

Description of Additional Supplementary Files

Supplementary Movie 1. Hammering nails task

LERL-enabled elephant-trunk robot strikes nails with a 370 g weighted hammer to bind two wooden boards. At the beginning of the task, the robot was controlled to grip the hammer handed to it by a human. The robot then used the hammer to quickly drive nails into both sides of the wooden board. This movie showcases the capabilities of soft robots powered by LERL for daily assistive and industrial applications.

Supplementary Movie 2. Serving drinks with safe interactions

This movie shows that LERL enables the elephant-trunk robot to complete the drinks-serving task with safe human-robot interactions, emulating a skilled human bartender. The elephant-trunk robot interacts with the human safely through a fist bump and handshake, adaptively adjusts its position and orientation to smoothly pour drinks into the cup, throws the bottle into the trash can, and hands the cup to the guest gently and safely. In addition, the robot remains stable during drinks-serving even under external human interventions. This movie demonstrates our approach's capability in precise and smooth control under dynamic loads of drinks, highlighting the potential in daily delicate task operations that require safe human-robot interactions.

Supplementary Movie 3. Calligraphy brush handwriting

LERL learns from environmental feedback to enable the hybrid soft robot, combined with two honeycomb and one soft-muscle segment, to perform flexible movements, writing characters "L", "E", "R", "L" with fluid and clear strokes, while ensuring stability in each brushstroke. LERL ensures that the brush tip, mounted at the robot's end, accurately and stably hovers at a specific height above the paper while precisely following the character strokes.

Supplementary Movie 4. Quick hand-eye reaction game

LERL enables the worm robot to play a quick hand-eye reaction game. A camera detects the movements of sticks to determine which stick falls. Then, the worm robot equipped with a net pocket on its tip moves quickly to catch the free-fall stick within 100 ms. This movie demonstrates the potential of our LERL framework for challenging tasks that require high-performing control in high-speed conditions.

Supplementary Movie 5. Policy adaptation performance validation

This movie first shows that the online learned control policies drive the honeycomb segment E_1 s to accomplish target reaching, circular tracking, and bow tie tracking tasks. Then, its policy is transferred and further updated online to drive three types of soft robots in diverse configurations to complete circular and bow tie tracking tasks. This movie validates the real-time policy adaptation of LERL to soft robots in multiple configurations.

Supplementary Movie 6. Empirical robustness validation

This movie presents the empirical robustness validation results of elephant-trunk robots. LERL enables elephant-trunk robots to achieve precise full-state tracking even under heavy loads of 200 g, 500g, and 1 kg, and actuator faults with 22 broken airbags. LERL's resilience to hardware degradation addresses a critical barrier for field applications, where material fatigue or actuator failure is inevitable. LERL enables the parallel–serial robot to quickly recover and achieve stable tracking after instantaneous external interventions at four different locations. The circular tracking performance of the elephant-trunk robot under varied acceleration profiles demonstrates the adaptability of LERL to different motion conditions.

Supplementary Movie 7. Performance improvement from online learning

Comparison of control performance before and after learning in elephant-trunk and worm robots. Control performance improves substantially throughout the learning process, validating the online learning capability of LERL.

Supplementary Movie 8. Fast-moving traction stick tracking

The elephant-trunk robot quickly and precisely tracks the fast-moving targets generated from a traction stick manipulated by a human, even under interventions. This movie demonstrates LERL's effectiveness in tracking rapidly moving targets.