Adaptive Vacuum Suction Cups with Fluid-Filled Skirts for Robotic Adhesion to Uneven Surfaces

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***Abstract*—Suction cups are widely recognized as a cost-effective and efficient adhesion solution across various practical applications. While traditional suction cups perform well on smooth surfaces such as glass and tiles, they face significant challenges on rough, uneven, or porous surfaces commonly encountered daily. Additionally, soft and deformable surfaces often render conventional suction cups ineffective. This study addresses these limitations by enhancing suction cup performance by incorporating flexible skirts. A suction cup with a diameter of approximately 90mm was constructed using 3D-printed components and 18-inch latex balloon materials with an approximate thickness of 1mm. The adhesion performance of the designed suction cups was systematically evaluated on uneven surfaces with different skirt-filling materials. The findings provide insights into improving suction cup adaptability and effectiveness for uneven surface conditions.**

***Index Terms*—suction cups, 3D-printed, skirt-filling, uneven surfaces**

I. Introduction

Suction cups are a cost-effective solution for adhesion, demonstrating exceptionally high adhesive capabilities on smooth surfaces. However, in practical applications, surfaces are often irregular, creating air leakage paths that compromise the vacuum seal. Even with continuous air evacuation using a vacuum pump, excessive leakage can significantly reduce suction force or prevent adhesion altogether. Therefore, minimizing air leakage paths is critical to improving the adaptability of suction cup mechanisms.

To address this challenge, the skirt of the suction cup must balance flexibility and rigidity. Flexibility enables conformance to irregular surfaces, reducing air leakage, while rigidity ensures that the adhered contact area resists deformation, preventing the formation of new leakage paths. To enhance suction cup adhesion without introducing additional forces (e.g., adhesive materials or surface tension), we fabricated a PLA plate with a square-patterned rough surface using a 3D printer. A conventional suction cup failed to adhere to this surface. When water was applied, temporary adhesion was achieved but quickly disrupted by the vacuum pump. We introduced a starch-water solution to improve adaptability to surface textures while reducing fluidity under external force. As shown in Fig. 1, the solution enabled adhesion for approximately 5 seconds before being removed by the vacuum pump. Therefore, while preserving this characteristic, we aim to introduce a membrane to restrict the solution's movement, preventing it from being removed by the vacuum pump.

Fig. 1: The suction cup successfully adhered to the PLA board using a starch-water solution.

Masahiro's universal vacuum gripper (UVG) design leverages the unique properties of coffee powder under vacuum and non-vacuum conditions, effectively improving adhesion on rough surfaces. This study also identified air leakage between the balloon and the target surface as a primary inefficiency, highlighting the need for material optimization to enhance suction cup adaptability [1].

UVG enhances adhesion to rough surfaces by utilizing the

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skirt's strength variation before and during suction. Before adhesion, its fluidity adapts to different surfaces; during suction, the vacuum-extracted skirt maintains suction strength.

Starch-water exhibits a similar behavior: fluid when unstressed but solid-like under force. More broadly, non-Newtonian fluids change their flow properties under external forces. Thus, we explore their feasibility in suction applications based on their characteristic curves.

Soft materials are widely recognized for their high compliance, which allows precise interaction with objects by conforming to surface geometries. This property has been extensively utilized in soft robotics, where flexibility enhances adaptability and precision [2, 3, 4, 5]. Inspired by this field, we propose using fluids as filling materials for suction cups. By dynamically controlling fluid properties, we aim to adjust the rigidity of the skirt, thereby improving adaptability to diverse surfaces and reducing air leakage paths.

The classification of non-Newtonian fluids varies significantly based on underlying mathematical models [6, 7, 8]. To enhance suction cup performance, we propose leveraging the unique properties of common non-Newtonian fluids. Specifically, the following key properties are of interest:

- **Shear-Thinning:** Fluids whose viscosity decreases under increasing shear rates. This behavior facilitates more effortless flow under high shear forces, such as stirring or squeezing, by reducing internal resistance. An example of a shear-thinning fluid is tomato ketchup [9].
- **Shear-Thickening:** Fluids whose viscosity increases under high shear rates. These fluids exhibit normal flow behavior at low shear rates, but particle interactions intensify under rapid stirring or impact, leading to increased resistance to flow. An example of a shear-thickening fluid is a starch-water mixture.
- **Bingham Plasticity:** Fluids that require minimum yield stress to flow. Below this stress, they behave like solids, while above it, they flow like viscous liquids. An example of a Bingham plastic is toothpaste [10, 11].

Therefore, we propose filling the skirt with a starch-water mixture, toothpaste, tomato ketchup, and water (as a typical Newtonian fluid) to develop suction cup models. We aim to investigate how the distinct properties of these fluids contribute to reducing air leakage and improving adhesion performance.

II. RELATED WORK

Suction cup performance can be enhanced through various structural design improvements. One feasible approach is to increase the contact area, thereby enhancing suction force. [12, 13, 14, 15], while another strategy involves increasing the number of micro-suction cups to enhance adhesion capability per unit area [16, 17, 18]. Furthermore, some studies suggest separating the vacuum chamber from the external environment, a design that not only improves functionality but also provides a dust-proofing effect [16, 19].

Numerous studies on suction cup design are deeply rooted in biomimetics. They draw inspiration from various organisms, such as geckos, frogs, and octopuses, which employ diverse strategies (e.g., suction cup structures and locomotion postures) to adhere to complex surfaces. By mimicking these successful natural examples, suction cup mechanisms have continuously evolved to overcome various challenges [16, 17, 20, 21].

A comprehensive review [22] categorizes recent advancements in suction cup design by working principles, presenting them in a detailed tabular format. One notable aspect involves using the mathematical model proposed by Hwang et al. (Eq. 1), highlighting key factors affecting suction cup performance on rough surfaces [20]. This model forms the theoretical foundation for our study, which aims to enhance suction cup performance.

$$F \approx -\triangle P \cdot \frac{1-\gamma}{\alpha \cdot R + 1} \cdot \frac{\pi D^2}{4} + \sigma \cdot A \tag{1}$$

In this equation, $\triangle P$ represents the pressure difference between the internal and external environments of the suction cup. γ is a compensation factor accounting for seal leakage between the suction cup and a perfectly flat surface. α denotes an adaptability constant or leakage parameter, while R) corresponds to the roughness factor of the substrate. D represents the diameter of the interface area.σ is a parameter that describes the interaction forces between the substrate and the suction cup. A represents the effective interface area.

The method we proposed by using fluids as skirt fillers can be considered a biomimetic approach inspired by the muscular contractions of octopus tentacles, simulating changes in suction cup strength. According to the mathematical model (Eq. 1), our approach can be classified as a strategy to enhance suction cup performance by adjusting mechanical properties and adjusting stiffness.

III. SUCTION CUP MECHANISM

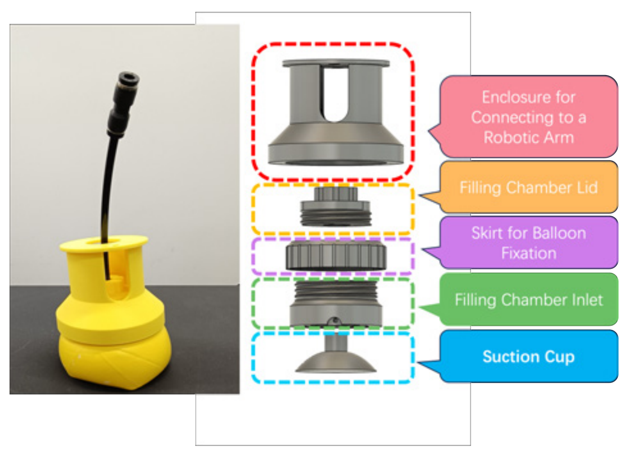
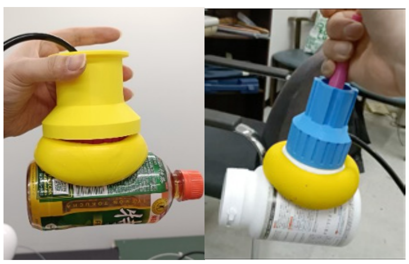


Fig. 2: Suction Cup Structure.

We employed 3D printing technology to fabricate the suction cup mechanism illustrated in Fig. 2. Compared to suction cups without skirts, adding a skirt significantly enhances the suction cup's performance, enabling reliable adhesion to rough surfaces, as shown in Fig. 3a and Fig. 3b, and demonstrating its capacity to lift a $1kg$ bottle, as shown in Fig. 3c and Fig. 3d. It should be noted that the filling material used in all Fig. 3 was a starch-water mixture.

We used 18-inch latex balloons as the skirt material, capable of holding approximately $160ml$ of fluid. Due to the balloon's elasticity, the actual volume of each filling material may vary slightly.

(a) (b)



(c) (d)

Fig. 3: Successful adhesion of the suction cup to different objects: (a) a box with engraved text, (b) a textured cutting board, (c) a bottle with an uneven surface, and (d) a relatively smooth paint bottle containing $1kg$ of coating material.

IV. EXPERIMENTS

A. Dynamic Response of Suction Cups to External Loads

This experiment evaluates the performance of suction cups with skirts filled with different materials on two types of surfaces. The simple surface (Fig. 5a) was used to analyze the effects of external forces on suction strength after successful adhesion, while the complex surface (Fig. 5b) was tested to determine the adhesion success rate. To evaluate success on the complex surface, two points were selected for testing, with each point tested 5 times for a total of 10 times. Tests on the simple surface were conducted 5 times to assess the response to applied forces. The detailed procedures are as follows:

- **Experimental Setup:**
  The suction cup system was mounted on the Ufactory xArm robotic arm, and a six-axis force sensor integrated into the robotic arm recorded force changes in the z-axis direction (as shown in Fig. 4). The vacuum generator was a $12V$ vacuum pump with a flow rate of $120L/min$.
- **Preparation of Test Surfaces:**
  Surface 1: A textured metal plate with a dense and compact structure, where air leakage occurs only at the textured areas, provides the relatively simple uneven surface for the experiment.(Fig. 5a).
  Surface 2: On the side of the concrete block, we tested a commonly used coating material for construction. To create additional surface roughness, the material was applied manually in an irregular pattern, resulting in a randomly roughened surface (Fig. 5b).
- **Adhesion Preparation:**
  The robotic arm gradually pressed the suction cup downward until it conformed to the test surface. The process continued until the force sensor detected a pressure less than -40 N along the z-axis (The direction of the blue arrow in Fig. 4 is defined as the positive z-axis.), indicating the suction cup was compressed. The system was held in this state for 2 seconds to ensure sufficient

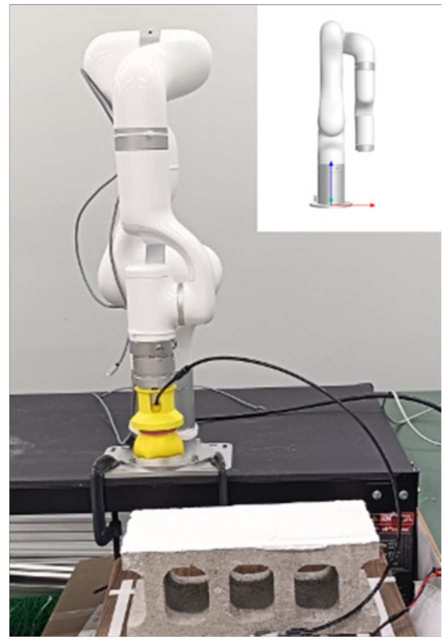
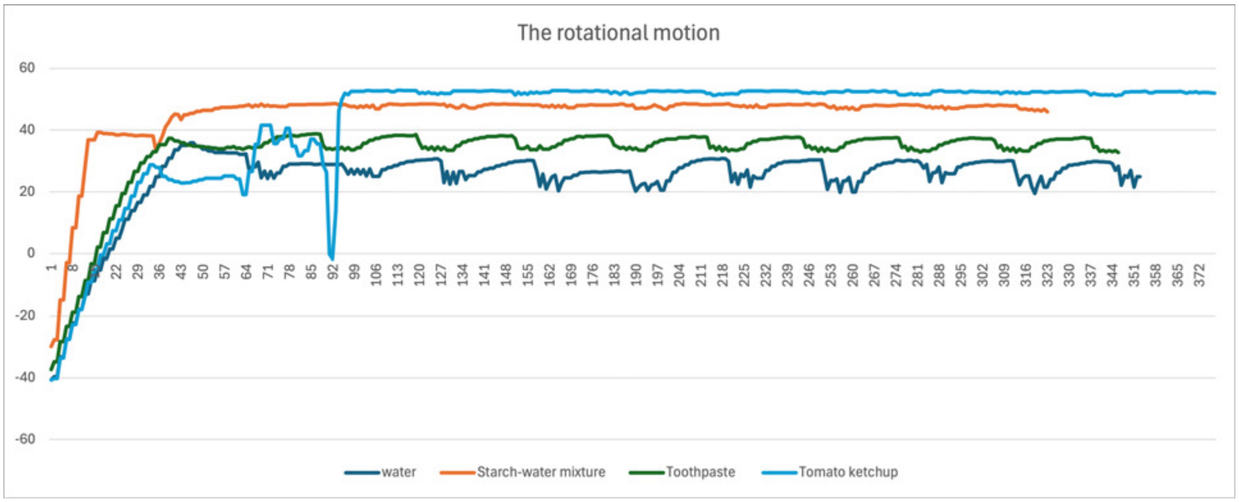


Fig. 4: The Ufactory xArm robotic arm.

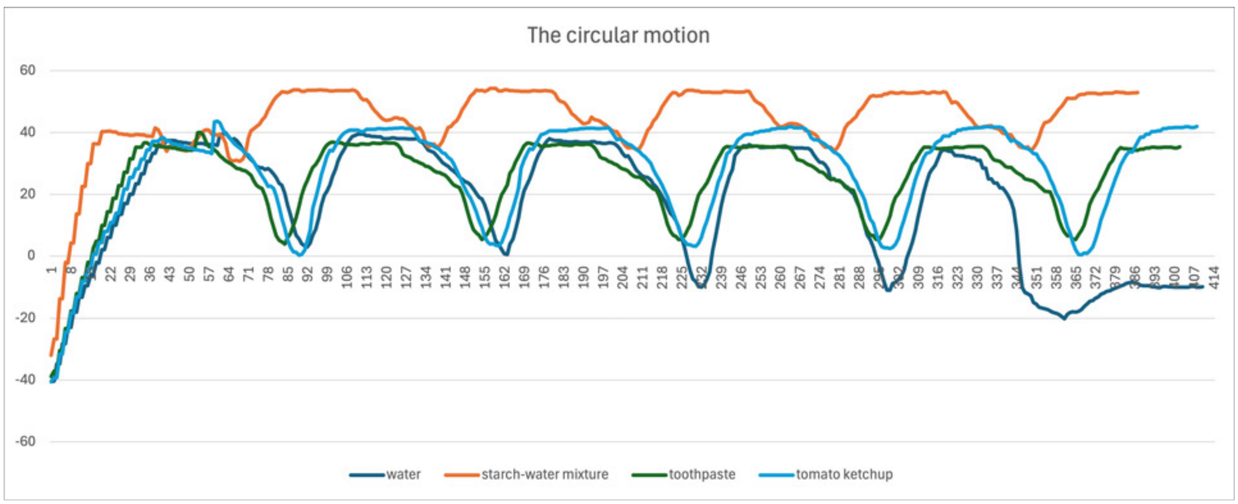
(a)

(b)

Fig. 5: Two test surfaces. (a) is a textured metal plate. (b) is a concrete block coated with construction-grade material.



(a) The rotational motion



(b) The circular motion

Fig. 6: The response of different fluids on a simple surface. The x-axis represents the program cycle, and the y-axis shows z-axis force readings in Newtons (N).

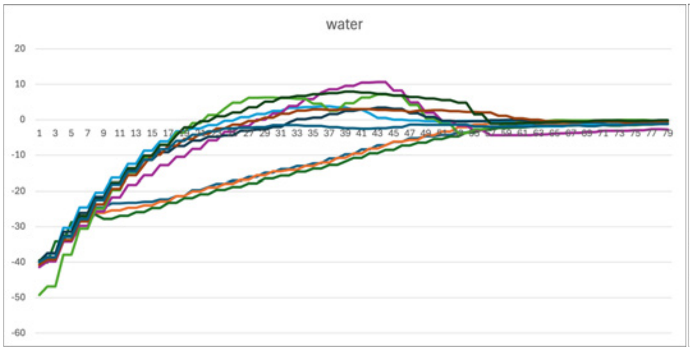
contact between the suction cup and the surface. The vacuum pump was then activated to initiate adhesion.

- **Adhesion Testing:**
  In the adhered state, the robotic arm slowly lifted the suction cup until the force sensor reading exceeded $35N$, approximately $3.57kg$ (using a gravitational acceleration of $9.8m/s^2$). Movement was stopped, and the system was held stationary for 2 seconds to eliminate the influence of fluid inertia and robotic arm motion on the sensor readings. The robotic arm performed the following motion patterns in the xy-plane around the z-axis: Simple rotation around the z-axis with an angle of 15 degrees. Circular motion around the z-axis.

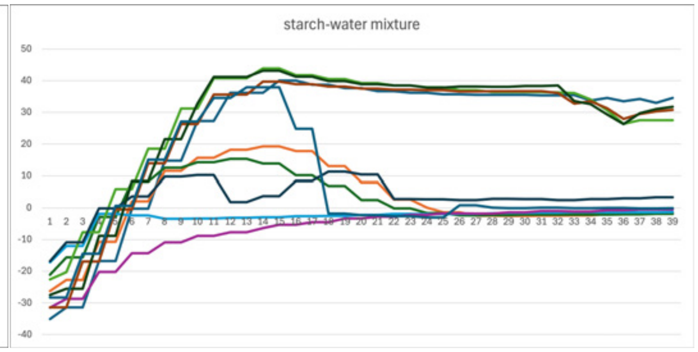
B. Behavior of Suction Cup Skirts on Vertical Surfaces

This experiment investigates the behavior of suction cups filled with different fluids after prolonged static settling and their adaptability during reuse. Examining skirt deformation under gravitational influence, particularly when oriented toward a vertical wall, is critical for ensuring suction cups function effectively across various wall angles. The detailed procedure is as follows:

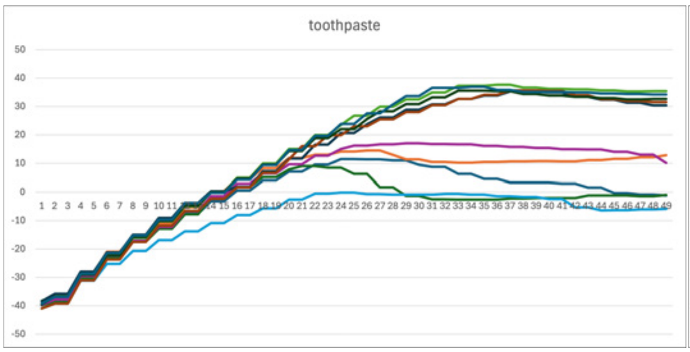
- **Experimental Setup:**
  Four suction cup mechanisms were mounted on a support frame and oriented toward a vertical wall. A recording device was used to capture the changes in the skirt over time, with a recording duration of 30 minutes.
- **Initial Test:**
  The suction cup mechanisms were oriented toward the vertical wall, and the recording device was activated to capture the changes in the skirt over a duration of 30 minutes.
- **Horizontal Resting:**
  The suction cup mechanisms were reoriented to face the



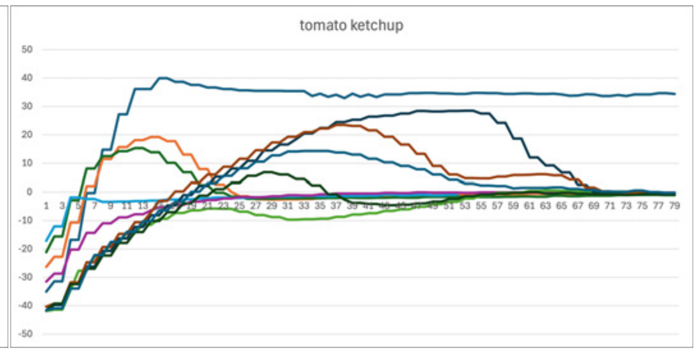
(a) Water



(b) Starch-water mixture



(c) Toothpaste



(d) Tomato ketchup

Fig. 7: The suction performance over 10 trials on a challenging surface.The x-axis represents the program cycle, and the y-axis shows z-axis force readings in Newtons (N).

horizontal plane and left to rest for 24 hour to allow the filling fluid to settle under static conditions.adhesion.

- **Secondary Test:**
  The suction cup mechanisms were then reoriented toward the vertical wall again, and the recording device was activated to capture the changes in the skirt for another 30 minutes.

V. Experimental Results

A. Dynamic Response of Suction Cups to External Loads

The Fig. 6 records the response of different fluids on a simple surface: Fig. 6a shows the rotational motion, and Fig. 6b illustrates the circular motion.

In the rotational motion experiment, the water-filled skirt succeeded once in five trials, the starch-water mixture and toothpaste succeeded four times each, and tomato ketchup succeeded once. Fig. 6a compares representative successful cases, showing that the starch-water mixture had the smallest force variation during rotation, followed by toothpaste. In the single successful trial of tomato ketchup, multiple re-adhesions were observed, likely due to its shear-thinning property, which increased fluidity under shear force. This improved contact area and reduced air gaps, enabling successful adhesion.

The Fig. 6b illustrates the circular motion experiment, designed to induce air leakage in the suction cup skirt. The water-filled skirt succeeded once in five trials, with significant suction loss during movement. The starch-water mixture achieved four successes, but three failed during movement due to insufficient adaptability. Toothpaste also succeeded four times, with only one failure during movement, while tomato ketchup succeeded three times, with one failure.

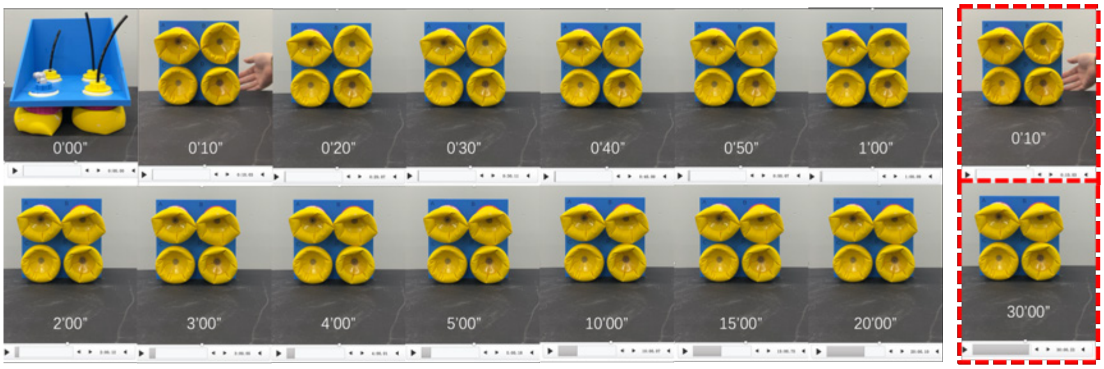
The results suggest that the starch-water mixture under shear force due to increased resistance but lacks sufficient fluidity to adapt quickly to new shapes. In contrast, toothpaste, with its strong Bingham plasticity, maintains its structural integrity, making it more suitable for tasks involving larger movement amplitudes.

The Fig. 7 presents the suction performance over 10 trials on a challenging surface.

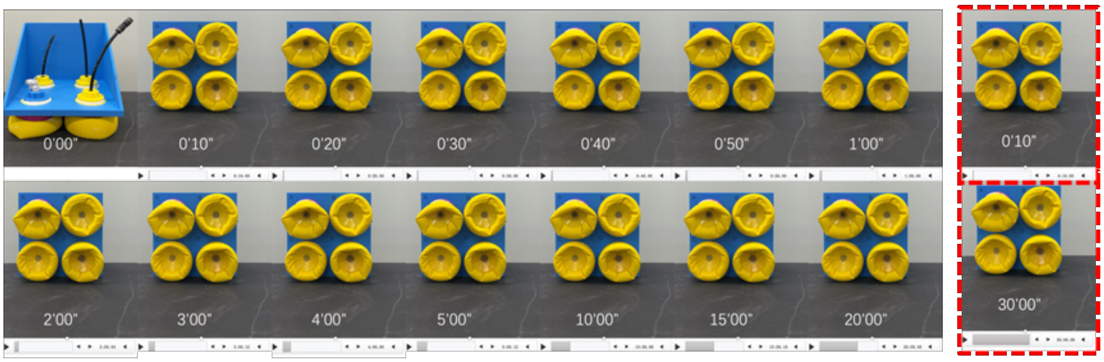
On complex surfaces, the starch-water mixture and toothpaste exhibited superior performance, achieving 9 successful adhesions out of 10 trials, with 4 trials in each case attaining a suction force of $35N$. Both materials also demonstrated excellent adaptability across various target points. In comparison, tomato ketchup achieved 6 successful adhesions, with only 1 instance reaching $35N$, while water achieved 7 successful adhesions but failed to reach $35N$ in any trial.

B. Behavior of Suction Cup Skirts on Vertical Surfaces

The Fig. 8 shows the time-dependent deformation of the skirt under gravity, with water (top left), a starch-water mixture



(a) With aging



(b) Without aging

Fig. 8: The time-dependent deformation of the skirt under gravity.

(top right), toothpaste (bottom left), and ketchup (bottom right) as its contents.

The Fig. 8a presents time-lapse images of the skirt facing a vertical wall before settling, and Fig. 8b shows the corresponding images after 24 hours. The most noticeable changes occur within the first minute, so the first row captures these changes at 10-second intervals. From the second row onward, changes become less significant, with images taken every minute until the fifth minute and then every 5 minutes thereafter.

The rightmost section, marked by the red dashed line, compares the initial state (immediately after setting the frame upright) with the state at 30 minutes, highlighting the differences between the start and end of the time-lapse images.

The Fig. 8a shows that water and ketchup deform almost completely as soon as the frame is set upright, and creating a significant risk of blocking the suction port. Although the starch-water mixture deforms more slowly, it also has the potential to obstruct the suction port. These issues would prevent the suction cup from functioning properly on vertical surfaces. In contrast, toothpaste shows minimal deformation over 30 minutes, making it more suitable for suction cup applications.

Comparing the Fig. 8a and the Fig. 8b, the starch-water mixture showed noticeable hardening after prolonged settling, leading to reduced fluidity. To reuse it, the water and starch must be remixed to restore the suspension. In contrast, toothpaste, with its strong Bingham plasticity, exhibited minimal deformation under gravity and was largely unaffected by sedimentation, maintaining its functionality without requiring reactivation.

VI. CONCLUSIONS AND FUTURE WORK

This study proposes a novel concept for suction cup skirts by exploring the properties of different fluids as skirt fillers through two experiments. The first experiment simulated force conditions while lifting a $3.57kg$ object. In contrast, the second examined the effects of various fluids on skirt deformation when oriented toward a vertical surface.

The results demonstrate that suction cups with flexible skirts achieve adequate adhesion to objects. Starch-water mixtures, representing shear-thickening properties, showed strong resistance to sudden external forces but were significantly affected by gravity. Additionally, after prolonged static settling, the starch layer hardened at the bottom, requiring reactivation into its non-Newtonian state for continued use. With its shear-thinning properties, Tomato ketchup showed a lower success rate in adhesion tasks. However, its improved fluidity under external forces enabled re-adhesion after vacuum breakage, making this characteristic beneficial for adhesion performance. As a Bingham plastic, toothpaste exhibited strong resistance to gravitational effects, achieving a sealing performance success rate comparable to that of starch-water mixtures.

These findings suggest that tailoring a fluid with properties optimized for specific stress conditions could significantly enhance suction cups' adaptability to irregular surfaces. This approach offers a promising avenue for improving suction cup performance in diverse applications.

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