

Grasping Point Estimation for EA Suction Cup Grippers on Curved Objects

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Abstract—Electroadhesion suction cup (EASC) are fully-electrical grippers (no air flow needed) with very low power consumption that can grasp flat to curved objects from the top. They conform to the shape of the object by zipping from the central contact point to their edges, driven by Electroadhesion forces. Zipping requires deforming elastically the EASC membrane. The object surface curvature at contact point strongly affects zipping ability, and therefore grasp feasibility. We developed a model for grasping point selection that predicts the voltage required for full zipping on a point of given local curvature. Feasible points are the ones where the estimated zipping voltage is lower than the breakdown voltage of the EASC. The model is based on an energy balance between electrostatic work and elastic deformation, explicitly including in-plane stretching on doubly curved surfaces. Experiments on cylinders, spheres, and ellipsoids validate the predicted thresholds and curvature-dependent trends.

I. INTRODUCTION AND MODEL

Soft end-effectors are used to handle fragile items and geometric variability [1] in logistics, assistive robotics, and agri-food. Electroadhesion suction cups (EASC) are the first EA-based soft grippers that can grasp heavy objects from the top [2]. They are a silent, electrical and energy-efficient alternative to conventional vacuum cups (Fig. 1a). As for other Electroadhesion (EA) grippers [3], reliable performance depends on adhesion at the interface [4]. They grasp by conforming on the object through EA zipping, which is strongly dependent on the object curvature at the grasping

point. The ability to automatically detect the grasping point for a given object is therefore of utmost importance and requires new models that account for the EA zipping mechanism.

This work addresses grasping point estimation for EASCs on curved objects by identifying contact locations where full zipping (conforming to the object) is achievable within dielectric breakdown limits. We propose a physics-based framework (Fig. 1b) that predicts the minimum activation voltage V_{req} required to obtain full zipping at a chosen contact point from the local surface geometry. The goal is to select points that lie within a safe operating range $V_{\text{req}} < V_{\text{breakdown}}$, classifying locations as feasible or unfeasible for full zipping under the EASC limits, which is a strong predictor of grasp success (Fig. 1c).

We model the EA membrane as a thin, circular elastic membrane [5] of nominal area α^* , thickness t , equivalent Young's modulus E , and Poisson ratio ν . Electrically, the pad is modeled as a variable capacitor where the capacitance scales linearly with the contact area α . We define c_0 as the base capacitance at initial point contact ($\alpha \approx 0$) and c^* as the maximum capacitance achieved at full zipping ($\alpha = \alpha^*$).

The local surface geometry at the contact point is described by principal curvatures (k_1, k_2), summarized by the mean curvature $H = (k_1 + k_2)/2$ and Gaussian curvature $K = k_1 k_2$.

The minimum voltage for full zipping V_{req} is obtained by equating the derivative of the electrostatic work to contact area

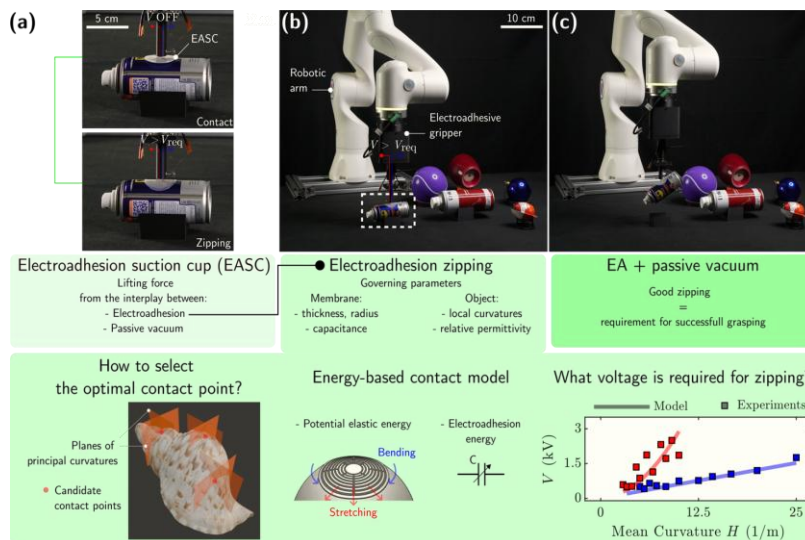


Figure 1. EASC concept and curvature-based voltage selection. (a) EASC concept: electroadhesion triggers zipping; full zipping yields a continuous rim seal and enables passive vacuum. (b) Pipeline: local surface curvature (H, K) \rightarrow predicted V_{req} \rightarrow feedforward voltage command for grasping. (c) Combined EA + passive vacuum leading to robust grasping once good zipping is achieved.

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with the elastic energy rate, using an approach previously developed by our group for EA zipping on cylindrical objects [6]. The elastic energy includes a bending (dominant on cylinders, $K = 0$) and a stretching term, present on spheres and ellipsoids $K > 0$ due to metric incompatibility [5]. The linear capacitance model defined above is used to define the electrostatic work.

$$V_{\text{req}} = \sqrt{\frac{2\alpha^*}{c^* - c_0} \left[\frac{E^* t^3}{12} (2H^2 - (1 - \nu)K) + \frac{GtK^2\alpha^{*2}}{16\pi^2} \right]}$$

where $E^* = E/(1 - \nu^2)$ is the effective elastic modulus and $G = E/(2(1 + \nu))$ is the shear modulus.

This equation maps the voltage threshold to local curvature invariants (H , K) and separates bending-dominated ($K = 0$) from stretching-dominated regimes ($K > 0$). We developed a novel elastic model for a flat membrane deforming to an ellipsoidal shape (frictionless) to obtain a closed form equation for V_{req} that could be used for both design and control.

II. EXPERIMENTAL VALIDATION AND ROBOTIC DEMO

We validated the model experimentally using EASC grippers consisting of a multilayer circular membrane (diameter 3.5 cm and thickness 350 μm) with a thin TPU contact bottom layer, screen-printed interdigitated electrodes, and a silicone top layer. We repeated the tests on two identical devices to assess repeatability.

Experiments are conducted on a benchtop rig that controls vertical approach of the EASC toward the object and measures the normal interaction force at the interface. The pad is brought into contact with the test objects; then a stepwise voltage ramp is applied up to a safe maximum voltage below dielectric breakdown. Two orthogonal cameras monitor the contact interface to identify the minimum voltage at which full zipping is observed. Test objects with controlled curvature are fabricated to span cylinders ($K = 0$), spheres ($k_1 = k_2$, $K > 0$), and ellipsoids ($k_1 \neq k_2$, $K > 0$). Each object is tested with repeated trials per pad, and thresholds are averaged.

Across cylindrical geometries (Fig. 2a), the model prediction closely overlaps measured full-zipping thresholds, consistent with bending-dominated conformation and a linear trend with mean curvature. On spheres (Fig. 2b), the model captures the non-linear increase in required voltage, with larger dispersion attributable to frictional stick-slip phenomena at the interface. On ellipsoids (Fig. 2c) the model captures the overall trend but tends to underestimate the threshold, suggesting that anisotropy of curvature and direction-dependent zipping-front propagation become relevant beyond the isotropic patch assumptions.

Robotic pick-and-place experiments (Fig. 1b) were performed on everyday objects (e.g. cans, balls, ceramic pot) whose local surface geometry can be approximated as cylindrical, spherical, or ellipsoidal. For each object, a candidate contact point was selected; the local principal curvatures (k_1, k_2) (and thus H and K) were used as input to the zipping model to predict the minimum activation voltage $V_{\text{req}}(H, K)$. The robot then executed a standard pick-and-place sequence, applying a voltage V such that $V_{\text{req}} \leq V < V_{\text{breakdown}}$ when feasible, to achieve full zipping and a stable grasp. When the predicted V_{req} exceeded the breakdown limit,

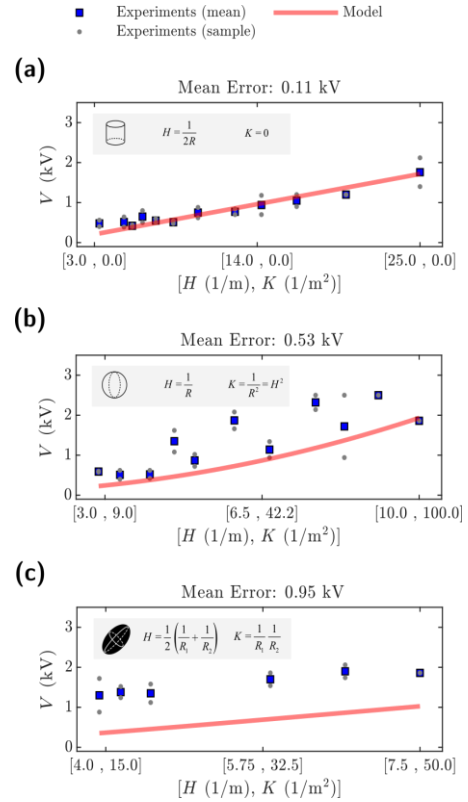


Figure 2. Validation of the predicted minimum voltage for full zipping across curvature classes. (a) Cylinders ($K=0$) exhibit bending-dominated behavior with excellent agreement, while spheres (b) and ellipsoids (c) ($K>0$) show increased dispersion due to stretching-dominated conformation and sensitivity to alignment and interface conditions.

the grasp at that location was classified as infeasible and full zipping was not expected.

III. CONCLUSION

We presented a curvature-based framework for voltage selection in electroadhesion suction cups. By expressing electrostatic work and elastic deformation energies for zipping, we derive a closed-form prediction of the minimum full-zipping voltage $V_{\text{req}}(H, K)$. This model directly identifies which points of a curved object are feasible for full-zipping and thus for reliable pick-and-place. Experiments validate the model on different geometries. Future work will use the same model for vision-based grasp-point estimation.

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