

Electrodynamic Self-Cleaning Glass for Visibility Improvement of Autonomous-Driving Optical Sensors

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Summary:

In this study, we propose a liquid-dielectrophoresis (L-DEP)-based self-cleaning glass capable of removing both conductive and non-conductive droplets from autonomous driving optical sensors. The device features a multichannel interdigitated electrode (IDE) array on a transparent glass substrate, with operating conditions systematically optimized through the analysis of voltage- and frequency-dependent droplet dynamics. Crucially, its practical applicability was validated through automated cleaning tests, demonstrating the complete restoration of object-recognition rates previously degraded by contamination.

Keywords: Autonomous-driving, Self-cleaning glass, Sensor cleaning, Liquid-dielectrophoresis (L-DEP)

Background, Motivation and Objective

Optical sensors are key components of autonomous driving systems because they acquire critical environmental information analogous to human vision [1-2]. However, in real-world driving environments, these sensors are continuously exposed to external liquid contaminants such as rain, snow, and oil. This exposure severely degrades image quality and sensing performance, potentially leading to fatal malfunctions in autonomous operations.

Various active cleaning approaches based on electric fields, heat, and acoustic waves have been developed to address this issue. Among them, electrowetting-based cleaning methods have attracted significant attention because of their rapid response, low power consumption, and ease of integration [3]. However, conventional electrowetting is primarily effective for conductive liquids and remains limited in manipulating non-conductive liquids such as oil, thereby restricting the range of removable contaminants.

To overcome this limitation, this study proposes a Liquid-dielectrophoresis (L-DEP)-based self-cleaning glass capable of removing both conductive and non-conductive liquid contaminants from physical AI optical sensor surfaces.

Description of the New Method or System

The proposed self-cleaning device utilizes a multichannel Interdigitated electrodes (IDE) array on

transport both conductive and non-conductive droplets through sequential electrode actuation for contaminant removal (Fig.1).

The droplets undergo interfacial deformation under a dielectrophoretic force induced by liquid polarization in a non-uniform electric field. By sequentially activating the electrodes in a preprogrammed manner, the droplets are guided across the surface, enabling removal of various liquid contaminants. This planar electrode architecture eliminates the need for mechanical moving parts and offers advantages for compact packaging and seamless system-level integration with miniaturized optical sensor modules. Consequently, the device provides a scalable, sensor-integrable self-cleaning platform that fundamentally enhances the operational reliability of automotive optical sensors.

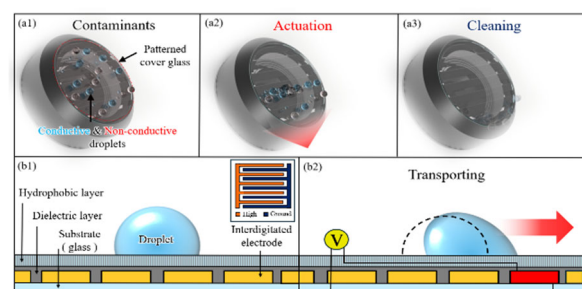


Fig. 1. Schematic of L-DEP based self-cleaning glass with sequential electrode control for the removal of conductive and non-conductive droplets

Results

First, to maximize the L-DEP force, the electric-field distribution in a parallel electrode configuration was numerically analyzed. The simulations revealed that strong fringing electric fields form at the electrode edges, generating a pronounced electric-field gradient primarily along the electrode-finger direction. Furthermore, the analysis further showed that minimizing the electrode gap increased the electric-field gradient, thereby enhancing the driving L-DEP force. Based on these findings, a six-channel IDE structure was designed, and interlocking electrode fingers with a width of 50 μm and a gap of 50 μm were incorporated between adjacent channels to enable continuous droplet transport. The designed L-DEP-based self-cleaning glass, consisting of IDE patterns, a dielectric layer, and a hydrophobic layer, was subsequently fabricated using standard semiconductor microfabrication processes (Fig. 2).

The fabricated device was then characterized in terms of device geometry, surface roughness, and optical transmittance to confirm its suitability for optical sensor applications.

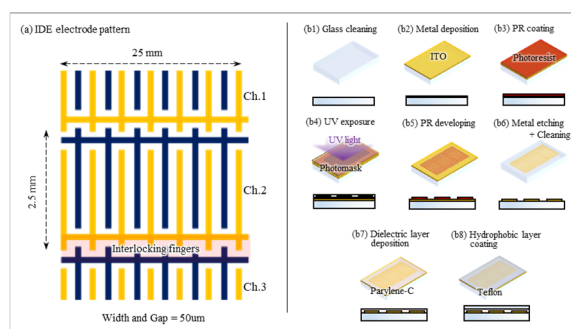


Fig. 2. Design and fabrication for L-DEP based self-cleaning glass: (a) IDE electrodes design; (b) Micro-fabrication processes

To investigate liquid-specific L-DEP response, the contact-angle variations of droplets with distinct electrical properties, including deionized water, propylene glycol, and silicone oil, were measured under different applied voltages and frequencies. For each liquid, the contact-angle modulation peaked near a characteristic actuation frequency and increased with applied voltage, thereby identifying the liquid-specific L-DEP response characteristics.

Based on these results, a programmable electrode-switching sequence for linear droplet transport was implemented on the proposed self-cleaning glass using an I/O board and a relay board. This precisely timed sequence enabled the linear transport and subsequent removal of both conductive and non-conductive droplets. Notably, this capability fundamentally broadens the spectrum of removable contaminants well

beyond the intrinsic limits of conventional electrowetting-based cleaning systems.

In addition, to maximize cleaning efficiency, the transport velocity of individual droplets was quantitatively measured under different applied voltages. The results showed that the transport velocity varied with liquid type, increased with applied voltage, and was higher for liquids with higher permittivity. Based on these findings, the electrode-switching interval for sequential cleaning was determined. And, The cleaning performance was quantitatively assessed with ImageJ through time-dependent analysis of the cleaning efficiency under mixed conductive and non-conductive liquid contaminant conditions.

Finally, when integrated into a camera module, the device effectively removed surface contaminants, and the object-recognition rate degraded by contamination was fully restored following automated cleaning.



Fig. 3. Sequential snapshots of conductive and non-conductive droplet cleaning on L-DEP-based self-cleaning glass for autonomous driving optical sensors

References

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