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# A Cost Effective and Light Weight Unipolar Electroadhesion Pad Technology for Adhesion Mechanism of Wall Climbing Robot

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***Abstract*****—**Electroadhesion technique being employed in variety of fields of science and technology is considered as a clamping technique for wall climbing robots. The focus of this research is to present a cost effective and light weight unipolar electroadhesion pad technology for wall climbing robots (WCR) capable of lifting a reasonable weight vertically. The literature demonstrates that most of the research related electroadhesion has been performed on bipolar electrode pads. The research presented in this paper indicates that unipolar electroadhesion pad showed favourable attachment on melamine and wood substrates giving encouragement for the realisation of unipolar WCR. Design considerations along with the attachment of anti-peeling tail are also considered for the realization of WCR. The controlling mechanism for unipolar wall climbing robot was not complex. In conculsion, unipolar electroadhesion pad of copper and aluminium is a feasible technique to develop a cost effective and light weight unipolar wall climbing robot.

***Keywords*****—**Unipolar electrostatic adhesion, Wall Climbing Robot (WCR), Electrostatic Adhesion (ESA), electrostatic force, unipolar electroadhesive robot technology, unipolar Wall Climbing Robot.

## I. Introduction

WALL climbing robots (WCR) are capable to adhere vertical walls and able to move vertically and horizontally with payload carrying capacity to perform various tasks. As in severe environmental conditions for human being, robots are means for observations and operations [1]. These are widely used for maintenance, inspection and surveillance works in places where there human access is difficult or very dangerous due to unfriendly environment of social infrastructures. These infrastructures such as buildings, bridges, nuclear power plants, oil reservoirs, marine structures, and space ships, which play very much important roles in our daily lives [2],[3]. To perform various tasks a WCR should be capable of high payload carrying capacity. The substitution of WCR to mitigate human beings, from performing variety of high-risk applications, has much attracted the attention of researchers over the past few decades [2].

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Wall climbing robots has two main design considerations. These are Adhesion and locomotion. The WCR are classified based on these considerations. Wall climbing robots are classified into different groups depending on the adhesion technology. The different adhesion technologies developed for WCR includes electromagnetic gripping [4],[5], gecko inspired (van der Waals forces) [6],[7], suction operated pad [6], [8-12], hot melt adhesion [13], Gripping to the surface [14], chemical adhesion [13] and most recently new invention known as Electroadhesion [15], [16].

Although the electrostatic adhesion technology was known to the researchers since decades but it was first used extensively in industries as electrostatic chucks for lithographic processes and silicon wafer-semiconductors [15],[17]. Another industrial application of electroadhesion is for handling fibrous materials [18-20]. Noticing the strong adhesion force of these electrostatic chucks researchers introduced this adhesion technology as a clamping pad for the wall climbing robots in recent years [16]. Since then different kinds of wall climbing robots have been made along with detailed simulation and theoretical modelling study on bipolar electroadhesion pads [2],[21-22]. However, there is a little study on unipolar electroadhesion pad for WCR. Geometries and the gaps between the electrodes make the fabrication of the robot difficult. However, the effect of unipolar electroadhesive pad for wall climbing robot is unknown. Previous research in this area has been very limited and very little work regarding the unipolar electroadhesion pad for wall climbing robot has been published. This paper is proposing a new cost effective and light weight unipolar electroadhesion pad for WCR.

## II. Deployment Method of Proposed Unipolar Pad Elecroadhesion Technology

Electroadhesion is an electrically controllable adhesion technology [23]. Electrostatic field is the basic principal of ESA (Electrostatic Adhesion). Electrostatic field can provide an attraction force, called electroadhesion [24]. However, the electroadhesion force is usually somewhat lower than the similar magnetic force. Therefore, the considerable force still can be produced with a suitable parameters selection of the electroadhesion pad.

*A. Working Mechanism of Unipolar Electroadhesion Pads*

As mentioned in [2], [16], [25] the electrostatic adhesion films (pads) composed of a uniform and isotropic dielectric medium having conductive unipolar electrode on its surface. When conductive electrode is charged by applying a high potential voltage, electrostatic forces are generated between electro-adhesive pads and substrates (conductive or non-conductive) materials, as shown in **Figure 1**. Electrons are free to travel in conductive materials, thus the negative electrons migrate under the positively charged electrode. This arrangement is similar to a capacitor. In case of non conductive walls, the electric field polarizes the wall (substrate) by developing an electrostatic adhesion force [26],[27],[28].

The unipolar electroadhesion involves inducing electrostatic charges on a wall substrate using a power supply connected to compliant pads situated on the moving robot. The technology works on conductive and non-conductive substrates [16], smooth or rough materials, and through dust and debris, the main purpose is to create an adhesion pad with reasonable size and enough adhesion force for wall climbing robot capable of climbing on multiple surfaces as glass, paper, concrete, wood etc [29]. Unlike conventional adhesives or dry adhesives, the electroadhesion can be modulated or turned off for mobility or cleaning.

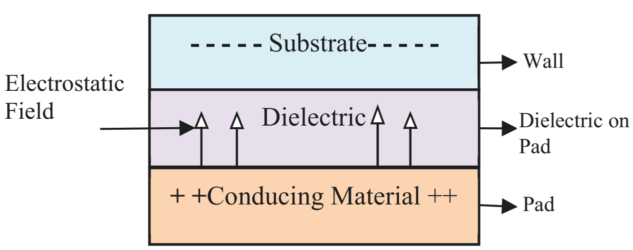



**Figure 1 Model structure of unipolar electro-adhesive pad design**

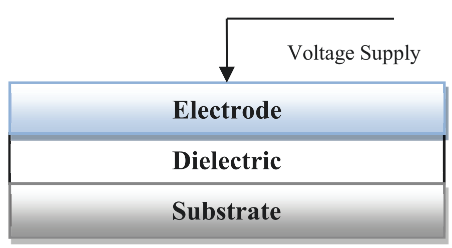



**Figure 2 Cross section of (proposed) unipolar electroadhesion pad on wall**

The conceptual schematic of unipolar electrostatic adhesion is shown in **Figure 1**. The dielectric material insulating film of the pad and the air gap between substrate and pad stop dielectric breakdown, if not causing high short-circuit in the currents and voltage drop [16]. The high voltage +V applied to the unipolar electrode with area of $A$. The dielectric insulating layer thickness is $d$ with dielectric constant $\varepsilon_r$ , and permittivityof free space is $\varepsilon_0$ . However, the wall thickness is infinite contrast to the unipolar electroadhesion pad.

As shown in **Figure 1** electroadhesion pad uses electrostatic forces between the substrate material and the electro adhesive pad. To this electro adhesive pad high voltage (unipolar) is applied. Positive voltage applied to pad induces positive charges on electro adhesive pad. Due to this opposite charges get induced on the substrate. This causes electrostatic adhesion between pad and substrate. The substrate can be wall, wood or glass etc.

*B. Modeling of Unipolar Electrostatic Adhesion Force*

Whenever there comes electrostatic force of conducting plates the principal theory behind the force generation is related to the model of parallel plate capacitor [2]. This should be kept in mind that the unipolar pad and substrate material, having different conductivity and permittivity, also direct the electroadhesion force generation.

$$F = \frac{\varepsilon_o \varepsilon_r \times A \times V^2}{2 \times d^2} \tag{1}$$

But the force formula for electroadhesion is for ideal conditions when both the plates of capacitor are conductive with ideal parameters. As in case of unipolar electroadhesion there is only single charged plate with a dielectric layer and the substrate acting as second plate is of materials (non-conductive) with varying permittivity.

The electrostatic force on unipolar electroadhesion pad is theoretically calculated by the Method of Images as the unipolar pad is single positively charged plate [30]. By method of images the unipolar electroadhesion force generation is

$$F = \frac{\varepsilon_o \varepsilon_r \times A \times V^2}{8 \times d^2} \tag{2}$$

where $\varepsilon_o$ is permittivity of free space, $\varepsilon_r$ dielectric constant of dielectric material, $V$ is applied voltage, $A$ is the contact area of electroadhesion pad and area of the wall under the unipolar pad, and $d$ is thickness of the dielectric material between electrostatic pad and substrate (wall).

This dielectric thickness should be small as electrostatic force is inversely proportional to the square of the thickness of dielectric but not too much small so that no dielectric breakdown occur [31]. From the mentioned force equation it can be easily noticed that to get the force of numerous N or Kg, it is noticeable that the thickness of d is in scale of 100 μm and that of voltage is in kilo volts. Keeping these parameters in consideration, the design specifications of a unipolar electroadhesion device gets the shape of a thin foil, shown in **Figure 8.**

The accuracy of the model will be calculated experimentally.

### C. Unipolar Electoadhesion Pad

The unipolar type of pads consists of conducting material carrying only one type of charge positive with high voltages in KV thereby the conducting pad is undivided shown in **Figure 3**. When this charged pad covered with a layer of dielectric is placed close to the substrate (wall), thus opposite charges induced on the substrate, get polarized by the electric field, thereby creating electroadhesion attraction between the pad and the substrate shown in **Figure 1** and **Figure 3**. However, it is noted that the behavior of unipolar electroadhesion changes with wall surface properties and with the conductivity of the unipolar pad material which will be detail studied in future. This paper proposed feasibility of cost effective and light weight unipolar electroadhesion pad for wall climbing robot adhesion mechanism.

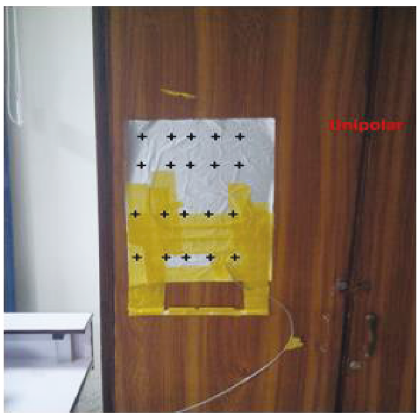



**Figure 3 Unipolar pad proposed by this research**

### D. Design Specifications of Unipolar Pad

Electroadhesion is implemented using a unipolar electro-adhesive pad. The pad consists of three layers conducting layer, dielectric layer and an insulating layer (polyethyrene tape) in order to increase strength as shown in **Figure 4b**. Dielectric layer sandwiched between conducting layer of the pad and the substrate on which the pad is attached acts as a capacitor, thus developing adhesion force. The electroadhesive pad is provided with only positive potential as this is unipolar pad as shown in **Figure 5a**.

In the electroadhesion technology in order to get strong adhesion, current (voltage) is not only the concerned factor. Reasonable voltage to get adhesion is quite possible. Besides voltage dielectric constant, thickness of dielectric, size of the pad and permittivity of air are also major influencing factors of electroadhesion force. More the charges greater will be the force between the substrate and the electroadhesion pad. In order to get more charges these two main approaches are considered: expansion of electric field [26] and lowering the quantity of neutralized charges shows that the insulate material is also an important factor of electroadhesion[32]. **Figure 6** shows the cross section of unipolar electroadhesion pad panel.

## III. Unipolar Electoadhesion Pad Fabrication

This The unipolar electroadhesion pads were made with the technique of covering the undivided conductive electrode with dielectric material. Applying this procedure it is possible to fabricate an electroadhesion pad that is both thin and flexible along with sturdy in shear direction. The material used for undivided unipolar pad is silicon with dielectric constant of 3.6. The commercially available silicon sealant in gel form is used as dielectric material. The conducting materials selected were copper and aluminium foils with 20-25 micrometer. Selection of the conducting and dielectric materials was based on cheap, locally available, economical and most important the higher conductivity with light in weight.

To fabricate the unipolar electroadhesion pad the selected materials for pad were cut in required dimensions and thickness. One side of the foil was then coated with the silicon acetoxy gel as dielectric and it took almost 24 hours to dry. Dust on the pad decreases the adhesion force so the pad was placed on dust free area to dry. Finally another side of the pad was covered with a layer of polystyrene tape in order to increase the sturdy. After it has treated the cost effective unipolar, undivided electroadhesion pad is ready as shown in **Figure 5**.

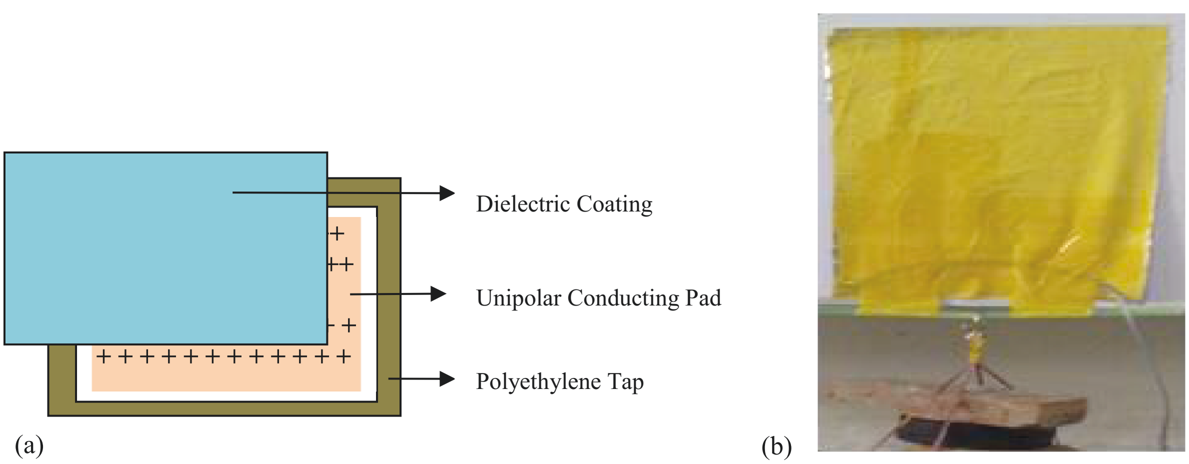



**Figure 4 Unipolar electroadhesion pad for robot**

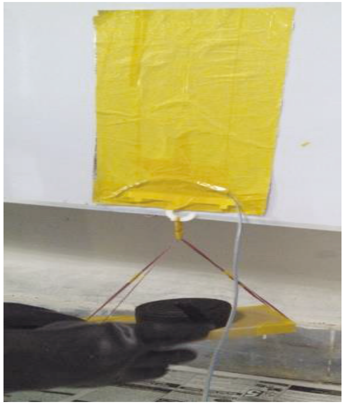


**Figure 5 Unipolar electroadhesion pad ready for experiment**

A combination of materials for the fabrication of unipolar electroadhesion pad is shown in TABLE I.The notation P Lx W means unipolar electroadhesion device having L length and W width. A total of four unipolar electroadhesion pads with different areas were fabricated with P8 x8, P12 x 12 , P15 x 15, and P20 x 20 in order to evaluate and validate the model through different level of adhesion force produced.

TABLE I UNIPOLAR ELECTROADHESION PAD'S MATERIAL COMBINATION

| Unipolar Electro-adhesion Pad | Thickness of Layers | | | |
|---|---|---|---|---|
| | Unipolar Electrode | | Dielectric Material | Top Insulation |
| $P\ L \times W$ | Copper | Aluminum | Silicone sealant | Polystyrene tape |
| | 25 µm | 23 µm | 100-150µm | 40 µm |

## IV. EXPERIMENTAL SETUP

**Figure 4** and **8** show the setup for testing the proposed unipolar electroadhesion pad technology of copper and aluminium on melamine wall and wood wall. The unipolar high voltage (HV) supply is labelled as unipolar (+ve) voltage with a single wire of +ve voltage. The lower weight holding mechanism is used to measure the weight lifting capacity of the unipolar pad. Also another way of evaluating the holding force is to pull an electronic portable pothook attached with the lower string instead of putting weight.

In order to evaluate the proposed design, experimental analysis was carried out on a scale of different adhesive pad configurations. These included two different electrode pad materials, copper and aluminium with four different unipolar pad areas mentioned above. Experiments were performed with self-made HV supply from 1-8 kilo volts of 6 steps with 1 kilo volts interval.

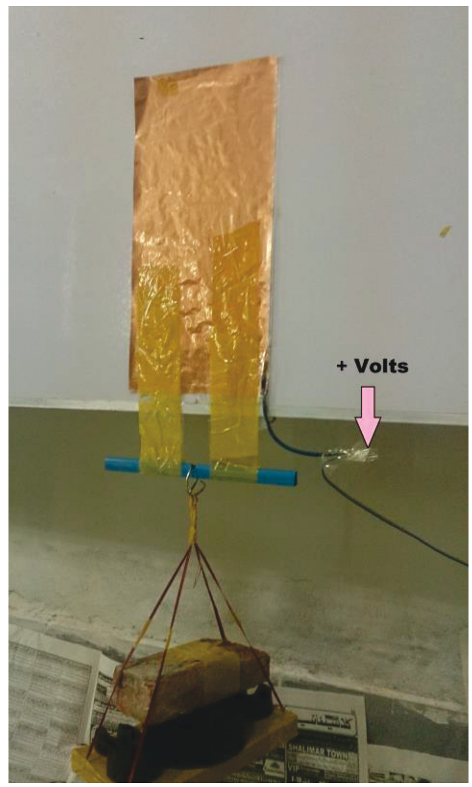



**Figure 7 Experimental setup showing unipolar electroadhesion copper pad on melamine wall**

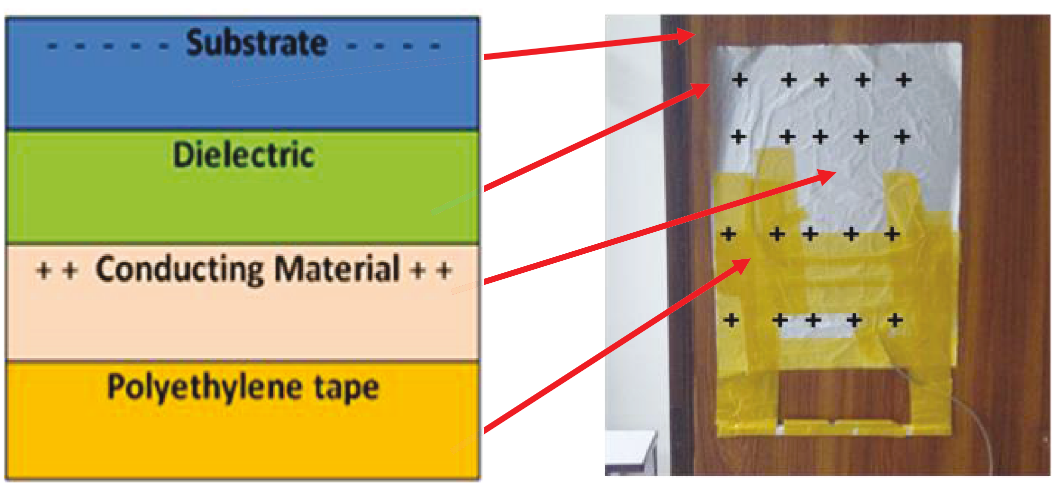



**Figure 6 Cross section view of unipolar adhesive pad on wall**

To begin with the experimentation process the starting positive voltages are + 1000 volts, + 2000 volts, + 3000 volts, + 4000 volts, + 6000 volts, + 7000 volts, + 8000 volts. The deviation of electroadhesion force in kilograms associated with the mentioned factors will be discussed. A simple series of experiment is applied to produce electroadhesion force with respect to voltage plot. First the electroadhesive pad is gently laid on the substrate surface without weight. The electroadhesion pad was then energized with unipolar high voltage provided by self-made AC-HV-DC converter (voltage multiplier). First, all the four pads of different areas were charged with 1 kilo volts and then weight is applied to the pad until it detaches from the surface attached with due to electroadhesion force. The weight or force just before the detachment of the pad is recorded as maximum adhesion force. This test sequence is then for 1 kV, 3 kV, 4 kV , 6 kV ,7 kV and 8 kv and readings were noted shown in **Figure 10**, **11**, **12** and **13**.

## V. Experimental Results and Wall Climbing Robot

*Lateral Force of the Unipolar Pad*

The unipolar electroadhesion pad showed rapid response when +ve HV dc is supplied to it. The unipolar electroadhesion pads showed attachment to the test surfaces within seconds when voltage applied. Weights were applied with gradual increment to overcome the electroadhesion force to the substrates (wall).The maximum forces measured before the unipolar electroadhesion pad gets slipped were considered the main practical unipolar electroadhesion force for wall climbing robots. A hissing sound was also noticeable during the voltage supply to the unipolar pad. The measured experimental results are shown in **Table II**.

From **Figure 9**, it can be clearly observed that the electroadhesion force, by unipolar pad, increases with the advancement in voltage. The force vs voltage relation is to some extent quadric parabola. Hence, it is possible to increase voltage in order to get high adhesion force. This research voltage limitation is 8 kV. However, increasing the HV supply should be in a limit so that the dielectric breakdown of the dielectric layer may be controlled otherwise leads to the failure of whole unipolar electroadhesion pad. The results depict that the high voltage range from 3 kV to 8 kV produces reasonable unipolar electroadhesion force.

## VI. Validation of Results

This proposed model has been validated experimentally. Figure  shows that the valuable unipolar electroadhesion force (lateral force) is experimentally achieved for the development of unipolar electroadhesion WCR. The experimentation results recommend that for larger payload WCR larger unipolar pad area should be considered.

### *A. Comparison with Experimental Data*

The theoretical model values were compared with experimental data. The theoraticall and experimental unipolar electroadhesion force is shown graphically in **Figure 10**, **11**, **12**, and **13** which indicates that the proposed model agreement is found to be good.In order to check the validity of the model voltage was changed at six different values in kilo Volts i.e. 1 kV, 3 kV, 4 kV, 6 kV, 7 kV and 8 kV and four unipolar electroadhesion pads were also taken into consideration with different areas. With all these parameters the the result of modal versus experiments were quite acceptable. The acceptable differences in the results may be due to ideal conditions which are difficult to achieve which will be fcused to minimized in future research. However, when the unipolar electroadhesion pads were operated on different non conductive walls with varying permittivity materials of substrate, it showed that walls with high permittivity produces more electroadhesion force than less permittivity. So further investigation of this subject will be carried out in future research in details.

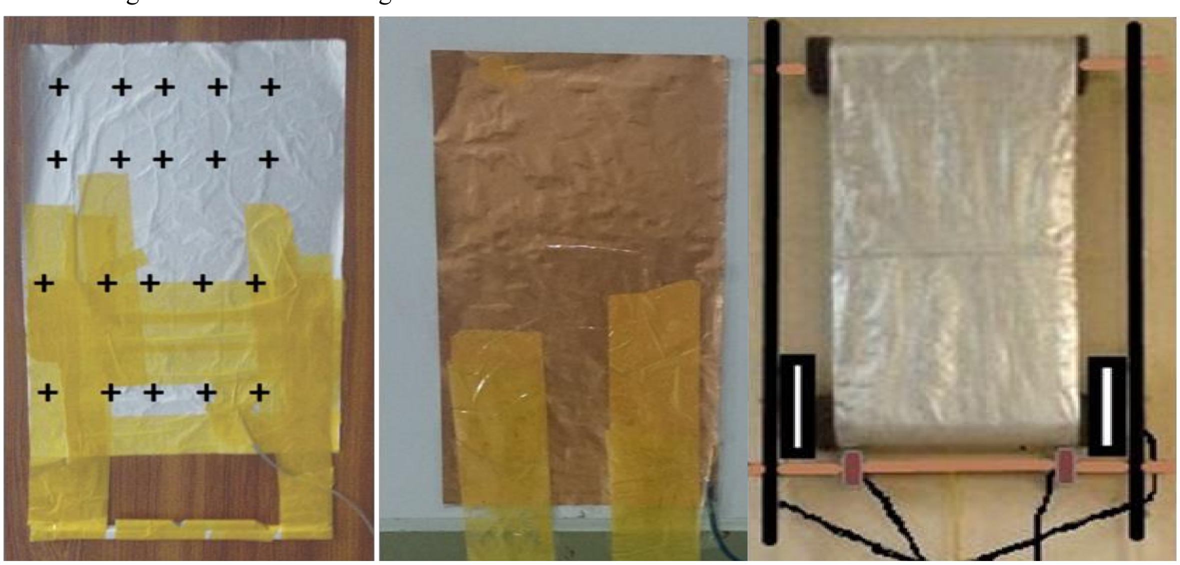
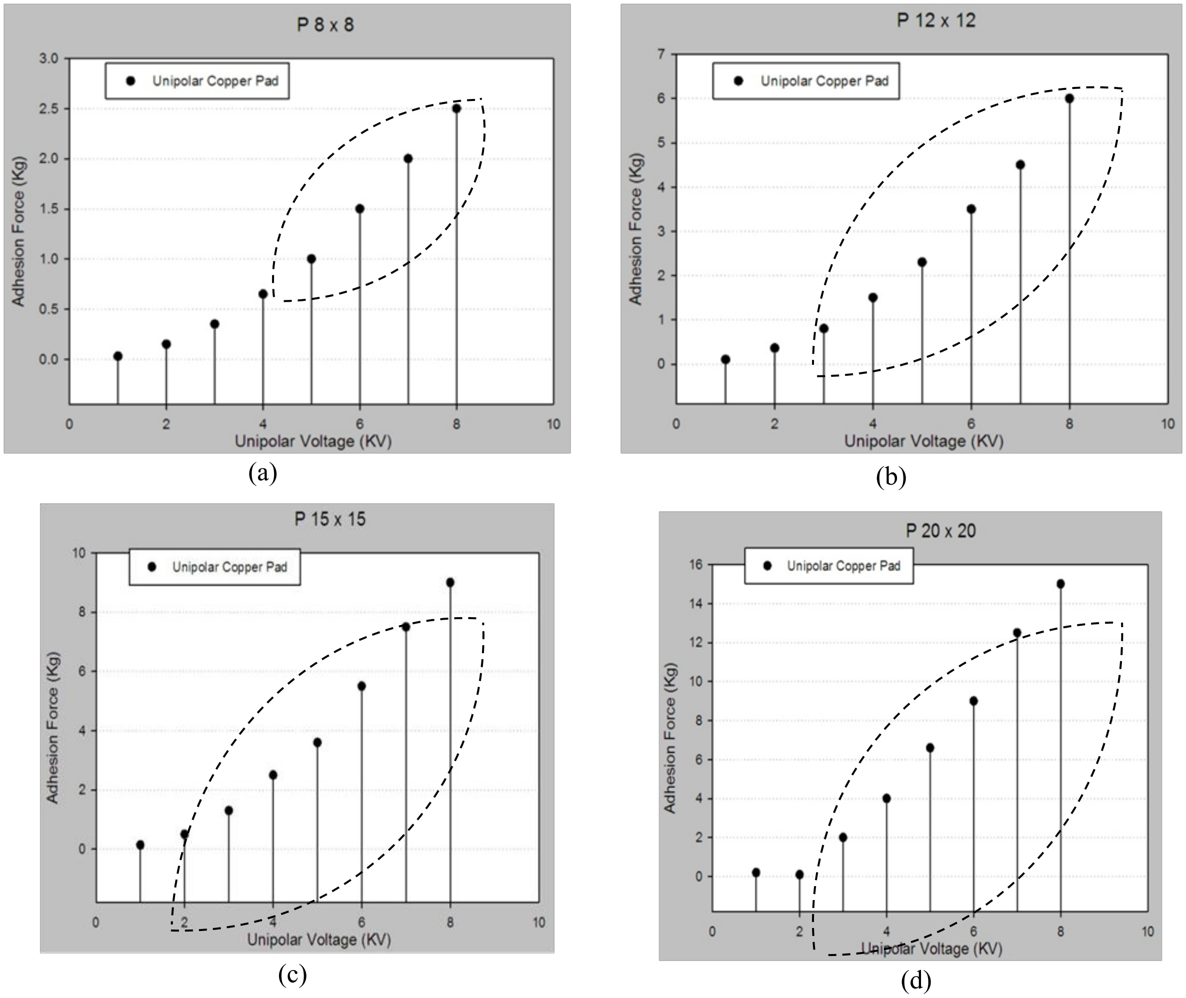


**Figure 8 (a), (b) Potential unipolar electroadhesion pads for WCR, (c) the unipolar electroadhesion pad which can be utilized on Wall Climbing Robot**




(a) (b) (c) (d)

**Figure 9 Experimental results of lateral force for unipolar electroadhesion pad of copper on melamine/wood wall surface: (a) P 8cm x 8cm (b) 12cm x 12 cm (c) 15 cm x 15 cm (d) 20 cm x 20 cm. The dotted regions are the lateral force regions which are practicable for Wall Climbing Robot**

### *B. Wall Climbing Robot Design*

**Figure 8(c)** is the basic skeleton of unipolar electroadhesion robot. It consists of two parallel plates of wood, since it is light in weight and non- conductor. The motors are attached to these plates. Top view and Side view of unipolar electroadhesion robot is shown in **Figure 14** and **15**, respectively. The unipolar electroadhesion pad wrap around the drive wheel and in contact with the ball bearing. The ball bearing moves as the unipolar electroadhesion pad moves with the wheel drive.

**Figure 15** shows the forces acting on the WCR. In order to climb for the robot to the wall, the two components lateral force and peeling force must be countered. Lateral force (holding force) can be countered by providing sufficient frictional coefficient between the robot and the wall. Peeling force can be countered by shifting the centre of gravity (CG) towards the wall. However, CG cannot be completely shifted towards the wall. To avoid peeling, anti-peeling supports were used such as tail supports.

There are two wheels, namely, rear wheel and front wheel. The two wheels are attached using the unipolar electroadhesion pad as belt drive, which is the mechanism for the locomotion of the robot. The high voltage power is applied to the unipolar pad, when the robot is in motion. An arrangement is made for this purpose. A wooden shaft is fixed to the skeleton and a ball bearing is attached on the shaft such a way that the ball bearing is always in contact with the belt. Ball bearing rolls as the unipolar electroadhesion pad moves, as both are in contact. The friction between them is less. The applied high voltage on ball bearing gets applied to adhesive pad (by ball bearing arrangement).The unipolar electroadhesion pad and the motors are attached mechanically but are operated separately as given in **Figure 16**. From the proposed schematic of unipolar electroadhesion WCR in **Figure 14** and **Figure 15**, M is motors, B is ball bearing, W is wheel driver, T is tail and F is wood frame for WCR.

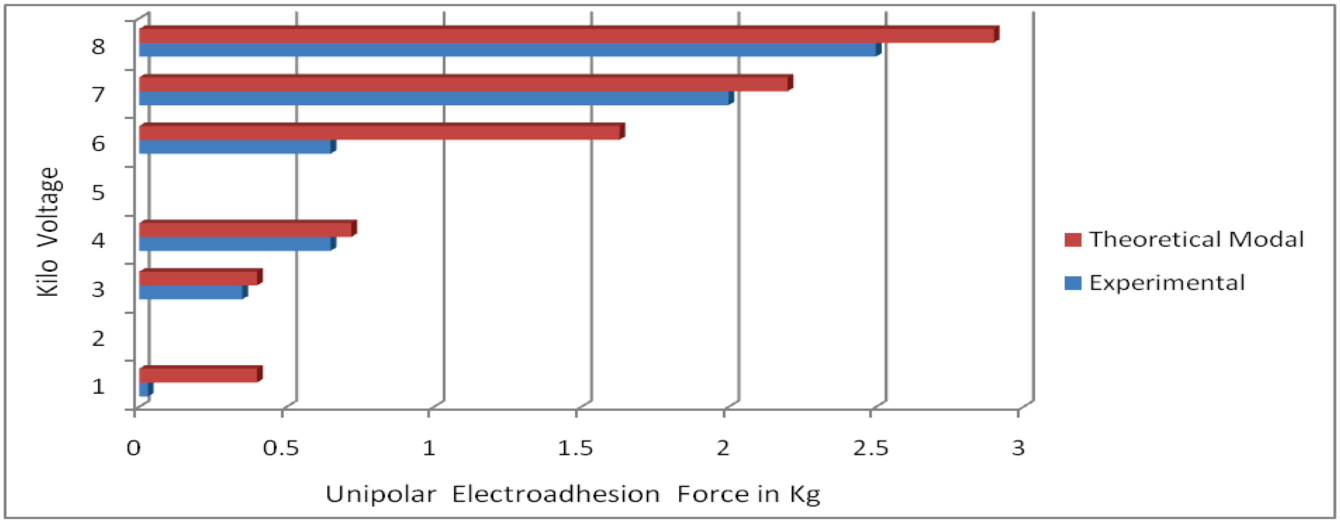



**Figure 10 Theoretical modal versus experimental unipolar electroadhesion force for pad area of 20 cm * 20 cm**

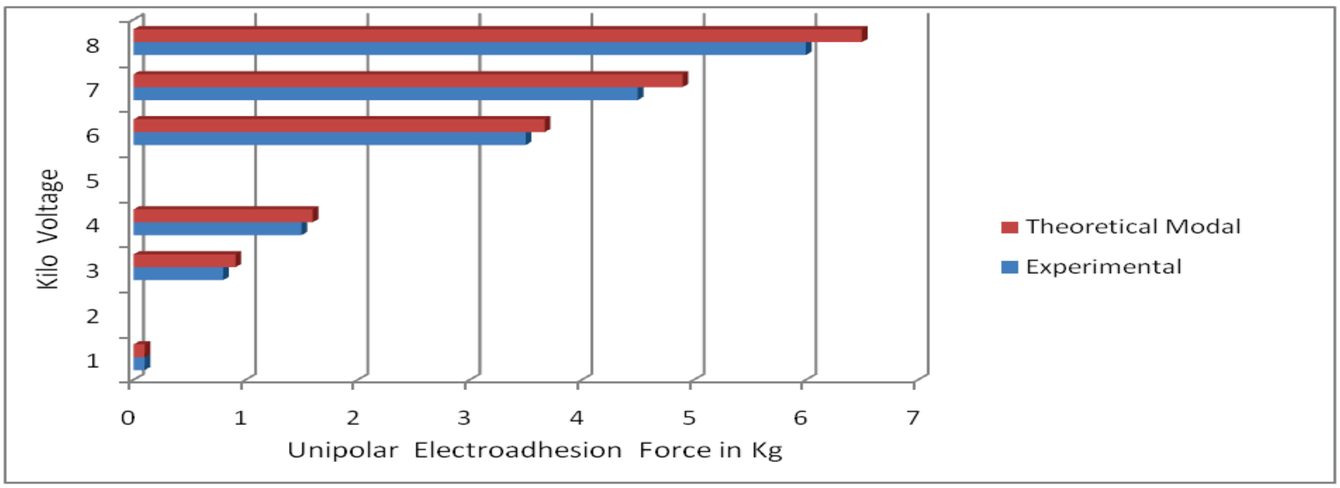



**Figure 11 Theoretical modal versus experimental unipolar electroadhesion force for pad area of 15 cm * 15 cm**

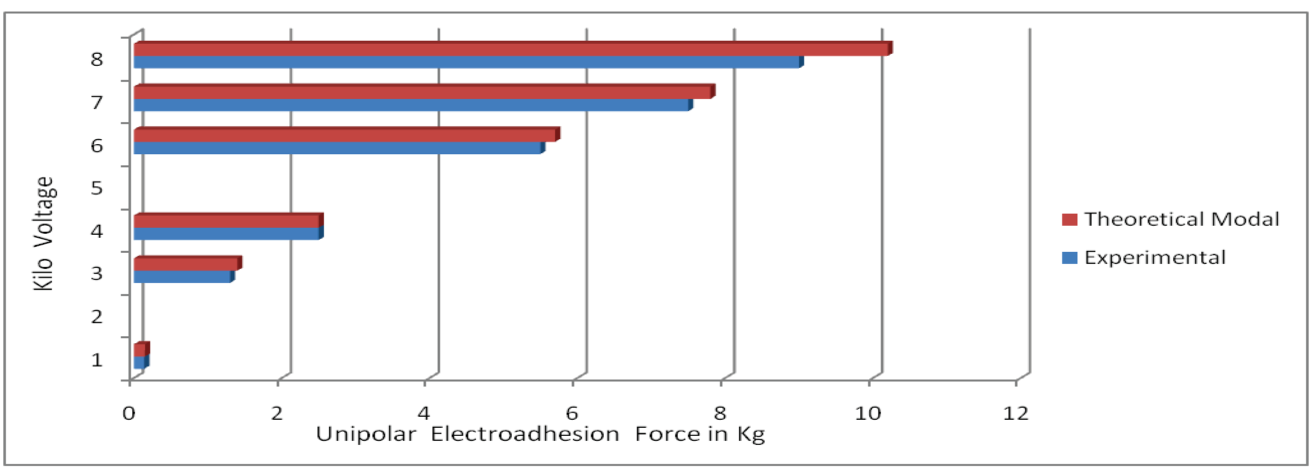



**Figure 12 Theoretical modal versus experimental unipolar electroadhesion force for pad area of 12 cm * 12 cm**

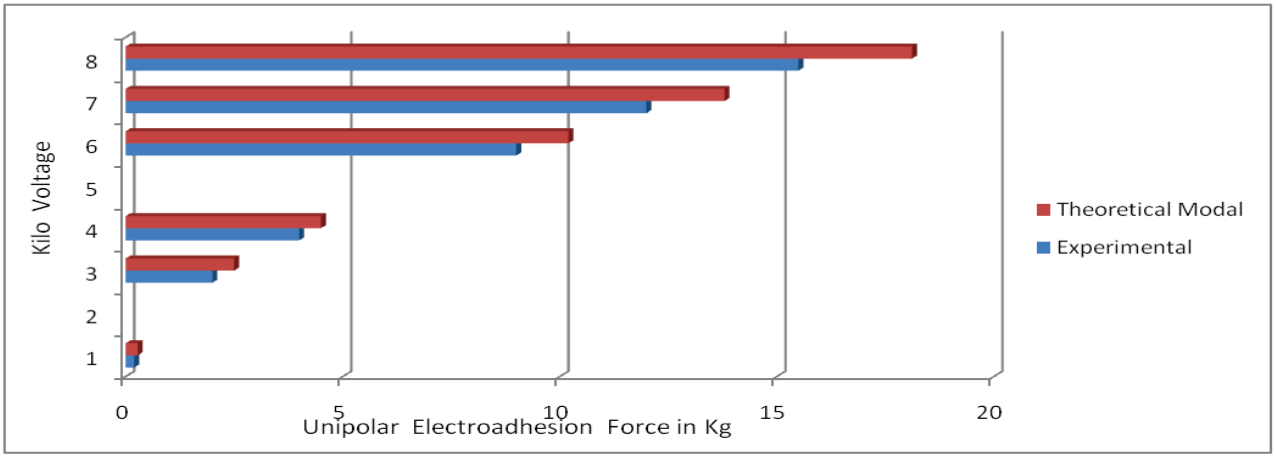



**Figure 13 Theoretical modal versus experimental unipolar electroadhesion force for pad area of 8 cm * 8 cm**

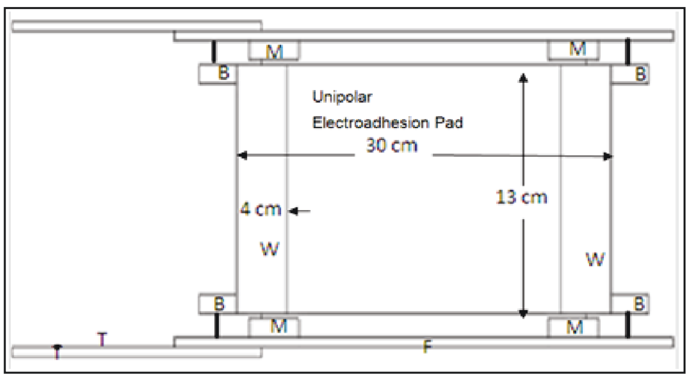



**Figure 14 Schematic of possible WCR (top view)**

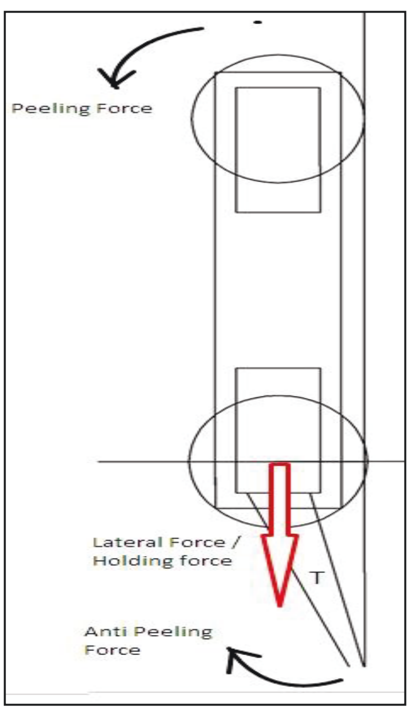



**Figure 15 Force specifications acting on Wall Climbing Robot**

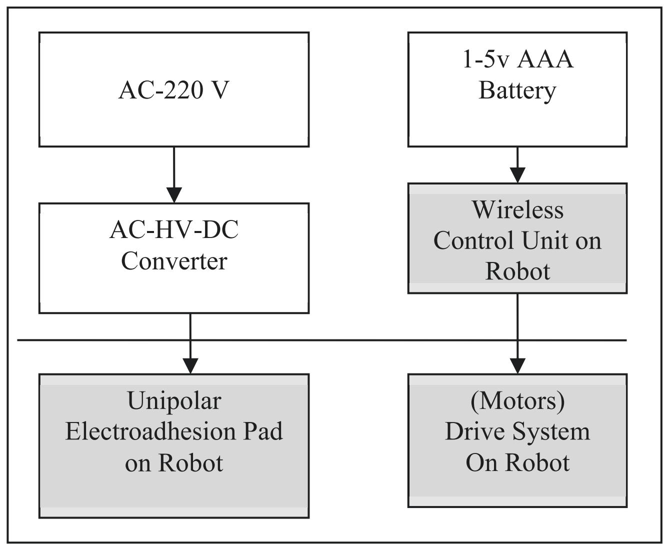



**Figure 16 Schematic of unipolar electroadhesion HV supply and driving system**

*C. Realization of Unipolar Electroadhesion Pad for WCR Adhesion Mechanism*

**Figure 8** is a likely technique of attachment of the unipolar electroadhesion pad with wall climbing robot skeleton. When the attached unipolar pad is provided HV-DC power the unipolar electroadhesion pad will adhere to melamine or wood substrate surface to an area of 390 square cm approximately by taking the pad P 20 x 20 cm as mentioned in **Table II**. When a 7-8 kV will be applied to the pad and considering a safety factor of 3 the robot is expected to produce a lateral force of 4-5 kg. That is why the cost effective and light weight unipolar electroadhesion pad is feasible for the development of wall climbing robots. At present the development of unipolar electroadhesion wall climbing robot is still in progress.

TABLE II EXPERIMENTAL RESULT-ADHESION FORCE IN KG AS A FUNCTION OF 1-8 KV FOR THE FOUR UNIPOLAR PADS WITH VARIATION IN AREA

| | **Unipolar electroadhesion pad's lateral force (holding force ) in kg** | | |
|---|---|---|---|
| **Unipolar electroadhesion pad** | 1 to 3 KV | 4 to 6 kV | 7 to 8 kV |
| P 20 x 20 | 0.2 -2 kg | 4 – 9 kg | 12-15.5 kg |
| P 15 x 15 | 0.14-1.3 kg | 2.5 - 5.5 kg | 7.5-9 kg |
| P 12 x 12 | 0.10–0.80 kg | 1.5-3.5 kg | 4.5 – 6 kg |
| P 8 x 8 | 0.03–0.35 kg | 0.65- 1.5 kg | 2 – 2.5 kg |

## VII. CONCLUSION

A cost effective and light weight unipolar electroadhesion pad technology on wall climbing robot was presented in this paper. The unipolar electroadhesion pad has produced favourable amount of electrostatic adhesion force on vertical substrate. It shows working on non conductive substrates such as melamine wall and glass wall. This success of reasonable unipolar electroadhesion force creation is the encouragement for the unipolar electroadhesion wall climbing robot. Model skeleton for fabrication of WCR is also discussed with design considerations along with tail for anti peeling force. As a whole the complete control approach is not that much complicated and contains only a separate power supply to the unipolar electroadhesion pad. In short, the unipolar electroadhesion technology is feasible technique to make a cost effective , light weight and multiple surface robot capable of adhering to vertical walls making it wall climbing robot.

## ACKNOWLEDGEMENTS

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