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Feasibility Study for Applying Electrostatic Adhesion on Wall Climbing Robots

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***Abstract*—This paper presents a feasibility study for applying electrostatic actuators on wall climbing robot (WCR). These film actuators have generated useful level of attachment force on vertical wall surface. It works on non-conductive surface such as ceramic tiles. The confirmed advantages of electrostatic adhesion are encouraging for the development of WCR. Design considerations for the WCR are also discussed, to particularly include an active tail for countering pitch-back moment. The control strategy for WCR is not complicated and involves only a separate circuitry to provide HVdc to the electrostatic actuators. As a short summary, electrostatic adhesion is a feasible method to empower ordinary tracked mobile robot for becoming a WCR.**

***Keywords*—electrostatic adhesion, wall climbing robot**

I. Introduction

The development of wall climbing robot (WCR) is motivated by the dangerous nature of climbing itself. Researchers worldwide are actively demonstrating ways of replacing human with robots that can perform useful tasks at vertical planes. Some notable examples are cleaning of outer building that is covered with ceramic tiles [1], inspection of nuclear pressure tank [2], inspection of steel storage tank [3], and inspection of inner surface of steel pipe [4]. The list of application for WCR grows as the technology develops over time. One can find comprehensive literature survey on WCR research domain in periodic updates [5-7]. To a large extent, WCRs are to be used on common building materials including rough and smooth surfaces such as brick, ceramic, concrete, glass, wood, and etc. Obviously, the challenge for the WCR is to lift its entire mass against gravity, to attach itself on the wall planes securely, and to maneuver along the wall surface in the most efficient manner. Thus it is necessary to understand the various techniques that are available for adhesion mechanism.

The adhesion mechanisms are briefly introduced here as vacuum suction [1, 2], vortex suction [8], magnetic adhesion [3, 4], mechanical grasping [9-12], elastomeric adhesion [13, 14], gecko-inspired adhesion [15, 16], hot melt adhesion [17], and electrostatic adhesion [18, 19].

One can easily appreciate the advantages of each mechanism but also recognize the disadvantages of an adhesion mechanism. For example, magnetic adhesion is a robust technique to fulfill the payload and locomotion requirement for WCR. However it limits the applicable surface to ferromagnetic material only. Another example is vacuum suction, where it was once a popular choice to be implemented on WCR. It requires a constant vacuum to create negative air suction, and this may require additional equipment to pump the air. Thus atmospheric adhesion methods usually have difficulties working on rough surface. Next example is mechanical grasping, which excels at attaching on rough surface such as concrete and brick. The tiny spines or hook exert force on the surface asperities based on the weight of WCR itself. However this method is sometimes damaging to the climbed surface by means of penetration, and it does not work well on smooth surface. Then next examples are elastomeric and gecko-inspired adhesion, which use similar silicone elastomer materials on the WCR’s contact point to the wall surface. These soft materials attach to the walls with van der Waals force, as they conform to the surface roughness easily. Thus these methods work well on most surfaces but they suffer from particle contamination, i.e. usage cycle can be short. A self-cleaning mechanism is required to overcome the challenge. Lastly the hot melt adhesion is an interesting idea, but the timing for attaching and detaching remains as a challenge.

For the electrostatic adhesion, one can find examples in industrial application such as electrostatic precipitation, painting and coating, and electrophotography. It is not a whole new idea, whereby the technique of applying electrostatic attachment force for grasp and release of parts can be found along side with conventional methods such as mechanical gripper, vacuum suction and magnetic adhesion. Various applications using electrostatic attachment include examples such as fabric handling [20-23], electrostatic chuck (ESC) for the pick and place of silicon wafer [24-27], and manipulation of objects [28-30] in general. The qualitative advantage of electrostatic adhesion is evident where it can be applied on a wide range of object material. Static force works well on both electrically conductive and insulating objects. Since an ideal electrostatic device does not conduct electrical current, the power consumption can be in the range of μW to mW. The adhesive force can also be controllable. Although it possesses much qualitative advantages, one may argue on its payload capacity. This paper presents a feasibility study of employing the electrostatic adhesion technique for WCR, particularly the results showing scalability of the generated adhesive force on ceramic tiles. Some design issues of WCR with electrostatic adhesion mechanism is also presented.

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II. Electrostatic Adhesion

A. Modeling of Electrostatic Force

The parallel plane capacitor model constitutes the principal theory to derive the electrostatic force. The theoretical electrostatic force model for an ESA actuator is given as [31]:

$$F_e = -\frac{\varepsilon_0 \varepsilon_r A V^2}{2d^2} \tag{1}$$

where ε_0 is the permittivity of free space (8.854×10^{-12} F.m^{-1}), ε_r is the relative permittivity of dielectric material, A is the contact area between electrode and object, V is the applied voltage, d is the thickness of the dielectric material, and the minus sign indicates that the force is attractive. It can be seen that the electrostatic (adhesion) force generated by the actuator is governed by material properties and geometrical properties of the dielectric and electrode, and acted upon by surface charge induced through applied high voltage. In order to obtain the F_e of several N, one can readily calculate that the d is in the range of 10^2 μm thickness and V is in the range of several kV. With this in mind, the design schematic of a simple electrostatic device may take the form of thin film, as shown in Fig. 1.

From (1) it is understood that the electrostatic actuator works best when the distance of separation is kept minimal between the electrode and wall surface. Thus the thickness of the dielectric shall be kept low while not causing electrical breakdown. The dielectric strength of the dielectric determines the electric potential that it can withstand per thickness of material until electrical breakdown. This separation of distance can quickly become large when the electrostatic actuator is peeled away from the wall surface. Thus peeling mechanism is not only a weakness of electrostatic device, but also a characteristic that can be exploited when quick detachment from wall surface is desired.

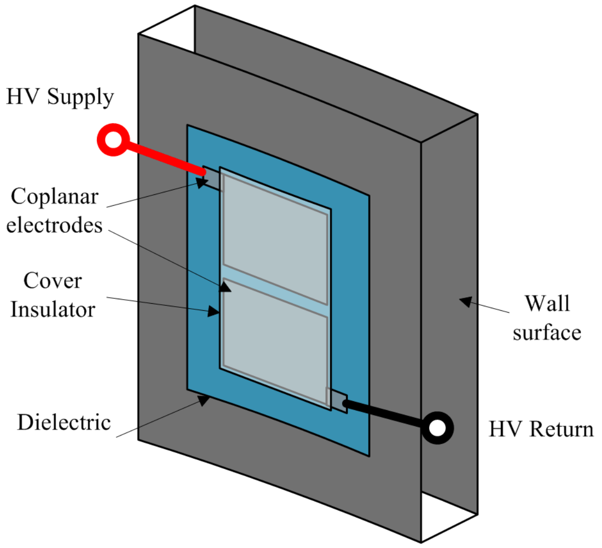

Fig. 1. Electrostatic actuator attached on wall surface.

Contact area is affected by the surface roughness of the wall surface and the compliance of the dielectric on the wall surface. A highly compliance dielectric increases the effective contact area by minimizing the air gap that is trapped. The load that it can support can be increased with larger contact area. Thus payload of WCR can be scaled up accordingly with electrostatic actuator of larger contact area.

Once an electrostatic device is designed with a defined material and geometrical parameters, the other controllable parameter is the applied voltage. From (1) one can assume that the force generated is quadratically proportional to the voltage. However the subsequent experimental results presented shall reveal some other characteristics of this F-V relation. The distance between the co-planar electrodes and the dielectric thickness determine the maximum level of voltage that can be applied to the electrostatic device to prevent electrical breakdown. The dielectric material may be permanently damaged or self-recoverable during breakdown.

B. Fabrication of Electrostatic Actuator and Experimental Setup

Table I shows the material combination to construct the electrostatic actuator. It is constructed with aluminum foil (electrode), transparency film (dielectric), and PVC tape (cover insulator) layers. Four types of the same material combination have been constructed with different electrode area. The notation B LxW means electrostatic device with length L and width W. Here we fabricated and tested

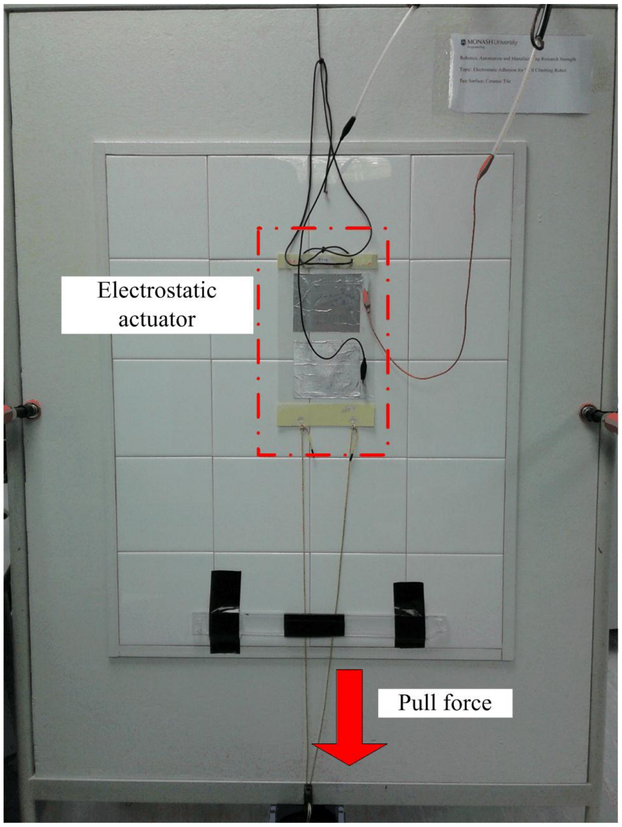

Fig. 2. Experiment setup photograph showing electrostatic actuator B7x4 on ceramic tiles wall surface.

electrostatic actuators B7x4, B7x5, B7x6 and B7x8 to compare the various output force level.

Fig. 2 shows the experimental setup of evaluating the constructed electrostatic actuators on ceramic tiles wall surface. The connection of HV Supply and HV Return on the electrode terminals is as shown. The upper strings are used to prevent extensive fall of the film actuator due to gravity, and is let loose during force evaluation. The lower strings are used to pull the film actuator downward to evaluate the holding force of the electrostatic actuator against external forces. The lower strings are tied to a force gauge to measure the applied external forces. At each voltage level, the holding force of the actuator on the wall surface is evaluated.

TABLE I. MATERIAL COMBINATION FOR ELECTROSTATIC DEVICES

Electrostatic actuators	**Layer thickness**		
	Electrode	***Dielectric***	***Cover insulator***
B LxW	Aluminium 24µm	Polypropylene, ε_r~2.2 90µm	PVC 42µm

III. Experimental Results and Wall Climbing Robot

A. *Scalability of Holding Force*

Electrostatic actuators responded instantly when HVdc is switched on. They conformed to the test surfaces within a second after static voltage is generated. “Hiss” sound is audible during excitation of the actuators. Pull force is applied to overcome their adhesion to the test surface. This measured force represents the main portion of the useful ESA force for WCR. The results are presented in Fig. 3. It is observed that electrical breakdown could occur at about 15kV, as shown. The high voltage power supply equipment automatically trips when current exceeds 100µA.

From Fig. 3, one can see that the holding force increases as the applied HVdc is increased. Up until 3kV, the *F-V* relation is somewhat quadratic as described by (1). However further increasing the HVdc does not push the holding force further as expected. Saturation of holding force is seen when the HVdc is above 10kV. This result shows that the HVdc region of between 5kV and 10kV generates optimum holding force.

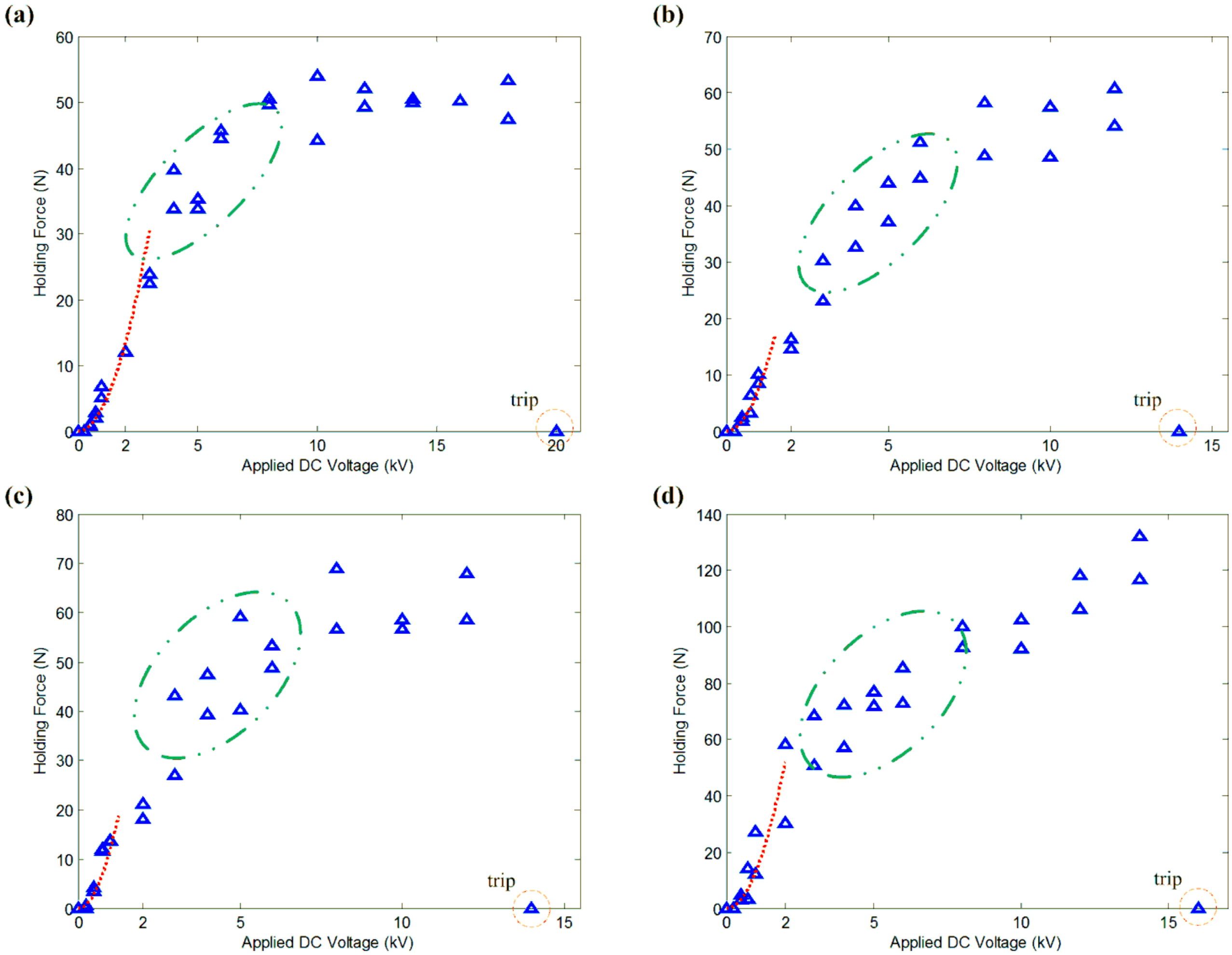

Fig. 3. Experiment results for the holding force of electrostatic actuators on Ceramic Tiles, shown with the tripped voltage level. **(a)** B7x4, **(b)** B7x5, **(c)** B7x6, and **(d)** B7x8. The green line circles a region of holding forces which is of interest to the WCR.

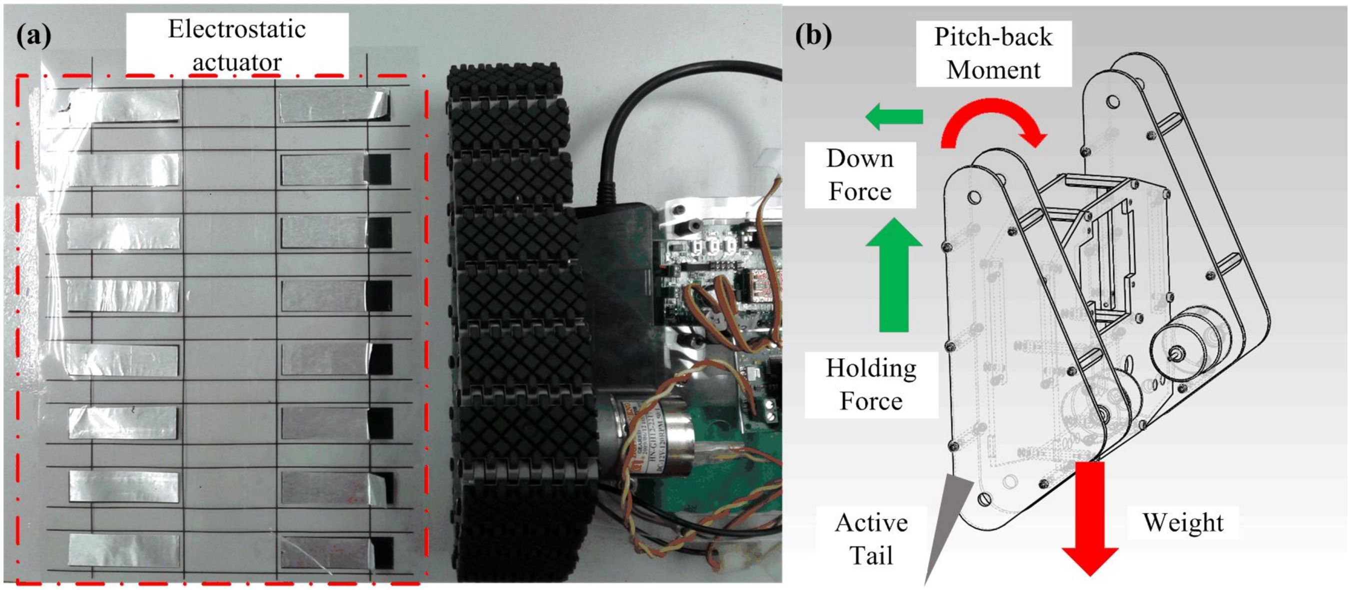

Fig. 4. Possible usage of electrostatic actuators on the WCR. **(a)** The individual actuators that can be applied on the WCR. Note the matching area to the rubber track segments. **(b)** A simplified force diagram on the WCR model.

From here, the useful holding force for the development of WCR is experimentally determined as in Table II. As the area of the coplanar electrodes is increased, the holding force scales up favorably. This outcome suggests that WCR which is designed for larger payload may consider a larger electrode area in the design parameter.

TABLE II. TYPICAL HOLDING FORCE ON CERAMIC TILES

Electrostatic actuators	Holding Force, N (@ 5kV to 10 kV)
B7x4	25 – 50
B7x5	25 – 55
B7x6	30 – 65
B7x8	40 – 110

B. *Design Considerations for WCR*

In order to employ largest contact area possible for the adhesion mechanism for WCR, the double track locomotion is chosen. An off-the-shelf mobile robot platform was chosen, as depicted in Fig 4(a). The equipped rubber tracks in left and right of the WCR can be driven separately for steering. The electrostatic actuators are being segmented into sections corresponding to the individual track segment. In Fig 4(b), the associated force on the WCR during stationary on wall surface is depicted in a simplified free body diagram. Holding force generated by the electrostatic actuator counters the weight of the WCR. An active tail can be added to provide down force at the nose to counter the pitch-back moment during movement of wall surface.

The electrostatic actuators and tracks are coupled mechanically but are driven separately, enabling differential drive locomotion as shown in Fig. 5. The robot uses an on-board power supply system separating power in watts to the motors and micro-watts to the electrostatic actuators. The micro-watts power supply may subject to a voltage conditioning circuitry for a voltage step-up to kilovolts range. A microcontroller coordinates between the on/off open-loop signals to the electrostatic actuators and the rotation of the driving tracks, with the aid of several angle position sensors.

C. *Coupling of Electrostatic Actuators on WCR*

Fig. 6 shows a possible method of coupling the electrostatic actuators onto the tracks. When all the individual actuators are supplied with HVdc, they are able to attach to ceramic tiles wall surface as expected. The contact area of the WCR to the wall surface is about 7 inches length and 4 inches wide, corresponding to the B7x4 evaluation as reported in Table II. It is expected to provide a holding force of about 2kg, and to allow some design safety factor. Therefore the electrostatic actuators are feasible to provide enough adhesion force for the WCR to counter against gravity. Currently, the development of WCR prototype is still in progress.

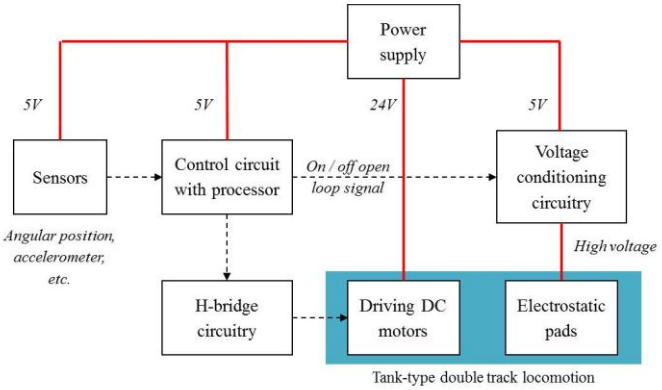

Fig. 5. System schematic for WCR

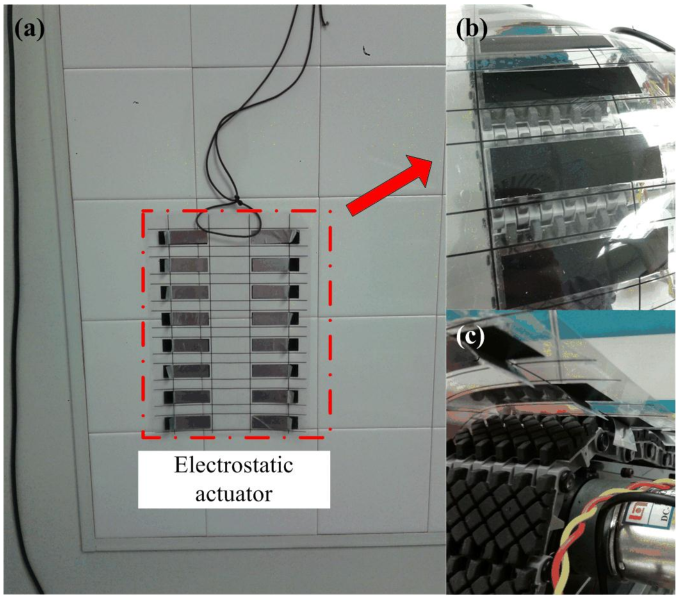

Fig. 6. Coupling of electrostatic actuator on the rubber tracks.

IV. Summary

A feasibility study for applying electrostatic actuators on wall climbing robot is presented. These film actuators have generated useful level of attachment force on vertical wall surface. It works on non-conductive surface such as ceramic tiles. The confirmed advantages of electrostatic adhesion are encouraging for the development of WCR. Design consideration for the WCR is also discussed, to particularly include an active tail for countering pitch-back moment. Overall the control strategy for the WCR is not complicated and involves only a separate circuitry to provide HVdc to the electrostatic actuators. As a short summary, electrostatic adhesion is a feasible method to empower ordinary tracked mobile robot for becoming a wall climbing robot.

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