

SOFT ELECTROADHESIVE DEVICES WITH IONIC GEL ELECTRODES**CROSS-REFERENCE TO RELATED APPLICATION**

[0001] This application claims the benefit of priority to the Singapore application no. 10202251469Y filed October 22, 2022, the contents of which are hereby incorporated by reference in their entirety for all purposes.

TECHNICAL FIELD

[0002] This application relates to soft devices or manipulators that can generate electroadhesive forces, and in particular, to actuators and manipulators capable of generating electroadhesive forces using ionic gel electrodes and elastomer layers.

BACKGROUND

[0003] In industrial applications, the material handling apparatus is often required to manipulate and/or transport various types of articles of various weight, shape, and surface roughness, etc. Owing to the nature of electroadhesion, it can be difficult to generate sufficiently robust forces for many manipulation tasks. Thus, conventionally, electroadhesion is generally used for holding small and/or flat objects of low mass.

SUMMARY

[0004] In one aspect, the present application discloses a device including a prestretched layer, a first passive layer, a first actuator electrode, and a second actuator. The prestretched layer has a first surface and a second surface defining a variable thickness therebetween. The first passive layer defines an actuator surface and a third surface. The first actuator electrode is disposed between the first surface of the prestretched layer and the actuator surface of the first

passive layer. The second actuator electrode is disposed on the second surface of the prestretched layer. The first actuator electrode and the second actuator electrode are characterized by an actuator electrode gap corresponding to the variable thickness of the prestretched layer. Each of the first actuator electrode and the second actuator electrode is formed of an ionic gel.

[0005] In another aspect, the device integrates a dielectric elastomer actuator with an electroadhesion member. The dielectric elastomer actuator includes a prestretched layer disposed between a first actuator electrode and a second actuator, in which the first actuator electrode and the second actuator electrode is each formed of an ionic gel, and in which the prestretched layer is formed of an elastomer. The first actuator electrode and the second actuator electrode define an actuator electrode gap across the prestretched layer. The device includes a first passive layer, in which one surface of the first passive layer is coupled to one of the first actuator electrode and the second actuator electrode, and in which another surface of the first passive layer is coupled to the electroadhesion member. The electroadhesion member includes a first electroadhesion electrode and a second electroadhesion electrode disposed on a contact layer, in which each of the first electroadhesion electrode and the second electroadhesion electrode is formed of the ionic gel, and in which the contact layer is formed of the elastomer. The first electroadhesion electrode and the second electroadhesion electrode include respective first electrode fingers and second electrode fingers, in which the first electrode fingers and second electrode fingers define an electroadhesion electrode gap therebetween. The first electrode fingers and the second electrode fingers are interleaved to define a sinuous electroadhesion electrode gap. The first electroadhesion electrode and the second electroadhesion electrode are disposed in a plane orthogonal to a stacking axis along which the first actuator electrode layer, the prestretched layer, and the second actuator electrode are stacked.

[0006] In another aspect, the present application discloses a gripper suitable for use in handling an object. The gripper includes a connector and two or more of the devices. Each device has a proximal end and a distal end. The proximal end is coupled to the connector with the respective first electroadhesion electrode and the second electroadhesion electrode being positioned at the distal end.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Various embodiments of the present disclosure are described below with reference to the following drawings:

[0008] **FIG. 1A** shows a schematic illustration of an ionic gel including crosslinked polymer chains and a swollen solvent;

[0009] **FIG. 1B** shows a inkjet printing process that patterns ionic gel features on an elastomer substrate;

[0010] **FIG. 1C** shows an optical microscopic image of inkjet-printed lines of an ionic gel;

[0011] **FIG. 1D** shows a 3D topography and cross-sectional profile of the inkjet-printed ionic gel captured by a confocal microscope;

[0012] **FIG. 2A** is a schematic exploded view of the present device illustrating structural features of a DEA hybridized with a soft electroadhesive member in accordance with embodiments of the present disclosure;

[0013] **FIG. 2B** is an exploded cross-sectional view of the device of **FIG. 2A**;

[0014] **FIG. 2C(i)** to **FIG. 2C(iii)** are schematic diagrams illustrating one method of integrating a bias in the DEA of **FIG. 2A**;

[0015] **FIG. 2D(i)** and **FIG. 2D(ii)** are schematic diagrams illustrating a bending mechanism of the DEA of **FIG. 2A**;

- [0016] **FIG. 2E** and **FIG. 2F** are perspective views of different embodiments of the device of **FIG. 2A**;
- [0017] **FIG. 2G** shows the equivalent circuit of the device of **FIG. 2A**;
- [0018] **FIG. 3A** is a schematic exploded view of an electroadhesive member showing an organized stack of ionic gel electrodes, elastomer layers, and a hydrophobic coating;
- [0019] **FIG. 3B** shows an equivalent circuit of the electroadhesive member of **FIG. 3A** with two capacitive EDL and one capacitive EA connected in series;
- [0020] **FIG. 3C** and **FIG. 3D** are schematic top views showing the geometry of an exemplary electroadhesive member;
- [0021] **FIG. 3E** is a schematic diagram showing an orientation of the electroadhesion electrode gap relative to the actuator electrode gap;
- [0022] **FIG. 4A** shows the electric field and charge distribution when a soft electroadhesive member is adhering to a conductive/semiconductive surface;
- [0023] **FIG. 4B** shows the electric field and dipole polarization when a soft electroadhesive member is adhering to a dielectric surface;
- [0024] **FIG. 5A** shows a setup for normal electroadhesive force measurement;
- [0025] **FIG. 5B** shows measured normal electroadhesive forces on aluminum and glass substrates;
- [0026] **FIG. 5C** shows a setup for shear electroadhesive force measurement;
- [0027] **FIG. 5D** shows normal and shear adhesion forces generated by the soft electroadhesive member on various materials under 1 kV (standard deviation: $n = 5$);
- [0028] **FIG. 6A** and **FIG. 6B** show schematic illustrations of electrodes with the voltage on and off respectively, revealing the mechanism behind a slow release from a metallic surface when an electrical conductor is used as the electrodes;

[0029] **FIG. 6C** and **FIG. 6D** show schematic illustrations of electrodes with the voltage on and off respectively, revealing the mechanism behind a rapid release from a metallic surface when ionic gel is used as the electrodes;

[0030] **FIG. 7A** shows recorded shear forces during an exemplary shear force test;

[0031] **FIG. 7B** shows recorded charge, discharge, and leakage current of an activated electroadhesive member on aluminum under 1 kV;

[0032] **FIG. 8A** and **FIG. 8B** are schematic diagrams illustrating a gripper in various states, according to embodiments of the present disclosure;

[0033] **FIG. 9A(i)** to **FIG. 9A(iv)** are images showing a process in which the present gripper grips, lifts, and then releases a metallic cube;

[0034] **FIG. 9B(i)** and **FIG. 9B(ii)** are images showing that the present gripper can lift a 215g object by harnessing the large shear forces generated between the electroadhesive end effectors and the metallic cube;

[0035] **FIG. 10A(i)** to **FIG. 10A(iii)** are images showing the present gripper conforming to the cylindrical profile of a glass bottle;

[0036] **FIG. 10B(i)** to **FIG. 10B(iii)** are images showing the gripper conforming to the spherical profile of a cherry tomato;

[0037] **FIG. 11A(i)** and **FIG. 11A(ii)** are images showing that the gripper can pick up a piece of soft and fragile tofu without damaging the tofu;

[0038] **FIG. 11B(i)** and **FIG. 11B(ii)** are images showing that the gripper can pick up a soft and deformable flower without compressing the flower;

[0039] **FIG. 11C** is an image showing that the gripper can pick up a piece of flat leaf utilizing normal electroadhesive force;

[0040] **FIG. 11D** are images showing that the gripper can collect paper shreds utilizing normal electroadhesive force;

[0041] **FIG. 11E** are images showing the gripper can collect micrometer-scale metallic particles utilizing normal electroadhesive force;

[0042] **FIG. 12A** is a schematic block diagram of a system in which a gripper of the present disclosure is incorporated with a proximity sensing function;

[0043] **FIG. 12B** is a plot of the relative capacitance change detected by a gripper of the system of **FIG. 12A**; and

[0044] **FIG. 12C** and **FIG. 12D** are images showing experimental results demonstrating the gripper's ability to distinguish between proximity of an object and physical contact with the object.

DETAILED DESCRIPTION

[0045] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0046] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0047] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0048] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0049] As used in the present disclosure, the term "ionic gel" refers to a composite material including a network of polymer that swells and which contains a solvent in which mobile ions are dissolved to render ionic conductivity. Ionic gels are mechanically soft and extendable (e.g., elastically deformable), with an elastic modulus ranging from about 1 kPa (kilopascals) to about 100 kPa. **FIG. 1A** depicts an exemplary illustration of the constituents of an ionic gel 850. The ionic gel includes a polymer network or a polymer matrix 856 distributed in a swollen solvent 854. The polymer matrix 856 may be either physically crosslinked via physical interactions, or chemically crosslinked via covalent chemical bonds. The degree of crosslinking 858 may be selected to define the mechanical, physical, and/or chemical properties of the ionic gel 850. The swollen solvent 854 may be a pure solvent or a mixture of a plurality of solvents, selected from water or organic solvents.

[0050] In some embodiments, the ionic gel 850 may include a crosslinked network of neutral polymers, a solvent swollen in the polymer network, and mobile ions (e.g., mobile cations and mobile anions) dissolved in the solvent. For use in forming part of the present device, neutral polymers capable of forming an ionic gel may be selected. Examples of suitable neutral polymers include, but are not limited to any one or more selected from the following: polyacrylate, polyacrylate derivatives, polyethylene glycol, polyethylene glycol derivatives, polyvinyl alcohol, polyvinylpyrrolidone, polyhydroxyethyl methacrylate, and/or a plurality of copolymers with abundant groups for crosslinking. In some embodiments, the ionic gel 850 may include: a crosslinked network of polyion whose backbone may be positively charged or negatively charged, a solvent swollen in the polyion network, and mobile counterions dissolved in the solvent. As used herein, the term "counterions" refer to mobile ions released from the polyion and are oppositely charged against (or relative to) the polyion backbone. Examples of polyions capable of forming ionic gels include, but are not limited to, polyacrylic acid, poly(2-

acrylamido-2-methylpropane sulfonic acid), poly(diallyl dimethylammonium chloride), and polystyrene sulfonate.

[0051] As used in the present disclosure, the term "elastomer" may be understood according to its ordinary meaning and refers to a polymeric material with elasticity. Elastomers may be amorphous polymers or semicrystalline polymers that exist above their glass transition temperature. Segmental motion in the polymer chains renders an elastomer soft and deformable. Covalent crosslinking among the polymer chains allows an elastomer to be highly stretchable under stress, and allows the elastomer to return to its original state when the stress is released or removed. Elastomers selected in various embodiments of the present disclosure may be selected from elastics having an elastic modulus in a range from about 100 kPa to 50 MPa (megapascals). Examples of elastomers that may be selected for use in making parts of the present device include, but are not limited to, any one or more of the following: polysiloxanes, polyurethanes, latex, acrylic elastomers, and styrene-butadiene elastomers.

[0052] The device of the present disclosure may be manufactured using a method involving a step of selectively depositing an ionic gel (selected as described above) in a predetermined pattern on a selected surface of a substrate, in which the substrate is made of an elastomer as described above. The method may be any one of various additive manufacturing methods, including but not limited to inkjet printing, extrusion 3D (three-dimensional) printing, and stereolithographic 3D printing. In some embodiments, the method employed is configured to deposit a pattern of one or more ionic gels at a relatively high spatial resolution in a range from about 100 nm (nanometers) to about 100 μ m (micrometers). A precursor ink or paste of the ionic gel 850 may be prepared in accordance with the rheological and chemical requirements of the selected method.

[0053] **FIG. 1B** is a perspective and partial cross sectional schematic diagram showing a drop-on-demand (DOD) inkjet printing apparatus 950 depositing ionic gel features 860 on a

substrate 870. According to various embodiments of the present disclosure, the ionic gel is configured to include a polyion polymer network and a water-glycerol binary solvent such that the viscosity of the ionic gel as extruded is suitable for DOD printing of a pattern on a polyurethane substrate. Inkjet-printed features such as ionic gel lines 860 can be characterized by a relatively high line-printing resolution of about 35 μm and a minimal discrimination of about 20 μm between the printed features. For example, as shown in the optical microscope image of **FIG. 1C**, the ionic gel lines 860 could be printed with substantially consistent widths of 71.5 μm , 54.0 μm , and 34.7 μm , respectively. In **FIG. 1D**, the corresponding 3D topography of a cross-sectional profile of the inkjet-printed ionic gel lines of **FIG. 1C** is presented with an image of the printed features as captured by a confocal microscope. The thickness of a single-layer printed path can be below 1 μm with a substantially uniform profile. The ionic gel proposed herein is therefore demonstrated to enable sufficiently precise 3D printing for making the present device.

[0054] In some embodiments, the present device 200 includes a beam-like (or elongate) dielectric elastomer actuator (DEA) 230 and a soft electroadhesive member 500 as depicted schematically exploded along a stacking axis 203 in a perspective view in **FIG. 2A** and in a cross-sectional view in **FIG. 2B**. Embodiments of the present device 200 includes a DEA 230 operable as a continuum actuator, in which the DEA 230 includes a first actuator electrode 301 and a second actuator electrode 302 disposed to define an actuator electrode gap 450 across a thickness of the prestretched layer 400. Embodiments of the electroadhesive member 500 includes a first electroadhesive electrode 501 and a second electroadhesive electrode 502 disposed on a surface (fourth surface 333) of the contact layer 330, such that the first electroadhesive electrode 501 and a second electroadhesive electrode 502 define an electroadhesive electrode gap 550 parallel to the surface (fourth surface 333).

[0055] The DEA 230 may be configured as a continuum actuator capable of imparting autonomous movement. In the present disclosure, the term "continuum actuator" refers to an actuator or an actuatable device that encompasses infinite degrees of freedom and number of joints for continuous deformation. The continuum actuator may be formed using soft materials in order not to restrain compliance to a target or an object of actuation. In this example, the DEA 230 can actuate with infinite degrees of freedom at least along a longitudinal axis 201.

[0056] In some embodiments, the device 200 may be described in terms of variations of a dielectric elastomer actuator (DEA) 230. The DEA 230 may include a dielectric prestretched layer 400 sandwiched by a pair of compliant first actuator electrode 301 and second actuator electrode 302. The two actuator electrodes (e.g., first actuator electrode 301 and second actuator electrode 302) may be respectively connected to either opposing surfaces 410,420 of the elastomer prestretched layer 400. In the DEA 230, two actuator electrodes (e.g., first actuator electrode 301 and second actuator electrode 302) may be oriented substantially parallel to one another and to the longitudinal axis 201. For easy reference, the longitudinal axis 201 and the stacking axis 203 are oriented orthogonally as illustrated. The first actuator electrode 301 and the second actuator electrode 302 are spaced apart by an actuator electrode gap 450 that corresponds to a thickness 440 of the prestretched layer 400.

[0057] Each of the first actuator electrode 301 and the second actuator electrode 302 may be provided by respective solid electrodes 340 (e.g., made of carbon, copper, or other suitable conductive metals, etc.) for electrical connection to the rest of a system 120, such that a potential difference may be provided across the first actuator electrode 301 and the second actuator electrode 302. As used herein, the terms "voltage drop", "voltage", and "potential difference" may be used interchangeably and generally refers to the provision of an electrical current or a "power on" state.

[0058] The DEA 230 may be encased in an elastomer. In some example, the DEA 230 may be sandwiched by a first passive layer 310 and a second passive layer 320. The first passive layer 310 and the second passive layer 320 may be contiguous or joined with one another along their perimeters. In various embodiments, the first actuator electrode 301 may be a volume of the ionic gel 850 deposited on the first passive layer 310 such that the first actuator electrode 301 forms an elongate body with a length generally extending parallel to the longitudinal axis 201 and the second actuator electrode 302. In various embodiments, the second actuator electrode 302 may be a volume of the ionic gel 850 deposited on the second passive layer 320 such that the second actuator electrode 302 forms an elongate body with a length generally extending parallel to the longitudinal axis 201 and the first actuator electrode 301.

[0059] The prestretched layer 400 is made of an elastomer or an elastic dielectric material. In some examples, the prestretched layer 400 is made of the same material as either or both of the first passive layer 310 and the second passive layer 320. In some examples, the first passive layer 310 and the second passive layer 320 are formed of the same elastomer of different thicknesses, and the prestretched layer 400 is substantially formed from a prestretched elastomeric material. For example, a piece of elastomer may be stretched (401) along a longitudinal axis 201, as depicted in **FIG. 2C(i)** to form a prestretched material 400'. The prestretched material 400' may be coupled to an unstretched material 310' such that the resulting composite 400'/310' is biased towards a curved or bent shape, as depicted in **FIG. 2C(ii)**. In various embodiments, the DEA 230 (and hence the device 200 as a whole) can be given a built-in bias towards a curve along the longitudinal axis 201 by a fabrication method such as this. **FIG. 2C(iii)** shows an example where a voltage is provided across electrodes on either side of the thickness of the prestretched material 400', causing the composite 400'/310' to deform into a straighter configuration (relative to the curved configuration of **FIG. 2C(ii)**).

[0060] To aid understanding, **FIG. 2D(i)** further shows a sample section of the prestretched layer 400 sandwiched between corresponding parts of the first actuator electrode 301 and the second actuator electrode 302. As shown in **FIG. 2D(ii)**, when a voltage drop (potential difference) is applied across the first actuator electrode 301 and the second actuator electrode 302, the prestretched layer 400 will be compressed (undergo compression 402) in response to the electrostatic attraction generated from the opposing charges on the opposing first actuator electrode 301 and second actuator electrode 302. The prestretched layer 400 is characterized by a constant volume of an elastomeric material under uniaxial stress (prestretched), such that an in-plane expansion (404) can be produced in response to a contraction in the thickness 440 of the prestretched layer 400. The in-plane expansion may be transformed into bumping or bending motions depending on the structural features of the device 200 or the DEA 230. In other words, responsive to an actuation of the pair of the first actuator electrode 301 and the second actuator electrode 302, elastic potential energy in the sandwiched elastomeric prestretched layer 400 is released, resulting in a bending curvature or a bending moment to the DEA 230, e.g., the DEA 230 may undergo an angular deformation (δ) relative to a default state of the DEA 230, as illustrated in **FIG. 2E**.

[0061] In some examples, the first passive layer 310 and the second passive layer 320 may be compositionally similar and geometrically different. In some examples, the first passive layer 310 is thicker than the second passive layer 320. In some examples, the first passive layer 310 is about 80 μm thick, the prestretched layer 400 is about 80 μm thick, and the second passive layer 320 is about 60 μm thick. The contact layer 330 may be an elastomer of about 60 μm in thickness. In the default state or the "power off" state, the device 200 in this example is curved (e.g., curved away from the contact surface or exposed surface 335 of the contact layer 330, or curved towards the second passive layer 320). In the actuated state or the "power on" state, the DEA 230 may straighten as a result of undergoing a deformation (δ). **FIG. 2F** illustrates another

configuration of the device 200 in which the device is biased in an opposite manner to the example of **FIG. 2E**.

[0062] As illustrated in the exploded views of **FIG. 2A** and **FIG. 2B**, the device 200 may further include an electroadhesive member 500. The electroadhesive member 500 may include a pair of a first electroadhesion electrode 501 and a second electroadhesion electrode 502, and a contact layer 330, with an electroadhesion electrode gap 550 between the first electroadhesion electrode 501 and the second electroadhesion electrode 502 (as will be described with reference to **FIGS. 3A** to **3D** below). The electroadhesive member 500 is configured to provide a flexible and/or soft area disposed at a distal end 210 of the device 200. The electroadhesive member 500 may be disposed on the third surface 313 of the first passive layer 310. The electroadhesive member 500 may be sandwiched between the first passive layer 310 and a fourth surface 333 of a contact layer 330. The electroadhesive member 500 includes the contact layer 330, with the contact surface 335 of the contact layer 330 facing outwards to interface with one or more objects 900 to be manipulated or handled.

[0063] The electroadhesive member 500 may be formed using a similar selection of materials as the DEA 230. For example, the first actuator electrode 301 and the second actuator electrode 302 of the DEA 230 may be made of the same materials as the first electroadhesion electrode 501 and the second electroadhesion electrode 502. For example, the contact layer 330 and the prestretched layer 400 may be formed of the same elastomer material. Advantageously, the device 200 can be formed layer-by-layer by additive manufacturing. The various layers may be stacked or formed as a monolithic article.

[0064] **FIG. 2G** depicts an electrical circuit representation of the hybridized device 200. According to various embodiments of the present disclosure, the DEA 230 (represented at the left side of the circuit) and the electroadhesive member 500 (represented at the right side of the circuit) can be activated individually, e.g., the DEA 230 and the electroadhesive member 500

may be actuated independently of one another, while yet cooperatively controllable to perform a material handling process. For example, a first voltage input across the first actuator electrode 301 and the second actuator electrode 302 may be provided to actuate bending motions in the distal ends of the device 200, bringing the respective electroadhesive member 500 into position near an object of interest. A second voltage input across the first electroadhesion electrode 501 and the second electroadhesion electrode 502 may then be provided to bring the electroadhesion member 500 into electroadhesive contact with the object of interest.

[0065] The electrical communication between an ionic gel electrode and power supply is established through an electronic/ionic interface, in which an electrical double layer (EDL) forms and behaves like a capacitor, also referred to here as an electrical double layer capacitor (C_{EDL}). As shown in the equivalent circuit of **FIG. 2G**, the DEA 230 includes two C_{EDL} connected in series with the dielectric capacitor (C_{DEA}) formed by the prestretched layer 400. The ionic-gel-based electroadhesive member 500 includes two C_{EDL} connected in series with the capacitor formed by the interdigitated electrodes (electroadhesive capacitor, C_{EA}), also referred to herein as the first and second electrode fingers 510/520. In the physically small electroadhesive member 500, the voltage distribution across the three capacitors is of concern when the voltage input is high, as the voltage drop on C_{EDL} should not exceed the electrochemical window of the electronic/ionic interface in order to obviate unwanted electrochemical reaction. Such requirement necessitates a large C_{EDL} and a small C_{EA} so that the voltage bias would mostly fall on the C_{EA} with a minimal portion (ideally < 1 V) coupled across C_{EDL} . In electroadhesive members 500 of decimeter-scale, metallic materials may be used to form electronic/ionic contact with the ionic gel electrodes. The capacitance of C_{EDL} in such examples can be increased by upscaling the lateral dimension of EDL. In electroadhesive members 500 of millimeter-scale or even smaller, the lateral dimension of EDL may be relatively constrained. The electrical conductors are configured to induce a large areal specific

capacitance (capacitance per area) in EDL so as to provide a robust interfacing with the ionic gel electroadhesion electrodes 501/502. In some examples, a nano-porous carbon conductor 340 can be selected for use. The nano-porous carbon conductor 340 of highly porous CNT-graphite composite allows for sufficient ionic gel infiltration and leads to the formation of volumetric capacitance. In some examples, it is possible to achieve a ratio of $C_{EDL}:C_{EA}$ above 10^3 , which would be sufficient to provide a robust electroadhesive performance under a high voltage bias.

[0066] Further miniaturization is possible by downscaling the electrodes design and employing high resolution patterning techniques, such as stereolithography. The materials used for prototype included a polyion-based ionic gel and the polyurethane as described above. Other material combinations could also be used.

[0067] **FIG. 3A** is an exploded perspective view of the layered structure of the electroadhesive member 500. The electroadhesive member 500 includes a first electroadhesive electrode 501 and a second electroadhesive electrode 502, both disposed on a fourth surface 333 of the contact layer 330. The fourth surface 333 is coupled to the third surface 313 of the first passive layer 310, with the electroadhesive member 500 disposed therebetween. The first electroadhesive electrode 501 and the second electroadhesive electrode 502 may be formed using the ionic gel 850 as described above. The pair of first and second electroadhesive electrodes 501/502 may be disposed between the first passive layer 310 (also serving as a support layer or a substrate 870 for the pair of first and second electroadhesive electrodes 501/502) and the contact layer 330. The electroadhesive member 500 may be alternatively described as including the pair of the first electroadhesive electrode 501/second electroadhesive electrode 502 disposed on one surface 333 of the contact layer 330, such that another (opposing) surface of the contact layer 330 serves as a contact surface 335. Such an electroadhesive member 500 can then be integrated with any of the passive layers 310/320 of the DEA 230.

FIG. 3B is an equivalent circuit of the electroadhesive member 500 of **FIG. 3A** with two C_{EDL} and one C_{EA} connected in series, similar to the part of the equivalent circuit diagram of **FIG. 2F** corresponding to the electroadhesive member 500.

[0068] As shown in a top view of **FIG. 3C** with a selected portion magnified in **FIG. 3D**, the electroadhesive member 500 includes a first electroadhesive electrode 501 and a second electroadhesive electrode 502, disposed on the contact layer 330. The first electroadhesive electrode 501 includes a first common bus line 511 with a set of first electrode fingers 510 extending transversely from the first common bus line 511. The second electroadhesive electrode 502 includes a second common bus line 522 with a set of second electrode fingers 520 extending transversely from the second common bus line 522.

[0069] Each of the plurality of first electrode fingers 510 is formed of the ionic gel 850 and is contiguous or joined at one end with the first common bus line 511 of the same ionic gel 850. The plurality of first electrode fingers are substantially parallel to and spaced apart from one another. The plurality of first electrode fingers 510 extend along a transverse direction 202 parallel to the third surface 313 (the first passive layer 310).

[0070] Each of the plurality of second electrode fingers 520 is formed of the ionic gel 850 and is contiguous or joined at one end with the second common bus line of the same ionic gel 850. The plurality of second electrode fingers 520 are substantially parallel to and spaced apart from one another. The plurality of second electrode fingers 520 extend along a transverse direction 202 parallel to the third surface 313 (the first passive layer 310).

[0071] Alternatively, each of the first electroadhesive electrode 501 and the second electroadhesive electrode 502 may be described as having a "comb" shape.

[0072] The first electrode fingers 510 and the second electrode fingers 520 are alternately patterned or interleaved to define a continuous and serpentine electroadhesion electrode gap 550 between the first electroadhesion electrode 501 and the second electroadhesion electrode

502. The second electroadhesion electrode 502 may share a similar geometry with the first electroadhesion electrode 501, with the second electrode fingers 520 displaced (in a longitudinal direction) from the first electrode fingers 610 of the first electroadhesion electrode 501. The first electroadhesion electrode 501 and the second electroadhesion electrode 502 are disposed on the same plane (e.g., on the same surface of the first passive layer 310) without any intersection. The width (W2) of the respective electrode fingers 510/520 and the pitch (P), or interval spacing between individual electrode fingers 510/520, may be varied based on the application scenario. In general, narrower widths and pitches enable a higher electroadhesion force for a length (L1) and width (W1) of the electroadhesive electrode fingers 510/520. The pitch (P) or the interval spacing between a first electrode finger 510 and a second electrode finger 520 corresponds to the electroadhesion electrode gap 550.

[0073] **FIG. 3E** schematically illustrates an orientation of the electroadhesion electrode gap 550 relative to the actuator electrode gap 450 and to the longitudinal axis 201 in the device 200 integrating the DEA 230 and the electroadhesive member 500, with the DEA 230 and the electroadhesion member 500 stacked along the stacking axis 203 (e.g., into/out of the paper in **FIG. 3E**).

[0074] The geometry of the actuator electrode gap 450 is defined by the prestretched layer 400 stacked between the first actuator electrode 301 and the second actuator electrode 302, stacked along the stacking axis 203 orthogonal to the longitudinal axis 201. In this example, the actuator electrode gap 450 is an active area 453 generally defined by a length L4 and a width L4.

[0075] The geometry of the electroadhesion electrode gap 550 is defined by the interstitial space between the interleaved/interdigital first electroadhesion electrode 501 and the second electroadhesion electrode 502. The interstitial space or electroadhesion electrode gap 550 is filled with some of the elastomer material of the contact layer 330. The total length L3 of the

electroadhesion electrode gap 550 corresponds to the length of the whole contiguous sinuous gap, as schematically shown in **FIG. 3E**.

[0076] The electroadhesion electrode gap 550 has a pitch P that is significantly shorter than the length total L_3 of the electroadhesion electrode gap 550. For the most part of the electroadhesion member 500, the pitch P of the electroadhesion electrode gap is measurable along a direction parallel to the longitudinal axis 201. As illustrated, in the device 200 integrating the DEA 230 and the electroadhesive member 500, the electroadhesion electrode gap 550 and the actuator electrode gap 450 are orthogonally oriented relative to one another.

[0077] In various examples, the first passive layer 310 is made of an insulative elastomer suitable for electrically insulating the first actuator electrode 301 from the pair of first and second electroadhesive electrodes 501/502. The thickness of first passive layer 310 may range from 50 μm to 1000 μm to provide structural support to the electroadhesive electrodes 501 and 502. The thickness of the contact layer 330 may be lower (e.g., ranging from about 10 μm to about 100 μm) to provide higher electroadhesion forces between the electroadhesive member 500 and the object to be handled. In some examples in which each of the first passive layer 310 and the prestretched layer 400 is about 80 μm thick, each of the contact layer 330 and the second passive layer 320 may be about 60 μm in thickness.

[0078] In the manufacturing of the present device 200, the thickness of the layers made of an elastomer may be controllably achieved through spin coating, Mayer bar coating, blade coating, or roll-to-roll coating, etc. The minimal achievable thickness of a layer of elastomer depends on the processibility and mechanical properties of a specific elastomer. The minimal thickness achievable in the production of the electroadhesive member 500 may be determined by the dielectric breakdown strength of the specific elastomer. A suitable elastomer candidate may be selected based on a balance of factors such as: elasticity, compliance, dielectric constant, and dielectric breakdown strength, etc. In some embodiments, the elastomer may be

selected from materials that are characterized by a relatively high transmittance (to visible light) to deliver a substantially transparent device 200 or electroadhesive member 500.

[0079] Ultra high-resolution patterning techniques such as stereolithography may be applied to produce ionic gel features (e.g., electrode fingers) of about 100 nm width and about 100 nm pitch. A miniature soft electroadhesive member 500 may offer novel functions in a microelectromechanical system (MEMS) or in a micro-robot. The width and pitch of an electrode finger 510/520 may be in a sub-millimeter, millimeter, or centimeter scale when the soft electroadhesive member is designed to interact with macroscopic objects. Other electrode geometries (e.g., concentric rings) and sizes can be adopted to produce soft electroadhesive members 500 across a wide range of form factors.

[0080] In some embodiments, a coating 332 may be applied on the outer surface (e.g., contact surface 335 opposing the fourth surface 333) of the contact layer 330. The coating 332 may be selected to confer various properties such as protective, dust-proofing, and self-cleaning, etc. In various applications when it is preferably that the contact surface 335 of the device 200 is not tacky, the coating 332 can be a hydrophobic coating provided on the contact surface 335. The coating 332 can reduce the collection of micro-debris by the electroadhesive member 500 during operation. The coating 332 may be in the form of a thin layer of self-assembled nanoparticles or small molecules that bond to the elastomer inwards and render hydrophobicity outwards. The coating 332 is preferably thin and compliant enough to avoid restricting the inherent deformability of the soft electroadhesive member 500.

[0081] In one embodiment, the electroadhesive member 500 can present an active electrode area of 16 mm × 16 mm. The thickness of the first passive layer 310 (serving as a support layer or a substrate for the electroadhesion member 500) and the thickness of the contact layer 330 are 200 μm and 40 μm respectively, and the width and pitch of the interdigitated electrode fingers 510/520 are 0.90 mm and 0.43 mm, respectively. The materials used to make the

electroadhesive member 500 include the polyion-based ionic gel and the polyurethane as described above. A layer of silicon oxide nanoparticles may be introduced as surface coating 332 to remove the tackiness of the polyurethane while preserving its softness and compliance. The coating 332 can also be selected to provide self-cleaning functionalities to achieve long-time service of the electroadhesive member 500.

[0082] In the experiments conducted, to activate the electroadhesive member 500, a positive voltage bias was provided to the first electroadhesion electrode 501 either directly or through an external control circuit, with the second electroadhesion electrode 502 electrically grounded to maintain a zero voltage bias. As a result of the voltage difference, the interdigitated electroadhesion electrodes 501/502 are polarized with alternating positive and negative charges held on adjacent electrode fingers 510/520. In one example, the positive charges in the ionic gel 850 include mobile potassium ions, and the negative charges in the ionic gel 850 include sulfonate groups fixed on the polyion backbones. These charges create fringe electric fields along the perimeter of the ionic gel electrodes, which distribute across the contact elastomer layer and further protrude outwards. As illustrated in **FIG. 4A**, when an activated electroadhesive member 500 approaches a conductive or semiconductive object surface 902, the fringe electric field 600 would immediately polarize the object surface 902 and induce net charges that mirror those accumulated in the ionic gel electrodes 501/502. Parallel-plate capacitors are thus formed and stably held by the electric potential, leading to an attractive force between the electroadhesive member 500 and the object surface 902. The electroadhesive force between the electroadhesive member 500 and the conductive, or semiconductive object surface 902 may be derived from the equation (1) below:

$$F = (\epsilon_0 \cdot \epsilon_r \cdot A \cdot V^2) / (2d^2) \quad (1)$$

where ϵ_0 is vacuum permittivity, ϵ_r is the dielectric constant of the elastomer in the contact layer, A is the interfacial area between the member and the foreign surface, V is the voltage

difference between the first electrode and the second electrode, and d is the thickness of the contact layer.

[0083] When the electroadhesive member 500 approaches an insulative, or dielectric object surface 902, the basic principle of force generation is different and the amount of electroadhesive force cannot be simply calculated. As illustrated in **FIG. 4B**, since dielectric materials possess no mobile charge carriers, they can only be polarized by the electric field 602 (induced by the electrodes 501/502) at the molecular or atomic level, and the temporarily induced dipoles 604 would produce a net adhesive force on the object surface 902. Such an effect is described as polarization and is correlated to the polarizability of dipoles.

[0084] As discussed above, the amount of electroadhesive force depends on various factors including the input voltage, the form factor, and material properties of the electroadhesive member 500, the surface roughness and material properties of foreign substrates, and a variety of environmental parameters. A set of improved tests suitable for benchmarking the performance of a soft electroadhesive member is described below. Prototypes of the present device 200 were fabricated and successfully tested as will be apparent from the following description. In some examples, a prototype of the device 200 occupied a lateral dimension of $9\text{ mm} \times 37\text{ mm}$ and an overall thickness of about $280\text{ }\mu\text{m}$.

[0085] In some embodiments, the electroadhesive force manifests as a normal force, or cohesive force, whose vector direction 131 is normal or perpendicular to the contact interface between the member and the foreign surface. Such normal forces could be measured using the setup 130 as illustrated in **FIG. 5A**. Specifically, the electroadhesive member 500 was connected to a rigid probe 132 through a piece of buffering foam 134, which is soft and can ensure a conformal contact between the electroadhesive member 500 and the test substrate 135 (object 900) beneath it. A force gauge with high sampling resolution is attached at the end of the probe 132 for dynamic force recording. During the test, a preload ranging from 0.1 N to 1 N is applied to press the electroadhesive member 500 onto the test substrate 135. Voltage bias

was then supplied and held for a certain period, followed by pulling the electroadhesive member 500 straight up using a motorized translation stage 136. The peak force recorded at the detaching moment is regarded as the normal force. In the specific embodiment described above, the normal electroadhesive forces of the electroadhesive member 500 is measured on both metallic (aluminum) and dielectric (glass) test substrates and could be normalized to the active electrode area to derive normal electroadhesive pressures. As shown in the plot of normal forces or normal pressure over the range of voltages applied in **FIG. 5B**, the normal force/pressure is positively related to the input voltage. When activated at 1 kV, the electroadhesive member 500 can apply a normal pressure as high as 2.08 kPa on an aluminum test substrate, and a remarkable value of 1.30 kPa on a test substrate of smooth glass. In contrast, a conventional electrode pair made of flexible and non-stretchable materials could only yield 0.21 kPa and 0.20 kPa normal pressures on aluminum and glass test substrates (under 1 kV DC bias), respectively. The improved performance exhibited by the present electroadhesive member 500 may be credited at least in part to the high dielectric constant and low thickness of the polyurethane contact layer. The dramatic improvement may also be attributed in part to a better compliance of ionic gel electrodes 501/502 with the test substrate, allowing the electroadhesive member 500 to form a more uniform physical contact between the electroadhesive member 500 and the test substrate.

[0086] In some other embodiments, the electroadhesive force manifests as a shear force, or a frictional force, e.g., the trend or direction 141 of relative movement resisted by the said force is substantially parallel to the contact interface between the electroadhesive member 500 and the object 900. Such shear forces can be measured using the setup 140 as illustrated in **FIG. 5C**, in which the electroadhesive member 500 is supported by a backing layer 144 (e.g., a 3M Scotch Magic Tape) and then attached vertically to a flat surface of the test substrate 145 (e.g., object 900). The friction forces upon pulling are recorded via a probe 142, and the peak force value featuring the transition from static friction to dynamic friction is regarded as the shear

force being measured. For static friction, shear adhesion force (F_T) is correlated to normal adhesion force (F_N) according to the following equation (2):

$$F_T = \mu F_N \quad (2)$$

where μ denotes the coefficient of static friction (COF) at the interface between the member and the foreign substrate.

[0087] Normal and shear adhesion forces/pressures of the electroadhesive member 500 described above were measured on aluminium, glass (smooth and grounded), polyvinylidene difluoride (PVDF) film, printer paper, natural leaf, and plywood under a voltage bias of 1 kV and shown in the chart of **FIG. 5D**. The electroadhesive member 500 generated larger shear pressures than normal pressure on all the tested substrates ascribing to the elastomeric and deformative characteristic of the contact layer. The derived COF values positively correlated with the average surface roughness of the test substrates. While a high surface roughness is detrimental to normal electroadhesive pressure, it results in a larger COF and subsequently a high shear adhesive pressure for rough object manipulation. For instance, when the average surface roughness of glass increased from 13.4 nm to 7.87 μm , the normal electroadhesive pressure dropped over 7 folds from 1.33 kPa to 0.19 kPa, yet the shear electroadhesive pressure on the rough glass maintained around 1 kPa. Such a unique trait of soft electroadhesive member 500 greatly expands the fields of application as it is also now possible to manipulate a wide range of materials with surface roughness spanning from nanometers to tens of micrometer.

[0088] Another benefit of the electroadhesive member 500 relates to its ability to rapidly detach, and this will be illustrated with the aid of **FIGS. 6A to 6D**. Electrostatic adhesion and detachment are time-dependent dynamic processes. Conventionally, engineering methods such as reverse polarity, air-jets repulsion, and resonant excitation are implemented to propel the detaching process. Such detaching processes inevitably complicate the adhesion system and consume extra energy. For metallic surfaces, the parallel-plated capacitors formed between the electrodes and the conductive surface could be retained. When power is turned off, the de-

clamping time can take hours owing to the slow self-discharging process of dielectric capacitors. This is schematically represented in the diagrams of **FIG. 6A** (in a "power on" state 151 with voltage applied, a capacitive effect can be formed between the metallic substrate 152 and the electrical electrode 154) and **FIG. 6B** (in a "power off" state 150 with no applied voltage, charges between the metallic substrate 152 and the electrical electrode 154 remain).

[0089] For our electroadhesive member 500 using ionic gel as electrodes, the acquisition and release times can be rapid. In tests of shear adhesion under 1 kV input, the residue force between the ionic-gel-based electroadhesive member 500 of the present disclosure and an aluminium test substrate can advantageously be decreased relatively rapidly such that the force is negligible within 6.2 s after switching off the voltage (as shown in the experimental results of **FIG. 7A**). The rapid detaching phenomenon could be attributed to the inclusion of additional EDL capacitors in the circuit. EDL capacitors possess a high specific capacitance yet endure the "drawback" of fast self-discharging under open-circuit condition. In the case of ionic-gel-based electroadhesion according to the present disclosure, the voltage drop (potential difference) across an EDL capacitor is minimal (< 1 V) when 1 kV is applied to the entire iontronic circuit. When such a voltage drop (potential difference) is removed, charges accumulated at an EDL can relax transiently through a mixed self-discharging mechanism of leakage current, faradaic charge transfer, and charge redistribution. Net ionic charges released from EDL may subsequently diffuse and neutralize the counterions in the polyelectrolyte matrix through an entropy-driven process, and subsequently reduce the electrostatic strength between the ionic gel electrodes and the opposing metallic surface. The charging rate of an EDL capacitor can also have an impact on its self-discharge behavior. In the present electroadhesive member 500, EDL is polarized instantly when the voltage input is supplied, and the short charging duration will in turn enhance its self-discharging rate under open-circuit condition. This is further illustrated schematically by the diagrams of **FIG. 6C** (in a "power on" state with

voltage applied via solid/carbon electrodes 166, a capacitive effect is formed between the metallic substrate 162 and the ionic gel electrode 164) and **FIG. 6D** (in a "power off" state with no voltage applied via the solid/carbon electrodes 166, charges between the metallic substrate 162 and the ion gel electrodes 164 self-discharge more rapidly than in the case of **FIG. 6B**).

[0090] Advantageously, the energy consumption of an electroadhesive member 500 is relatively low when compared with other adhesion technologies. In one experiment, the charging, discharging, and leakage current of the ionic-gel-based member at 1 kV on aluminum substrate was determined. The test results shown in the plot of **FIG. 7B** indicate a relatively small leakage current (about 50 nA) for the electroadhesive member 500 that is suggestive of a low power consumption (about 50 μ W) while the electroadhesive member 500 adheres tightly on a metallic test substrate.

[0091] **FIG. 8A** and **FIG. 8B** schematically illustrate a method of material handling using one embodiment of the present gripper 100 to approach and pick up an object 900. The gripper includes a plurality of the devices 200 coupled to a connector 110. The gripper 100 may be moved to approach an estimated location of the object 900. Each of the devices 200 may be provided with a voltage input to the device 200 to extend the devices outward, e.g., radially extended. Each of the devices 200 may serve as a proximity sensor such that the outwardly flared devices 200 enable a larger area of proximity detection. The devices 200 can be collectively actuated to bend towards the object 900 in a gripper or picking motion. The gripper 100 may be configured to respond to a contact of the device 200 with the object 900 by activating an electroadhesive effect at the electroadhesive members 500 to ensure a sufficient grip on the object 900. The gripper 100 can be moved to transport and/or manipulate the object 900.

[0092] In one aspect, a plurality of the hybridized DEA-electroadhesive devices 200 may be integrated to form a soft electroadhesive gripper 100, in which each electroadhesive member

500 is configurable to serve as an electroadhesive end effector capable of exerting normal or shear adhesion forces on one or more object, independently of any other electroadhesive member 500 of the same gripper 100. In another aspect, the present disclosure provides a set of standardized testing methods to characterize the normal force and shear force generated between the surface of the said electroadhesive member 500 and the flat surface of an object. The methods are not limited by the material property or surface roughness of a test surface so that they can benchmark the electroadhesive performance of the device 200 on a wide range of objects.

[0093] Experimental Prototypes

[0094] The following includes references to images captured during experiments conducted using prototypes of a gripper 100.

[0095] Prototypes of the gripper 100 and the device 200 were fabricated for testing. Ionic organohydrogel (OHGel) and an elastomer were synthesized and assembled. The elastomer may be selected from commercially available thermoplastics (TPU), such as Elastollan[®] 1185A10 (BASF), or a polydimethylsiloxane (PDMS), such as Sylgard 184 (DOW). The prototype device 200 was a millimeter-scale ($9 \times 32 \text{ mm}^2$) unit including a dielectric elastomer actuator (DEA) 230 integrated with an iontronic-adhesive / electroadhesive member 500.

[0096] P(SPMA_{0.5}-r-MMA_{0.5}) polyelectrolyte was synthesized by atom transfer radical polymerization (ATRP). Monomer 1 (3-sulfopropyl methacrylate potassium salt, SPMA) (4.9 g, 20.0 mmol), catalyst (copper(I) bromide, CuBr) (14.3 mg, 0.1 mmol), and ligand (*N,N,N',N'',N'''*-Pentamethyldiethylenetriamine, PMDETA) (17.3 mg, 0.1 mmol) were firstly dissolved in 12 ml water/DMF cosolvent (40/60 vol%). The mixture consisting of monomer 2 (methyl methacrylate, MMA) (2.0 g, 20.0 mmol), initiator (Ethyl α -bromoisobutyrate, EBiB) (19.5 mg, 0.1 mmol), and 3 ml cosolvent was then incorporated and the solution was stirred at

70 °C for 50 hours. After that, the polyelectrolyte was precipitated in DMF (4.9 g, 71% yield, colorless solid).

[0097] Polytetramethylene ether glycol (PTMEG, Sigma-Aldrich, $M_n \approx 1000$) and 1,4-butenediol (1,4-BuD, Sigma-Aldrich, 99%) were dried in vacuum oven at 100 °C for 1 hour before usage. Isophorone diisocyanate (IPDI, Alfa Aesar, mixture of isomers, 98%), hexamethylene diisocyanate (HDI, SigmaAldrich, $\geq 99\%$), guanidine carbonate (GDN, Sigma-Aldrich, 99%), triethanolamine (TEA, SigmaAldrich, 98%) ethyl acetoacetate (EAA, Sigma-Aldrich, 99%), and N,N'-dimethylacetamide (DMAc, Alfa Aesar, anhydrous 99.8%) were used without further purification. Dibutyltin dilaurate (DBTDL, 95%), pyridine (=CH-, anhydrous, 99.8%), pentane (anhydrous, $\geq 99\%$), acetone (anhydrous, $\geq 99.5\%$), chloroform (CHCl_3 , $\geq 99.5\%$), diethyl ether (DEE, anhydrous, $\geq 99.7\%$) and other chemicals were purchased from Sigma-Aldrich and used as received unless otherwise specified.

[0098] A suspension of GDN (0.16 mol) and EAA (0.36 mol) in ethanol (150 ml) was heated under reflux for 12 h, then filtered with a büchner funnel to receive a white paste-like mixture. The mixture was kept at 0 °C for 0.5 hour, and subsequently washed with ethanol, deionized (DI) water, and acetone in sequence. The dissolution-precipitation decantation process was repeated for five times and the final product was dried at 50 °C under vacuum overnight to obtain MIC (2-Amino-4-hydroxy-6-methylpyrimidine or 6-methylisocytosine).

[0099] MIC (60 mmol), 1,6-hexamethylene diisocyanate (350 mmol) and pyridine (8 mL) were added into a flask and reacted at 100 °C (24 hours, nitrogen atmosphere) with magnetic stirring and reflux condensation. After that, the flask was cooled down to room temperature, followed by adding 50 mL n-pentane to quench the reaction. The mixture was then kept at 0 °C for 0.5 h to precipitate, and the upper clear solution was decanted. The precipitation was rinsed by acetone then subjected to vacuum evaporation at 50 °C to obtain the UPy-NCO (1-(6-isocyanatohexyl)-3-(6-methyl-4-oxo-1H-pyrimidin-2-yl)urea) powder.

[00100] Dynamically crosslinked supramolecular, hierarchically H-bonded polyurethane (SHPU) was synthesized through step-growth polymerization. PTMEG (29 mmol) was firstly fed into a flask and heated at 100 °C for 1 hour to remove residue moisture. IPDI (63.95 mmol) and DBTDL (0.06 wt%) dissolved in DMAc were then added dropwise into the flask and stirred at 85 °C (3 hours, nitrogen atmosphere) for primary isocyanate reaction (Step I). Afterwards, 1,4-BuD (14.50 mmol) in 10 mL anhydrous DMAc was added to the prepolymer solution and allowed for secondary isocyanate reaction at 75 °C (4 hours, nitrogen atmosphere) (Step II). After the synthesis of OCN-PU-NCO, TEA (14.50 mmol) and UPy-NCO (4.5 mmol) were introduced and stirred until fully dissolved. Reactions of chain extending and telechelic UPy jointing were carried out at 75 °C (3 hours, nitrogen atmosphere) to get the SHPU resin (Step III), which could be further drop casted on glass and cured (90°C, 12 hours) to remove the solvent and achieve a transparent elastomer film.

[00101] Experiments

[00102] **FIGS. 9A(i) to 9A(iv)** are images of the prototype gripper 100 having four devices 200 in tests where the gripper 100 was used to manipulate a metallic cube under 600 V voltage input. Such a manipulating voltage is much lower than the conventional electroadhesive devices which function in a voltage range from 1 kV to 5 kV. The bending of the continuum DEA 230 of the present disclosure brought the end effectors into contact with the cube (object 900). The activated normal adhesive force kept the distal ends 210 of the devices 200 in conformal physical contact with the cubic surfaces, and the shear adhesive force provided sufficient friction for the gripper 100 to lift the cube 911.

[00103] The active components in the gripper 100 weigh only 0.32 g but could lift a 215 g object (> 670 times of self-weight) by harnessing the large shear force generated between the electroadhesive members 500 and the metallic surfaces of the object 900 (**FIGS. 9B(i)** and

9B(ii)). A rapid release from the metallic cube was also observed ascribing to the fast charge relaxation in EDL as described above.

[00104] The present gripper 100 can also handle objects with 3D surface profiles. For example, a gripper 100 with two devices 200 of the present disclosure can wrap the devices 200 around the cylindrical profile of a glass bottle which exhibits a zero Gaussian curvature, as shown in the images of **FIG. 10A(i)** to **FIG. 10A(iii)**. It can also adapt to surfaces of positive Gaussian curvature, such as the surface of a cherry tomato, as shown in **FIGS. 10B(i)** to **10B(iii)**, e.g., demonstrating that the soft electroadhesive members can not only flex but can also extend in all directions. At the microscale, the compliance of the electroadhesive member 500 can also help to expel air, gas, or air bubbles between the contact surface 335 and the object surface 902. This advantageously can contribute to a stronger adhesive force.

[00105] Electroadhesive forces are atractive, e.g., the electroadhesive-based gripper such as the present gripper 100 can provide a continuous holding force along a shear direction without the application of compressive force. The present gripper 100 demonstrated a dexterous prehension of a wide range of soft objects, e.g., a piece of tofu that is fragile and wet on its surface (**FIGS. 11A(i)** to **11A(ii)**), and a flower (*Eustoma russellianum*) that is easily crushed by even a light handling force (**FIGS. 11B(i)** to **11B(ii)**). The present gripper 100 successfully handled these and other fragile objects, demonstrating its potential for handling living organisms, e.g., to harmlessly secure insects, or even microbes for examination or photography. The present gripper 100 is useful for handling lightweight objects in the form of film, sheets, or powder. For example, the present gripper 100 could pick up a soft, easily deformable, substantially flat leaf (generally lacking grasping sites) using a normal electroadhesive force (**FIG. 11C**). The normal electroadhesive force provided by the present gripper 100 can also pick up flat objects of much smaller geometries, e.g., confetti-like paper shreds (**FIG. 11D**), and micrometer-scale metallic particles (**FIG. 11E**).

[00106] In various embodiments of the present disclosure, each of the electroadhesive member 500 can be configured as a part of an end effector with a proximity sensing capability. This can be useful in applications where the exact location of the object 900 is indeterminate or changeable. This can also be useful in applications where the surface of the object 900 is easily damaged if unintentionally brushed against an end-effector. With a proximity sensing capability incorporated at the distal end 210 of each device 200, the gripper 100 can be stopped in its motion in response to sensing that the object 900 is in proximity, and the gripper 100 can switch from a moving operation to a picking up operation. In other examples, the device 200 may be operated as a proximity sensor as the device 200 is moved towards an object 900 to be handled. Upon the device 200 detecting physical contact between the distal end 210 of the device 200 and the object 900, the device 200 may be operated as part of an end effector by providing the device 200 with electroadhesive forces at the distal end 210. For example, the capacitive sensing function of the device 200 may be in operation until a predefined proximity or a contact with the object is detected, in response to which the electroadhesive function of the device 200 is then activated. In some embodiments, the system 210 can communicate with a translational stage to which the gripper 100 is attached so as to properly position the gripper 100 with respect to the location and shape of the object 900. In some other embodiments, the system 120 is configured to controllably vary the voltage applied to each or both of the actuator electrodes 301/302 and the electroadhesive electrodes 501/502 to operably effect selected functions of the gripper 100.

[00107] The electroadhesive electrodes 501/502 of the electroadhesive member 500 can form a coplanar capacitor that projects a fringe electric field under a voltage bias. Such a fringe field is prone to disturbance by a nearby object, e.g., the fringe electric field is disturbed in response to the presence or proximity of an object 900, which in return results in a reduced capacitance from a baseline value of the coplanar capacitor. The capacitive sensing functionality may be

activated under an AC (alternating current) input with the frequency ranging from about 1 kHz to about 100 kHz, and with the amplitude ranging from about 50 mV to about 5 V.

[00108] **FIG. 12A** is a schematic block diagram of a system 120 configured to control a gripper 100 of the present disclosure. The system 120 includes a microcontroller unit (MCU) 122 configured for signal processing, and a capacitance-to-digital converter (CDC) 124 configured to collect capacitance signal from the gripper 100. The output of the system 122 may be further processed by a computing device 126 for display or used to control a translational stage supporting the gripper 100. As shown in the plot of relative capacitance change (plot 130) in **FIG. 12B**, the gripper 100 could distinguish between the grape being in proximity (-2.4% relative capacitance change) and the grape being in contact (-7.2% relative capacitance change) based on the size of the relative capacitance change. The system 120 may be calibrated to set a first threshold 133 to distinguish between a state where there is an object in proximity and a state where there is no object in proximity. The system 120 may be calibrated to set a second 134 threshold to distinguish between a state where there is an object in proximity (not in contact) and a state where there is contact with an object. The system 120 may be calibrated such that a relative capacitance change within a first range or a first band 131 of values correspond to an object in proximity to the gripper 100. The system 120 may be calibrated such that a relative capacitance change within a second range or a second band 132 of values correspond to an object in (physical) contact with the gripper 100, in which the absolute value (or modulus) of any value in the second band 132 is greater than the absolute value (or modulus) of any value in the first band 131.

[00109] **FIG. 12C** and **FIG. 12D** are images of two states of the system 120 in which the output of the system is provided in the form of visual indicators. In this example, as shown in **FIG. 12C**, the system 120 correctly turned on only a blue light emitting diode (LED) 128 when the object 900 (e.g., a grape) is in proximity to an electroadhesive member 500 that is at a distal

end of a device 200/gripper 100. As shown in **FIG. 12D**, when the electroadhesive member 500 (of the device 200/gripper 100) is in physical contact with the object 900 (e.g., the grape), the system 120 correctly turned on both the blue LED 128 and a white LED 129. This experiment demonstrated the beneficial and useful ability of the device 200 / the gripper 100 to provide real-time integrated sensing of its own position relative to any object. Such functionality can provide useful feedback to a localization and/or navigation control system. Advantageously, such additional functionality does not involve the use of additional or bulky apparatus.

[00110] The above describes various embodiments of a device 200 including a prestretched layer 400, a first passive layer 310, a first actuator electrode 301, and a second actuator electrode 302. The prestretched layer 400 has a first surface 410 and a second surface 420 defining a variable thickness 440 therebetween. The first passive layer 310 defines an actuator surface 311 and a third surface 313. The first actuator electrode 301 is disposed between the first surface 410 of the prestretched layer 400 and the actuator surface 310 of the first passive layer 310. The second actuator electrode 302 is disposed on the second surface 420 of the prestretched layer 400. The first actuator electrode 301 and the second actuator electrode 302 are characterized by an actuator electrode gap 450 corresponding to the variable thickness 440 of the prestretched layer 400. Each of the first actuator electrode 301 and the second actuator electrode 302 is formed of an ionic gel 850.

[00111] The device 200 may include a first electroadhesion electrode 501 and a second electroadhesion electrode 502. The first electroadhesion electrode 501 and the second electroadhesion 502 may be disposed on the third surface 313 of the first passive layer 310, in which each of the first electroadhesion electrode 501 and the second electroadhesion electrode 502 is formed of an ionic gel 850.

[00112] The device 200 may include a contact layer 330, in which the first electroadhesion electrode 501 and the second electroadhesion electrode 502 are disposed between the contact layer 330 and the first passive layer 310.

[00113] The device 200 may further include a hydrophobic coating 332 coated on the contact layer 330.

[00114] The device 200 may further include a second passive layer 320 disposed on the second actuator electrode 302, in which the second passive layer 320 and the first passive layer 310 are compositionally similar, and wherein the first passive layer 310 is thicker than the second passive layer 320.

[00115] Each of the first electroadhesion electrode 501 and the second electroadhesion electrode 502 of the device 200 may include respective first electrode fingers 510 and second electrode fingers 520, in which the first electrode fingers 510 and the second electrode fingers 520 are interleaved with one another and define an electroadhesion electrode gap 550 therebetween.

[00116] The electroadhesion electrode gap 550 may be oriented orthogonally to the actuator electrode gap 450.

[00117] The first actuator electrode 301, the prestretched layer 400, and the second actuator electrode 302 may be elongate along a longitudinal axis 201, in which the first electroadhesion electrode 501 and the second electroadhesion electrode 502 may be coplanarly disposed on a third surface 313 that is parallel to the longitudinal axis 201.

[00118] The ionic gel 850 may include mobile ions dissolved in a solvent swollen in one or more polymer matrix.

[00119] The one or more polymer matrix may include any one or more selected from the group consisting of: neutral polymers and one or more polyions, in which the one or more

polyions include any one or more selected from the group consisting of: positively charged polyions and negatively charged polyions.

[00120] The neutral polymers may include any one or more selected from the group consisting of: polyacrylate, one or more derivatives of polyacrylate, polyethylene glycol, one or more derivatives of polyethylene glycol, polyvinyl alcohol, polyvinylpyrrolidone, polyhydroxyethyl methacrylate, and any copolymer with a plurality of cross-linkable groups.

[00121] The ionic gel 850 may be a neutral polymer-based ionic gel including a crosslinked network of a neutral polymer, a solvent swollen in the crosslinked network, mobile cations dissolved in the solvent, and mobile anions dissolved in the solvent.

[00122] The one or more polyions may include any one or more selected from the group consisting of: polyacrylic acid, poly(2-acrylamido-2-methylpropane sulfonic acid), poly(diallyl dimethylammonium chloride), and polystyrene sulfonate.

[00123] The ionic gel 850 may be a polyion-based ionic gel comprising a polyion with a charged polyion backbone, a solvent swollen in a network of the polyion, and a solvent with mobile counterions dissolved in the solvent, in which the mobile counterions are mobile ions released from the polyion and oppositely charged from the charged polyion backbone.

[00124] The ionic gel 850 may be characterized by an elastic modulus in a range from 1 kPa to 100 kPa.

[00125] The prestretched layer 400 may be formed of an elastomer characterized by an elastic modulus in a range from 100 ka to 50 MPa.

[00126] The first passive layer 310 may be formed of an elastomer characterized by an elastic modulus in a range from 100 ka to 50 MPa. The elastomer may be any one or more selected from the group consisting of: polysiloxanes, polyurethanes, latex, acrylic elastomers, and styrene-butadiene elastomers.

[00127] The contact layer 330 may be formed of an elastic material. The elastic material may be any one selected from the group consisting of: polysiloxanes, polyurethanes, latex, acrylic elastomers, and styrene-butadiene elastomers.

[00128] The above also describes various embodiments of a gripper 100 suitable for use in handling an object 900. The gripper 100 includes a connector 110 and two or more of the devices 200, according to any described above. Each device 200 has a proximal end 220 and a distal end 210. The proximal end 220 is coupled to the connector 110. The respective first electroadhesion electrode and 501 the second electroadhesion electrode 501 are positioned at the distal end 210.

[00129] The gripper 100 may further include a controller voltage supply to the gripper 100. The voltage supply may be configured to provide a first voltage signal across the first actuator electrode 301 and the second actuator electrode 302. Responsive to a first voltage difference across the first actuator electrode 301 and the second actuator electrode 302, the two or more devices 200 are operable to each bend relative to the longitudinal axis 201.

[00130] The gripper 100 may further include a voltage supply coupled to the gripper 100. The voltage supply may be configured to provide a second voltage drop (e.g., potential difference) across the first electroadhesion electrode 501 and the second electroadhesion electrode 502, in which, responsive to a second voltage difference across the first electroadhesion electrode 501 and the second electroadhesion electrode 502, electroadhesive forces are generated at respective distal end 210 to provide a conformal electrostatic adhesion between the respective device 200 and the object 900.

[00131] The gripper 100 may include a controller coupled to the gripper 100, in which the controller is configured to determine a proximity or a contact between the respective device 200 and the object 900 responsive to sensing a change in a capacitance across the respective

first electroadhesion electrode 501 and the respective second electroadhesion electrode 502 of the respective device 200.

[00132] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding, and are not intended to be limiting or exhaustive. Modifications may be made by one of ordinary skill in the art without departing from the scope of the invention as claimed.

CLAIMS

1. A device comprising:

a prestretched layer, the prestretched layer having a first surface and a second surface defining a variable thickness therebetween;

a first passive layer, the first passive layer defining an actuator surface and a third surface;

a first actuator electrode, the first actuator electrode being disposed between the first surface of the prestretched layer and the actuator surface of the first passive layer;

a second actuator electrode, the second actuator electrode being disposed on the second surface of the prestretched layer, the first actuator electrode and the second actuator electrode being characterized by an actuator electrode gap corresponding to the variable thickness of the prestretched layer, wherein each of the first actuator electrode and the second actuator electrode is formed of an ionic gel.

2. The device according to claim 1, comprising:

a first electroadhesion electrode; and

a second electroadhesion electrode, the first electroadhesion electrode and the second electroadhesion being disposed on the third surface of the first passive layer, wherein each of the first electroadhesion electrode and the second electroadhesion electrode is formed of an ionic gel.

3. The device according to claim 1 or 2, further comprising: a contact layer, wherein the first electroadhesion electrode and the second electroadhesion electrode are disposed between the contact layer and the first passive layer.

4. The device according to claim 3, further comprising a hydrophobic coating coated on the contact layer.
5. The device according to any one of claims 1 to 4, further comprising a second passive layer disposed on the second actuator electrode, wherein the second passive layer and the first passive layer are compositionally similar, and wherein the first passive layer is thicker than the second passive layer.
6. The device according to any one of claims 2 to 5, wherein each of the first electroadhesion electrode and the second electroadhesion electrode comprises respective first electrode fingers and second electrode fingers, and wherein the first electrode fingers and the second electrode fingers are interleaved with one another and define an electroadhesion electrode gap therebetween.
7. The device according to any one of claims 2 to 6, wherein the electroadhesion electrode gap is oriented orthogonally to the actuator electrode gap.
8. The device according to any one of claims 2 to 7, wherein the first actuator electrode, the prestretched layer, and the second actuator electrode are elongate along a longitudinal axis, and wherein the first electroadhesion electrode and the second electroadhesion electrode are coplanarly disposed on a third surface that is parallel to the longitudinal axis.
9. The device according to any one of claims 1 to 8, wherein the ionic gel includes mobile ions dissolved in a solvent swollen in one or more polymer matrix.

10. The device according to claim 9, wherein the one or more polymer matrix comprises any one or more selected from the group consisting of: neutral polymers and one or more polyions, and wherein the one or more polyions include any one or more selected from the group consisting of: positively charged polyions and negatively charged polyions.

11. The device according to claim 10 wherein the neutral polymers comprises any one or more selected from the group consisting of: polyacrylate, one or more derivatives of polyacrylate, polyethylene glycol, one or more derivatives of polyethylene glycol, polyvinyl alcohol, polyvinylpyrrolidone, polyhydroxyethyl methacrylate, and any copolymer with a plurality of cross-linkable groups.

12. The device according to any one of claims 1 to 9, where the ionic gel is a neutral polymer-based ionic gel comprising a crosslinked network of a neutral polymer, a solvent swollen in the crosslinked network, mobile cations dissolved in the solvent, and mobile anions dissolved in the solvent.

13. The device according to claim 10 wherein the one or more polyions comprises any one or more selected from the group consisting of: polyacrylic acid, poly(2-acrylamido-2-methylpropane sulfonic acid), poly(diallyl dimethylammonium chloride), and polystyrene sulfonate.

14. The device according to any one of claims 1 to 9, wherein the ionic gel is a polyion-based ionic gel comprising a polyion with a charged polyion backbone, a solvent swollen in a network of the polyion, and a solvent with mobile counterions dissolved in the solvent, and wherein the mobile counterions are mobile ions released from the polyion and oppositely charged from the charged polyion backbone.

15. The device according to any one of claims 1 to 14, wherein the ionic gel is characterized by an elastic modulus in a range from 1 kPa to 100 kPa.
16. The device according to any one of claims 1 to 15, wherein the prestretched layer is formed of an elastomer characterized by an elastic modulus in a range from 100 ka to 50 MPa.
17. The device according to any one of claims 1 to 15, wherein the first passive layer is formed of an elastomer characterized by an elastic modulus in a range from 100 ka to 50 MPa.
18. The device according to claim 16 or claim 17 , wherein the elastomer is any one or more selected from the group consisting of: polysiloxanes, polyurethanes, latex, acrylic elastomers, and styrene-butadiene elastomers.
19. The device according to claim 3, wherein the contact layer comprises an elastic material, the elastic material being any one selected from the group consisting of: polysiloxanes, polyurethanes, latex, acrylic elastomers, and styrene-butadiene elastomers.
20. A gripper suitable for use in handling an object, the gripper comprising:
a connector; and
two or more devices as recited in any one of claims 2 to 19, each of the two of more devices having a proximal end and a distal end, the proximal end being coupled to the connector, wherein the respective first electroadhesion electrode and the second electroadhesion electrode are positioned at the distal end.

21. The gripper according to claim 20, further comprising: a controller voltage supply to the gripper, the voltage supply being configured to provide a first voltage signal across the first actuator electrode and the second actuator electrode, wherein responsive to a first voltage difference across the first actuator electrode and the second actuator electrode, the two or more devices are operable to each bend relative to the longitudinal axis.

22. The gripper according to claim 20, further comprising: a voltage supply coupled to the gripper, the voltage supply being configured to provide: a second voltage drop across the first electroadhesion electrode and the second electroadhesion electrode, wherein responsive to a second voltage difference across the first electroadhesion electrode and the second electroadhesion electrode, electroadhesive forces are generated at respective distal end to provide a conformal electrostatic adhesion between the respective device and the object.

23. The gripper according to claim 20, further comprising: a controller coupled to the gripper, the controller being configured to determine a proximity or a contact between the respective device and the object responsive to sensing a change in a capacitance across the respective first electroadhesion electrode and the respective second electroadhesion electrode of the respective device.