Electroadhesion Technologies for Robotics: A Comprehensive Review

Jianglong Guo, *Member, IEEE*, Jinsong Leng, and Jonathan Rossiter, *Member, IEEE*

***Abstract*—Electroadhesion (EA) is an electrically controllable adhesion mechanism that has been studied and used in fields including active adhesion and attachment, robotic gripping, robotic crawling and climbing, and haptics, for over a century. This is because EA technologies, compared to other existing adhesion solutions, facilitate systems with enhanced adaptability (EA is effective on a wide of range of materials and surfaces), reduced system complexity (EA systems are both mechanically and electrically simpler), low energy consumption, and less-damaging to materials (EA, combined with soft materials, can be used to lift delicate objects). In this survey, we comprehensively detail the working principle, modeling, design, fabrication, characterization, and applications of EA technologies employed in robotics, aiming to provide guidance and offer potential insights for future EA researchers and applicants. Joint and collaborative efforts are still required to promote the in-depth understanding and mature employment of this promising adhesion and gripping technology in various robotic applications.**

***Index Terms*—Controllable adhesion, crawling and climbing robotics, electroadhesion (EA), grasping, grippers and other end-effectors, haptics.**

I. Introduction

ELECTROADHESION (EA) [1], coined by two Danish scientists, Alfred Johnsen and Knud Rahbek, in the 1910s, has been used to denote the electrostatic attraction between two contacting materials when there is an electrical potential difference between them [2]. The traditional Johnsen–Rahbek (J-R) effect describes the attractive force experienced between a conductor and a semiconductor when the two materials are in contact and a voltage is applied across them. The J-R effect has proven to be effective in electrostatic chucking systems in the semiconductor industry, where wafers are transported and processed. EA technologies extend the applicability of electrically controllable adhesion to many more materials and applications, including object fixation [3], [4], robotic crawling [5], [6] and climbing [7]–[9], mechanical and electrical interconnections [10], [11], perching [12], anchoring [13], and robotic end effectors and grippers for material handling tasks [14]–[18].

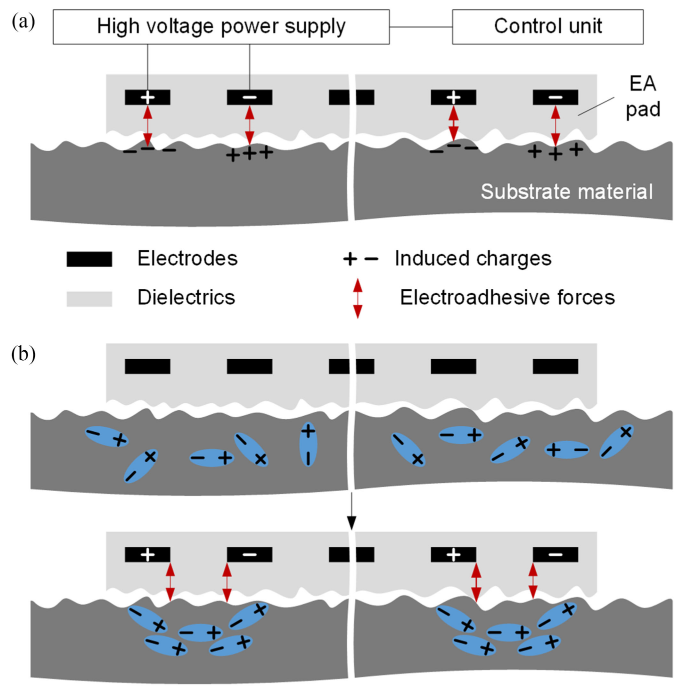

Fig. 1. Cross-sectional view of a typical EA system. (a) Electroadhesion on conductive materials. (b) Electroadhesion on insulating materials. "+" denotes a positive voltage whereas "–" denotes a negative voltage or ground. Thicknesses are not shown to scale.

Typically four components are employed in an EA system [19]:

1) an EA pad;
2) a high voltage power source;
3) a control unit;
4) a substrate material to be adhered onto or picked up, as shown in Fig. 1.

The EA pad consists of pairs of planar interdigitated electrodes embedded in a thin dielectric. A high voltage power

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source is connected to the electrodes and supplies direct or alternating current with unipolarity, bipolarity, or multipolarity excitation. The dielectric material not only plays an important role in the adhesive action, but also acts as a mechanical support for the electrodes and helps prevent charge neutralization and dielectric breakdown. Two or more dielectric materials can be used depending on the used fabrication methods specified in Section III-B below. A control unit is connected to the high-voltage power source to dynamically control the voltages applied to the EA system. When a high voltage is applied across the electrodes, electroadhesive forces will be induced between the EA pad and the substrate material [20]. Deadhesion can be achieved by switching OFF the power supply [15], [20].

EA technologies have been studied and used for almost a century worldwide. This is because EA, compared to other adhesion methods such as magnetic, pneumatic, and bioinspired adhesion mechanisms [21]–[23], has several key benefits. These include the following [24], [25]:

1) EA offers systems with enhanced adaptability as it can be used to adhere onto or lift almost any material and surface, ranging from aluminum films and sandpapers to concretes, and glass plates;
2) EA can be used in dusty environments, at low pressures, and even in space;
3) EA reduces system complexity because it exploits mechanically lightweight and simple materials and structures and simple electrical control components. In contrast, alternative adhesion and gripping systems commonly use energy-intensive pumps or control-intensive electric motors;
4) EA enables systems with low energy consumption as only a low current (usually in the range of μA) flows through the EA pad despite that a relatively high voltage (typically in the range of kV) should be applied;
5) EA can lift delicate and high-value objects through non-contact suspension [26] or soft EA pads [27], [28].

Due to these distinctive advantages, there has been a steady increase in the number of published papers on electroadhesion technologies. Fig. 2 shows the number of publications per year from Google Scholar search terms <electrostatic adhesion>, <electroadhesion>, or <electroadhesive>. It should be noted that EA is not a perfect adhesion technology and it has its own limitations. For instance, a relatively high voltage is required, and a relatively low and unstable adhesion pressure is usually obtained.

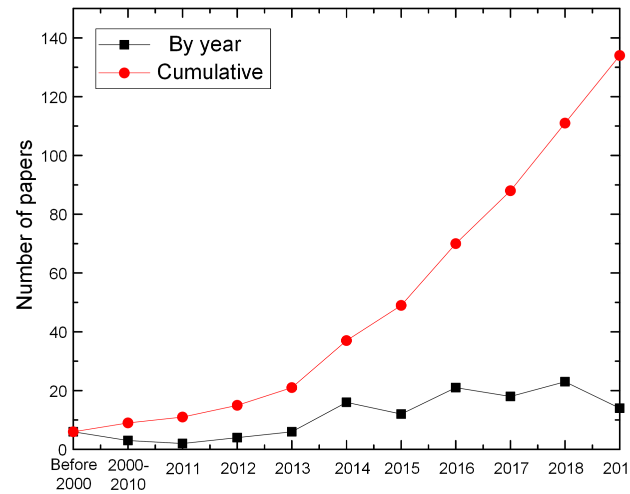

Fig. 2. Number of EA papers from Google Scholar in June 2019 using keywords: <electrostatic adhesion>, <electroadhesion>, and <electroadhesive>.

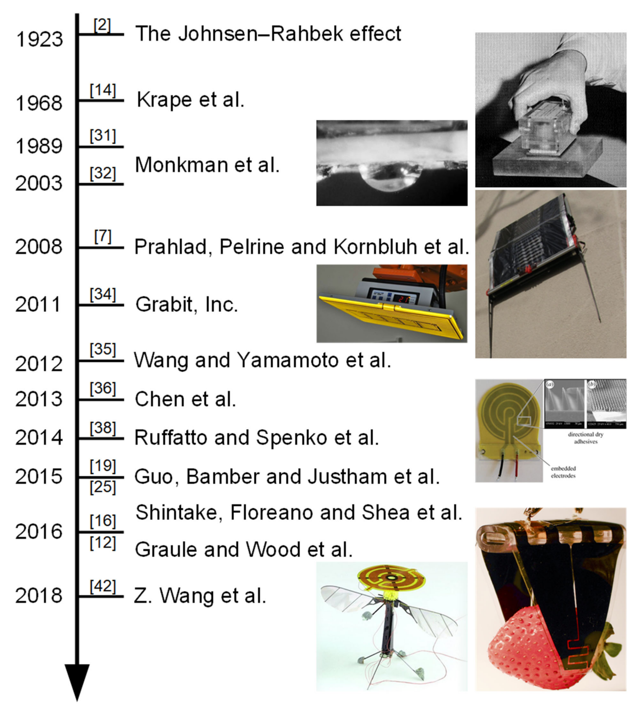

Fig. 3. Milestone EA work and key EA researchers worldwide.

The timeline and milestones in the development of EA are summarized in Fig. 3. These include: the J-R effect that forms the basis of electrostatic chucks [29], [30] that have been extensively used in semiconductor industry; the first rigid and flexible EA end effectors for aerospace applications developed by the Chrysler Corporation Space Division under a NASA contract completed by Krape *et al.* [14]; the identification and application of EA for fabric or textile handling [15], the first EA microgripper [31], the first EA conveyor belt, and the first surface compliant EA gripper developed by Monkman [32]; the first successful EA crawling and climbing robot developed by Prahlad *et al*. [7], [33]; the first company commercializing EA technologies, Grabit, Inc. [34], a spin-off from SRI; the first thin crawling and climbing device integrating EA and electrostatic film actuators developed by Wang *et al.* [35]; the first dynamic analytical EA model developed by Chen *et al.* [36]; the first graceful integration of EA and gecko-inspired adhesion (a significant step after the electro-dry-adhesion work developed by Krahn and Menon [37]) with a geometrically optimized concentric EA electrode design implemented by Ruffatto *et al.* [38]–[40]; the first experimentally validated EA model [25], the first environmentally stable EA [41], the intelligent and adaptive EA concept [17], [19] developed by Guo *et al.* [19]; the first entirely soft EA gripper integrating EA and dielectric elastomer actuation developed by Shintake *et al.* [16]; the first elegant integration of EA with micro air vehicles for perching on various materials by Graule *et al.* [12]; and the first self-powered EA gripper developed by Wang *et al.* [42].

EA is a multidisciplinary, complicated, and dynamic adhesion technology with 33 known variables [24] influencing the electroadhesive forces obtainable between the EA pad and the substrate material. These influencing factors include environmental factors, EA electrode parameters, EA dielectric parameters, substrate parameters, and power source parameters [25]. It should be noted that EA is a contact physics phenomenon [24], where the EA dielectric surface texture and resistivity, substrate surface texture and resistivity, and contact or interface resistivity must be taken into account when designing, manufacturing, and testing EA pads. Large-scale textured surfaces, especially those with μm features, can be obtained from traditional high precision manufacturing solutions [43].

In order to better use this technology in robotics applications, an in-depth understanding of the EA principle, design, fabrication, and testing is required. A comprehensive survey of EA technologies used in robotic is highly desirable for guiding and providing potential insights for future EA users or practitioners. This survey aims to fill the gap and fulfill this urgent need. The remainder of this article is organized as follows. The working principle of the EA phenomenon and its theoretical, simulation, and empirical modeling are presented in Section II. A summarization of EA pad designs, fabrication methods, and characterization approaches is demonstrated in Section III. Applications of EA technologies, including robotic grippers, crawling and climbing robotics, haptics, active adhesion, and space uses are described in Section IV. Discussions on recent developments in EA rapid adhesion and deadhesion capability, intelligent EA, shape-adaptation, advanced EA understanding, and potential avenues for future joint development efforts are outlined in Section V. Section VI concludes this article.

II. EA Working Principle and Modeling

A. Principle of EA

When a high voltage, typically 1 to 6 kV, is applied across the spaced electrodes within an EA pad, a strong electric field is formed between the electrodes. When the charged pad is placed in contact with a conducting surface, image charges are developed at the surface of the conductor and an attraction force develops between it and the pad [see Fig. 1(a)]. Alternatively, when the pad is placed in contact with an insulating surface, orientational and interfacial electrical polarization [20], [44] occur within the insulating materials, resulting in attraction between proximal charges within induced dipoles and the pad [see Fig. 1(b)]. This charge build-up (and hence the build-up of net EA force) takes a finite time which is dependent on materials and the form of applied potential. When the high voltage is removed, the adhesive force decays. This decay also takes a finite time, typically within seconds, but can extend to hours depending on the type of insulating and substrate materials. These build-up and decay times significantly affect the adhesion/deadhesion cycle.

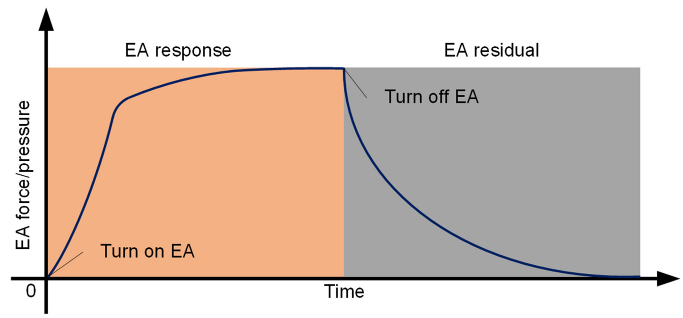

Fig. 4. Typical dynamic electroadhesive response and residual force/pressure curve against time.

Here we define EA response as the process from the start of the application of a high voltage to the achievement of the maximum electroadhesive force when the accumulation of induced charges is saturated. We define EA residual as the process from the point when the high voltage is disconnected to the complete dissipation of residual or trapped charges in the EA dielectrics. This dynamic feature (see Fig. 4) is mainly caused by the time-dependent polarization and depolarization of the dielectrics covering the electrodes and molecules within the adhered surfaces (for non-conducting objects). Careful attention should be taken regarding this dynamic feature when one undertakes the design, manufacturing, characterization, and application of EA technologies. The dynamic nature of the EA phenomenon not only presents a practical challenge but also opens an interesting research topic that requires cost-effective and robust solutions to speed up the EA adhesion and deadhesion processes. This is especially important when adhering to relatively heavy or difficult-to-polarize objects or deadhering from extremely lightweight and flexible materials.

B. EA Modeling

It is desirable to establish finite element or theoretical models for any engineering solutions or products as these models may provide optimal design rationales and minimize the time and resources for extensive physical experiments or tests. The analytical modeling of electroadhesive forces exerted on a substrate material for a given EA pad has been obtained by using the Maxwell stress tensor method [36], [45], [46] [usually based on a simplified 2-D representation]. The electrostatic (neglecting the effects of magnetism) Maxwell stress tensor, T_{ij}, is defined, in component form, as follows:

$$T_{ij} = \varepsilon \left(E_i E_j - \frac{1}{2} \delta_{ij} E^2 \right) \tag{1}$$

where ε is the dielectric permittivity, δ_{ij} is the Kronecker delta, and the electric field E can be readily calculated by $-\nabla\Phi$, where the electric potential, Φ, in a dielectric medium of the case of a source-free region, satisfies the Laplace equation, $\nabla^2\Phi = 0$. Taking the space between the middle points of two adjacent electrodes as a period, the normal EA force acting on a substrate material of unit length can then be calculated as follows:

$$f_{\text{EA\_normal}} = \oint_S T_{yy} dS = \frac{1}{2}\varepsilon_0 \int_0^{w+s} [E_y^2(x,y,t) - E_x^2(x,y,t)]dx \quad (2)$$

where ε_0 is the permittivity of the vacuum, w is the EA electrode width, s is the space between the two EA electrodes, E_x and E_y are the electric field components in the air-gap between the EA device and the substrate material.

Due to the time-dependent polarization involved after the application of a high voltage, the magnitude of the electric field strength between the electrodes increases over time and then saturates. This dynamic polarization process further generates a varying air gap, d_t, between the EA pad and the substrate material, $E_t = \Phi/2d_t$. The electroadhesive force initially increases rapidly and then the rate of increase falls (see the slope change in the EA adhesion process in Fig. 4) due to the balance between increasing polarization and excessive accumulation of charges as the saturation point is approached.

The overall theoretical normal EA force of n pairs of EA periods exerted on a substrate material of width, l, can then be described as follows:

$$F_{\text{EA\_normal}} = \frac{1}{2} n \varepsilon_0 l \int_0^{w+s} [E_y^2(x,y,t) - E_x^2(x,y,t)]dx. \quad (3)$$

EA pads and substrates are usually not grounded. If we take the possible dielectric breakdown into consideration, we have [46]

$$F_{\text{EA\_normal}} = \frac{1}{2} n l \varepsilon_0 \left[\left(\frac{\varepsilon_r}{\varepsilon_0}\right)^2 - 1\right] \bar{C}\left(\frac{w}{w+s}, \frac{2(t+d_t)}{w+s}\right)\left(E_{\text{BD}}^{\text{air}}\right)^2 \quad (4)$$

where ε_r is the relative permittivity of the dielectric film, $E_{\text{BD}}^{\text{air}}$ is the breakdown electric strength of air, and $\bar{C}(\frac{w}{w+s}, \frac{2(t+d_t)}{w+s})$ is defined as a dimensionless function of geometric parameters comprising the electrode width w, the space between the electrodes s, the air gap between the dielectric film and the substrate d_t, and the thickness of the dielectric film t.

The larger the applied voltage and the relative permittivity of the dielectric, and the smaller the air gap and the thickness of the dielectric, the greater the obtainable normal EA force. There is an optimum value of $\frac{w}{w+s}$, and this value is influenced by $\frac{t+d_t}{w+s}$(details and suggested optimum values can be further seen from [46]).

One can derive the theoretical forces under specific boundary conditions [36], [46]. The theoretical model is, however, always based on several assumptions [36], [45], [46] including that

1) edge effect is neglected;
2) electric field distributions are uniform in the electrode longitudinal direction, allowing for the simplification of the problem from 3-D to 2-D;
3) EA materials are linear, isotropic, and homogeneous.

It should be also noted that time domain electric field components should be used here to match the dynamic EA effect. Furthermore, modeling the simplified interaction between two electrodes and the substrate (as above) does not comprehensively represent the whole interdigital EA patterns or more complex electrode geometries such as spiral shapes.

If one defines the relative EA normal force as $F = \frac{F_{\text{EA\_normal}}}{F_{\text{EA\_normal\_saturated}}}$, where $F_{\text{EA\_normal}}$ is a time-dependent force and $F_{\text{EA\_normal\_saturated}}$ is the saturated force when the voltage is employed for a long enough time, the response time and residual time to represent the dynamic nature of the EA phenomenon can be expressed as follows [47]:

$$t_{\text{response}} = \frac{\rho_c(t)\rho_v\varepsilon_0(d+\delta(t)\varepsilon_r)}{\rho_v d + \rho_c(t)\delta(t)} \ln(1-\sqrt{F}) \quad (5)$$

$$t_{\text{residual}} = -\frac{\rho_c(t)\rho_v\varepsilon_0(d+\delta(t)\varepsilon_r)}{\rho_v d + \rho_c(t)\delta(t)} \ln(\sqrt{F}) \quad (6)$$

where ρ_c is the EA contact resistivity which is time dependent due to the increasing EA adhesive pressure, ρ_v is the EA pad volume resistivity, d is the dielectric layer thickness, δ is the air gap thickness which is also time dependent due to the increasing EA adhesive pressure, and ε_r is the relative dielectric permittivity of the dielectric.

Existing EA theoretical models, except the one developed by Chen *et al.* [36], are all static and do not fully capture the dynamic characteristic nature of the EA phenomenon. In addition, only Chen *et al.* [48] and Nakamura and Yamamoto [49] have considered the dynamic mechanical behaviors induced during EA operations. It should be noted that, however, it is non-trivial to derive analytical models that can accurately predict the theoretical electroadhesive forces due to the time-dependent nature of the EA effect and inhomogeneous materials and electric fields existing in nature. Notwithstanding, simplified EA force modeling based on practical assumptions is helpful for both understanding the EA phenomenon and providing an idea of the scale of the EA forces obtainable. This may help guide the design, manufacture, testing, and application of electroadhesives.

Finite-element methods are useful tools to simulate the 3-D electric field distributions of EA pads and potentially compare different EA designs. Existing FEA models have typically been based on the electrostatic energy method embedded in FEA software [50]–[52]. Results obtained from published FEA models, except that developed by Ruffatto *et al.* [50], do not accurately match their experimental results.

Since it is challenging to include varying environmental conditions, surface texture, and dynamic material property changes induced by high-voltage-based polarization/depolarization into analytical and FEA models, empirical modeling based on experimental data may be a solution to an advanced model that can predict the EA pad performance and aid the pad design and fabrication. Koh *et al.* [53] employed an empirical comb capacitance calculation equation into a simplified EA theoretical model. Guo *et al.* [54] developed data-driven empirical models representing the relationship between the EA force obtainable

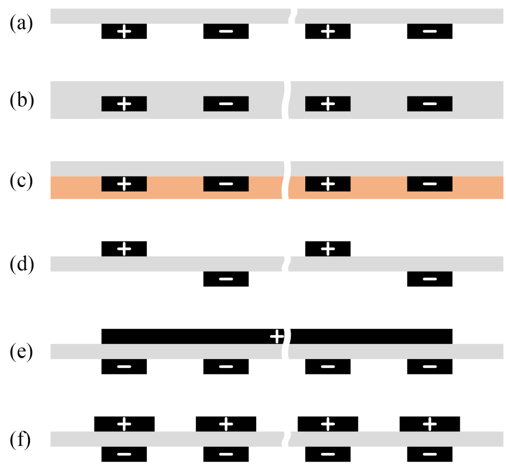

Fig. 5. Bipolar EA pad configurations. (a) Spaced coplanar electrodes (denoted in black color) attached to a dielectric substrate (denoted in a gray color). (b) Spaced coplanar electrodes embedded in a dielectric. (c) Spaced coplanar electrodes embedded in two dielectrics (one denoted in gray and one denoted in orange). (d) Spaced double-sided electrode design 1. (e) Spaced double-sided electrode design 2. (f) Spaced double-sided electrode design 3. Thicknesses are not shown to scale.

TABLE I
EA PAD FABRICATION METHODS

EA fabrication methods	Specific techniques	Representative references
Additive	Inkjet printing	[61][62][63]
	Molding	[17][27]
	Screen printing	[64][65]
Subtractive	Manual cutting	[75][76][77]
	Machining	[18][78][83]
Additive-subtractive	PCB or FPCB	[24][25][39][41][58]
	Customized	[12][79][84]

and applied voltage up to 20 kV. Chen and Bergbreiter [55] experimentally derived a basic friction model to predict tangential EA forces. Recently, Choi *et al.* [56] presented an interesting empirical EA model comprising the interfacial polarization, the applied voltage, and the proposed boundary edge length, which offers a viable insight into future robust empirical EA models.

III. EA PAD DESIGN, FABRICATION, AND CHARACTERIZATION

A. EA Pad Designs

An EA pad consists of one or spaced electrodes bonded to, or embedded into, a dielectric or semiconductive material [see Fig. 5(a) and (b)]. Two or more dielectric or semiconductive materials [see Fig. 5(c)] can also be used depending on the fabrication methods used. Unipolar or bipolar high-voltage power sources can be applied to the electrodes. The unipolar or single pole design requires the application of a high voltage source with either positive or negative output. It is more common for grasping conductive or semiconductive materials due to its simplicity and reduced risk of dielectric breakdown. The unipolar design is however not efficient or effective in gripping dielectric materials [57]. The bipolar or dual pole design requires the application of a high-voltage source with both positive and negative outputs. It is useful for lifting both conductive and insulating materials. In this survey, we only present the most common bipolar EA pad designs, as shown in Fig. 5.

The most common EA pad design consists of spaced coplanar electrodes embedded in two dielectrics [7], [24], [39]. Double-sided EA electrode configurations [17], [33], [40] [see Fig. 5(d)–(f)] have shown advantageous features in achieving slightly higher adhesive forces and are better at resisting dielectric breakdown [40]. Electrode geometries or patterns can be categorized into symmetrical and nonsymmetrical designs. Symmetrical electrode patterns include concentric [6], [12], [38], [58], [59] and spiral [58] designs that can output more uniform EA forces than nonsymmetrical electrode patterns such as two-electrode [54] and interdigital or comb [7], [16], [33], [52] designs. The most common EA electrode pattern used in the EA community has been the comb pattern which can be regarded a periodic series of opposite-polarity electrode pairs. The popularity of this design may be due to its ease of fabrication and its relatively good adhesion performance on both conductive and insulating substrates.

B. EA Pad Fabrication Methods

Fabrication methods associated with EA technologies can be classified into additive, subtractive, and additive-subtractive solutions, as summarized in Table I and Fig. 6. Resultant EA pads can be categorized into rigid (the EA pad is not bendable and stretchable) [3], [14], flexible (the EA pad is bendable but not stretchable) [6]–[8], [12], [59], and stretchable (the EA pad is bendable and stretchable) [17], [27], [28] forms.

The advantages and disadvantages of different EA fabrication methods have been summarized in the work by Xie *et al.* recently [60]. We define additive EA pad manufacturing methods as fabrication solutions to form EA pads by depositing dielectric and electrode materials in a layer-by-layer manner, as shown in Fig. 6(a), consisting mainly of the following three steps:

1) base dielectric layer deposition;
2) electrode material layer deposition;
3) cover dielectric layer deposition (optional).

Existing additive EA manufacturing methods include inkjet printing [61]–[63], screen printing [64], [65], and molding [17], [27] techniques. Inkjet printing EA pads usually involves printing conductive traces (such as silver inks) onto a substrate (such as papers) using an inkjet printer. One key benefit of this method is that inkjet printing allows direct writing of electronics onto

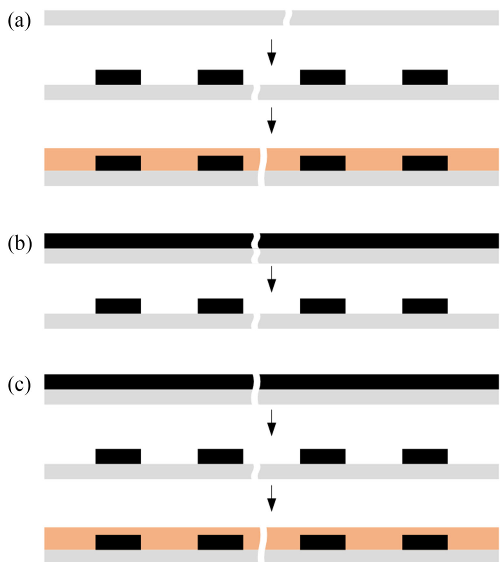

Fig. 6. EA pad fabrication methods. (a) Additive EA manufacturing approach. (b) Subtractive EA manufacturing approach. (c) Additive-subtractive EA manufacturing approach. Thicknesses are not shown to scale.

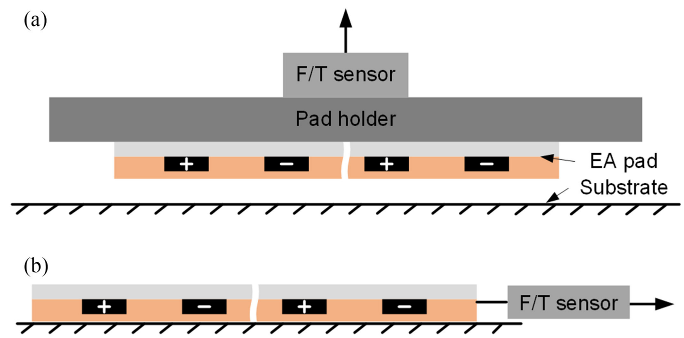

Fig. 7. Electroadhesive force/pressure measurement methods. (a) Normal EA force measurement. (b) Tangential EA force measurement. Dimension not shown to scale.

flexible substrate materials [66], [67]. Inkjet printing is, however, limited to a small subset of materials and is slow, expensive, and not well suited to in-house mass-production [68]. Screen printing EA pads involves transferring materials onto a substrate through mesh masks using blades or squeegees [69]. Different masks are, however, needed for different EA electrode patterns. Molding methods have been used to produce stretchable EA pads, but require different molds for different EA electrode geometries [17], [27]. Various other printing [70]–[73] and soft lithography techniques [74] have not been implemented but are worthwhile to investigate their feasibility for future EA uses.

We define subtractive EA pad manufacturing methods as fabrication solutions to produce EA pads by removing unwanted electrode and/or dielectric materials, as shown in Fig. 6(b), comprising mainly of two steps: 1) unwanted electrode or dielectric material removing and 2) electrode and dielectric bonding or laminating together (optional). The most straightforward and easiest EA fabrication method involves manual cutting of electrode pattern and bonding them to a dielectric film [75]–[77]. This method is low cost and easy-to-implement, but it is limited in terms of repeatability and accuracy. Laser cutting and desktop 2-D material cutting can be used to improve the electrode fabrication repeatability and accuracy but still involves manual bonding procedures [18]. Conventional machining methods such as milling and laser ablation have been used to remove unwanted electrode materials from a rigid copper laminate [78] and a gold-P(VDF-TrFE-CFE) film [79].

We define additive–subtractive EA pad manufacturing methods as fabrication solutions to make EA pads by removing unwanted electrode materials and then depositing dielectric materials to seal the electrodes, as shown in Fig. 6(c), comprising mainly of the following three steps:

1) electrode-dielectric laminate preparation;
2) unwanted electrode area removal;
3) cover dielectric deposition.

The most commonly used EA pad fabrication methods in the EA community have been printed circuit board (PCB) or flexible PCB (FPCB) based fabrication methods [24], [25], [39], [41], [58]. This usually consists of a chemical etching of copper laminates or electroplating of copper, followed by a dielectric film lamination [25] or conformal dielectric coating [41] for dielectric covering. These methods are easy to be implemented in-house or are easy to be procured commercially. They are cost-effective and efficient for large quantity in-house testing and mass-production.

Other complex fabrication methods, combining two or three additive and subtractive techniques, have also been used to manufacture miniature and high-resolution EA pads. Graule *et al.* [12] and Rivaz *et al.* [59] utilized electrode sputter deposition through a laser machined mask followed by a dielectric chemical vapor deposition. Zhang and Follmer [79] applied laser ablation to remove unwanted customized deposited electrode area, followed by a dielectric film lamination. More precision and customized EA pad manufacturing solutions, suitable for cost-effective and efficient mass-production, are needed. Insights from other mature flexible and stretchable electronics fabrication approaches [80]–[82] have potential and should be taken into consideration for EA pad fabrication.

C. *EA Pad Characterization Methods*

Characterizing the EA pads, in terms of material electrical and mechanical properties such as stiffness and resistivity [18] or impedance [56], surface conditions such as surface topography [24], and physical performances such as adhesive pressure [38], is required before their applications. The most commonly used EA pad characterization method is the measurement of the obtainable adhesive forces or pressures in normal (or direct) [24], [25] and tangential (or indirect) [39], [76] directions against time. We define the normal force direction as the one when the EA pad is pulled perpendicularly away from a substrate material [see Fig. 7(a)], and the tangential force direction as the one when the EA pad is sliding along a substrate material [see Fig. 7(b)]. A certain amount of charging time, be it 60 or 90 s [24], [28], is necessitated to produce stable forces before such force tests are conducted. Proper discharging methods, such as polarity reverse and natural discharging [25], [42], [59], and surface cleaning [49], [85], are always required to ensure repeatable measurement of forces. For stretchable EA pads, a two-axis stretching platform [27] or the inclusion of an inflating mechanism [18] is necessary to measure the adhesive forces whilst deforming the pads. In addition, the electroadhesive force is directly related to the capacitance of an EA pad. Measuring the capacitance of EA pads can be achieved via a capacitance measurement device [17] or finite element software [52].

For any controllable adhesion mechanisms including EA, it is essential to have a rapid and robust ON/OFF feature and long lifecycles for robotic pick-and-place. Measuring the release time of a designed EA pad is therefore essential for efficient and effective material handling applications, especially for extremely lightweight and flexible objects [86]. Consideration of the intrinsic surface adhesion that is a characteristic of some dielectric polymers is also required because this can result in unwanted residual stiction and slow disengagement. Removal of this intrinsic adhesion is required for reliable release time measurement and can be achieved by additional surface treatments or the application of a fine powder to the surface. The electric field developed around an EA pad can be measured using an electrostatic voltmeter and the dynamic electric field can be visualized via charging and discharging the pad in a fluid containing suspended particles. These methods are helpful to understand the dynamic EA phenomenon and to indicate field distributions of different pad geometries [87]. Lifecycle testing of EA pads is important in order to provide information for practical material handling applications [88].

As aforementioned, environment conditions such as humidity and temperature significantly influence the measured adhesive pressure. It is therefore necessary to conduct EA force tests in an environment-controlled chamber or in environmentally stable and clean lab conditions such as testing platforms developed by Guo *et al.* [25]. In addition, residual charges always exist in EA pads after turning OFF the high voltage application. In order to achieve repeatable adhesive pressure in a quicker way, methods including reversing the polarity, such as the work implemented by Brecher *et al*. [89] and natural residual charge dissipation, such as the work described by Guo *et al.* [24] should be taken to minimize the residual charges trapped in EA dielectrics.

IV. Applications of EA Technologies in Robotics

Due to the aforesaid benefits including enhanced adaptability, reduced complexity, low energy consumption, and gentle material handling characteristics, EA technologies have been extensively employed in robotics fields including gripping, crawling/climbing robotics, controllable and active adhesion units, and haptics. The following five sections aim to detail and categorize these applications.

A. Robotic End Effectors

Robotic end effectors are needed in various autonomous material handling applications. Robotic gripping or prehension methods are classified into four categories [90]:

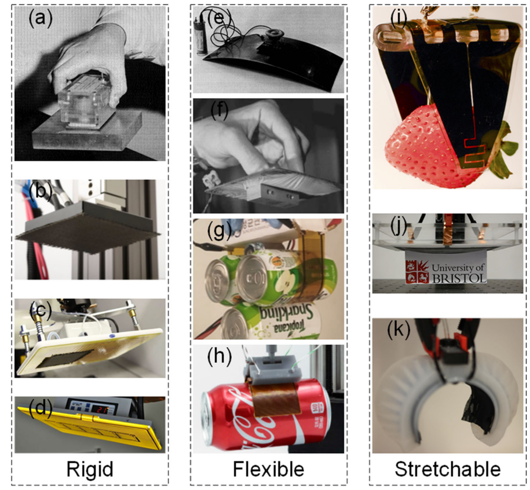

Fig. 8. Representative EA grippers. Rigid, including (a) NASA electroadhesor [14], (b) Fraunhofer IPT EA gripper [89], (c) Schmalz EA gripper, and (d) Grabit EA gripper [34]. Flexible or compliant, including (e) NASA flexible electroadhesor [14], (f) Monkman's compliant EA gripper [32], (g) Choi's flexible EA gripper [56], and (h) JPL flexible EA gripper [91]. Stretchable, including (i) Shintake's DEA-EA soft gripper [16], (j) Guo's EA-DEA soft composite gripper [17], and (k) Guo's PneuEA gripper [28].

1) Impactive methods that physically lift materials by a direct impact, including jaws and clamps;
2) Ingressive methods that physically penetrate into materials, including pins and hackles;
3) Astrictive methods that employ controllable and attractive forces applied to material surfaces, including suction, magnetoadhesion, and electroadhesion;
4) Contigutive methods that employ adhesion through direct contact, including chemical and thermal adhesion mechanisms.

Each technology has its strengths and weaknesses and has its own specific applications [90]. EA robotic grippers have unique advantageous over other methods, especially for pick-and-place of delicate, flexible, and porous materials in assembly lines. The most common and prominent use of EA technologies is as robotic end effectors for gripping, manipulation, or assembly tasks [14], [16], [17], [28], [32], [34], [83], [88], [89], [91], [92]. We classify existing robotic EA grippers into rigid, flexile/compliant, and stretchable forms, as shown in Fig. 8.

Rigid EA grippers include the NASA electroadhesor [14], the Fraunhofer IPT EA gripper [89], the Schmalz EA gripper, and the Grabit EA gripper [34]. Rigid EA grippers are useful for picking up large-area, relatively heavy and flat objects but cannot be used to lift non-flat shapes. Flexible or compliant grippers include the NASA flexible electroadhesor [14], the Monkman compliant EA gripper [32], the Choi flexible EA gripper [56], and the JPL flexible EA gripper [91]. Flexible EA grippers can be used to grip a wider range of challenging surfaces than rigid grippers, such as convex surfaces. Stretchable grippers include the Shintake DEA-EA soft gripper [16], the Guo EA-DEA soft composite gripper [17], and the Guo PneuEA gripper [28]. Stretchable EA grippers are usually equipped with shape-changing capability, which means they can be used to morphologically adapt to complex shapes using their morphing ability and then pick them up using their EA function.

B. Crawling and Climbing Robotics

Crawling and climbing robots are useful mobile robots that can adapt to various 2-D/3-D surfaces and terrains to conduct given tasks [6], [22], freeing human beings from risky tasks in hazardous (such as nuclear power plants) or difficult-to-access (such as confined pipelines) environments [22]. There are three key technologies associated with designing and prototyping crawling and climbing robots:

1) A robust and cost-effective adhesion method that enables them to reliably stick onto wall and floor surfaces;
2) An agile locomotion mechanism that enables them to move;
3) An energy efficient actuation and control system for activating the locomotion functions.

EA has been used as active feet or adhesion pads for climbing and crawling robotics since the first publication by Yamamoto *et al.* [79] in 2007. We classify the existing EA crawling or climbing robots into tracked, legged-1D (one-direction movement), and legged-2D (planar or two-direction movement) ones, as shown in Fig. 9.

Tracked locomotion-based EA climbing robots have the highest locomotion speeds but have limited capability crossing obstacles. Double tracks can be employed for turning. Representative tracked EA climbing robots include those developed by Yamamoto *et al.* [93], Prahlad *et al.* [7], Chen *et al.* [9], Koh *et al.* [65], and Wang *et al.* [8]. Legged-1D locomotion-based EA climbing robots typically employ in-plane sliding of two or more EA pads in a relatively thin body or connecting a linear artificial muscle with two EA feet. However, they are limited to low speeds, and cannot readily overcome cracks and obstacles. Representative legged-1D-based climbing robots include those developed by Yamamoto *et al.* [93], Prahlad *et al.* [7], and Wang and Yamamoto [95]. Legged-2D locomotion-based EA crawling and climbing robots further separate the EA pads from the actuation components and commonly employ a locomotion style resembling the inchworm. They can move across more complicated terrains such as gaps, cracks, and obstacles, but are still limited in speed. Representative legged EA crawling and climbing robots include those developed by Chen *et al.* [96], Zhu *et al.* [5], Digumarti *et al.* [97], Gu *et al.* [6], Wood *et al.* [59], Wu *et al.* [98], and Li *et al.* [100].

The most recent soft EA crawling robot developed by Qin *et al.* combined two vacuum-actuated spring actuators (for sliding and turning) with two EA feet and showed rapid (climbing speed of 0.049 body length/s) and effective locomotion in confined spaces and across gaps (0.15 body length) [99]. Control of simple EA crawling and climbing robots is straightforward and not complicated due to EA's inherent adaptability on various surfaces. Recently, Cao *et al.* [94] developed a data-driven control method for a dielectric elastomer actuator driven soft EA crawling robot that has environment adaptation capability on surfaces with different materials and inclined angles. Currently, there is a lack of fully autonomous EA crawling and climbing robots and there is consequently a need for fully untethered and autonomous robots which exploit EA for locomotion and gripping. This will require further development of EA pads, controllers, and energy components.

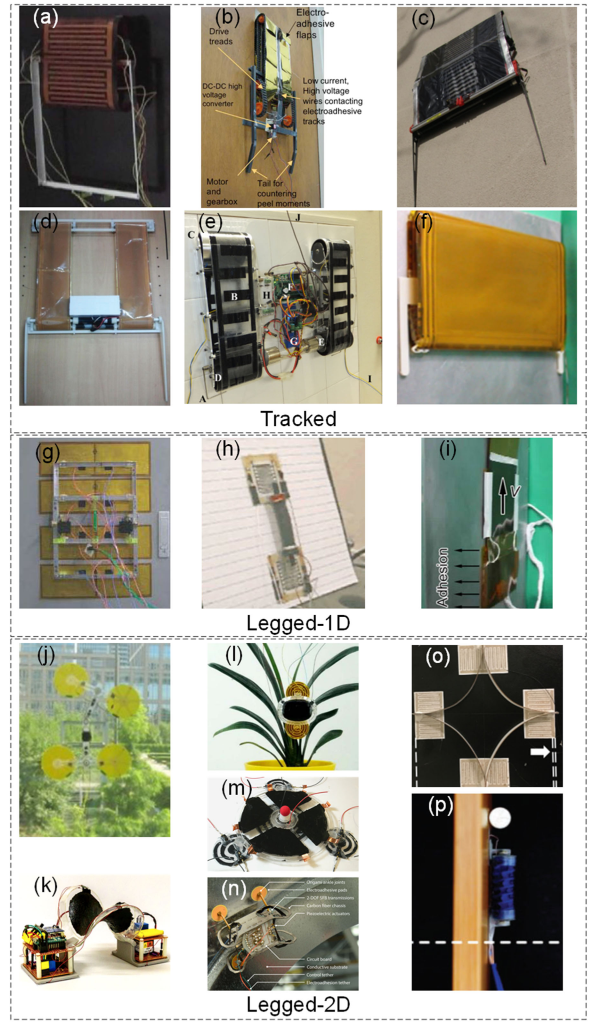

Fig. 9. Representative EA crawling and climbing robots. Tracked EA climbing robots include those developed by (a) Yamamoto [93], (b) and (c) Prahlad [7], (d) Chen [9], (e) Koh [65], and (f) Wang [8]. Legged-1D EA climbing robots include those developed by (g) Yamamoto [93], (h) Prahlad [7], and (i) Wang [95]. Legged-2D EA crawling and climbing robots include those developed by (j) Chen [96], (k) Zhu [5], (l) Gu [6], (m) Digumarti [97], (n) Wood [59], (o) Wu [98], and (p) Qin [99].

C. Active and Robotic Adhesion Units

Active and controllable (i.e., ON and OFF capability) adhesion and attachment mechanisms are useful for joining robotic elements [10], [11] and assisting robotic adhesion applications. These include composite stiffness tuning [101], surface traction [102], [103], surface anchoring [13], perching [12], clutching [104]–[106], page-turning [107], and improved sealing [108] (see Fig. 10). EA-based active and controllable adhesion has the feature of low energy consumption, making it a tantalizing solution for long-endurance robotic adhesion units.

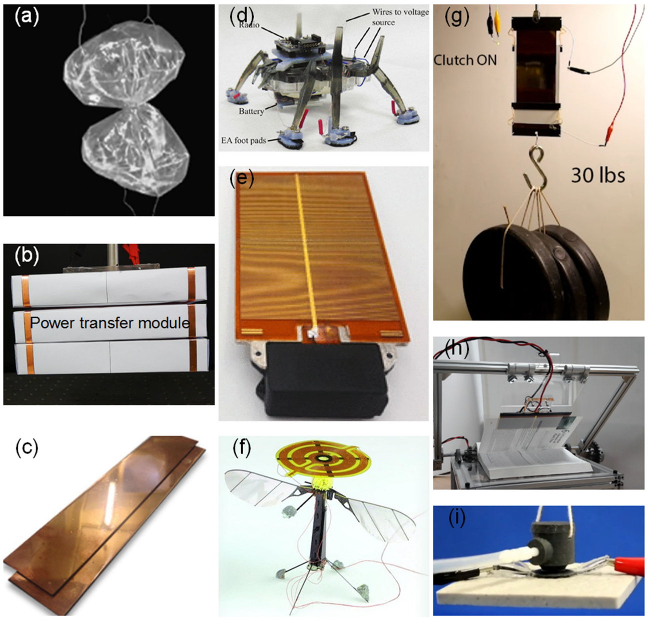

Fig. 10. Representative robotic applications using EA robotic adhesion. (a) Active connection mechanism for modular robotics [10]. (b) Electrically controllable connection and power transfer using paper EA [11]. (c) Composite structures with stiffness tuning [101]. (d) Crawling robots with dynamic turning capability [102]. (e) Active and controllable surface anchor [13]. (f) Controllable perching mechanism for flying robotics [12]. (g) Electroactive clutches for wearable applications [105]. (h) Page turning for automatic book scanning [107]. (i) Suction cups with enhanced seal and lifting capability [108].

In addition, EA has an appealing potential to produce extremely lightweight modular robots. Germann *et al.* [10] employed EA as an active connection mechanism for modular soft robotics. Guo *et al.* [11] applied low-cost paper EA to realize controllable connection and power transfer for self-assembling of modular parts. Heath *et al.* [101] used EA as a reversible latching mechanism and a means of controllable internal connection for fabricating composite structures with added functionality. Chen and Bergbreiter [102] and Wu *et al.* [103] applied EA as surface traction units for turning and crawling. Ruffatto *et al.* [13] integrated EA with a gecko-inspired adhesive as a surface anchor for extending task durations. Graule *et al.* [12] utilized EA as an active and controllable unit for robotic perching to save flying energy whilst conducting surveillance tasks. Diller *et al.* [104] and Ramachandran *et al.* [106] used EA for robotic clutching in wearable applications [105]. Lee *et al.* [107] utilized EA as a controllable adhesion unit assisting page turning for automatic book scanning. Okuno *et al.* [108] combined EA with a stretchable suction cup for enhanced sealing and lifting capability.

D. Haptic Devices

Haptic technologies are those techniques that can create a sense of touch by artificially stimulating the touch mechanoreceptors in human skin. This is normally achieved by employing mechanical mechanisms (e.g., ultrasonic vibration [109]) to physically stimulate the skin or electrical simulations to target subdermal nerve endings. Haptic devices such as touchscreens

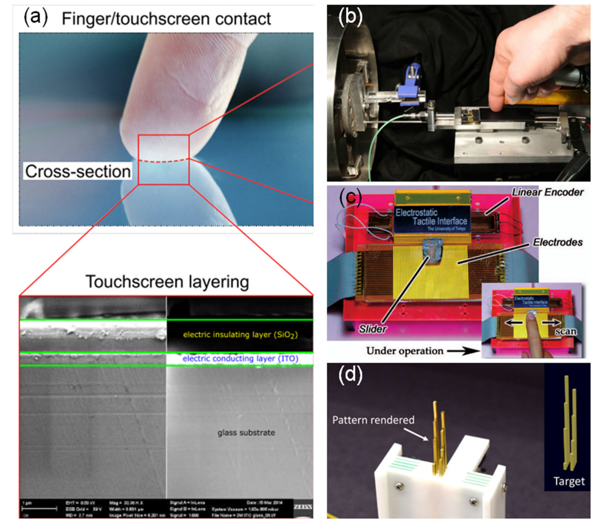

Fig. 11. Representative EA haptic devices. (a) EA capacitive touchscreen [114]. (b) eShiver EA artificial finger [119]. (c) EA tactile display [122]. (d) EA 2.5D tactile shape display [79].

and tactile displays have been developed for portable consumer electronics such as smartphones and tablet computers, and human–robot or human–computer interactions [110].

Two methods of exploiting EA in haptic feedback for touchscreen applications have been developed: electrovibration [111], [112], which uses ac voltages with varying amplitudes, frequencies, and waveforms; and electroadhesion [113], [114], which uses dc voltages. Tactile sensations are produced by modulating the friction between users and touchscreens in both methods. Both electrovibration and electroadhesion-based haptic rendering approaches involve the application of a voltage to a conductive electrode layer on a touchscreen, inducing electrostatic attractive or electroadhesive forces between the touchscreen and the user's finger. The ac signal used in electrovibration stimulates one or more of the tactile receptors in the finger (Merkel disks, Ruffini end organs, Meissener's corpuscle, and Pacinian corpuscle). By tuning the signal, different receptors can be targeted and hence different tactile sensations can be generated. The dc signal in electroadhesion tactile surfaces affects the apparent friction of the surface and therefore users must move their fingers in order to feel the tactile effect. Ayyildiz *et al.* [114] developed a theoretical model explaining the contact mechanics between the human finger and a touchscreen under EA and developed a soft capacitive touchscreen [113], as shown in Fig. 11(a). Vardar *et al.* [115], [116] developed roughness and sharpness perception electrovibration touchscreens. Shultz *et al.* [117] and Colgate *et al.* [121] developed several EA surfaces or artificial finger devices to deliver haptic sensations for touchscreen applications [118]–[120], as shown in Fig. 11(b).

Apart from touchscreens, tactile displays are important haptic devices for virtual reality applications and people with visual impairments. Various tactile displays based on dc motors, shape memory alloys, piezoelectric elements, pneumatic actuators, electrostatic actuators, and dielectric elastomer actuators (DEAs) [122]–[124] have been developed. EA-based tactile

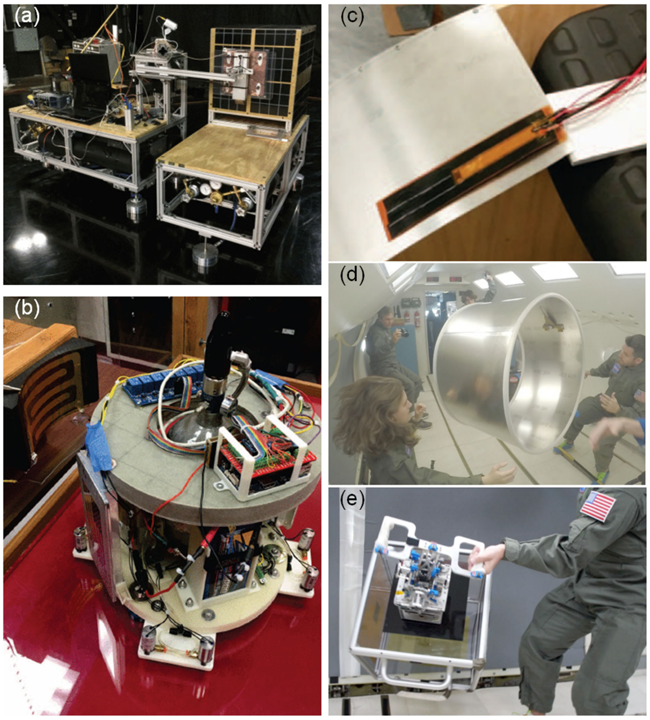

Fig. 12. Representative EA devices designed for space applications. (a) and (b) EA devices for docking tasks in space [125], [126]. (c) Surface adaptive EA pad designed to retrieve orbital debris [127]. (d) Climbing robot used in a NASA zero gravity airplane [128]. (e) EA material handling device for space applications [128].

displays, in comparison, are lightweight, low-cost, and offer higher resolutions. Examples include the electrostatic tactile display developed by Yamamoto *et al*. [122] [see Fig. 11(c)] and a cost-effective and high spatial resolution refreshable 2.5D tactile shape display (EA units were employed as active brakes) developed by Zhang and Follmer [79], as shown in Fig. 11(d).

E. Space Applications

Space is an intriguing but challenging area to be explored. This is because the space environment is extremely harsh. Specific characteristics include zero gravity, high vacuum (no air), ultra-high or low temperature, and intensive ultraviolet irradiation. The challenging environment in space must be considered when designing and manufacturing EA materials and structures. EA technologies have been playing important roles in aerospace activities both outside and inside of aerospace cabins. Their applicability in space tasks, such as docking [125], [126], orbital debris removal [127], surface crawling and climbing [128], and material handling [14], [128]–[130], is shown in Fig. 12.

Specifically, Leung *et al.* [125] and Ritter and Barnhart [126] employed EA as a controllable docking method, aiming for spacecraft and satellite servicing tasks in harsh space environment. Saravia and Udrea presented a surface adaptive EA gripper, combining macro fiber composites with EA pads, aiming for retrieving orbital debris [127]. Parness *et al.* [128] applied EA technologies into crawling/climbing and material handling devices and tested them in a NASA zero gravity airplane. Krape [14], and Beasley *et al.* [129], and Bryan *et al.* [130] utilized EA grippers as end effectors for pick-and-place of materials in a simulated spacecraft environment. Recently, a collaboration between Stanford University and Jet Propulsion Laboratory has been funded to develop stretchable and cloth EA for spacecraft docking, astronaut space suits, and spacewalk gripping applications [131].

V. Discussions

Although EA has unique benefits, as aforementioned, there are several limitations associated with this technology. These include the following:

1) The application of EA requires a relatively high voltage which brings extra health and safety considerations if living creatures are involved (although this is mitigated by the small currents, typically in the range of μA, that are used);
2) The resultant EA adhesive pressure is relatively low and can be unstable;
3) Current EA devices lack rapid adhesion and deadhesion capability on a wide range of materials;
4) Current EA devices are still not robust (intelligent and adaptive) enough to adhere to, or lift, challenging surfaces in changing environments.

It is suggested to regard these limitations as drivers for research opportunities rather than obstacles for further development.

A. EA Rapid Adhesion and Deadhesion Capability

EA is a complicated and dynamic electrostatic attractive effect [87]. The dynamic behavior means that it takes a finite time for the maximum EA force to be generated (adhesion) when the EA system is turned ON, and a finite time for force to decay (deadhesion) when the EA system is turned OFF, due to the residual charges trapped in the EA dielectrics [87]. This motivates the development of methods to speed up the EA adhesion and deadhesion processes. In order to increase the adhesion speed, the temporary application of a high voltage above the normal holding voltage can be used. Once the EA force has developed, this voltage can be reduced to the holding voltage. Various de-electroadhesion methods have been proposed and implemented to accelerate the EA dechucking process. These can be classified into mechanical and electrical methods. Mechanical solutions include the use of vibrations [31], [132], pegs, and air jets [20], as proposed and implemented by Monkman *et al*. These significantly complicate the EA system, but they can deliver almost instantaneous release of objects. In addition, Gao *et al*. [86] implemented a vibration-based rapid release method by exploiting the resonant vibration of an embedded dielectric elastomer actuator. Xiang *et al*. [18] employed a pneumatic actuation-based vibration method to facilitate fast EA release. Electrical solutions include advanced voltage control methods and their associated electronics. Horwitz (ElectroGrip Co., USA) patented two methods using oscillating release waveforms and adaptive release voltages [133]. Brecher *et al*. [86]

(Fraunhofer IPT, Germany) implemented a method using an exponentially decreasing reverse polarity voltage. Prahlad *et al.* [134] (SRI International, and Grabit Inc., USA) patented a varying polarity voltage (based on different output voltages) method. These methods usually require skilled or experienced experts to be implemented. Singh *et al*. [78] demonstrated that EA pads made of bare electrodes were good at releasing rubber gloves quickly, although seconds were still needed for most of the results presented and only a limited number of materials were studied. We therefore still need a cost-effective, easy-to-implement, lightweight, and robust rapid EA deadhesion solution for dechucking all materials.

B. Intelligent EA

In order to pick-and-place materials and objects in unstructured and changing environments in a robust and safer way, EA systems capable of proprioceptive and exteroceptive sensing are inextricably needed. We define exteroceptive EA systems as those that can sense and react to external stimuli such as material types, contact conditions, and environmental conditions. We define proprioceptive EA systems as those which can sense their own deformations or internal strains. This proprioceptive EA concept is analog to the self-sensing methods employed for DEAs, where simultaneous actuation and sensing are achieved without any additional external sensors [135]–[137]. In response, Guo *et al.* [19] proposed the adaptive and intelligent EA concept to equip EA systems with intelligence and autonomy so that EA grippers can output robust adhesive forces on a range of materials and different humidity levels. Saravia and Udrea [127] combined macro fiber composite actuators with a flexible EA pad so that it can sense its own deformations (proprioceptive sensing). Guo *et al.* [28] integrated two soft touch sensors onto a soft EA gripper so that it can detect the external proximity and contact (exteroceptive sensing). In addition, Guo *et al.* [17] developed a EA-DEA composite gripper that is not only proprioceptive as it can sense its internal deformations but also exteroceptive as it can sense and differentiate between surfaces that it touches. Recently, Guo *et al.* [84] proposed and developed a customized capacitance measurement method to enable an autonomous material handling system without embedding external sensors due to the fact that the EA pad can not only be used as an end effector but also as a sensor. This self-sensing EA concept can be used to detect a wide range of materials, surface conditions, and environmental conditions. Joint and further efforts on the development of robust, high-resolution, and quicker proprioceptive and exteroceptive sensing algorithms are necessitated.

C. Shape-Adaptive EA

Conventional rigid EA grippers can only be used to lift flat surfaces. Equipping EA gripper with shape-changing capability is highly desirable so that EA robotic end effectors can be used to lift complex-shaped and uncooperative materials and surfaces [138]. To this end, Shintake *et al*. [16] developed an elegant and ultra-lightweight DEA-EA (a combination of DEA and a soft EA pad) soft gripper that has morphologically adaptive functionality to grip both flat, convex, and deformable objects. Guo *et al.* [17] also produced an EA-DEA shape-adaptive gripper to lift complex concave surfaces. Schaler *et al.* [91] implemented a flexible EA gripper that can be used to grip curved surfaces, although a tendon driven mechanism was used. Guo *et al.* [17] proposed a soft PneuEA gripper, a combination of a two fingered soft pneumatic actuator and a soft EA gripper, to handle flat materials and flexible objects from convex surfaces, and a soft TacEA gripper, an integration of a pneumatically actuated visio-tactile sensor and a stretchable EA pad, which was able to sort different 2D sizes and shapes and actively grip flat, concave and convex objects [18]. These two shape-adaptive EA grippers, however, require the employment of a cumbersome and energy-intensive pneumatic actuation unit. Further cost-effective and lightweight shape-adaptive EA robotic end effector designs, drawing insights from existing morphable materials and structures [139], [140] or nature [141], are still needed in the EA community.

D. Advanced EA Modeling

Currently, there is still a lack of comprehensive and in-depth understanding of the EA phenomenon. No accurate and reliable dynamic EA models (such as for the dynamic coplanar EA force) have been published due to the challenge of modeling the high voltage polarization and dielectric relaxation effects and difficulties in experimentally validating the fundamental molecular-level interactions. FEA simulations may eliminate some of the difficulties associated with analytical EA modeling. Advanced 3-D EA simulation models may provide hints to optimized EA pad designs. Currently, there is, however, no EA simulation model that can represent the dynamic EA force after the application of a high voltage and the dynamic EA residual force after the termination of the power supply. Clearly, a better understanding of the EA problem and future effective exploration of EA technologies are contingent on more advanced modeling of the EA phenomenon.

E. Advanced EA Pad Design and Fabrication

EA pad patterns play a significant role in achieving adhesive forces. It was found that nonsymmetrical EA pad patterns can develop nonuniform adhesive forces [10], whereas symmetrical EA pad geometries develop more uniform adhesive forces [58]. EA structural configurations are also important. A bilayer EA electrode configuration may bring a greater adhesive force and better resilience to higher voltages [40]. EA material selection is a key to an improved adhesive pressure and more stable force output. The limitations of using high voltages mean that in practice, relatively smaller forces are generated compared to other adhesion mechanisms. Additionally, the adhesive force can be unstable if there is a significant environment change. Coating EA pads with novel dielectric materials would produce environmentally stable forces in a range of changing humidities and temperatures [41]. The EA community still lacks advanced EA electrode pattern designs, better electrode/dielectric configurations, novel electrode and dielectric materials, and cost-effective, mass-producible EA pad fabrication methods. We can, however, borrow manufacturing techniques from flexible and

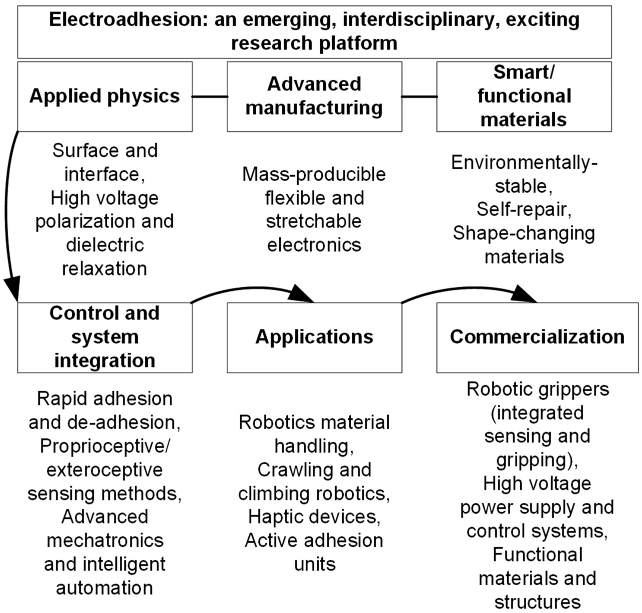

Fig. 13. Complete development pipeline from theoretical understanding to commercialization of EA technologies.

stretchable electronics [80]–[82], in order to produce EA pads with greater and more robust adhesive forces in changing environments, quicker adhesion/deadhesion response, lower voltage application, and longer life-cycles.

VI. Conclusion

Since the inception of electroadhesion in the 1910s, several key applications have been introduced, enabling technological advances that range from robotic gripping, crawling, and climbing to active adhesion/attachment, haptics, and applications in space applications. If we use the NASA technology readiness level (TRL) from 1 to 9, most current EA technologies, however, may only be regarded as TRL 1-3. This is because it takes a significant endeavor in terms of time and resources to completely understand the physical EA effect, to repeatably design, fabricate, and test the EA pads, to integrate parts together for a specific task reliably, and to commercialize the technology. The lack of this understanding and dedicated efforts devoted to EA technologies precludes their rapid integration into everyday life.

It has been identified that a continuous increase in research on EA is foreseeable and required. There is no detailed and comprehensive summarization and discussion of EA technologies yet. To this end, a survey of the working principle, modeling, design, fabrication, characterization, and applications of EA technologies in robotics was presented in this article. Discussions on existing EA rapid adhesion and deadhesion, intelligent EA, shape-adaptive, advanced EA understanding solutions and their limitations were also described, showing that joint efforts are urgently needed.

To unleash the vast potential of EA technologies, a concerted effort across the development pipeline from fundamental physics and materials to advanced manufacturing and control is required. EA can be regarded as an emerging, interdisciplinary, fertile, and exciting research platform to study the related fundamental physics such as high voltage-based dynamic polarization and depolarization, to inspire and develop advanced EA pad fabrication methods, to promote the engineering of environmentally stable, shape-changing (for shape-adaptive adhesion and gripping), soft-smart (for delicate adhesion and gripping), and self-repair (for generating self-healing EA with enhanced robustness and life cycle) materials, and to develop advanced sensing and control algorithms (for intelligent EA). With these in place the EA community will be able to satisfy the needs of many more industries and applications and thereby ensure the mature technology commercialization of electroadhesion (see the development pipeline in Fig. 13). Further and more applications beyond robotic material handling, crawling/climbing robotics, surface haptics, and active/controllable adhesion are set to benefit from future advanced EA technologies.

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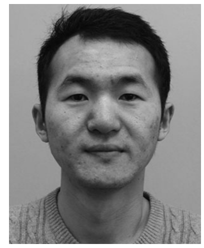

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