Supplementary Materials

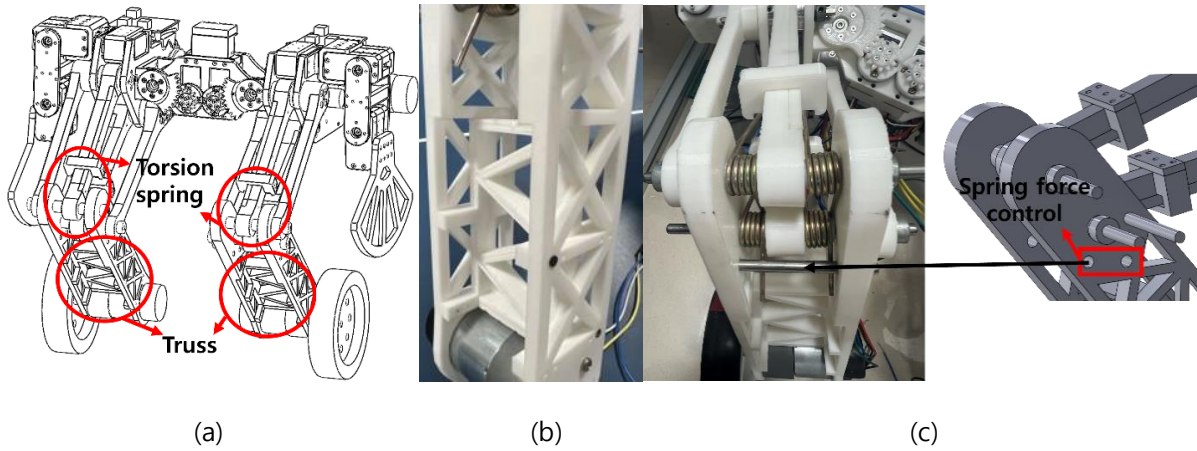## 1. OLEBOT Leg Design

(a)　　　　　　　　　(b)　　　　　　　　　(c)

Figure S1. Comprehensive sketch and detailed images of leg joints of OLEBOT. (a) the basic stance sketch of OLEBOT; (b) the leg joint designed with a truss structure; (c) the spring position and the principle of force adjustment.

As shown in Figure S1, the leg link of OLEBOT, where the passive and actuated links are connected, is designed with a truss structure to prevent bending and breaking of the frame, as it is the part that is subject to the most forces. This also allows for the design to be as lightweight as possible. Additionally, up to four torsion springs can be mounted on each leg, and the angle of the springs can be adjusted based on the motor specifications or the desired force of the torsion springs.

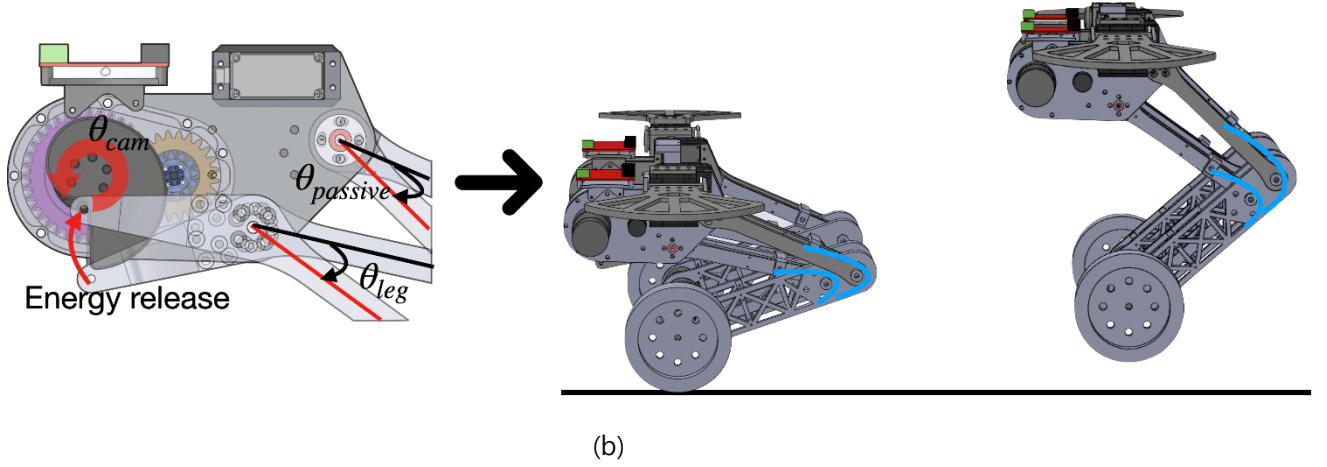## 2. Leg Joint System of Cam Structure

(a)

(b)
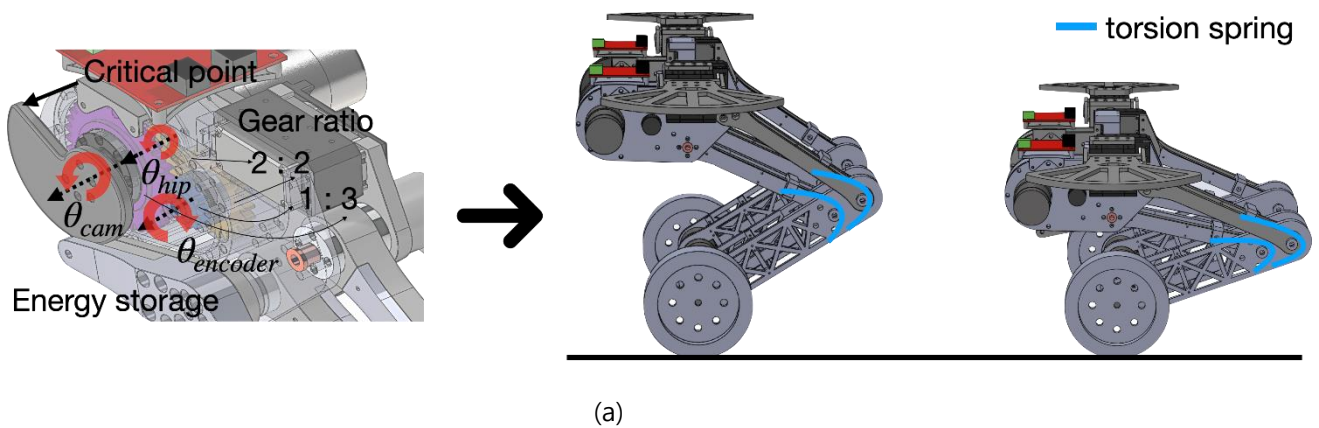
Figure S2. Leg system consisting of a cam-structured hip joint and a knee joint with a torsion spring. (a) the rotation of the cam driven by the hip motor, storing energy in the torsion spring according to the leg angle; (b) the release of energy from the torsion spring as the leg link in contact with the cam passes through the critical point.

As shown in Figure S2, the hip motor and encoder are designed with a 2:2 gear ratio, and the encoder and cam are designed with a 1:3 gear ratio, resulting in a total gear ratio of 1:3 from the hip motor to the cam. The torque of the cam with a 1:3 gear ratio is designed to be greater than the maximum release energy of the torsion spring.

3. Kinematics Modeling

parameters	m, kg, s	parameters	m, kg, s	parameters	m, kg, s	parameters	m, kg, s
m_1	0.135	m_{11}	1.25519	l_8	0.0352	l_{18}	0.10444
m_2	0.32033	m_{12}	0.03669	l_9	0.0594	l_{19}	0.10444
m_3	0.07339	m_{13}	0.17387	l_{10}	0.06003	l_{20}	0.07882
m_4	0.07339	l_1	0.072	l_{11}	0.13796	l_{21}	0.0285
m_5	1.99867	l_2	0.108	l_{12}	0.07882	l_{22}	0.06392
m_6	0.34938	l_3	0.03	l_{13}	0.0285	l_{23}	0.02685
m_7	1.25519	l_4	0.107	l_{14}	0.06392	l_{24}	0.03315
m_8	0.03669	l_5	0.043	l_{15}	0.02685	l_{25}	0.02739
m_9	0.17387	l_6	0.087	l_{16}	0.03315	K	2.58204
m_{10}	0.28202	l_7	0.063	l_{17}	0.02739	r	0.05

Table S1. The parameters for OLEBOT include mass (m), link length (l), spring constant (K), and wheel radius (r). The units for each parameter are m, kg, and s, where m represents mass, l represents link length, and K represents the spring constant, while r represents the wheel radius.

Kinematics represents the positional components of each mass element in matrix form according to established dynamic models. The parameters for modeling, including mass, link length, spring constant, and wheel radius, are specified in Table S1. Equations (S1) to (S6) describe the positional components of the lateral kinematic model.

$$m_1 = \begin{bmatrix} x_{m1} \\ z_{m1} \end{bmatrix} = \begin{bmatrix} x \\ z \end{bmatrix} \tag{S1}$$

$$m_2 = \begin{bmatrix} x_{m2} \\ z_{m2} \end{bmatrix} = \begin{bmatrix} x_{m1} + l_1 c_1 \\ z_{m1} + l_1 s_1 \end{bmatrix} \tag{S2}$$

$$m_3 = \begin{bmatrix} x_{m3} \\ z_{m3} \end{bmatrix} = \begin{bmatrix} x_{m2} + l_2 c_1 + l_4 c_{1,2} \\ z_{m2} + l_2 s_1 + l_4 s_{1,2} \end{bmatrix} \tag{S3}$$

$$m_4 = \begin{bmatrix} x_{m4} \\ z_{m4} \end{bmatrix} = \begin{bmatrix} x + (l_1 + l_2 + l_3)c_1 + l_6 c_{1,3} \\ z + (l_1 + l_2 + l_3)s_1 + l_6 s_{1,3} \end{bmatrix} \tag{S4}$$

$$m_5 = \begin{bmatrix} x_{m5} \\ z_{m5} \end{bmatrix} = \begin{bmatrix} x + (l_1 + l_2)c_1 + (l_4 + l_5)c_{1,2} + l_8 c_{1,2,-4} \\ z + (l_1 + l_2)s_1 + (l_4 + l_5)s_{1,2} + l_8 s_{1,2,-4} \end{bmatrix} \tag{S5}$$

$$m_6 = \begin{bmatrix} x_{m6} \\ z_{m6} \end{bmatrix} = \begin{bmatrix} x + (l_1 + l_2 + l_3)c_1 + (l_6 + l_7)c_{1,3} + l_9 c_{1,3,-5} + l_{10} c_{1,3,-5,6} \\ z + (l_1 + l_2 + l_3)s_1 + (l_6 + l_7)s_{1,3} + l_9 s_{1,3,-5} + l_{10} s_{1,3,-5,6} \end{bmatrix} \tag{S6}$$

where $c_{1,2} = \cos(\theta_1 + \theta_2)$, $s_{1,2} = \sin(\theta_1 + \theta_2)$, $c_{1,2,-4} = \cos(\theta_1 + \theta_2 - \theta_4)$, $s_{1,2,-4} = \sin(\theta_1 + \theta_2 - \theta_4)$.

Equations (S7) to (S13) depict the positional components for each mass element in accordance with the frontal kinematic model.

$$m_7 = \begin{bmatrix} y_{m7} \\ z_{m7} \end{bmatrix} = \begin{bmatrix} y + l_{11} c_{r,-h} \\ z + l_{11} s_{r,-h} \end{bmatrix} \tag{S7}$$

$$m_8 = \begin{bmatrix} y_{m8} \\ z_{m8} \end{bmatrix} = \begin{bmatrix} y_{m7} + (l_{12} + l_{13})c_{r,-h} + l_{14} s_{r,-h} + l_{15} s_{r,-h,7} \\ z_{m7} + (l_{12} + l_{13})s_{r,-h} + l_{14} c_{r,-h} + l_{15} c_{r,-h,7} \end{bmatrix} \tag{S8}$$

$$m_9 = \begin{bmatrix} y_{m9} \\ z_{m9} \end{bmatrix} = \begin{bmatrix} y_{m8} + l_{16} s_{r,-h,7} + l_{17} s_{r,-h,7,8} \\ z_{m8} + l_{16} c_{r,-h,7} + l_{17} c_{r,-h,7,8} \end{bmatrix} \tag{S9}$$

$$m_{10} = \begin{bmatrix} y_{m10} \\ z_{m10} \end{bmatrix} = \begin{bmatrix} y_{m7} + l_{12} c_{r,-h} + l_{18} c_r \\ z_{m7} + l_{12} s_{r,-h} - l_{18} s_r \end{bmatrix} \tag{S10}$$

$$m_{11} = \begin{bmatrix} y_{m11} \\ z_{m11} \end{bmatrix} = \begin{bmatrix} y_{m10} + l_{19} c_r + l_{20} c_{r,h} \\ z_{m10} - l_{19} s_r - l_{20} s_{r,h} \end{bmatrix} \tag{S11}$$

$$m_{12} = \begin{bmatrix} y_{m12} \\ z_{m12} \end{bmatrix} = \begin{bmatrix} y_{m11} - l_{20} c_{r,h} + l_{21} c_{r,-h} + l_{22} s_{r,-h} + l_{23} s_{r,-h,9} \\ z_{m11} + l_{20} s_{r,h} + l_{21} s_{r,-h} - l_{22} c_{r,-h} - l_{23} c_{r,-h,9} \end{bmatrix} \tag{S12}$$

$$m_{13} = \begin{bmatrix} y_{m13} \\ z_{m13} \end{bmatrix} = \begin{bmatrix} y_{m12} - l_{23} s_{r,-h,9} + (l_{23} + l_{24})s_{r,-h,-9} + l_{25} s_{r,-h,-9,10} \\ z_{m12} + l_{23} c_{r,-h,9} - (l_{23} + l_{24})c_{r,-h,-9} - l_{25} c_{r,-h,-9,10} \end{bmatrix} \tag{S13}$$

where $c_{r,-h} = \cos(\theta_r - \theta_h)$, $s_{r,-h} = \sin(\theta_r - \theta_h)$, $c_{r,-h,7} = \cos(\theta_r - \theta_h + \theta_7)$, $s_{r,-h,7} = \sin(\theta_r - \theta_h + \theta_7)$.

4. Sensor & Control Input Filtering
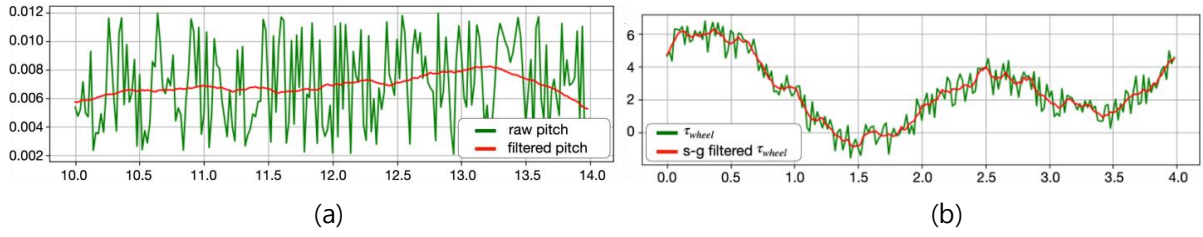

(a)   (b)

Figure S3. Filtering results used in the model prediction controller. (a) the measured pitch values of the IMU sensor after noise and disturbances are eliminated using the Kalman filter. The y-axis corresponds to the pitch measurement, while the x-axis represents time in seconds; (b) the optimized wheel torque values obtained from the model prediction controller, which are further smoothed as the control input for OLEBOT using the S-G filter. The y-axis denotes the wheel torque, and the x-axis represents time in seconds.

To reduce errors in IMU sensor and encoder values, a Kalman filter is employed, while a Savitzky-Golay filter (S-G filter) is utilized for stabilizing the control input. The Kalman filter estimates the roll, pitch, and yaw values of the raw IMU measurements by considering the error as a Markov process at each time step. On the other hand, the S-G filter establishes a fixed window size and applies polynomial regression model within the window to smooth the control input values.
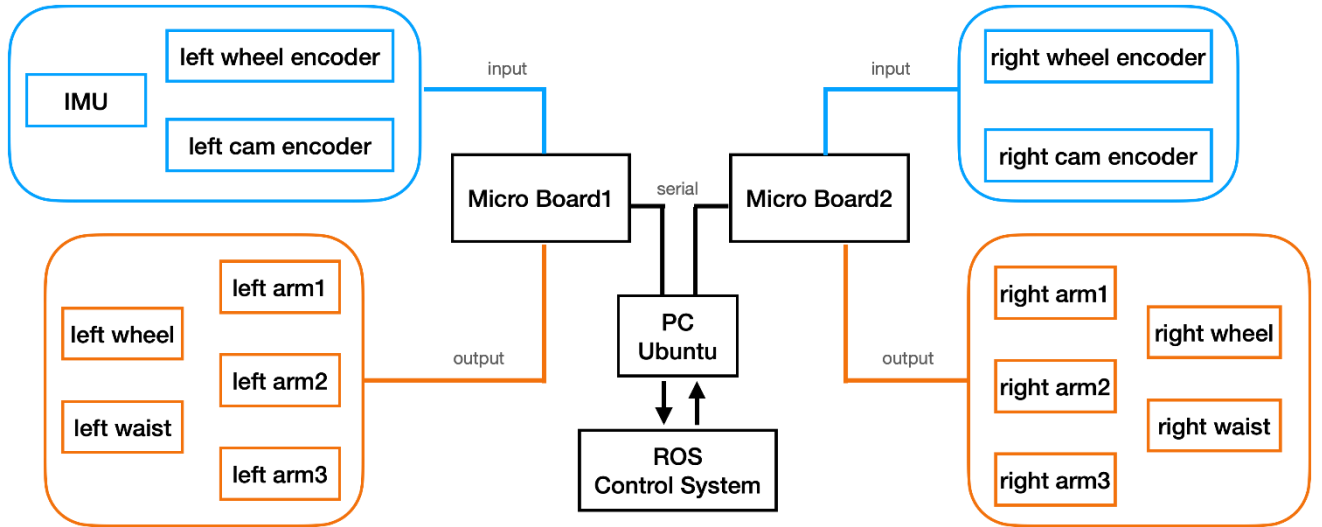
5. Micro Board Communication System

Figure S4. Sensor and actuator micro board communication system. The blue line represents the sensor, while the orange line represents the actuator.

In a real-world setting, the sensor data and actuator input values are communicated through a serial communication system using two micro boards, as shown in Figure S4. Micro board 1 handles the serial communication with the left sensor and actuator of OLEBOT, while Micro board 2 handles the serial communication with the right sensor and actuator of OLEBOT.