L\,\tau_f)\ sign(\xi_2)\right)\end{bmatrix}$$

$\xi_1 := \varphi \in \mathbb{R}$ is the angular position of the robot

$\xi_2 := \dot{\varphi} \in \mathbb{R}$ is the angular velocity of the robot

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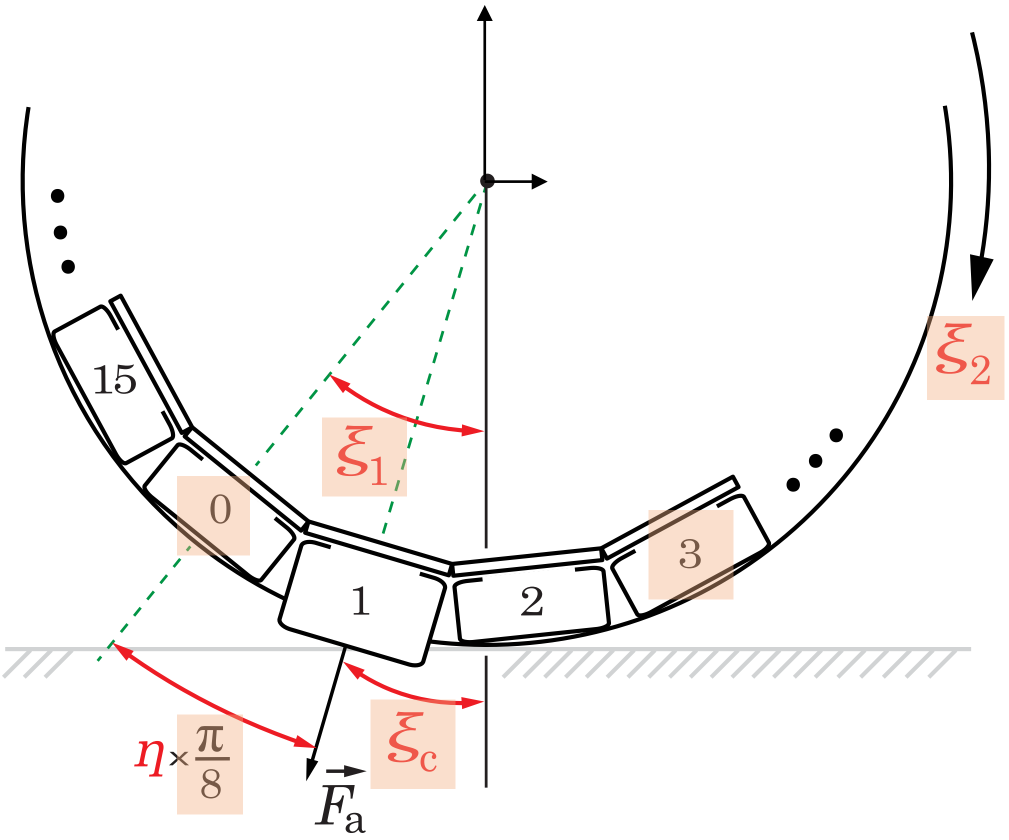
2. Hybrid State-space model of the rolling robot



$$u = \begin{bmatrix} n_a \\ \varphi_a \\ \varphi_d \end{bmatrix}$$

- n_a: the target actuator to be activated
- φ_a: activation angle
- φ_d: deactivation angle

Current actuator index : $\eta = \lfloor \xi_1/(\pi/8) \rfloor$

Contact angle of actuator η^{th} : $\xi_c = \xi_1 - \eta\ (\pi/8)$

$q \in \{0,1\}$: where 0 means not activated, 1 means activated

Activation angle down counter: $\dot{\Delta} = -(1 - q)\ \xi_2$

Deactivation angle down counter: $\dot{\delta} = -\xi_2$

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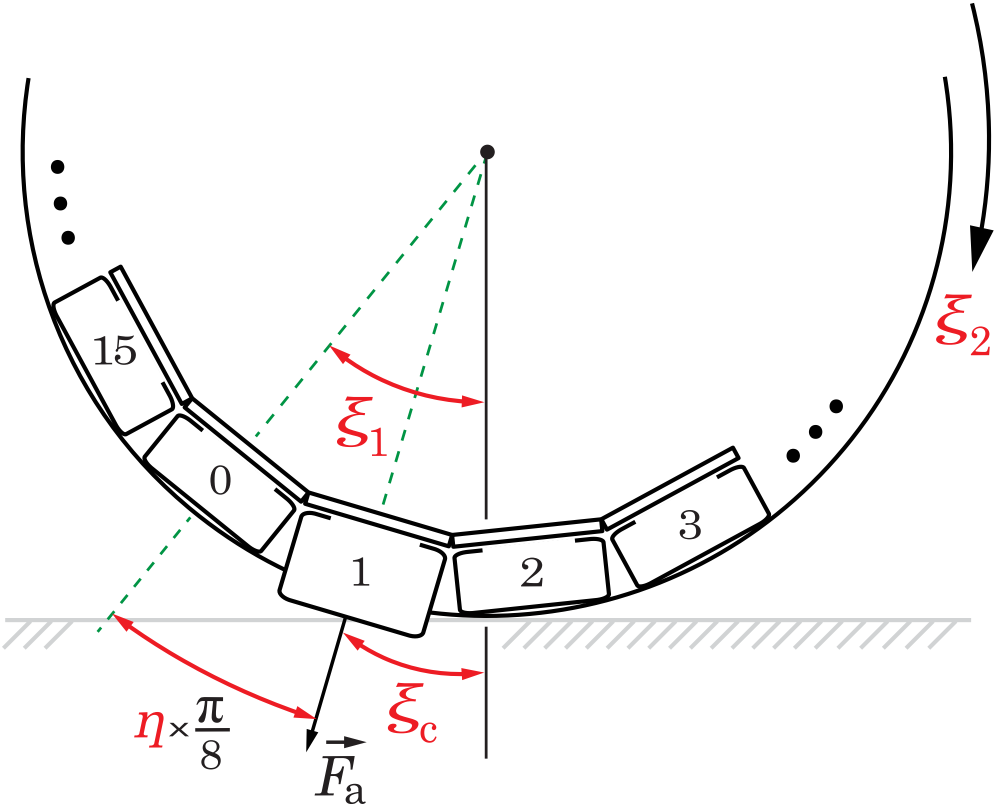
2. Hybrid State-space model of the rolling robot



$$f(x,u) = \begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \\ \dot{q} \\ \dot{\Delta} \\ \dot{\delta} \\ \dot{\eta} \end{bmatrix} = \begin{bmatrix} \xi_2 \\ \dfrac{1}{LI_1 + LMr^2 + I_{33}\dfrac{r^2}{L}}\left(L\, r\, (F_a \sin(\xi_c) - (r\tau_f + L\tau_f) sign(\xi_2)\right) \\ 0 \\ -(1-q)\,\xi_2 \\ -\xi_2 \\ 0 \end{bmatrix}$$

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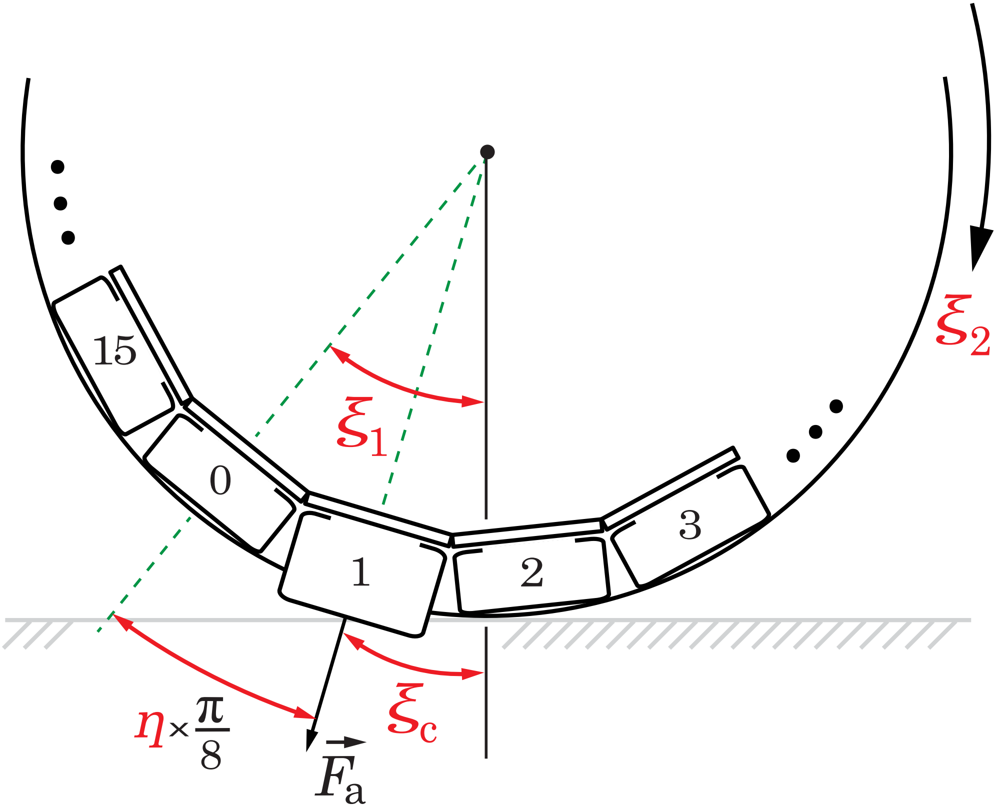
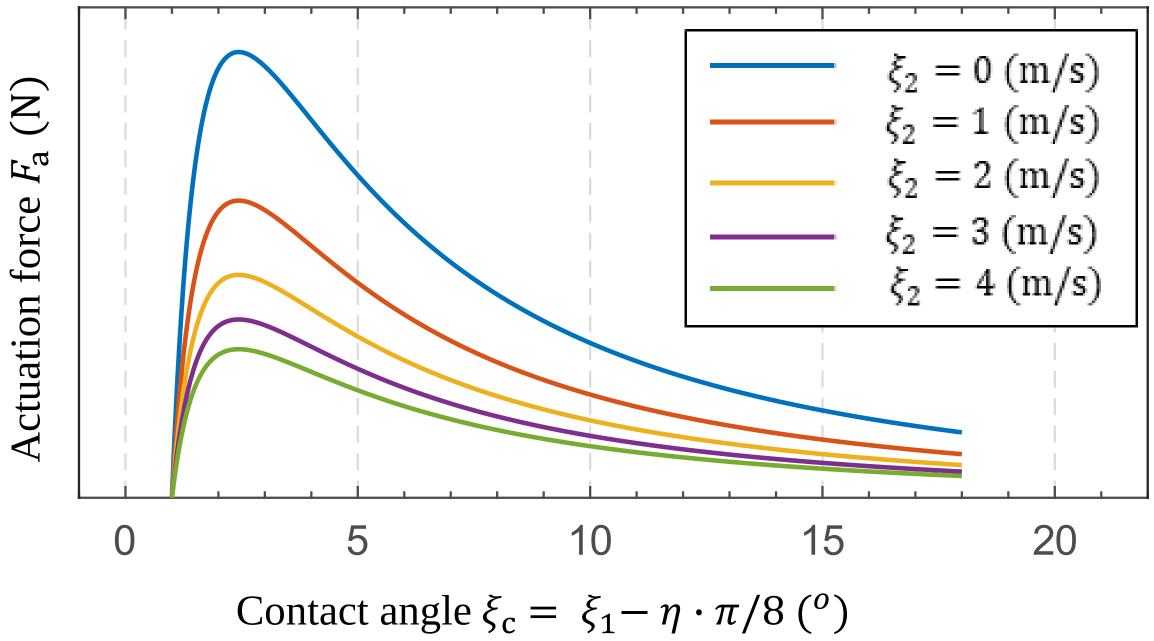
2. Hybrid State-space model of the rolling robot



$$F_a(\xi_c, \xi_2, q, \varphi_a) = \frac{1}{\xi_c^{\ \sigma_1}} \frac{1}{\sigma_2\ \xi_2 + \sigma_3}\ e^{-\frac{(\ln(\xi_c) - \sigma_4)^2}{\sigma_5^{\ 2}}}\ q\ \sigma_6\ (\xi_c - \varphi_a)$$



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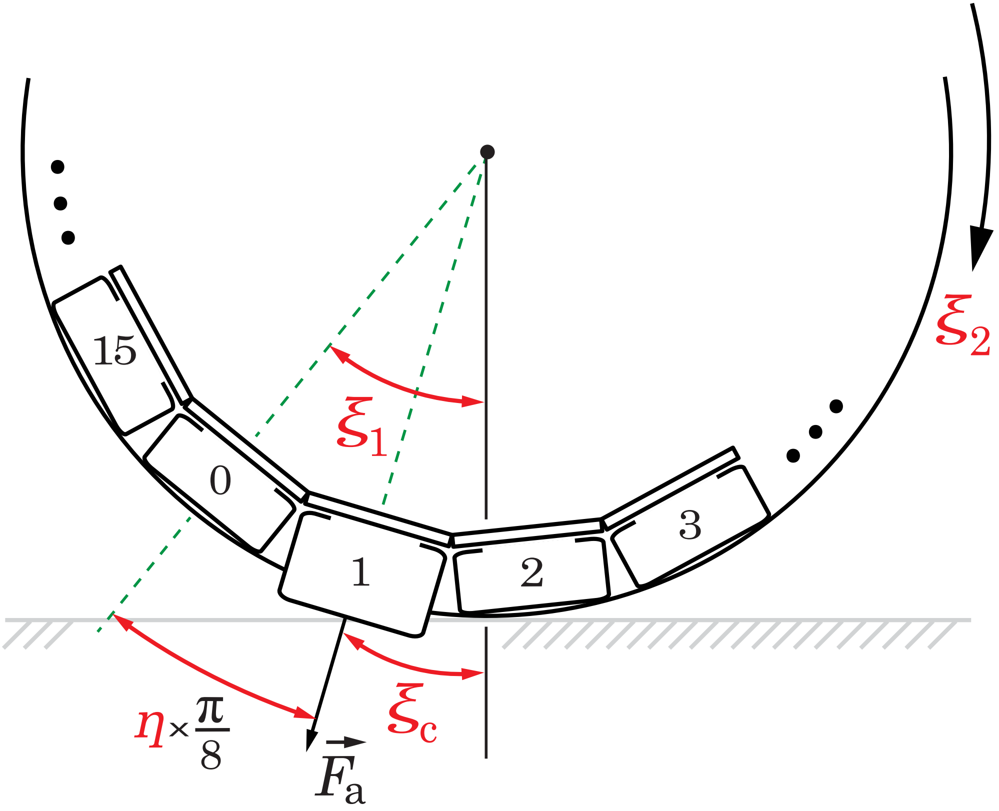
2. Hybrid State-space model of the rolling robot



$$\mathcal{H} = (\boldsymbol{C}, f, \boldsymbol{D}, g)$$

$$\mathcal{H} = \begin{cases} \dot{x} = f(x, u) & (x, u) \in \boldsymbol{C} \\ x^+ = g(x, u) & (x, u) \in \boldsymbol{D} \\ y = h(x) \end{cases}$$

$$q^+ = 1 - q$$

$$\Delta^+ = q\left(\varphi_a + n_a\left(\frac{\pi}{8}\right) - \xi_1\right)$$

$$\delta^+ = \varphi_d + n_a\left(\frac{\pi}{8}\right) - \xi_1$$

$$\eta^+ = q\, n_a + (1 - q)\,\eta$$

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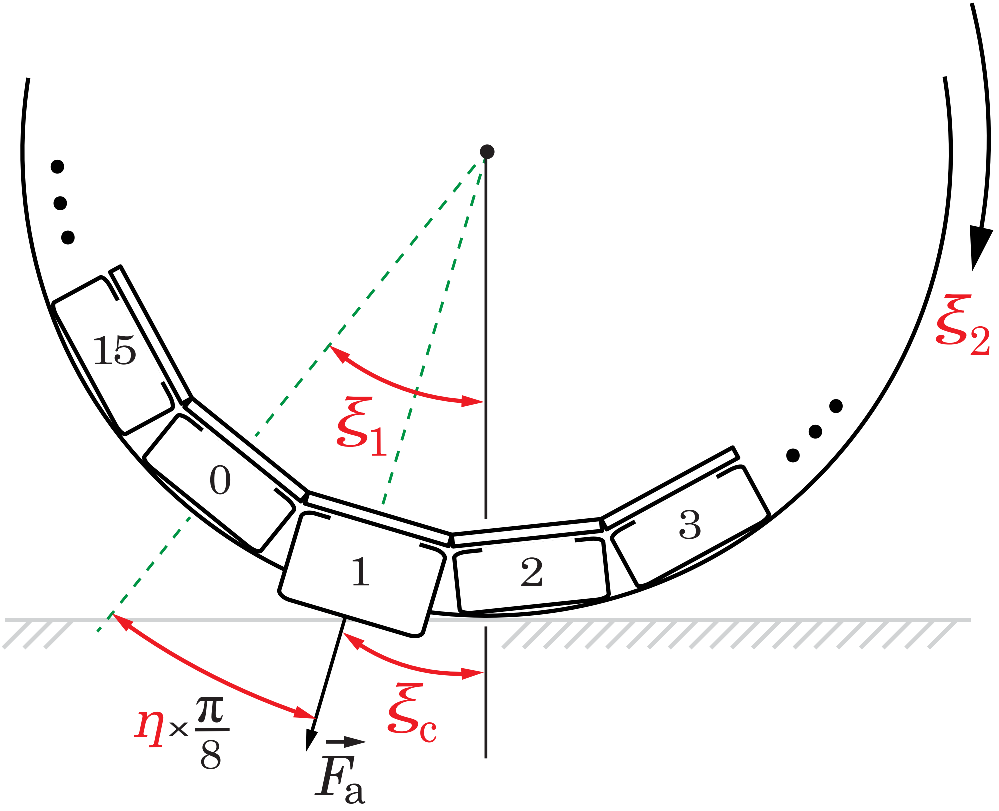
2. Hybrid State-space model of the rolling robot



$$\begin{bmatrix}\dot{\xi}_1\\ \dot{\xi}_2\\ \dot{q}\\ \dot{\Delta}\\ \dot{\delta}\\ \dot{\eta}\end{bmatrix} = \begin{bmatrix} \xi_2 \\ \frac{1}{LI_1 + LMr^2 + I_{33}\frac{r^2}{L}}\left(L\, r\,(F_a \sin(\xi_c) - (r\tau_f + L\tau_f) sign(\xi_2)\right) \\ 0 \\ -(1-q)\,\xi_2 \\ -\xi_2 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix}\xi_1{}^+\\ \xi_2{}^+\\ q^+\\ \Delta^+\\ \delta^+\\ \eta^+\end{bmatrix} = \begin{bmatrix} \xi_1 \\ \xi_2 \\ 1-q \\ q\left(n_a\left(\frac{\pi}{8}\right) + \varphi_a - \xi_1\right) \\ n_a\left(\frac{\pi}{8}\right) + \varphi_d - \xi_1 \\ q\, n_a + (1-q)\,\eta \end{bmatrix}$$

$$\boldsymbol{C} \coloneqq \{ x \in \mathbb{R}^2 \times \{0,1\} \times \mathbb{R}^2 \times \mathbb{N}_{\geq 0} | \sim(\Delta = 0 \wedge \delta \neq 0 \wedge q = 0) \wedge \sim(\Delta = 0 \wedge \delta = 0 \wedge q = 1)\}$$

$$\boldsymbol{D} \coloneqq \{ x \in \mathbb{R}^2 \times \{0,1\} \times \mathbb{R}^2 \times \mathbb{N}_{\geq 0} | (\Delta = 0 \wedge \delta \neq 0 \wedge q = 0) \vee (\Delta = 0 \wedge \delta = 0 \wedge q = 1)\}$$

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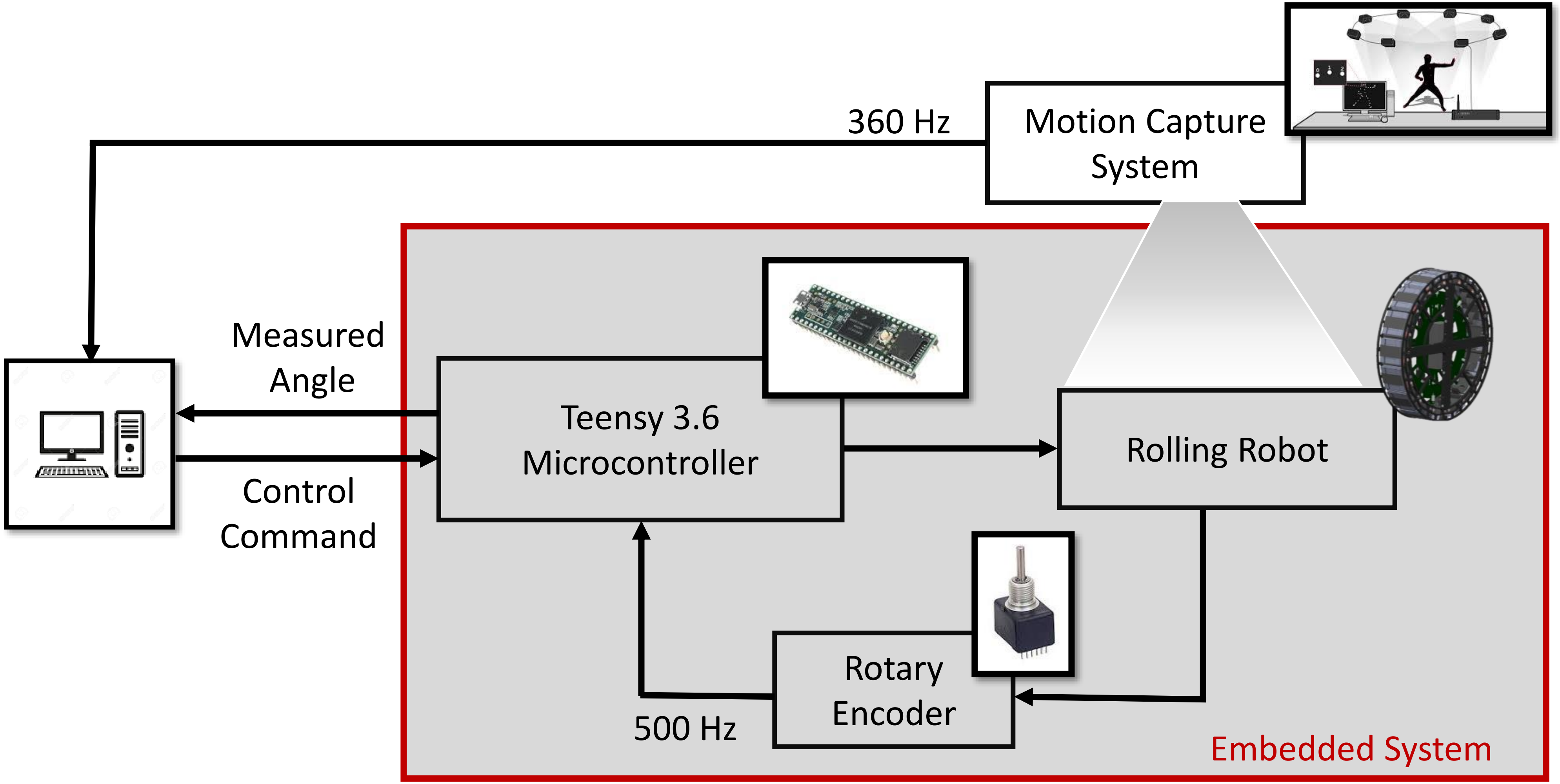

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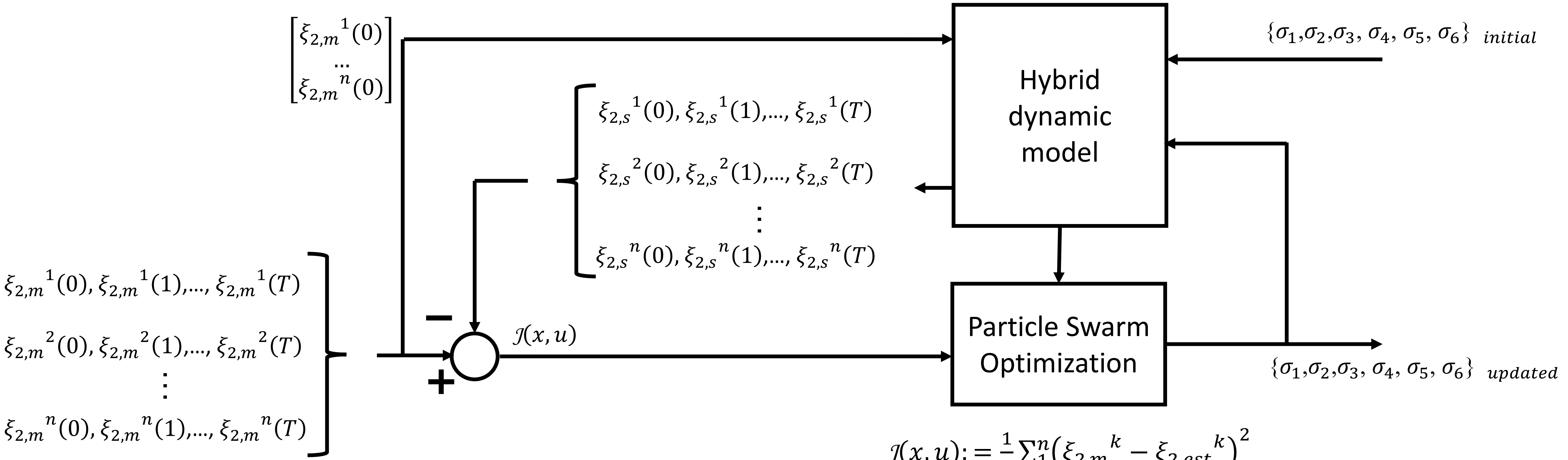
3. Estimation of actuation force function based on measured kinematic data

$$u = \begin{bmatrix} n_a = 16 \bmod (\eta + 1) \\ \varphi_a \\ 22^o \end{bmatrix}$$

$$F_a(\xi_c, \xi_2, q, \varphi_a) = \frac{1}{\xi_c^{\ \sigma_1}} \frac{1}{\sigma_2\ \xi_2 + \sigma_3}\ e^{-\frac{(\ln(\xi_c) - \sigma_4)^2}{\sigma_5^{\ 2}}}\ q\ \sigma_6\ (\xi_c - \varphi_a)$$



$$\mathcal{J}(x, u) := \frac{1}{n} \sum_1^n \left(\xi_{2,m}{}^k - \xi_{2,est}{}^k\right)^2$$

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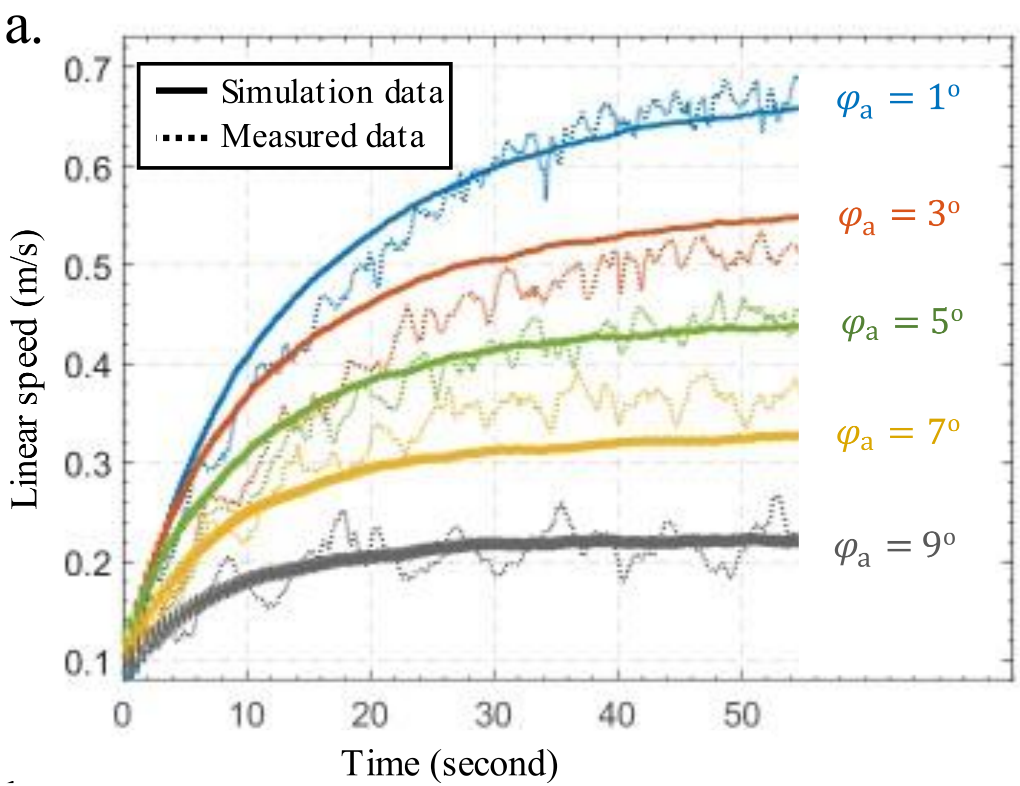
4. Evaluation of actuation force function

$\{\sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6\} = \{1.214, 1.997, 3.836, -1.004, -0.1009, 22.357\}$



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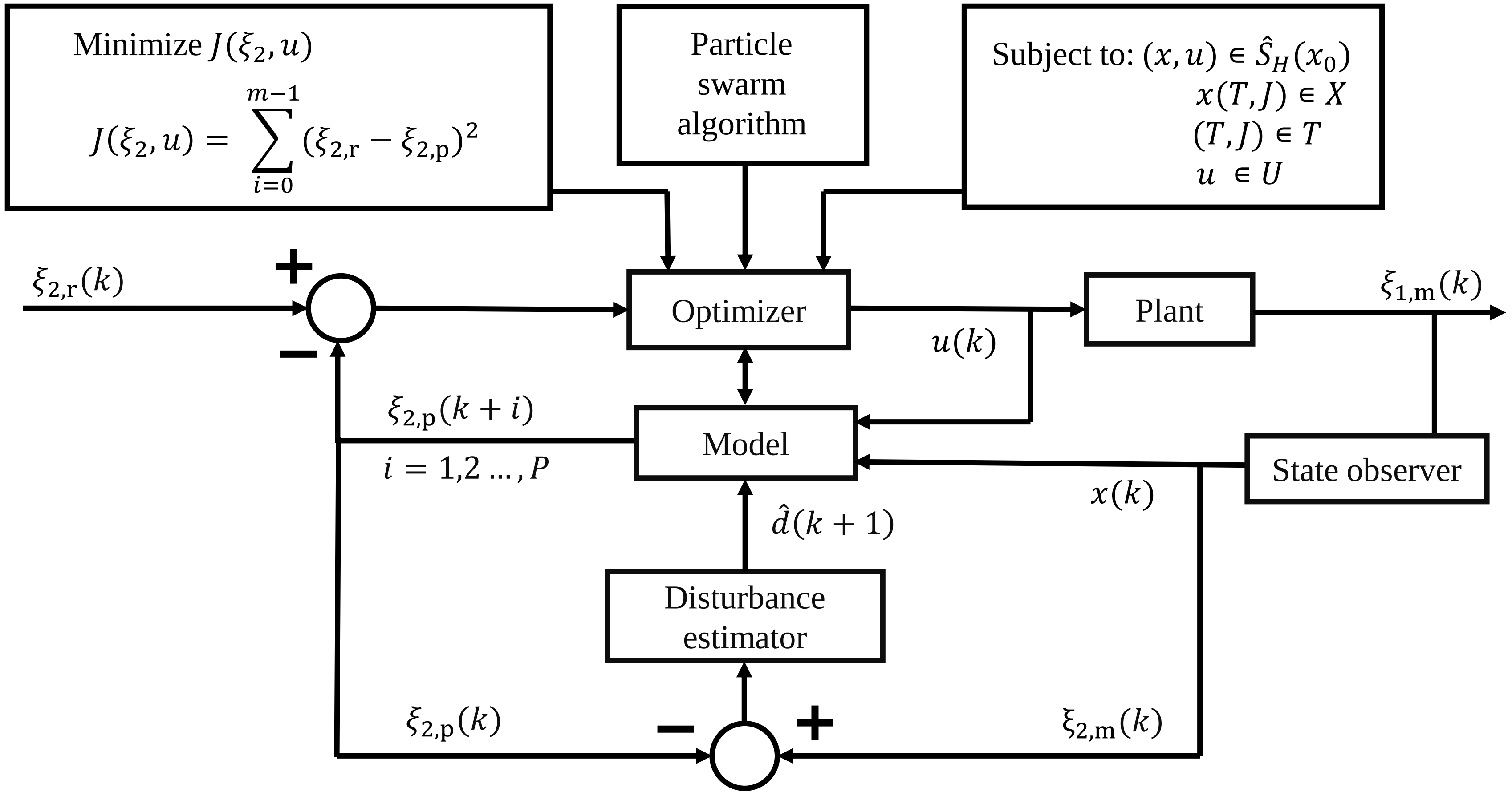
1. Description of controller



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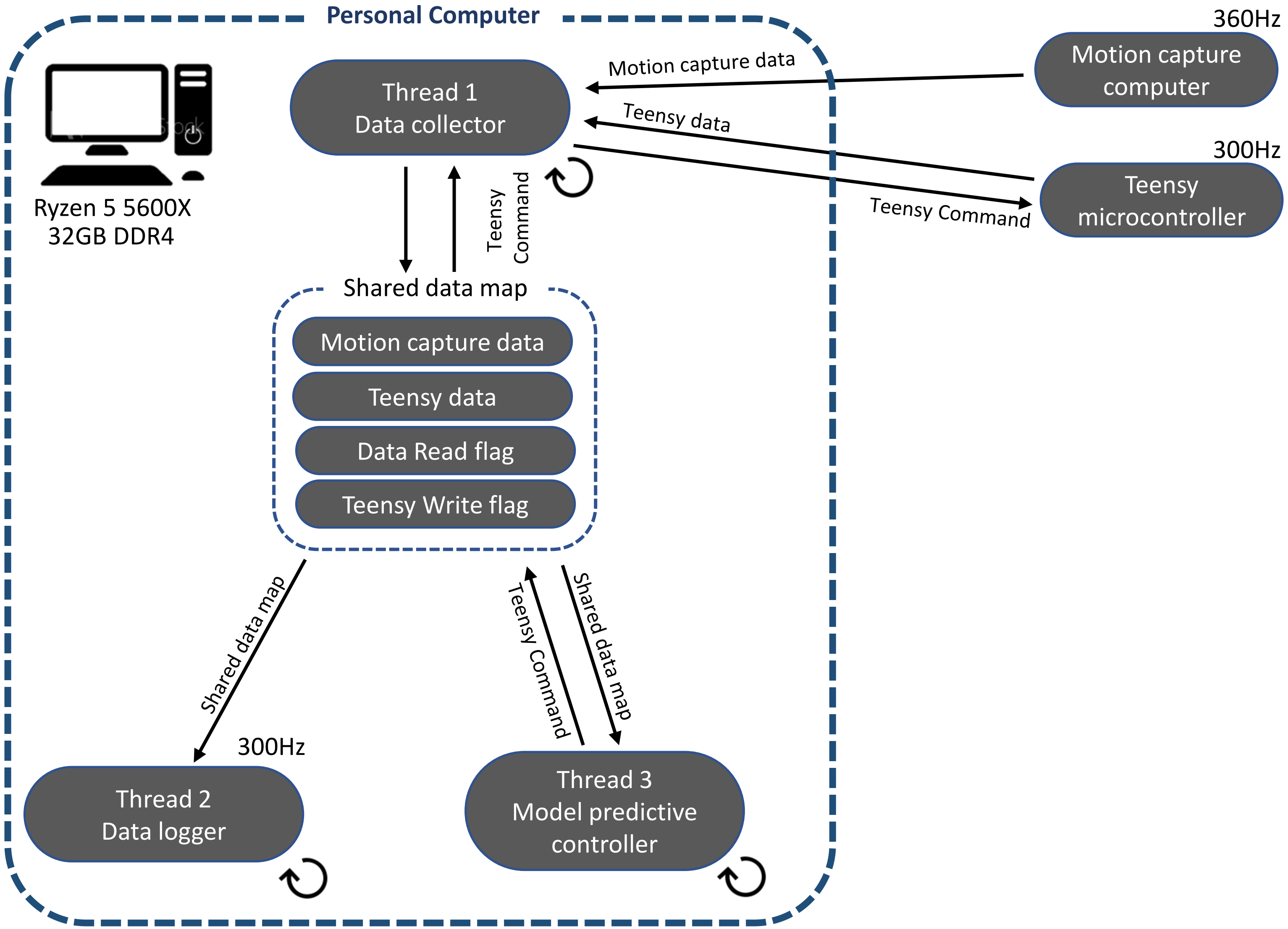
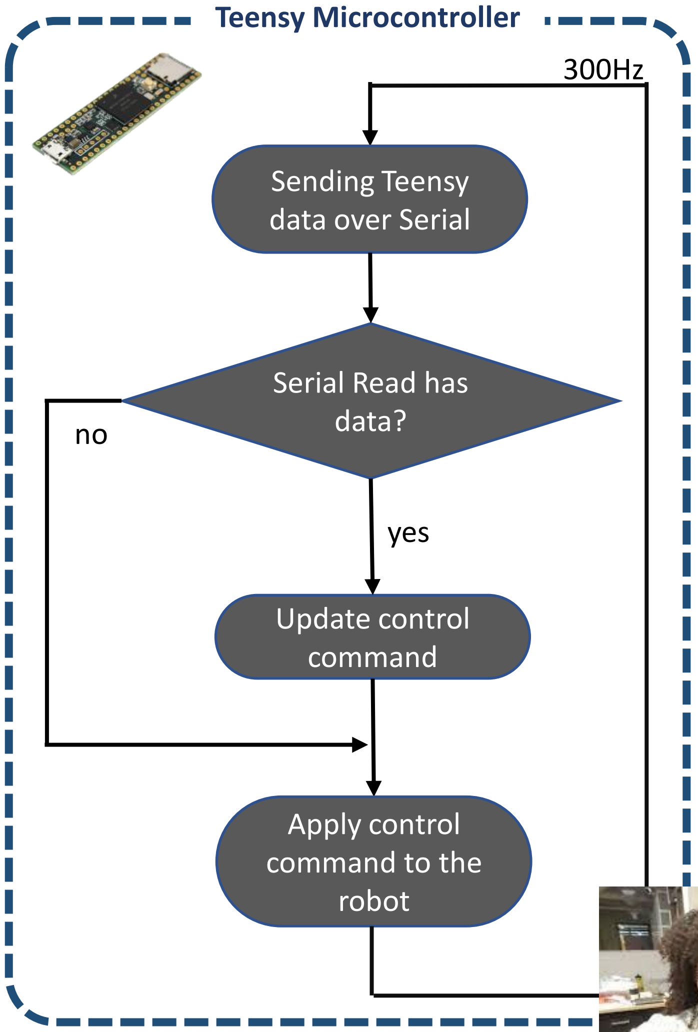
2. Real-time, multi-threaded implementation





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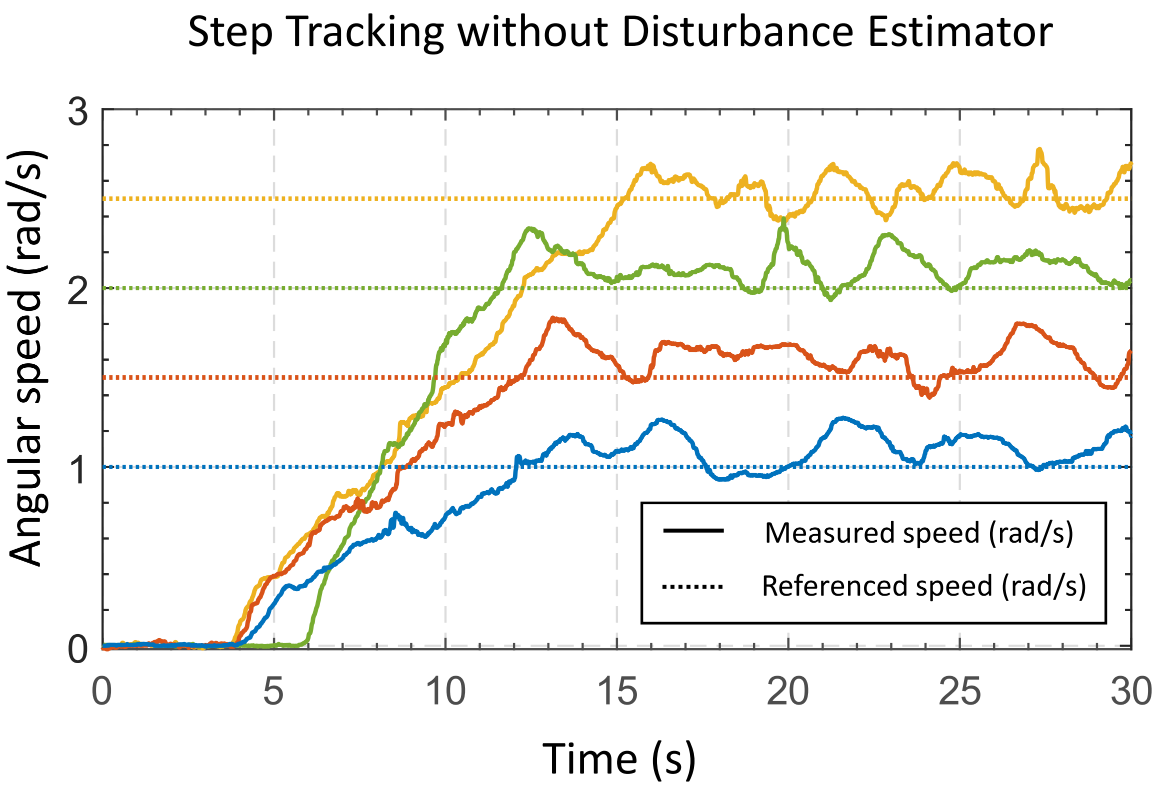
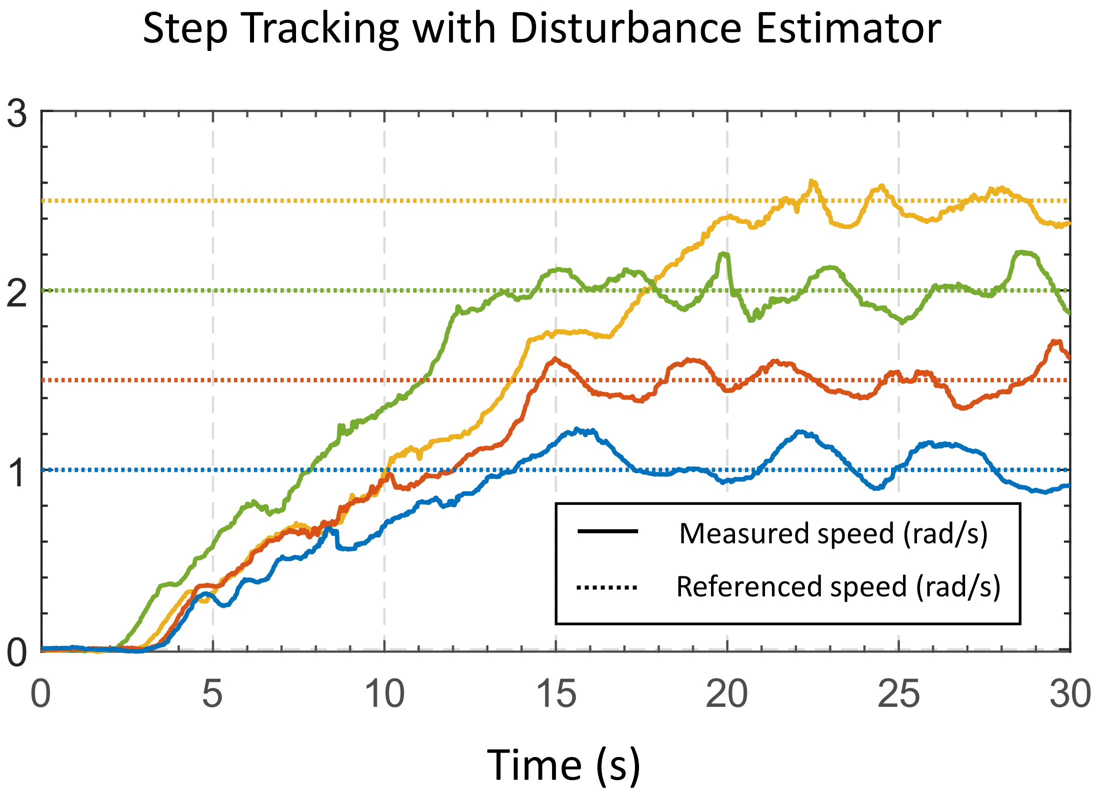
3. Preliminary Results





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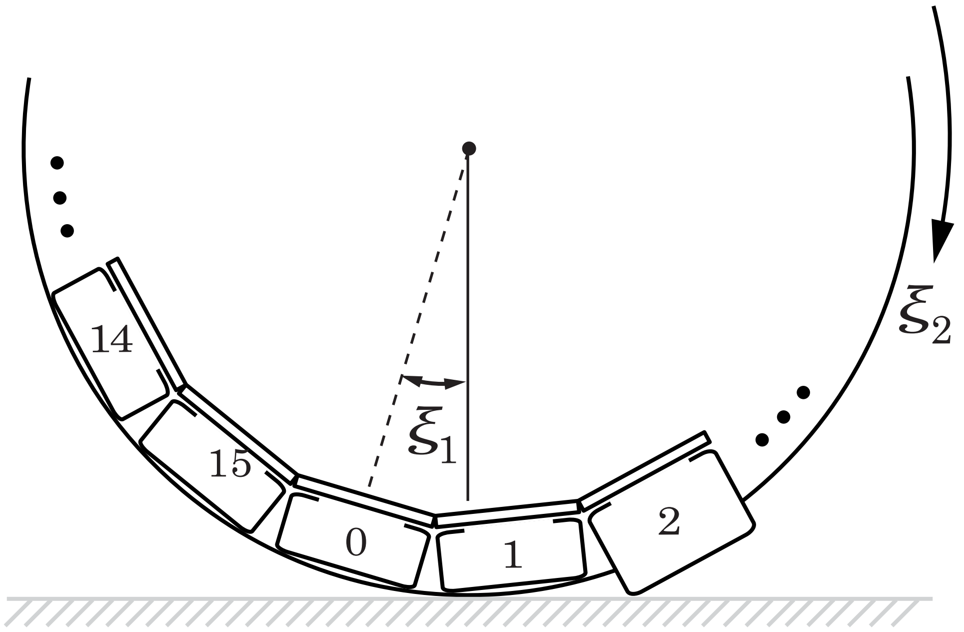
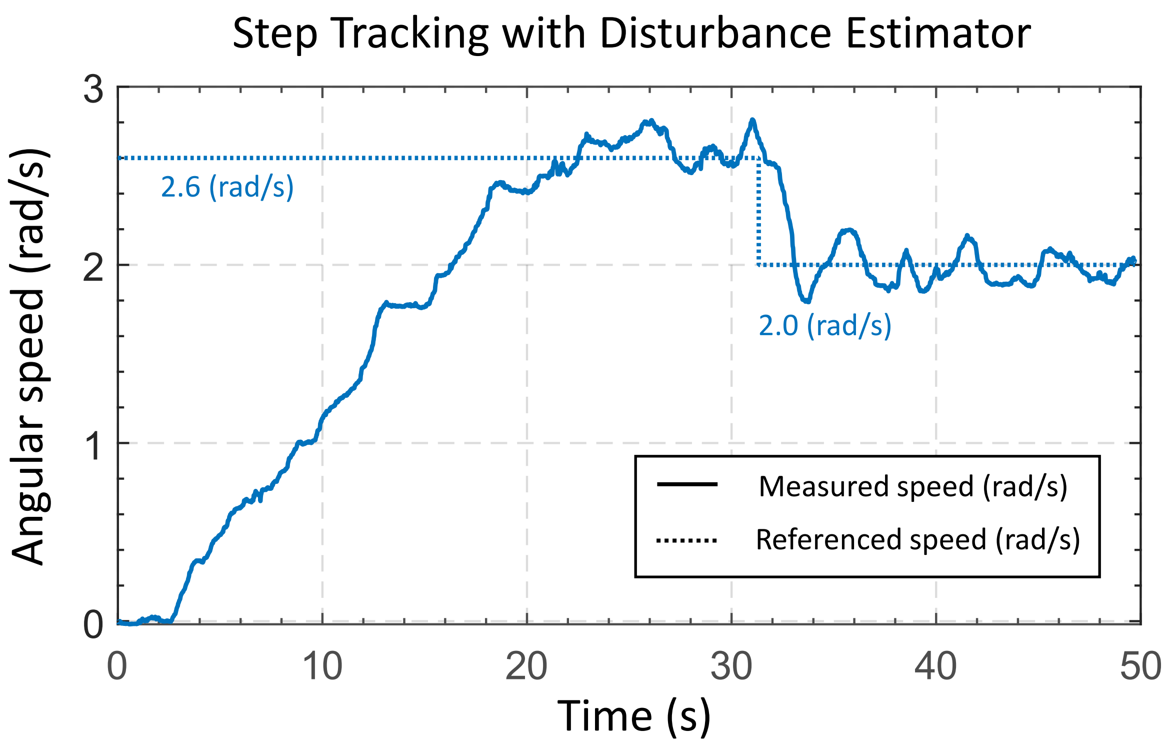
3. Preliminary Results



Braking Input:

$$u = \begin{bmatrix} n_a = 16 \bmod (\eta + 2) \\ -22^o \\ -22^o < \varphi_d < 0 \end{bmatrix}$$



Ly, et. al. (In preparation)

Summary of Contributions

3 Firsts of shell-bulging soft rolling robots:

- **The mobile embedded system** driven by electro-hydraulic actuators
- **The mathematical model**
- **The MPC-based controller** for speed regulation

Future work

- Modeling and validating the actuation force functions for acceleration and braking
- Untethering the system with onboard power supply and controller.
- Redesigning into a spherical robot or adding an additional wheel-based robot with axle

Thank you