MOTION & TRANSPORT

Pressure-Sensitive Reversible Adhesion for Soft Robotics

How biology achieves switchable grip across irregular surfaces

5	3	1–5	5
convergent strategies	principle clusters	TRL range	featured strategies

PROBLEM FRAMING

Soft robotics requires grippers that can handle delicate, irregular objects without surface damage or grip failure. Biological pressure-sensitive adhesion provides high adhesion under normal load and clean release on demand — without energy-intensive pneumatic actuation.

Application domains: robotics, medicine, materials

Principle cluster: adhesion, elasticity, mechanosensing

Physics & Mechanism

Underlying physics

[DRAFT] Pressure-sensitive adhesion (PSA) is governed by contact mechanics at the interface. For fibrillar adhesives (gecko-inspired), adhesion scales with contact area (A) and van der Waals surface energy (w): $F = \sqrt{(8Ew \cdot A)/\pi}$, where E is the effective Young's modulus of the fibril material. Reversibility requires that detachment occurs below the fracture strength: low preload → low contact area → low adhesion; high preload → high contact area → high adhesion. This makes grip force proportional to applied normal load — the pressure-sensitive characteristic. Octopus suckers implement pneumatic actuation within each sucker cup: muscular actuation creates negative pressure (suction) directly at each sucker, independently controlled. Tube feet (echinoderms) rely on enzymatic regulation of adhesive secretion timing — a chemical switchability mechanism. Engineering implementations: PDMS micropillar arrays (50–100 µm pillars, 2:1 aspect ratio) in elastomeric substrate achieve 0.1–0.5 N/cm^2 controlled adhesion. Carbon nanotube arrays approach gecko performance in total adhesion (~100 N/cm^2) but with limited cycling durability. [END DRAFT]

Biological Strategies

Attach Temporarily Venus flytrap · TRL 3/9 · 22 genera

Bioinspired artificial surfaces with tailored adhesive properties have attracted significant interest. While fibrillar adhesive pads mimicking gecko feet are optimized for strong reversible adhesion, monolithic microsphere arrays mimicking the slippery zone of the pitchers of carnivorous plants of the genus Nepenthes show anti-adhesive properties even against tacky counterpart surfaces. In contras…

Design principle: This RH-independent robustness of the anti-adhesive properties of NMMAs significantly contrasts the adhesion enhancement by humidity-induced softening on nanoporous fibrillar adhesive pads made of the

Move in/on Solids Common octopus · TRL 5/9 · 41 genera ✦ Evidence File

Fish locomotion is enabled by fin rays-actively deformable boney rods, which manipulate the fin to facilitate complex interaction with surrounding water and enable propulsion. Replicating the performance and kinematics of the biological fin ray from an engineering perspective is a challenging task and has not been realised thus far. Constructed in minutes using origami/kirigami and paper joinery t…

Design principle: This work introduces a prototype of a fin ray-inspired origami electromagnetic tendon-driven (FOLD) actuator, designed to emulate the functional dynamics of fish fin rays. Constructed in minutes using

> What's actually hard: The single deepest unsolved engineering obstacle is sensorimotor control. The octopus utilizes a highly distributed nervous system where low-level reflexes and sucker actuation are handled locally within the arm. Developing closed-loop control algori…

Transform Mechanical Energy Venus flytrap · TRL 3/9 · 36 genera

Rapid muscular movements in carnivorous plants, such as VFT, which are triggered by antenna-like sensors (trigger hair), present a golden key to study distributed biomolecular motors. Carnivorous plants, such as VFT, possess built-in intelligence (trigger hairs), as a strategy to capture prey, that can be turned on in a controlled manner. In the case of the VFT, the prey that is lured by the sweet…

Design principle: Rapid muscular movements in carnivorous plants, such as VFT, which are triggered by antenna-like sensors (trigger hair), present a golden key to study distributed biomolecular motors. Carnivorous plan

Move in/on Liquids Common octopus · TRL 5/9 · 59 genera ✦ Evidence File

The common octopus propels itself through water by expelling fluid in controlled pulses from its siphon, a funnel-like organ located at the base of its mantle. Muscle tissue in the mantle wall contracts rhythmically to force water through the siphon and generate forward thrust. Each pulse forms a vortex ring that transfers momentum efficiently to the surrounding water. The octopus modulates pulse …

Design principle: Design pulsed-jet propulsion systems that mimic the octopus siphon's muscular control architecture rather than using steady-flow thrusters. Implement variable-velocity profiles with triangular or trap

> What's actually hard: The single deepest unsolved engineering obstacle is achieving low-level 'embodied intelligence' without centralizing computation. Replicating the biological distributed nervous system—where local fluidic circuitry within the arm autonomously couples …

Move in/Through Gases Common octopus · TRL 1/9 · 31 genera

The common octopus generates thrust through jet propulsion via a muscular siphon, a funnel-like organ located at the base of its mantle. The octopus draws seawater into its mantle cavity—a flexible, bag-like muscular chamber surrounding its internal organs—then contracts the mantle's radial and longitudinal muscle fibers to expel water at high velocity through the siphon. The siphon itself is a sp…

Design principle: Design decoupled propulsion systems where thrust generation operates independently from body structure by employing a compact, directionally controllable jet actuator. Engineer a flexible pressure cha

Combination Intelligence

Strategies that address different aspects of the same problem and are not redundant when combined.

Move in/on Solids + Move in/on Liquids

Shared principles: adhesion, elasticity, self organization

These strategies share 3 underlying principles including adhesion and elasticity and self organization. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

Move in/on Solids + Move in/Through Gases

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Move in/on Liquids + Move in/Through Gases

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EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

`https://atlasofnature.org/challenge/pressure-sensitive-adhesion`

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