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# Effects of residual charge on the performance of electro-adhesive grippers

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# Study of effect of residual charge on the performance of Electro-adhesive gripping solution, when used in automation of pick and place of insulating materials

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**Abstract.** Electro-adhesion is the new technology for constructing gripping solutions that can be used for automation of pick and place of a variety of materials. Since the technology works on the principle of parallel plate capacitors, there is an inherent ability to store charge when high voltage is applied. This causes an increased release time of the substrate. This paper addresses the issue of residual charge and suggests ways to overcome the same, so that the performance of the gripper can be improved in a cycle of pick and release. Also a universal equation has been devised, that can be used to calculate the performance of any gripping solution. This equation has been used to define a desired outcome (K) that has been evaluated for different configurations of the suggested eletro-adhesive gripper.

**Keywords:** Advanced Technology, Robot Grippers, Dielectric materials, Automation

## 1 Introduction

Automation has rapidly grown in the last century from small to large scale industries, impacting the global economy [1]. An important aspect of automation is the end effector or the gripper, which is the end part of the system that directly interacts with the environment. This has been previously compared to a human hand [2]. Traditional gripping techniques include vacuum suction, chemical adhesion and micro-spines that have been used in the pick and place mechanism. These are well established, but in the case of flexible material handling these techniques do not provide distortion free and efficient handling [3]. For handling flexible material, electro-adhesive grippers (EAG) have been previously explored [6]. This forms the basis for the current research and here we explore the possibility of a pick and place mechanism using an Electro-adhesive gripper.

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Although force calculations have been the primary basis for analysis of performance of an EAG, yet there are many other key parameters that need to be considered for the same. Since EAG works as a parallel plate capacitor, the amount of storage of charge becomes one such key component, which needs to be taken into account while working with an EAG.

This paper presents a simplistic equation that can be used as a tool for analysis of desired outcome, thereby reflecting the performance of any gripping solution. Using this equation, experimental results can be evaluated and analyzed for a complete cycle of pickup and release of various substrates. Experiments have been performed to support the theory of EAG working as a parallel plate capacitor, thereby storing charge and recommendations have been made to optimize this solution of using EAG as an improved gripping solution for insulating material. The key focus is on the use of dielectric in the configuration of EAG that causes the storage of charge, thereby impacting the performance of gripping solution. There recommendations can be useful for further development and deployment of EAG in an industrial environment to achieve desired results.

## 2 Background

Grippers are divided into mainly four types depending upon the application they are deployed. Ranging from microspines to vacuum suction techniques, each gripper technology has its own advantages and disadvantages. For application of automating material pick up usually astrictive grippers are preferred. As the name suggests astrictive grippers use some kind of binding force for adhesion. Key techniques in this category of grippers include vacuum suction, electro-adhesion and Van Der Waals forces based gripper. With capability of electrostatic attraction known from ancient Greeks times and the ability to attract small particles after charging an ebony rod known to every school child having an interest in science [4], research on electro-adhesion has led the technique to be used in different industries for applications including grippers [5, 6], electrostatic chucks [7-9], cloth manufacturing robotics [10] and, recently, wall climbing robots [11, 12, 14].

With substantial potential and efficient results (<50ms clamping and unclamping, [11]) obtained in some applications, electro-adhesion may be an appropriate technique for automating the pick and place of different materials specifically insulating materials. It has the advantage of giving uniform and controlled grip on the materials. Also there is no contamination or deformation of any kind. Being light weight, this gripper can be used efficiently with repeatable and reliable results. The use of this technique in automating pick and place of different materials was inspired by research on the effects of electro-adhesive forces in fabric handling in 1986 by Monkman [12]. Different configurations were studied and positive conclusions were made with electro-adhesion shown to be a successful technique for handling materials.

Even though electro-adhesion is proven to be at a relatively advanced stage of practical development and researchers have explored some of its capabilities, yet analysis on key component of EAG on a production level scale has been missing from the literature till date.

## 3 Theory

### 3.1 Principle of an Electro-Adhesive Gripper

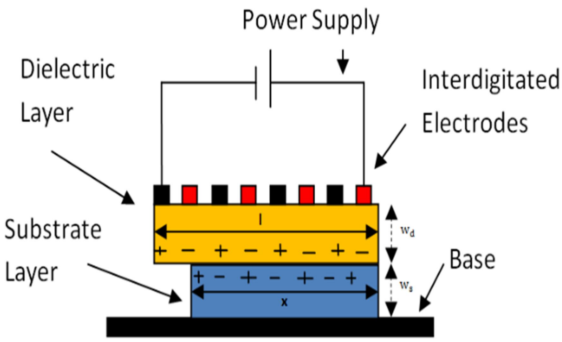



**Fig. 1.** Principles of Electroadhesion

1. Electrodes: Conductive metal that acts as the plates of the parallel plate capacitor. These are provided with high voltage so as to charge the EAG.
2. Dielectric: Insulating layer attached to the electrodes that allows for storage of charge between the plates.
3. Substrate: Object to be picked up by the EAG.
4. Base material: Material on which the substrate is placed.
5. Power Supply: High voltage supply used to charge the EAG

We follow the theory of parallel plate capacitor [18] for explaining the science behind EAG. The above setup represents a parallel plate capacitor formed due to charge being stored on the electrodes when power supply is switched on. Charge is allowed to collect due to the presence of the dielectric layer as it holds the charge helping in polarizing the substrate to be picked up. Thus the circuit acts as a parallel plate capacitor circuit with a finite time to charge and discharge. Attraction of the substrate takes place due to polarization of the substrate in the presence of the electric field generated between the electrodes as a result of storage of charge.

The principle of EAG has been best described as a parallel place capacitor in many research papers [3, 2, 18]. In [3], the concept is explained in terms of a single pole gripper, in which electrode plate forms one plate and the base material forms the second plate of the parallel plate capacitor. The dielectric material and the substrate together form the insulating material between the parallel plates of the capacitor. Thus the whole system forms a method of charge storage. In [3], it has been demonstrated that the net charge accumulation is directly proportional to the dielectric strength of the dielectric material used as well as the substrate. Mathematical modelling of dynamic properties (pick up and release time) has been shown for actual calculation which proves that the pickup and release times are directly proportional to the total number of charges developed.

The performance of an EAG is measured by doing force calculations based on parallel plate capacitance. A standard equation to calculate force is [18,15]

$$f = \frac{\varepsilon_r \varepsilon_0 V^2}{2d^2} \tag{1}$$

Where f is the force between the two plates (N), $\varepsilon_r$ is the relative permittivity of the dielectric, $\varepsilon_0$ is the relative permittivity of the vacuum, V is the voltage applied to the plate's measure in Volts (V) and d is the distance between the plates (mm).

As f is directly proportional to the dielectric constant therefore higher the dielectric constant more is the force generated by the EAG. This would suggest that an EAG with high dielectric constant is more efficient for picking heavier loads. Using a high dielectric constant causes more charge to build up in the electrodes as capacitance is increased [18] and that may result in the increase in release time [17], when the voltage is shut off (as will be seen later in experiments). Therefore this forms a trade off in the design of an EAG. The experimental work done in this report has been concentrated on the importance of dielectric layer in an EAG and experiments have been devised accordingly.

## 3.2 Safety measures

As safety is an important aspect while dealing with high voltage, a Faraday's cage is necessary to conduct the trials in an isolated and safe environment. The voltage supplied to the electrodes is quite high (kV), but the current is expected to be very low (10-20 nA/N of force). For example, if a force of 0.5N is required for the substrate to be lifted off, the current passing through the gripper will range from 5-10 nA [11], but as a safety measure a Faraday's cage is necessary to ensure any leakage of current does not lead to any accidents (electrocution). Earth plugs are typically used to ground the Faraday's cage at multiple places.

## 3.3 Parameter (K) that defines an effective gripping solution.

For successful pick up and release of polymeric material such as gloves on a production line running 24 hours a day, repeatable and reliable (R2) gripping results are required.

R2 can be defined as achieving consistent results (that is desired outcome is achieved) for every cycle of pick up and release. Thus the R2 needs to be analyzed in terms of efficiency of the gripping solution. A measure to calculate efficiency is needed to judge the effectiveness of the gripper on a production line scale. Therefore we define efficiency as the ratio of number of successful pick up and release cycles/trials to the total number of cycles/trials performed. Higher the efficiency (ŋ), higher is the ability to achieve R2 results.

$$ŋ = \frac{no. of\ trials\ with\ desired\ outcome}{total\ number\ of\ trials} * 100 \qquad (2)$$

This is a universal equation that can be used to analyze not only electro-adhesive griping solution but any gripping solution. Thus to analyze ŋ, first we need to define what is a desired outcome (successful pick and release). Since we are focusing on analyzing an effective gripping solution for pick and release cycle, in order to achieve R2, a successful outcome depends on the following relationship:

$$\text{Desired outcome}\ \alpha\ \frac{assured\ pick\ up * assured\ release}{(Time\ to\ pick) * (Time\ to\ release)} \qquad (3)$$

Thus we define parameter for desired outcome

$$K = \frac{P \times R}{T_P \times T_R} \qquad (4)$$

Where, P = {0,1} 0 = Substrate not picked up
1 = Substrate picked up
R = {0,1} 0 = Substrate not released
1 = Substrate released
$T_P$ = Time to pickup
$T_R$ = Time to release

(Units for desired outcome: $sec^{-2}$ )

By setting desired values of above variables, the desired outcome (K) can be defined and thereby analysis on efficiency can be performed. Thus this equation can be used to analyze and compare experiments involved in this application for not only electro-adhesive grippers but for any gripping solution.

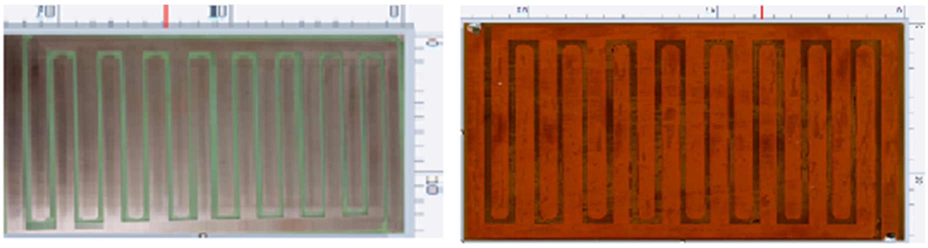
From the equation, it can be seen that in order to achieve a desired outcome, P and R must have a value 1. This means that in a cycle, if the substrate is not picked up, P = 0 and therefore desired outcome K = 0. Same case exists for release cycle (R is 0 if P is 0). Also, for maximum K, Tp and $T_R$ value must be as small as possible (instantaneous pick and release). For analysis on electro-adhesive gripper it has been agreed for Tp and $T_R$ to have a minimum value of 1 (anything below 1 is rounded off to 1 due to measurement constrains and inefficiencies). In this paper, equation (4) has been used to analyze the output of the EAG in two configurations; with dielectric and without dielectric layer. Further work will be done to calculate the overall efficiency by performing repeated experiments. This will therefore help in achieving a gripping solution with optimum R2 results.

## 4 Experimental Setup

The aim of the experiments is to show the impact of the dielectric layer on the performance of an EAG in completing one cycle of pick up and release of a substrate. For this purpose, we have chosen four different substrates. (i) High density polyethylene (HDPE) (ii) Polycarbonate (iii) Mobile phone screen glass (iv) Nitrile Glove. The selection of these substrates was based on the fact that electro-adhesion has different impact on different materials due to materials having different molecular structure, and different electrical properties.

Two different configurations of gripper were developed. The electrode structure in both was inter-digitated structure, as inter-digitated structure has been the most effective of all the structure [13]. Two configurations prepared are as follows

1. Bare Electrodes: B Electrodes as further defined in the study
2. Bare Electrodes and Polyimide (as dielectric): D electrodes as further defined in the study



**Bare Electrodes (B Electrodes)**

**Electrodes with polyimide dielectric layer (D Electrodes)**

**Fig. 2.** Two configurations of grippers

The bare electrode (B electrode) was prepared using copper and a printed circuit board (PCB) and milling process was used to obtain the required electrode dimensions, as shown in fig. 2. A polyimide sheet (thickness 0.075mm) with a dielectric constant 3.5 sourced from RS Components ltd [16], was used as the dielectric material to create the D electrode. The sheet was cut in size of 26cm x 16cm which covers the area of the electrodes fully (as shown in fig. 2). It was glued to the plate using non-conductive glue. Polyimide was used as a dielectric since due to ease of availability and has been previously proven as a good dielectric medium for EAG experimentation [12]

The experiments were performed using a VP series Denso robot fig. 3 to replicate the environment of a production line. The constructed electrode was placed as an End effector fig. 3 on the Denso arm.

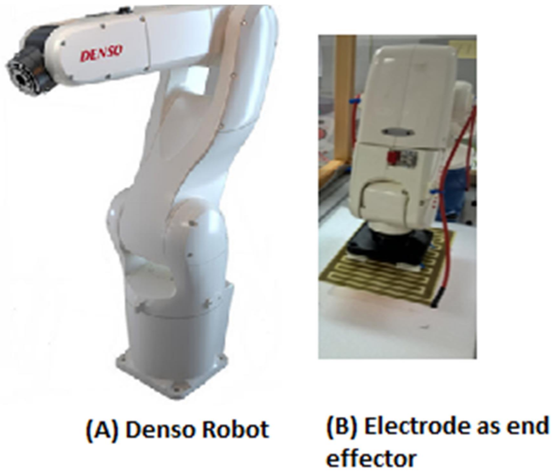



**Fig. 3.** VP Series DENSO robotic arm

A cycle for the experiment is defined as the pick-up and release of the substrate by the robot arm. The substrate is placed in a known location on the base. These coordinates are fed into the Denso arm. As shown in Figure 4, the arm begins the cycle from a known position A to the position B of the substrate on the base. It then attempts to pick up the substrate by pressing the end effector on the substrate. The next step is for the arm to travel to a known position C. After this, the voltage is cut off and the time to release the substrate is noted down.

The experiments were performed for each substrate and electrode combination and results for the desired outcome were noted down (as per equation (4)). The parameters for desired outcome for our experiments are defined as:

$P = 1$ (substrate should be picked up)
$R = 1$ (substrate should be released)
$T_P = 1$ sec (Pick up must be instantaneous)
$T_R = 1$ sec (Release must be instantaneous when voltage is shut off)

The experiments were performed with incremental voltage input (steps of 500V) starting from 500V.

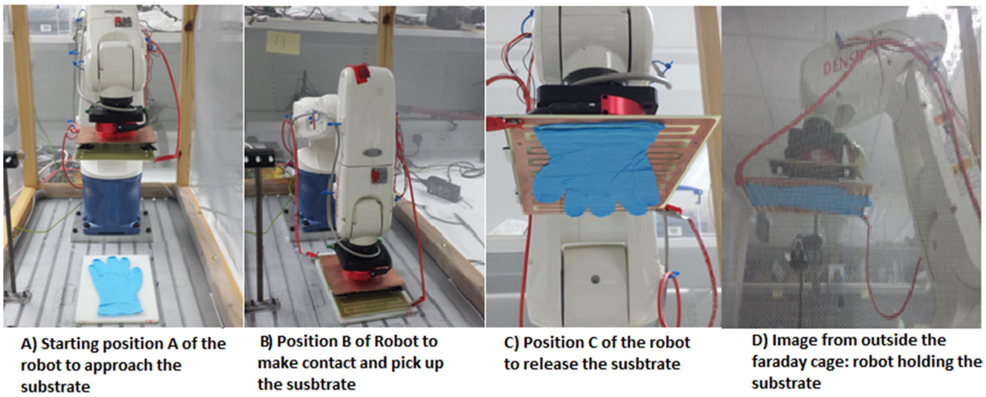



**Fig. 4.** Robotic arm positions during the experiment

# 5 Results

## 5.1 D Electrodes

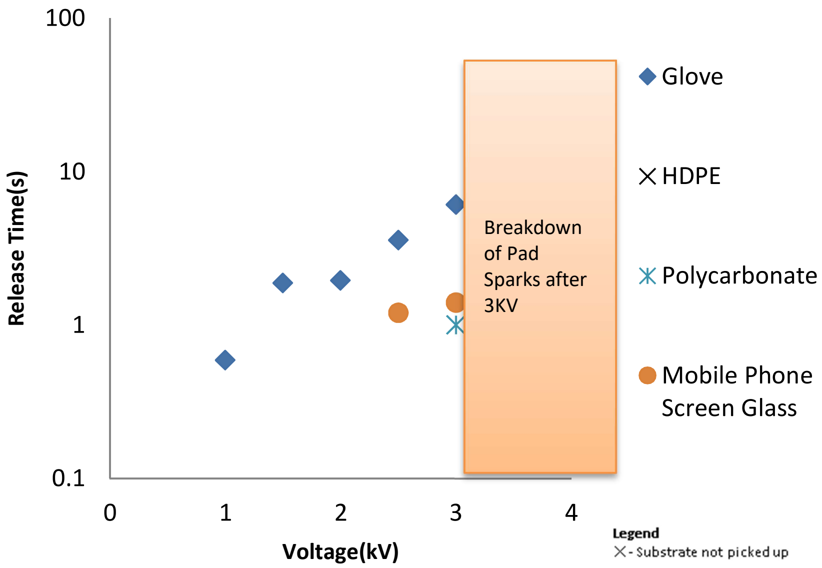



**Fig. 5.** Release time results of D electrodes

The results for D electrodes show that the EAG is unable to pick up HDPE. For glass and polycarbonate, adhesion was possible only above 2500 V and 3000 V respectively, whereas the glove has been picked up at 1000V. It was also observed that the release time for the glove increased considerably at high voltage. The D electrode started to arc at 3kV restricting any further testing on this particular pad as arcing can lead to substantial damage to the properties of the substrate and the EAG, thereby providing misleading results to the experiment.

### 5.2 B Electrodes

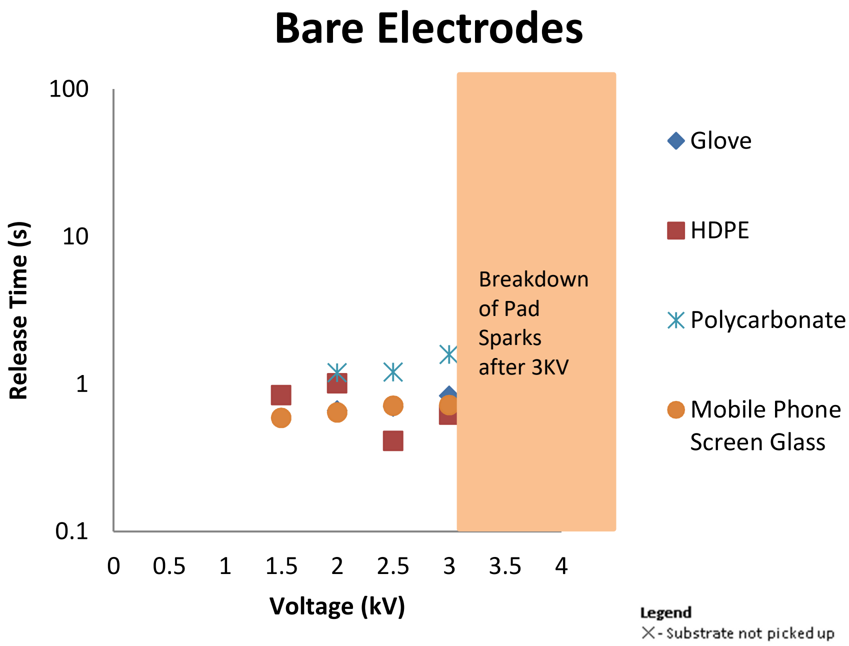



**Fig. 6.** Release time results for B electrodes

When compared to the D electrodes, the results for B electrodes show that the pick-up voltage for gloves was increased to 2000V, for glass it was 1000V and for polycarbonate it was 1500V. The B electrodes were also able to pick up HDPE at 1000V. Also all the substrates demonstrated instantaneous releases. Also with increase in voltage, the release time for glove was not increased.

Overall table for desired outcome (as calculated based on equation 4) is shown below:

**Table 1.** Desired outcome measurements for both gripper configurations (D and B electrodes) (Units for desired outcome: sec-2)

| | Mobile Phone Screen Glass | | Nitrile | | HDPE | | Polycarbonate | |
|---|---|---|---|---|---|---|---|---|
| Voltage (V) | D | B | D | B | D | B | D | B |
| 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1000 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1500 | 0 | 1 | 0.5 | 0 | 0 | 1 | 0 | 0 |
| 2000 | 0 | 1 | 0.5 | 1 | 0 | 1 | 0 | 1 |
| 2500 | .83 | 1 | 0.2 | 1 | 0 | 1 | 0 | 1 |
| 3000 | .71 | 1 | 0.125 | 1 | 0 | 1 | 1 | 1 |
| Number of trials desired outcome achieved | 0 | 5 | 1 | 3 | 0 | 4 | 1 | 3 |

## 6 Analysis of Results

The above experiments show promising results for the B electrodes. All the substrates were released instantaneously and the pick-up voltages were also reduced (with nitrile glove as exception). HDPE was of particular interest, since it was not picked at all by the D electrode whereas the B electrode was successfully able to pick and release it. This proves that even though there is storage of charge, enough force is not generated to pick HDPE, therefore force calculations alone cannot be used to determine the performance of an EAG.

Since the desired outcomes were better for B electrodes, it supports our theory of storage of charge causing an increase in the release time of an EAG. Therefore for applications where quick Tp and Tr are required, B electrodes are more suitable whereas for applications where it is necessary to hold the substrate for longer duration, D electrodes are to be used.

## 7 Conclusion

In this paper, we have determined how the performance of an EAG can be improved in an application involving pick up and release of various substrates (insulators). We have defined a desired outcome to be one cycle of successful pick up and release within the shortest time possible to complete the cycle.

We conclude that traditional method of mere force calculations are not enough for evaluating the performance of an EAG. There are various other parameters that must be taken into account. One such parameter is the storage of charge in the substrate and dielectric, which plays a vital role in achieving the desired outcome. To evaluate the effect of storage of charge on the EAG, two configurations of electrodes were built; electrodes with polyimide as dielectric (D electrodes) and bare electrodes, with no dielectric attached (B electrodes).

Through experimentation and evaluation of results using the equation devised to check desired outcome, we concluded that the B electrodes provided more desired results, as they had a smaller pick up and release time, when compared to the D electrodes. This supports the theory of EAG working as a parallel plate capacitor. Since D electrodes contain the dielectric layer, they are able to store charge even after the voltage supply is shut off. Since the charge is not able to dissipate through the dielectric, it leads to a longer release time. Also this residual charge increases with increase in voltage that is applied to the EAG. The B electrodes on the other hand, do not have any charge storage mechanism and therefore release time for them is significantly less. (Instant release time = 1 seconds). In theory, there should be no release time delays with B electrodes since they only contain conductors, but practically some release time is seen as air between the substrate and the electrode also acts as a dielectric.

We also conclude that B electrodes can only be used to pick up substrates that are insulators since conductive substrates will create a short circuit on the electrodes, thereby causing large current to flow through them and destroying them. Therefore for applications that require quick pick up and release cycle for insulating materials, bare electrodes must be used in the construction of an EAG.

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