

GRIPPER AND GRIPPER SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority to the Singapore application no. 10202302998W filed October 23, 2023, the contents of which are hereby incorporated by reference in their entirety for all purposes.

TECHNICAL FIELD

[0002] This application relates to the field of material handling, and more particularly to a gripper and a gripper system.

BACKGROUND

[0003] Soft robotics, particularly soft grippers, have the potential for handling fragile objects such as fruits and vegetables, and is able to meet stringent sanitation standards. Conventional grippers often lack the versatility demonstrated by the biological counterparts, i.e. the biological hand/limbs. The disparity becomes increasingly apparent when gripping objects which vary significantly in size, shape, and weight. In addition, reliability of the gripper is often compromised when the contact surface(s) between the gripper and the target object is limited or insufficient, resulting in a lack of grip. This is further exacerbated when the target objects are soiled, wet, and densely clustered.

SUMMARY

[0004] According to an aspect, disclosed herein a gripper. The gripper comprising: a housing; a finger body movable relative to the housing along a finger axis, the finger body comprising: a plurality of actuating members, each of the plurality of actuating members

defining: a pair of contact surfaces disposed opposing each other and a path formed passing through the pair of contact surfaces; a plurality of connecting members, each of the plurality of connecting members movably coupled between a respective pair of the plurality of actuating members; and an elongated member passing through the respective path of selected ones of the plurality of actuating members to define a respective first axis, the elongated member being fixedly coupled to a distal one of the plurality of actuating member, wherein for each of a selected first ones of the plurality of actuating members, at least one of the pair of contact surfaces forms a first tilt in relative to the respective first axis, the first tilt being characterized by: in relative to the respective first axis, forming a first oblique angle about a respective second axis and forming a second oblique angle about a respective third axis, wherein the respective first axis, the respective second axis, and the respective third axis are orthogonal to each other.

[0005] According to another aspect of the disclosure, disclosed herein a gripping system.

The gripper system comprising: any of the above gripper; and a controller in signal communication with the gripper, the controller being configured to perform a method of gripping, the method comprising: applying a pulling force on the elongated member towards the housing to form a helical shape with the selected first ones of the plurality of actuating members about a first gripping axis.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Various embodiments of the present disclosure are described below with reference to the following drawings:

[0007] FIG. 1 is a schematic diagram of a gripper system according to embodiments of the present disclosure;

- [0008] FIG. 2 shows an exemplary gripper system and a gripper comprising phalanx members according to various embodiments;
- [0009] FIG. 3 shows the gripper of FIG. 2 in an operational state;
- [0010] FIG. 4 shows the gripper of FIG. 2 in another operational state;
- [0011] FIG. 5 shows a perspective view of a finger body comprising phalanx members according to various embodiments;
- [0012] FIG. 6 shows another perspective view of the finger body of FIG. 5;
- [0013] FIG. 7 shows a top view of FIG. 5;
- [0014] FIG. 8 shows a side view of FIG. 5;
- [0015] FIG. 9 shows an actuation of the finger body of FIG. 5;
- [0016] FIG. 10 shows a gripper system gripping an object according to various embodiments;
- [0017] FIG. 11 shows a perspective view of a finger body according to various embodiments;
- [0018] FIG. 12 shows a top view of FIG. 11;
- [0019] FIG. 13A shows a perspective view of a finger body according to various embodiments;
- [0020] FIG. 13B shows a top view of FIG. 13A;
- [0021] FIG. 14 shows a perspective view of a gripper with multiple finger bodies according to various embodiments;
- [0022] FIG. 15 shows a perspective view of a gripper with multiple finger bodies gripping an object according to various embodiments;
- [0023] FIG. 16 shows a perspective view of a gripper with a finger body and an additional tool according to various embodiments;

[0024] FIG. 17A shows a perspective view of a gripper with two finger bodies according to various embodiments;

[0025] FIG. 17B shows the gripper of FIG. 17A gripping an object;

[0026] FIG. 17C shows a perspective view of a manual pinching gripper according to various embodiments of the present disclosure;

[0027] FIG. 18A shows a perspective view of a finger body according to various embodiments of the present disclosure;

[0028] FIG. 18B shows a top view of FIG. 18A showing multiple sectional views;

[0029] FIG. 18C shows sectional view 706 of FIG. 18B;

[0030] FIG. 18D shows sectional view 707 of FIG. 18B;

[0031] FIG. 18E shows sectional view 708 of FIG. 18B;

[0032] FIG. 18F shows a partial perspective view of FIG. 18A;

[0033] FIG. 18G shows a top view of FIG. 18F;

[0034] FIG. 18H shows a top view of a finger body according to various embodiments;

[0035] FIGs. 19A to 19D shows steps of a method of fabricating a finger body according to various embodiments;

[0036] FIGs. 20A to 20D shows the interior structure of various phalanx members according to various embodiments;

[0037] FIG. 20E shows an actuation of a finger body according to various embodiments;

[0038] FIGs. 21A to 21C show perspective views of a finger body with side wing members according to various embodiments;

[0039] FIG. 21D shows a perspective view of a finger body with cutting members according to various embodiments;

[0040] FIG. 22 shows an exemplary gripper system and a gripper comprising spring members according to various embodiments;

- [0041] FIG. 23A shows a perspective view of a finger body comprising spring members according to various embodiments;
- [0042] FIG. 23B shows a side view of FIG. 23A;
- [0043] FIG. 24A shows a partial perspective view of the finger body of FIG. 23A;
- [0044] FIG. 24B shows a front view of FIG. 24A;
- [0045] FIG. 24C shows a top view of section A of FIG. 24A;
- [0046] FIG. 24D shows a side view of section A of FIG. 24A;
- [0047] FIG. 25A shows a perspective view of a finger body comprising spring members with reducing diameter according to various embodiments;
- [0048] FIG. 25B shows a side view of FIG. 25A;
- [0049] FIG. 26A shows a side view of a finger body comprising a symmetrical pair of linear-routed elongated members according to various embodiments;
- [0050] FIG. 26B shows side views of a finger body comprising a movable sleeve according to various embodiments;
- [0051] FIG. 27 shows a sectional side view of a finger body and a sleeve according to various embodiments;
- [0052] FIG. 28A and 28B show the opposing rotations of the sleeve in relative to the finger body of FIG. 27;
- [0053] FIG. 29 shows a perspective view of an elongated member actuator according to various embodiments;
- [0054] FIG. 30 shows a perspective view of a flexible rack and pinion system according to various embodiments;
- [0055] FIG. 31 shows a rigid rack and pinion system according to various embodiments;
- [0056] FIGs. 32A to 32C show the integration of the various drivers to the gripper system according to various embodiments;

[0057] FIG. 33A and 33B show perspective views of an actuatable/bendable sleeve in respective neutral and actuated state according to various embodiments;

[0058] FIG. 34 shows a perspective view of a gripper system according to various embodiments;

[0059] FIG. 35 is a schematic diagram of a finger body comprising a sensor according to various embodiments;

[0060] FIG. 36 shows a partial perspective view and a sectional perspective view of the finger body of FIG. 35;

[0061] FIG. 37 shows a partial sectional side view of the finger body of FIG. 35;

[0062] FIG. 38 shows a partial perspective view and a sectional perspective view of a connector of the finger body of FIG. 35;

[0063] FIG. 39 is an image of an exemplary finger body;

[0064] FIG. 40 is a plot showing a test result from a sorting of vegetables using sensors in the finger body of FIG. 39;

[0065] FIG. 41 shows perspective view and sectional view of a contact sensor according to various embodiments;

[0066] FIG. 42 is a schematic diagram of a finger body comprising a sensor according to various embodiments;

[0067] FIG. 43 shows a top view, a side view and sectional side views of the finger body of FIG. 42;

[0068] FIG. 44 is a schematic illustrating the formulation of a sensor;

[0069] FIG. 45 is an image of an exemplary sensor;

[0070] FIGs. 46A and 46B are plots showing calibration test results and repeatability test results for the sensor of FIG. 45;

- [0071] FIG. 47 is a schematic diagram of a finger body comprising a sensor according to various embodiments;
- [0072] FIG. 48 shows a side view and sectional side views of the finger body of FIG. 47;
- [0073] FIG. 49 is a schematic diagram of a finger body comprising a sensor according to various embodiments;
- [0074] FIG. 50 shows a front view and a sectional side view of the finger body of FIG. 49;
- [0075] FIG. 51 is a flow chart showing a gripping procedure of a gripper according to various embodiments;
- [0076] FIG. 52 is a flow chart showing a motor control procedure according to various embodiments;
- [0077] FIG. 53 is a flow chart showing a decision process for gripping according to various embodiments;
- [0078] FIG. 54 shows a structure of a neural network for object classification according to various embodiments;
- [0079] FIG. 55 is a schematic diagram showing a signal flow in a gripper system according to various embodiments;
- [0080] FIG. 56 shows the various perspective views of a multi-phalanx gripper undergoing Grow-then-Twine gripping motion;
- [0081] FIG. 57 shows the perspective views of a multi-phalanx type gripper undergoing Grow-and-Twine gripping motion;
- [0082] FIG. 58 shows the perspective views of a spring-type gripper undergoing Grow-and-Twine gripping motion; and
- [0083] FIG. 59 is a flow chart illustrating a method of gripping according to various embodiments.

DETAILED DESCRIPTION

[0084] 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.

[0085] 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.

[0086] 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.

[0087] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0088] The term “position” may refer to a location or coordinate (for example, X-coordinate, Y coordinate, Z coordinate) of an object or part of an object in a space or a frame. The term “orientation” may refer to a facing or angle (for example, a X-direction vector, a Y-direction vector, a Z-direction vector) of an object or part of an object in a space or a frame.

[0089] The term “tilt” may refer to an oblique or non-orthogonal orientation of an object or a surface relative to a reference, such as an axis. The term “tilt” may also refer to a directional pivoting of an object or a surface in relative to a reference. The term “tilt” may also refer to an inclination or a slant of an object or a surface relative to a reference.

[0090] As used herein, the term “helical” or “spiral” generally refers to forming a shape of a helix, or in other words, forming a curve that goes around a central axis in the form of a spiral.

[0091] The present disclosure proposes a soft gripper and a gripper system according to various embodiments. The soft gripper may include one or more finger bodies for gripping a target object. Departing from conventional gripper which are typically actuated in one or two dimensions, the finger body of the proposed gripper may be provided with an extra dimension of extension during operation, allowing the gripper to grow and twine itself around the target object. In various embodiments, the gripper may form a helical shape or spiral shape upon actuation to grip onto the target object. With the inclusion of the extra dimension, i.e. the “height dimension” of the spiral/helix, an increase in the contact surface between the gripper and the target object may be achieved, improving the robustness of the gripping operation.

[0092] In various embodiments, a grip diameter or a helical diameter may be varied based on a working length of the gripper or the finger body. The working length may correspond to an operable length of the finger body which may be actuated. Provision of a variable working length allows the finger body to be adjusted for gripping objects of different sizes or dimensions. In some embodiments, the finger body may include a varying stiffness along the working length of the finger body. The varying stiffness may allow a portion of the finger body to bend before other portions of the finger body. Hence, the variable working length and the varying stiffness of the finger body enables a varying in actuated shape of the finger body for gripping objects of a variety of shapes and sizes.

[0093] In various embodiments, flexible sensors may be coupled or integrated with the gripper, providing contact status detection, force sensing, and shape sensing to facilitate a closed-loop control of the gripper system. According to various embodiments, the gripper may be used in various applications, such as: agriculture, the food industry, underground/underwater exploration, warehouses, and logistics for handling objects of various sizes, shapes, and weights.

[0094] FIG. 1 illustrates a gripper system 50 according to various embodiments of the present disclosure. The gripper system 50 may include a gripper 100 in signal communication with a controller 130. The gripper 100 may be coupled to a robotic arm 140. The robotic arm 140 may control a position and an orientation of the gripper 100 to vary a pose of the gripper 100. In some embodiments, the robotic arm 140 may also be in signal communication with the controller 130. The controller 130 may be configured to concurrently control the gripper 100 as well as the robotic arm 140. In other embodiments, the gripper 100 may be mounted on or coupled to a mobile platform, such as on Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), or other moving frames, etc. The configuration forms a system capable of realizing Pick-n-Place tasks.

[0095] In various embodiments, the gripper 100 may include a housing 120 and a finger body 110 movable relative to the housing 120. The finger body 110 may be linearly displaceable relative to the housing 120 along a finger axis 81. For example, the finger body 110 may translate relative to the housing 120 along the finger axis 81. In other embodiments, the finger body 110 may bend relative to the housing 120 away or towards the finger axis 81. In yet other embodiments, the finger body 110 may rotate relative to the housing 120 about the finger axis 81.

[0096] In various embodiments, the finger body 110 may include a plurality of actuating members 112 and a plurality of connecting members 114. The actuating members 112 and the connecting members 114 may be coupled juxtaposedly in series to form the finger body 110. In various embodiments, each of the plurality of connecting members 114 may be movably coupled between a respective pair of actuating members 112. In other words, each connecting member 114 is coupled between a pair of actuating members 112. The connecting members 114 may be deformable elastic members.

[0097] In various embodiments, each actuating members 112 may define a pair of contact surfaces 113 disposed opposing each other, or in other words, disposed on opposing sides of the actuating member 112. In some embodiments, each of the pair of contact surface 113 may be a planar surface or may define a plane. Each pair of contact surfaces 113 may also define a path 117 formed passing through the pair of contact surfaces 113.

[0098] In various embodiments, the finger body 110 may further include an elongated member 116 passing through the path 117 of the actuating members 112. The elongated member 116 may be fixedly coupled or anchored to a distal actuating member 112d. The elongated member 116 may be a tendon or a cable, such as a taut elongated member. The tendon may be a tensionable rope that is soft and inextensible rope. In various embodiments, the elongated member 116 may define a length axis. The elongated member 116 may be bendable away from the length axis. The elongated member 116 may not extend nor contract in length along the length axis. The distal actuating member 112d may be the last or one of the last actuating members 112 disposed away from the housing 120. In some embodiments, the distal actuating member 112d may be disposed at a tip of the finger body 110. Alternatively, the finger body 110 may include further structural members extending from the distal actuating member 112d.

[0099] Alternatively, in other embodiments, the elongated member 116 may be an elastic member in tension. The elongated member 116 may have superelastic property. In an example, the elongated member 116 may be a superelastic rod. In various embodiments, the elongated member 116 may be configured to exert a pulling force and a pushing force on the distal actuating member 112d. In other embodiments, the elongated member 116 may have shape memory property such that the elongated member 116 straightens responsive to an elevated temperature.

[00100] In various embodiments, the elongated member 116 may pass through the respective path 117 of selected ones of the actuating members 112 to define a respective first axis 83. In other words, the elongated member 116 passes through each path 117 along a direction which defines a respective first axis 83. It may be appreciated that each of the respective first axis 83 may be individually defined by the elongated member 116 and the path 117. In some embodiments, the elongated member 116 may pass through all of the actuating members 112. In other examples, the elongated member 116 may pass through each of the actuating members 112 with the exception of the distal actuating member 112d. In various embodiments, each pair of contact surface 113 may define a respective pair of openings. The elongated member 116 may pass through each path 117 via respective pair of openings. Therefore, each path 117 may be defined by a respective pair of openings and a path through the respective actuating member 112.

[00101] In various embodiments, the elongated member 116 may define a respective first axis 83 passing through each path 117 of the actuating member 112. Therefore, the elongated member 116 may define multiple first axes 83 which passes through respective multiple paths 117 of the actuating members 112. In some embodiments, the multiple first axes 83 may be coaxial to each other. Alternatively, the multiple first axes 83 may also be non-coaxial to each other.

[00102] In various embodiments, for selected ones or all of the actuating members 112, one or both of the contact surfaces 113 may form a first tilt in relative to the respective first axis 83 of the actuating member 112. The first tilt may include respective inclinations/slants of the contact surface 113 in a first dimension and a second dimension relative to the respective first axis 83. The first tilt of the contact surfaces 113 may be characterized by: i) the contact surface 113 forming a first oblique angle about a respective second axis 85 in relative to the respective first axis 83 and ii) the contact surface 113 forming a second oblique angle about a respective

third axis 87 in relative to the respective first axis 83. Each of the first oblique angle and the second oblique angle may be either an acute angle or an obtuse angle. The respective first axis 83, the respective second axis 85, and the respective third axis 87 being orthogonal to each other. It may be appreciated that in various embodiments, there will be multiple pairs of respective second axes 85 and respective third axes 87, each pair corresponding to a respective first axis 83.

[00103] In some embodiments, each of the first oblique angle may be formed in a respective first plane defined by the respective first axis 83 and the respective third axis 87. It may be said that in relative to the respective first axis 83, the contact surface 113 forms the first oblique angle about the respective second axis 85, as the first oblique angle may be changed or varied responsive to a rotation of the contact surface 113 about the respective second axis 85. Similarly, each of the second oblique angle may be formed in a respective second plane defined by the respective first axis 83 and the respective second axis 85. Hence, it may be said that in relative to the respective first axis 83, the contact surface 113 forms the second oblique angle about the respective third axis 85, as the second oblique angle may be varied responsive to a rotation of the contact surface 113 about the respective third axis 85.

[00104] In various embodiments, when the finger body 110 is in a neutral state (as shown in FIG. 1), the actuating members 112 and connecting members 114 may be substantially positioned aligned along the finger axis. The finger body 110 may be said to be in an actuated state when the finger body is in a helical shape 92 or spiral shape.

[00105] In various embodiments, the finger body 110 may be generally compliant, or is not biased towards any states. In other words, the finger body 110 may assume a plurality of states or shapes when no external actuating force is applied to the finger body 110. In these embodiments, responsive to a pulling force exert by the elongated member 116 pulling the distal actuating member 112d towards the housing 120, the finger body 110 may be actuated from the

neutral state to the actuated state, in which the actuating members 112 collectively form a helical shape 92 or spiral shape about a first gripping axis 82. Similarly, the finger body 110 may be actuated from the actuated state to the neutral state responsive to a pushing force, exerted by the elongated member 116 on the distal actuating member 112d. In some embodiments, the pulling force may be exerted by moving the finger body 110 relative to a stationary elongated member 116. Similarly, this pulls onto the distal actuating member 112d towards the housing, to actuate the finger body 120 to the actuated state.

[00106] In other embodiments, the finger body 110 may be biased towards the neutral state. In other words, the finger body 110 may assume the neutral state when no external force is applied to the finger body 110. When the finger body 110 is in the neutral state, responsive to a pulling force 91 applied to the elongated member 116 pulling the distal actuating member 112d towards the housing 120, the finger body 110 may be actuated to the actuated state, in which the actuating members 112 collectively form a helical shape 92 or spiral shape about a first gripping axis 82. When the elongated member 116 is released, the finger body 110 returns to the neutral state due to the bias in the finger body 110.

[00107] Alternatively, the finger body 110 may be biased towards actuated state. In other words, the finger body 110 may assume the actuated state when no external force is applied to the finger body 110. When the finger body 110 is in the actuated state, in which the actuating members 112 collectively form a helical shape 92, responsive to a pushing force applied to the elongated member 116 pushing on the distal actuating member 112d, the finger body 110 may be actuated to the neutral state in which the finger body 110 is generally straight. When the elongated member 116 is released, the finger body 110 returns to the actuated state due to the bias in the finger body 110.

[00108] In some examples, the pair of contact surfaces 113 of the actuating member 112 may form a pair of symmetrical first tilts about a centre plane of the actuating member 112 in relative

to the corresponding first axis 83. In some examples, both of the pair of contact surfaces 113 may have an identical first tilt. In other examples, the first tilt of each of the contact surfaces 113 may not be identical nor symmetrical. In other words, the first oblique angle and second oblique angle of one of the contact surfaces 113 may be different from the first oblique angle and second oblique angle of another of the contact surfaces 113.

[00109] In various embodiments, the gripper 100 may further include a finger actuator 124 coupled to the finger body 110. The finger actuator 124 may be configured to move or displace the finger body 110 relative to the housing 120 along the finger axis 81. In some embodiments, the finger actuator 124 may extend or retract the finger body 110 along the finger axis 81 with the housing 120 being kept stationary. In other embodiments, the finger actuator 124 may extend or retract the housing 120 along the finger axis 81 with the finger body 110 being kept stationary. In various embodiments, the finger actuator 124 may move the finger body 110 as well as the housing 120 along the finger axis 81 to provide a relative movement between the finger actuator 124 and the finger body 110. As examples, the finger actuator 124 may be one or more linear driver(s) or a linear actuator(s).

[00110] In various embodiments, the gripper 100 may further include an elongated member actuator 126 coupled to the elongated member 116. The elongated member actuator 126 may be configured to apply a pulling force on the elongated member 116 towards the housing 120, to release on the elongated member 116 away from the housing 120, or to apply a pushing force on the elongated member 116 away from the housing 120.

[00111] FIG. 2 illustrates an exemplary gripper system 50 according to various embodiments. The gripper system 50 may include a gripper 100 in signal communication with a controller 130. The controller 130 may control and vary a state of the gripper 100. A robotic arm 140 may be coupled to the gripper 100 to controllably vary a position and an orientation of the gripper

100. In some embodiments, the robotic arm 140 may also be in signal communication with the controller 130.

[00112] FIGs. 3 and 4 illustrate a phalanx-based gripper 100 according to various embodiments of the present disclosure. FIG. 3 illustrates the gripper 100 in a first orientation and FIG. 4 illustrates the gripper 100 in a second orientation rotated relative to the first orientation. It may be appreciated that the orientation of the gripper 100 may be controlled by the robotic arm 140. According to various embodiments, the gripper 100 may include a finger body 110 movably coupled to a housing 120. The finger body 110 may be movable 90 relative to the housing 120 along a finger axis 81. In various embodiments, the housing 120 may include a base 121 and a sleeve 122 extending from the base 121. The sleeve 122 may define a conduit and the finger body 110 may be disposed in the conduit and movable 90 relative to the sleeve 122 along the finger axis 81. Responsive to actuation of the finger body 110, such as applying a tension force on a distal end of the finger body 110, the finger body 110 may form a helical shape 92 or spiral shape about a first gripping axis 82.

[00113] FIGs. 5 to 8 illustrate embodiments of the finger body 110 according to various embodiments. The finger body 110 may include a plurality of actuating members and a plurality of connecting members. The actuating members may be phalanx members 112. The connecting members may be flap members 114 or elastic/deformable flaps. The flap members 114 may be deformable or bendable allowing the phalanx members 112 to move relative to each other. The phalanx members 112 and the flap members 114 may be coupled juxtaposedly in series to form the finger body 110. In various embodiments, each of the plurality of flap members 114 may be movably coupled between a respective pair of phalanx members 112.

[00114] According to various embodiments, each phalanx member 112 may include a pair of contact surfaces 113a/113b (see FIGs 7 and 8) disposed opposing each other. In some embodiments, the contact surfaces 113a/113b may be planar surfaces. In other words, each

contact surface 113 may define a plane or may be formed from a planar structure. Each of the contact surface 113 may also include one or more openings 115 (see FIG. 6). Each pair of contact surfaces 113a/113b and hence the openings 115, may define a path 117 formed passing through the respective phalanx member 112.

[00115] According to various embodiments, each phalanx member 112 may include a gripping surface 118 and a base surface 119 opposing the gripping surface 118. The gripping surface 118 and the base surface 119 may be disposed between a pair of contact surfaces 113a/113b. The base surface 119 of each phalanx member 112 may be coupled to a flap member 114. In some embodiments, each flap member 114 may extend between and couple a respective pair of base surfaces 119.

[00116] In various embodiments, the finger body 110 may further include an elongated member 116 passing through each of the path 117 of the phalanx members 112. The elongated member 116 may be fixedly coupled or fixed to a distal phalanx member 112d. In various embodiments, the elongated member 116 may pass through the respective path 117 of the phalanx members 112 to define a respective first axis 83. Each path 117 may pass through a respective pair of openings 115 through the respective phalanx member 112. In various embodiments, the elongated member 116 may define a respective first axis 83 passing through each path 117 of the actuating member 112. In the embodiments as shown in FIGs. 7 and 8, in an unactuated state where the finger body is substantially straight, the multiple first axes 83 may be coaxial and parallel to each other.

[00117] In various embodiments, referring to FIGs. 7 and 8, the contact surfaces 113a/113b of the phalanx member 112 may each form a first tilt in relative to the respective first axis 83 of the phalanx member 112. The first tilt formed by each pair of contact surfaces 113a/113b may be symmetrical to each other. The first tilt of each of the contact surfaces 113 may be characterized by: the contact surface 113 forming a first oblique angle θ_1 about a respective

second axis 85 in relative to the first axis, and the contact surface 113 forming a second oblique angle θ_2 about a respective third axis 87 in relative to the first axis. The respective first axis 83, the respective second axis 85, and the respective third axis 87 are orthogonal to each other.

[00118] In some embodiments, the first oblique angle θ_1 may be formed in a first plane 84 defined by the respective first axis 83 and the respective third axis 87 (as shown in FIG. 8). Hence, in relative to the respective first axis 83, the contact surface 113 forms the first oblique angle θ_1 about the respective second axis 85, as the first oblique angle θ_1 may be changed or varied responsive to a rotation of the contact surface 113 about the respective second axis 85. Similarly, the second oblique angle θ_2 may be formed in a second plane 86 defined by the respective first axis 83 and the respective second axis 85 (as shown in FIG. 7). Hence, in relative to the respective first axis 83, the contact surface 113 forms the second oblique angle θ_2 about the respective third axis 85, as the second oblique angle may be varied responsive to a rotation of the contact surface 113 about the respective third axis 85.

[00119] In some embodiments, only one (e.g. contact surface 113a) of the pair of contact surfaces 113a/113b of the phalanx members 112 may form a first tilt in relative to the respective first axis 83. In some embodiments, the first tilt for each of the pair of contact surfaces 113a/113b may not be identical or may not be symmetrical, in other words, the first oblique angle θ_1 and second oblique angle θ_2 of each of the contact surfaces 113 may be different from each other.

[00120] Referring to FIGs. 9 and 10, in various embodiments, responsive to a pulling force 91 applied to the elongated member 116 towards the housing 120, the distal phalanx members 112d is pulled towards the other phalanx member 112 with the adjacent contact surfaces 113 contacting each other. This results in the actuation of the finger body 110 to form a helical shape 92. The first tilt (orientation) of the contact surfaces 113 and the contact therebetween enable the phalanx member 112 to collectively form a helical shape 92 or spiral shape (or a

predetermined shape) about a first gripping axis 82 to grab an object 70. It may be appreciated that increasing the working length of the finger body 110 (length of the finger body 110 protruding from the sleeve 122) and/or increasing the elongated member pulling distance or elongated member tension, allows the finger body to form a larger twine/spiral around the object 70 with an increased contact area and/or contact force, robustly holding onto the object 70.

[00121] Referring to FIG. 11 and 12, in various embodiments, in the neutral state, each path 117 and respective first axis 83 may be non-coaxial and parallel to each other. The paths 117 may be inclined paths 117. In comparison to paths which are coaxial in the neutral state, the inclined paths 117 allows an exit point (opening 115a) of one path 117a to be closer to an entry point (opening 115b) of another adjacent path 117b, thus resulting in a helical shape with a larger pitch in comparison to. The larger pitch of the finger body 110 may be formed due to a closer distance between respective pairs of entry point/exit point when the finger body 110 is in the actuated state. This may be due to a shift in the respective entry points/exit points along the first gripping axis 82 (a height dimension of the helical shape) when the finger body 110 is in the actuated state.

[00122] According to various embodiments, the finger body 110 may further include one or more sensors detachably coupleable to the finger body 110. The sensors may be in an array configuration. The sensors may be in an array configuration in which a portion or a whole of the sensor array may be detachable. The sensors may be optical sensors or optical fiber-based sensors. As examples, the sensors may include one of or more of: a force sensor, a pressure sensor, and a bending sensor. In various embodiments, the finger body 110 may further include a first sensor path formed extending through the elastic flap members 114 and a bending sensor disposed in the first sensor path. The bending sensor may be configured to measure a bending

state or bending angle of the finger body 110. As an example, the bending sensor may be an optical sensor such as a Fiber Bragg Grating (FBG) sensor.

[00123] In some embodiments, in addition to the paths 117, each of the phalanx members 112 may further define a second sensor path passing through each of the pair of contact surfaces 113. A contact sensor may be disposed passing through the second sensor paths. The contact sensor may be configured to measure the contact or contact force(s) between the phalanx members 112 and the object gripped by the finger body 110. Similarly, the contact sensor may be an optical sensor such as a Fiber Bragg Grating (FBG) sensor.

[00124] FIGs. 13A and 13B illustrate a finger body 210 according to various embodiments. The finger body 210 may include a plurality of phalanx members 212. The plurality of phalanx members 212 may include a plurality of first phalanx members 212a and a plurality of second phalanx members 212b. The first phalanx members 212a may include a pair of opposing contact surfaces. Similar to previous section, each of the contact surfaces of the first phalanx members 212a may form a first tilt in relative to the respective first axis, the first tilt being characterized by: in relative to the first axis, the contact surface forming a first oblique angle about a respective second axis and forming a second oblique angle about a respective third axis.

[00125] Similarly, the second phalanx members 212b may include a pair of opposing contact surfaces. Each of the contact surfaces of the second phalanx members 212b may form a second tilt in relative to the respective first axis, the second tilt being characterized solely by: in relative to the first axis, the contact surface forming a first oblique angle about a respective second axis only. In various embodiments, the plurality of phalanx members 212 may further include a third phalanx member 212c. The third phalanx member 212c may include a pair of opposing contact surfaces. One of the contact surfaces of the third phalanx member 212c may form the first tilt and another of the contact surfaces of the third phalanx member 212c may form the second tilt.

[00126] In various embodiments, responsive to a pulling force applied to the elongated member towards the housing, the first phalanx members 212a may collectively form a helical shape about a first gripping axis responsive and the second phalanx members may form a circular shape about a second gripping axis. Therefore, when actuated, the finger body 210 may include a combination of a spiral form and a circular form. In other words, a part of the finger body 210 may be in a spiral form and another part of the finger body 210 may be in a circular form. Due to the different tilt formed by the respective contact surfaces, the second gripping axis may be oblique to the first gripping axis.

[00127] According to various embodiments as illustrated in FIG. 14, the gripper 300 may include multiple finger bodies 301a/301b/301c for gripping multiple targeted objects 302a/302b/302c at different locations simultaneously. The objects 302a/302b/302c may include a variety of or varying sizes, shapes, and weights. The gripper 300 as illustrated is an example and the number of finger bodies and the respective working length of the finger bodies may be varied/adjusted to suit specific requirements and application scenarios.

[00128] According to various embodiments, as illustrated in FIG. 15, to improve the gripper's robustness and performance when handling a single object 403, a gripper with multiple finger bodies 400a may be employed to achieve envelope grasping. This enables secure and stable grasping, enhancing overall gripping efficiency. The finger configuration allows for the formation of a helical shape in opposite directions 402a/402b, providing enhanced adaptability to grasp objects with varying geometries and surface contours.

[00129] In various embodiments, the multi-functional capabilities of the gripper may be demonstrated in a multiple-tool gripper system 400b (FIG. 16). The finger 402a may serve as a holding tool to hold the object firmly in place, creating a stable and controlled environment for another tool, such as a cutter tool 404 to perform an operation effectively, such as cutting. Without being limiting and based on the application, apart from a cutter, the tool may be a

scissor, a snare, a needle, a maker, a brush, etc. In some embodiments, the cutter tool 404 may be integrated and disposed within the sleeve 401 or implemented as another finger, enabling a large range of use cases for the gripper. It is noted that two tools as shown are merely illustration and the number of tools may be adjusted to meet the requirements of the application scenario. This collaborative system enables seamless integration with different tools, expanding the finger's utility in various industrial and manufacturing processes.

[00130] Referring to FIGs. 17A and 17B, in various embodiments, apart from the extension and twining capabilities, the gripper demonstrates proficiency in performing pinch grasping using multiple fingers. The profiles of the finger bodies 502 may be formed with a planar arc shape when actuated. This enables the gripper 500 to easily execute pinch grasping and manoeuvres on object(s) 503, with the pair of finger bodies 502, each fitted with a sleeve 501. Further, as shown in FIG. 17C, apart from being part of automation, a manual pinching gripper 600 comprising two finger bodies 603 is disclosed. The finger bodies 603 may be positioned at the distal side of a gripper body 601 with a handle 604 with a trigger 602 positioned at the proximal side. By holding on to the handle 604 and pressing the trigger 602, the finger bodies 603 may be in tension or tightened to pinch the object 503 securely.

[00131] FIGs. 18A to 18H discloses an exemplary finger body 710 according to various embodiments of the disclosure. The finger body 710 may include multiple phalanges 712 or phalanx members, which are linearly arranged with connections 714 or connecting members. A connection section 718 may be provided at the proximal end of the finger body 710. A distal phalanx 712d may be provided at the distal end of the finger body 710. The finger body 710 may incorporate path(s) 717 that traverses through all of the phalanx members and connecting members.

[00132] Various sectional views of the focused area 705 show the structural details of the finger body 710 of FIG. 18B. The longitudinal sectional view along a cutting plane 706 (FIG.

18C) depicts wire slots 719 for wires made of super-elastic material (e.g., nitinol) or shape memory material (e.g., SMA). The longitudinal sectional view along a cutting plane 707 (FIG. 18D) shows the sensor wires slots 720. The transverse sectional view along a cutting plane 708 (FIG. 18E) shows the arrangement of path 717 for an elongated member, wire slot 719 for elastic wire(s), sensor wires slots 720 specifically for sensor wire(s), and elastic wire(s) 721. The elastic wire(s) 721 made of super-elastic material (e.g., nitinol) or shape memory material (e.g., SMA) are integrated to improve the elasticity of the finger body. A side view of the focused area 705 (FIG. 18F) shows the inclined angle of phalanx 722 (first oblique angle). The top view of focused area 705 (FIG. 18G) shows the twist angle of phalanx 723 (second oblique angle). Collectively, the inclined angle of phalanx θ_1 and the twist angle of phalanx θ_2 forms the first tilt.

[00133] The phalanx height, phalanx length, inclined angle of phalanx 722, twist angle of phalanx 723, and finger body width determine the inner and outer diameters of the finger body's helical shape after the elongated member upon tension/ tightening. When the path 717 is not parallel to the wire slot 719, the inclined angle 724 (FIG. 18H) is non-zero, which affects the pitch of the finger body's final helical shape. When the path 717 is parallel to the wire slot 719, the inclined angle is zero as illustrated in FIG. 18G.

[00134] According to various embodiments, as shown in FIGs. 19A to 19D, the finger body may be fabricated using methods including: moulding, 3D printing, and more. In an exemplary method, 3D printing of the finger body 801 was employed with fused deposition modelling (FDM) using Thermoplastic polyurethane (TPU) as shown in FIGs. 19A to 19D. During the 3D printing process, as the printing layer reaches the top surface of the wire slots 802, elastic wire(s) 803 made of super-elastic material (e.g., nitinol) or shape memory material (e.g., SMA) were embedded into the wire slots 802 (FIG. 19A). The number of slots and wires may be varied and adjusted according to the desired elasticity and responsiveness of the finger body. In various

implementations, multiple slots and wires may be evenly distributed across all phalanges. Upon embedding the wires, the slots in phalanx 804 are fully or partially occupied (FIG. 19C). Then, the FDM 3D printing continues to cover the slots and complete the fabrication of the finger (FIG. 19B and 19D).

[00135] To achieve a soft and flexible finger, two approaches, a phalanx with cavity 902 (FIG. 20A), or a phalanx with soft interface 903 (FIG. 20B) may be employed in place of a solid phalanx 901. The phalanx with cavity 902 may be formed by mounting a shell structure 904 onto the middle section 905, resulting in the formation of a phalanx with a hollow interior. An alternative soft finger configuration may be realised by using a phalanx with a soft interface 903. To achieve this configuration, a soft cover 906, made from a flexible material like silicone rubber, is installed over the middle section 905 of the finger body.

[00136] Referring to FIG. 20E, to enable the actuation of the single-finger gripper 1000, an elongated member 1001 is inserted along the path, running through both the connection section 1003 and the finger body 1002. The elongated member 1001 may be securely fixed to the distal phalanx of the finger body 1002. By fixing the connection section 1003 and pulling the elongated member 1001, the finger body 1002 undergoes deformation gradually, resulting in the formation of a variety of helical shapes. As the elongated member 1001 is gradually pulled to its maximum (right figure of FIG. 20E), a distinct helical shape is achieved.

[00137] As shown in FIGs. 21A to 21C, the phalanx member of the finger body 1101 may be provided with functional structures. In some embodiments, each of the phalanx members may further comprise a side-wing member 1102. The side-wing member 1102 may extend parallelly from a respective base surface 1101a to end at a narrowed tip portion 1102a. To control the closing and opening of the side-wing members 1102 or the narrowed tip portion 1102a, a second elongated member 1103 may be provided operably coupled to each of the narrowed tip portions 1102a. When both elongated members 1103 and 1104 are pulled, each of the narrowed tip

portions 1102a moves towards each other such that the side-wing members 1102 are closed together, deforming the finger body 1101. This results in the formation of a bag-like enclosure (FIG. 21C).

[00138] In some embodiments shown in FIG. 21D, cutting members 1105 or blades may be coupled to the phalanx members of the finger body 1101. The cutting member extending parallelly from the respective base surface to end at a cutting edge. As the finger bends to grip the object, the cutting members 1105 or blade may cut or break the object at a gripping location.

[00139] FIGs. 22 to 25B illustrates a spring-based gripper 1200 according to various embodiments of the present disclosure. The gripper 1200 may include a finger body 1210 moveable relative to a housing 1220 along a finger axis 81. The finger body 1210 may include a plurality of actuating members and a plurality of connecting members. According to various embodiments, the actuating members may be plate members 1212 or disks, and the connecting members may be spring members 1214 or segmental springs. Hence, the finger body 1210 may be a spring-based finger body 1210. The spring-based finger body 1210 may be housed in the sleeve 1220 or housing initially, and upon actuation, extends or moves out of the sleeve 1220 follow by twining around a targeted object along the gripping axis or spiral axis 82 responsive to applying a pulling force on an elongated member 1216.

[00140] According to various embodiments, each plate member 1212 may include a pair of contact surfaces 1213 (see FIG. 24A) disposed opposing each other. In some embodiments, the contact surfaces 1213 may be planar surfaces. Each of the plate members 1212 may include a plurality of through-openings or openings 1215. In some embodiments as shown in FIGs. 24A and 24B, the plate member 1212 may define a central axis 1211. The plurality of through-openings or openings 1215 may be disposed rotationally symmetrical about the central axis 1211 (see FIG. 24B). Each pair of contact surfaces 1213 and hence openings 1215 (or through-holes), may define a path 1217 formed passing through the respective plate member 1212. The

elongated member may pass each plate through a different hole in clock-wise direction or anti-clockwise direction, which in return forms a helical structure when the elongated member is pulled.

[00141] According to various embodiments, each of the spring members 1214 defines a pair of opposing ends. Each end of the spring member 1214 may be coupled to a respective plate member 1212. To enhance the bonding between the spring members 1214 and the plate members 1212 (or the segmental springs and the disks), adhesive materials such as super-glue or epoxy may be used. In the case where both the springs and disks are made of metal or alloy, laser welding may be a viable option. The spring members 1214 may be deformable or elastic, allowing the plate members 1212 to move relative to each other. The plate members 1212 and the spring members 1214 may be coupled juxtaposedly in series to form the finger body 1210.

[00142] In some embodiments as shown in FIG. 23B, an elastic sleeve 1218 or membrane skin may be provided encapsulating and enclosing the plate members 1212 and the spring members 1214. In addition to acting as a cover or enclosure for the plate members 1212 and spring members 1214, the elastic sleeve 1218 may increase a contact surface or a frictional force with the object during gripping.

[00143] In various embodiments, the finger body 1210 may include an elongated member 1216 disposed passing through one of the through-openings 1215 / path 1217 of each plate member 1212 to define a respective first axis 83. The elongated member 1216 may be fixedly coupled to a distal plate member 1212d. In various embodiments, the elongated member 1216 may pass through one of the multiple through-openings 1215 of the plate members 1212 to define a respective first axis 83. The elongated member 1216 may define a respective first axis 83 passing through each path 1217 of the plate member 1212. In the embodiments as shown in FIGs. 24A and 24B, the multiple first axes 83 may be coaxial and non-parallel to each other. In an exemplary embodiment, the elongated member 1216 may define a respective first axis 83a

with plate member 1212a. Further, the elongated member 1216 may define a first axis 83b with plate member 1212b and define a respective first axis 83c with plate member 1212c.

[00144] The elongated member 1216 may pass through the openings 1215 in a clockwise or counterclockwise sequence across the different plate members 1212, with the last or distal plate member 1212d acting as an end of the finger body 1210. The distal plate member 1212d may be coupled to the distal plate member 1212d through a crimping bead or a tied knot.

[00145] In various embodiments, referring to FIGs. 24A to 24D, the contact surfaces 1213 of the plate members 1212 may form a first tilt in relative to the respective first axis 83 of the plate member 1212. In some embodiments, the first axis 83 is non-parallel to the finger axis 81. The first tilt formed between the elongated member 1216 and the respective plate members 1221 may be characterized by: i) the plate member 1221 forming a first oblique angle θ_1 about a respective second axis 85 in relative to the respective first axis 83 and ii) the plate member 1221 forming a second oblique angle θ_2 about a respective third axis 87 in relative to the respective first axis 83. The respective first axis 83, the respective second axis 85, and the respective third axis 87 are orthogonal to each other.

[00146] FIGs. 24C and 24D shows a top view and a side view of Section A of FIG. 24A. In an example, the plate member 1212a may form a first tilt relative to the respective first axis 83a. The contact surface 1213a of the plate member 1212a may form a first oblique angle θ_1 about a respective second axis 85 in relative to the respective first axis 83 (FIG. 24C). Similarly, contact surface 1213b may also form a first oblique angle θ_1' about a respective second axis 85 in relative to the respective first axis 83. It may be appreciated that the first oblique angle θ_1 may not be equal to the first oblique angle θ_1' . In addition, contact surface 1213a of the plate member 1212a may form a second oblique angle θ_2 about a respective third axis 87 in relative to the respective first axis 83 (FIG. 24D). Similarly, contact surface 1213b may also form a second oblique angle θ_2' about a respective third axis 87 in relative to the respective first axis

83. It may be appreciated that the second oblique angle θ_2 may not be equal to the second oblique angle θ_2' .

[00147] In some embodiments, the first oblique angle θ_1 may be formed in a first plane 84 defined by the respective first axis 83 and the respective third axis 87 (as shown in FIG. 24C). Hence, in relative to the respective first axis 83, the contact surface 113 forms the first oblique angle θ_1 about the respective second axis 85, as the first oblique angle θ_1 may be changed or varied responsive to a rotation of the contact surface 113 about the respective second axis 85. Similarly, the second oblique angle θ_2 may be formed in a second plane 86 defined by the respective first axis 83 and the respective second axis 85 (as shown in FIG. 24D). Hence, in relative to the respective first axis 83, the contact surface 113 forms the second oblique angle θ_2 about the respective third axis 85, as the second oblique angle may be varied responsive to a rotation of the contact surface 113 about the respective third axis 85.

[00148] Similarly, in another example, the plate member 1212c may form another first tilt relative to the respective first axis 83c. Referring again to FIG. 22, responsive to a pulling force applied to the elongated member 1216 towards the housing 1220, the plate members 1212 are pulled towards each other to collectively form a helical shape or spiral shape about a first gripping axis 82. In other words, pulling the non-linear routed elongated member 1216 enables or results in the formation of a helical shape that wraps tightly around a targeted object, ensuring a secure grip.

[00149] Depending on the application scenarios, the spring members 1214 may be regular compression springs (FIGs. 24A and 24B). In various embodiments, each of the spring members 1212 may include different spring stiffnesses. For example, the spring stiffness of spring member 1214a may be higher than the spring stiffness of spring member 1214b. Similarly, the spring stiffness of spring member 1214b may be higher than the spring stiffness of spring member 1214c. In an example, spring member 1214a may have a higher spring

thickness than spring member 1214b, and spring member 1214b may have a higher spring thickness than spring member 1214c.

[00150] In other embodiments as shown in FIGs. 25A and 25B, the spring members 1214 may be conical springs. The spring members 1214 may form a reducing diameter along the finger axis 81. For example, the spring stiffness of spring member 1214a may be higher than the spring stiffness of spring member 1214b. Similarly, the spring stiffness of spring member 1214b may be higher than the spring stiffness of spring member 1214c. It may be appreciated that the quantity, shape, as well as the stiffness of spring members may be modified to accommodate any other number based on the specific application scenario.

[00151] Further, the spring stiffness may be varied by a variation in the outer diameter, wire diameter, and coil number. The base spring member 1214a may exhibit the highest stiffness, the middle spring member 1214b may have medium stiffness, and the tip spring member 1214c may have the lowest stiffness. This enables the twining motion to initiate from the tip when the elongated member is pulled. With the configuration of a solitary elongated member with a non-linear routing along with segmented springs and disks, the finger body is able to form three-dimensional bending or twisting motions beginning the tip. It may be appreciated that the tip spring member 1214c need not have the lowest stiffness, and the respective spring stiffness of the spring members 1214a/1214b/1214c may be configured according to application.

[00152] The increasing or decreasing of the working length of the finger body protruding from the sleeve changes the twine/spiral formed by the finger body around the object. Referring to FIG. 26A, in some embodiments, a symmetrical pair of linear-routed elongated members 1309 may facilitate the extension and retraction movement of the finger body 1300. Given that the stiffness decreases progressively along the finger body 1300 from the finger's tip to the base, the finger body 1300 initiates to grow from the tip when the pair of linear-routed elongated members 1309 is released. Correspondingly, when the finger body 1300 is fully extended,

pulling the pair of linear-routed elongated members 1309 triggers the retraction of the finger body 1300.

[00153] In various embodiments as shown in FIG. 26B, when the outer sleeve or housing is moved forward in relative to the finger body, both the working length of the finger body and the corresponding stiffness/elasticity will change. In embodiments where the distal portion of the finger body has a lower stiffness, for the grasping of smaller or lighter objects, the outer sleeve/ housing may be moved towards the finger body/finger body tip, shortening the working length and reducing the stiffness to form a smaller spiral diameter / twine diameter around a small object.

[00154] In various embodiments as shown in FIGs. 27 to 28B, the sleeve 1311 or housing of the gripper may further include a stopper 1310. As shown in FIG. 28A, responsive to rotating the finger body 1300 about the finger axis 81 along a first rotational direction, a distal end of the finger body 1300 translates along the finger axis 81 away from the sleeve 1311. As shown in FIG. 28B, responsive to rotating the finger body 1300 about the finger axis 81 along a second rotational direction, the distal end of the finger body 1300 translates along the finger axis 81 towards from the housing. In an exemplary implementation, a stopper 1310 is provided inside a sleeve 1311 or a housing. When the sleeve 1311 is rotated by an actuator 1312, the spring members of the finger body 1300 (with the base spring member fixed to a stator) may extend or retract relative to the sleeve 1311.

[00155] As shown in FIG. 29, the gripper may further include an elongated member actuator 1400 or driving mechanism for actuating the finger body. The elongated member actuator 1400 may include a fixed housing 1401, a pulley 1402, an elongated member 1403, and a sheath 1404. The elongated member 1403 may be inserted into the sheath 1404, and the elongated member-sheath may be disposed in a channel in the fixed housing 1401. The sheath 1404 may act as a protection layer for the elongated member 1403. Coating such as Teflon may be applied

to or coated on the elongated member 1403 to reduce the friction between the elongated member 1403 and the sheath 1404. By rotating the pulley 1402, the elongated member 1403 may be retracted or released, leading to the bending/twisting motion of the finger body. In addition to the elongated member actuator 1400, the bending/twisting motion of the finger may also be achieved by alternative methods such as electro-active polymers (EAP), shape memory polymer (SMP), shape memory alloy (SMA), pneumatic/fluid actuation method, and magnetism.

[00156] Referring to FIG. 30, in various embodiments, for extending and retracting the finger body, a rack and pinion configuration 1500a/1500b may be utilized. The rack and pinion configuration allows rectilinear translation which may be achieved through various ways such as: SMA, SMP, lead screw, pulley systems, fluid actuation, linear motors, piezoelectric actuators, flexure mechanisms, etc. In some embodiments, the rack and pinion configuration 1500a may include a flexible rack 1501a, a pinion gear 1502a, and a fixed housing 1503a. The flexible rack, fitted into the channel of the fixed housing 1503a and constrained by the wing profile 1504, may be pushed forward or backward by rotating the pinion gear, resulting in the extension and/or retraction of the finger body. The flexible rack may be deformably spooled within the fixed housing 1503a. This configuration provides a compact system, as the rack may be spooled, allowing for higher packing efficiency and achieving a longer growing distance. As an alternative, a rigid rack and pinion design 1500b is also presented in FIG. 31. The rack 1501b, constrained by the fixed housing 1503b, may translate with the turning of the pinion gear 1502b. This configuration requires a base length of at least half of the extended length, resulting in a longer gripper.

[00157] In similar fashion, referring to FIGs. 32A to 32C, the sleeve extension 1600a/1600b/1600c may be achieved using similar configurations. The configurations incorporate a movable sleeve 1601a/1601b/1601c and a fixed sleeve 1602a/1602b. In the lead screw configuration 1600a, a motor actuates a lead screw 1603, and a lead nut 1604 connected

to the movable sleeve is propelled along a straight direction in motion. In order to achieve similar effect, the lead screw configuration may be replaced with a linear actuator 1605. Alternatively, a flexible rack 1606 and pinion 1607 mechanism, similar to the one previously described, may be utilized. Opting for the flexible rack and pinion configuration not only provide a more compact solution but also introduces compliance by allowing the rack to buckle when subjected to heavy loads. This enhances the overall reliability and safety of the sleeve extension mechanism.

[00158] In various embodiments, the gripper comprising the finger body and the sleeve may include four degrees of freedom, namely: bending/twisting of the finger body, extension/retraction of the finger body, extension/retraction of the sleeve, and flexion of the sleeve. In embodiments incorporating flexion and extension of the sleeve as illustrated in FIGs. 33A and 33B, the sleeve 1700 may include a continuum structure. In various embodiments, a distal portion 1705 of the sleeve 1700 may be movable relative to the base. In some embodiments, a distal portion 1705 of the sleeve 1700 may be controllably bendable relative to the base. In an exemplary embodiment, the sleeve may include a rigid portion 1701 and a flexible portion 1702. The flexible portion 1702 may include a multiple ring structure. The maximum bend angle can be adjusted by altering the thickness of each ring structure or adjusting the gaps between them. Tendons 1730/1704 may be provided to actuate the flexible portion 1702 of the sleeve 1700.

[00159] For flexion, the tendons 1703/1704 may be pulled in opposite directions, causing the flexible portion 1702 and/or distal portion 1705 to bend. To straighten the sleeve 1700, the tendons 1703/1704 are adjusted to achieve equal lengths, effectively restoring the sleeve 1700 to an original state. For enhanced control and versatility, additional tendons may be introduced to each individual ring, allowing for a greater degree of freedom depending on the specific application requirements.

[00160] An exploded view 1800 is shown in FIG. 34 as an illustration of a compact actuation system for the proposed gripper and gripper system, including multiple degrees-of-freedom (DoFs) for sleeve extension, finger body extension/retraction and finger body twisting.

[00161] In various embodiments, as shown in FIGs. 35 to 39, a contact sensor array 1900 may be embedded with the finger body 1901 and the flexible rack 1902 to provide the gripper with smart gripping capabilities. This allows the gripper to distinguish the size and shape of the targeted object. As shown in the top figure of FIG. 36, each phalanx member of the finger body may be provided with conductive material 1903, such as copper fabrics, affixed to the contact surface or top surface of the phalanx member. The conductive material 1903 may be selectably and detachably coupled to the phalanx member. Electrical wires 1904a to 1904f may be disposed passing through the vertical channels 1905a to 1905f formed in each phalanx member and subsequently converge at the common horizontal channel 1906 at the bottom of the finger body 1901, as depicted in the sectional view at a cutting plane 1907 (bottom figure of FIG. 36).

[00162] In addition, the electrical cables may converge at the common horizontal channel 1909 at the bottom of the flexible rack 1902, as depicted in the sectional view at a cutting plane 1908 (FIG. 38). A connector 1910 or connection may act as a bridge, effectively uniting the finger body 1901 and the flexible rack 1902. One end of the electrical cables is attached to the conductive material 1903 while the other end is connected to the capacitance sensors like touch sensors within the ESP-32 control board. The configuration and compact wiring arrangement allows the contact sensor array to efficiently capture and transfer the sensing signal to the control board during gripping operations. A successful grip may be determined when a specific number of contact sensors are activated, and the elongated member retraction stops upon confirmation of the successful grip. The extent of elongated member retraction provides a basis for calculating the size of the targeted object, enabling effective size-based sorting. According to an exemplary embodiment as shown in FIG. 39, the capacity of the contact sensor array is

demonstrated as shown in the plot of FIG. 40. The contact sensor array was able to differentiate between the sizes of baby Chinese cabbages and cucumbers.

[00163] In various embodiments as illustrated in FIG. 41, another sensor 2000 may be implemented to discern the contact status between the gripper and the targeted object. A switch sensor 2002, such as an on/off sensor, may be attached to a flat surface 2004 of the sleeve 2001. At a distal side, two electrical wires 2003 may be respectively connected to two flexible conductive layers 2005. The two electrical wires may be subsequently interconnected in a sequence to a proximal side. A small gap 2006 may be formed between the two layers (bottom left of FIG. 41). When the gripper twines around the targeted object with gradually increasing contact forces produced to grasp the object firmly, the outer flexible layer may deform to form or establish a contact with the inner flexible layer. The change in the state of the contact status (on or off) generates an electrical signal that is sent to a control board or device, such as a programmable logic controller (PLC), indicating the successful completion of the gripping operation.

[00164] In various embodiments, the integration of Fiber Bragg Grating (FBG)-based sensors with the finger body and/or gripper enables both force sensing and shape sensing capabilities. The specific wavelength of light reflected by the FBG, a.k.a. the Bragg wavelength λ_B , shifts with respect to strain and temperature changes, as in $\Delta\lambda_B/\lambda_B = k_T\Delta T + k_\epsilon\epsilon$, where k_T , ΔT , k_ϵ , and ϵ are the thermal sensing coefficient, temperature change, strain sensing coefficient of the fiber material, and axial strain along the fiber, respectively. When the sensor is integrated to the finger body at constant temperature, such as room temperature, the temperature cross-sensitivity is minimized, and the wavelength shift $\Delta\lambda_B$ is proportional to the change in strain, i.e. $\epsilon = \Delta\lambda_B/k_\epsilon\lambda_B$.

[00165] Referring to FIGs. 42 and 43, according to various embodiments, an FBG-array fiber 2101 which is incorporated in the phalanx-type finger 2102, forms a smart gripper 2100 that

may detect contact force at each of the various phalanx members. The FBG-array fiber 2101 may be connected to an interrogator, which captures the wavelength shifts automatically. A cavity configuration for the phalanx member is proposed to achieve this functionality, as illustrated in the sectional view at a cutting plane 2103 (FIG. 43). The elongated member passes through the upper path 2104, while the FBG-array fiber 2101 passes through the lower path 2105 along the body of the phalanx-type finger 2102. Within the cavity, a dedicated uvula feature 2106 is provided, positioned beneath the grating areas 2108 along the FBG-array fiber 2101. As shown in FIG. 43, the FBG-array fiber 2101 is fixed to the phalanx-type finger 2102 at two ends of each phalanx member within the cavity with adhesive materials 2109 such as epoxy.

[00166] Alternatively, the fiber may be placed at the bottom of the finger body during the 3D printing process, forming a strong bond between the fibers and the finger body. A gap 2107 may be formed between the uvula and the bottom surface of the cavity. When the phalanx member comes to contact with the target object, the uvula feature 2106 may be pressed towards the sensor disposed at the bottom of the finger body. The deformation of the grating area may be sensed or captured by one or more FBG sensor(s), reflected by a respective wavelength shift, thereby providing real-time force sensing capability to the finger body and gripper. It is noted that three cavities in the smart gripper 2100 are shown as an illustration, and the number of cavities may be adjusted to any other number in accordance with a specific application scenario. The FBG sensor array may be replaced by other types of sensors such as strain gauges, depending on the various application scenarios.

[00167] The deformation of the optical fiber may be schematically represented by the deformation of a simply supported beam (FIG. 44). The side supports for the optical fiber may be labelled as point A and point B respectively. L is the original length of fiber between the two supports, i.e., $AB = L$; P is the contact force that applied to the top surface of the sensing module;

L' is the deformed length of fiber when there is a contact force, i.e., $AB' = L'$. We suppose there is a constant curvature AB' of the bent optical fiber. α is the bending angle of the constant curve, i.e., $\angle AEB = \alpha$. R is the radius of the bending curve, i.e., $AE = BE = R$. The constant curve is thus $AB' = L' = \alpha R$. Since point D is the middle point of length AB , we have $\angle AED = \angle BED = \angle AEB/2 = \alpha/2$. It is easily derived that $\triangle ADE$, $\triangle CAE$, $\triangle CDA$, $\triangle BDE$, $\triangle CBE$, and $\triangle CDB$ are similar triangles. Thus, $\angle CAD = \angle CBD = \alpha/2$. According to cantilever beam theory, the slope at support points A and B is $PL^2/16EI$, i.e., $\angle CAD = \angle CBD = \alpha/2 = PL^2/16EI$. The area inertia property for the fiber is $I = \pi d^4/64$, where d is the diameter of the fiber. Equation $\alpha = PL^2/8EI$ is obtained. In $\triangle ADE$, there is $\sin \alpha/2 = AD/AE = L/2R$. Thereafter, the following expression $R = L/2 \sin(PL^2/16EI)$ is obtained. For the strain change, $\epsilon = \Delta\lambda_B/k_\epsilon\lambda_B = \Delta L/L = \alpha R - L/L$. Upon setting constant values as $c_1 = k_\epsilon\lambda_B$ and $c_2 = L^2/8EI$, the following equation $\Delta\lambda_B = c_1c_2P/[2\sin(c_2P/2)] - c_1$ is obtained, which discloses the relationship between the wavelength shift $\Delta\lambda_B$ of the FBG sensor and the applied contact force P . As epoxy and flexible material are used in the sensing module, strain transfer efficiency η between the flexible material/epoxy and the fiber should be considered in the equation $\Delta\lambda_B = \eta c_1c_2P/[2\sin(c_2P/2)] - \eta c_1$.

[00168] A contact force sensor prototype was fabricated for one single phalanx member (FIG. 45), and the obtained calibration result and repeatability test result for three runs of tests are provided to show the mapping between the contact force and the wavelength shift (FIG. 46A and 46B). The modelling equation $\Delta\lambda_B = \eta c_1c_2P/[2\sin(c_2P/2)] - \eta c_1$ was verified with an R-square of 0.973. The RMSE error between the actual test data and the modelling fitting data is 61.432 pm, which may be due to a non-constant curvature deformation of the fiber. In addition, instead of a single point contact force, the force applied to the top surface of the fiber from the uvula may be uniformly distributed on the optical fiber, contributing to the error of the modelling as well. It was noted that as sensitivity may vary, depending on the pretension

condition of the fiber, materials of the finger and adhesive, bonding condition, etc. For the repeatability test, three runs of test results were generally consistent, indicating that the sensor has good repeatability. In addition to the modelling equation, a second-order equation $\Delta\lambda_B = 8.602P^2 + 107.730P + 24.881$ was used as the calibration equation to represent the relationship between the wavelength shift and the contact force, with a higher R-square of 0.993. The sensing structure can be seamlessly integrated into the phalanx-type gripper or configured as a detachable, standalone sensor that can be easily removed from the gripper.

[00169] According to various embodiments as shown in FIGs. 47 and 48, a single-core FBG-array fiber 2201 may be embedded to a bottom of a phalanx-type finger 2202. This forms a smart gripper 2200 which is able to realize a 2D shape sensing along a length of the finger body. The FBG fiber may be connected to an interrogator, which captures the wavelength shifts automatically. The grating areas 2204a to 2204h may be located at intervals/connections between each phalanx member, where the bending occurs, as illustrated in the sectional view at a cutting plane 2203 (FIG. 48). The optical fiber 2201 passes through the lower path 2207 with an offset distance t_{offset} from the finger's neutral axis 2205, as shown in the side view of FIG. 48. In addition, the elongated member passes through the upper path 2206. The optical fiber 2201 is secured to the finger body with adhesive materials 2208, such as epoxy. Alternatively, the optical fiber 2201 may be placed at the bottom of the finger during the 3D printing process, thus forming a strong bond between the fibers and the finger body integrally. A linear relationship may exist between the 2D bending curvature κ and each Bragg wavelength shift $\Delta\lambda_B$, as in $\kappa = \Delta\lambda_B / k_e t_{offset} \lambda_B$. Therefore, by assigning different central wavelengths to different FBGs positioned at intervals along each phalanx member, the 2D bending of the finger body may be captured and monitored continuously. It is noted that eight grating areas in the smart gripper 2200 are shown as an illustration, and the number of grating areas may be adjusted to any other number depending on the length of the finger. The FBG sensor array can be

replaced by other types of sensors such as strain gauges, depending on the various application scenarios.

[00170] In various embodiments as illustrated in FIGs. 49 and 50, multiple single-core FBG-array fibers 2301a (one fiber located at the centre and the rest equally spaced apart from each other) or a multi-core FBG-array fiber 2301b may be embedded at the bottom of the phalanx-type finger body 2302. This forms a smart gripper 2300 which is able to realize 3D shape sensing along a length of the finger body. The FBG fibers may be in signal communication with an interrogator which captures the wavelength shifts of the FBG fibers automatically. The grating areas 2307a to 2307c are located at the intersections/connections between adjacent phalanx members, where the helical bending occurs, as illustrated in the sectional view at the cutting plane 2303 (FIG. 50). The optical fibers 2301a/2301b passes through the lower path(s) 2306, offset from the finger's neutral axis 2304 in the side view of FIG. 50. In addition, the elongated member passes through the upper path 2305. The optical fibers 2301a/2301b are secured to the finger body with adhesive materials such as epoxy. Alternatively, the optical fibers 2301a/2301b may be placed at the bottom of the finger during the 3D printing process, thus forming a strong bond between the fibers and the finger body integrally. While four single-core fibers are shown as an illustration, the number of fibers may be adjusted to any other number. In addition, three grating locations in the smart gripper 2300 are shown as an illustration, and the number of grating locations may be adjusted to any other number depending on the length of the finger. The FBG sensor array may be replaced by other types of sensors such as strain gauges, depending on the various application scenarios.

[00171] In various embodiments, the gripper may be mounted on an external platform. FIG. 51 is a functional block diagram for illustrating an operation and communication of the gripper with one or more external platforms. Sensors may be configured to provide input signals for the automated gripper system. When a signal is sent to start the gripping 2401 operation, object

distance from gripper 2402 is obtained from sensors such as Lidar or stereo cameras. Depth measurement is used to determine the operational sleeve extension distance. Upon determination of the parameters, the sleeve, finger body, and elongated member are extended to a predetermined length, such as of equal length 2403. Using position feedback sensor(s) such as encoder sensors 2404, the respective positions of the components are measured for determining whether the goal position is reached 2405. Upon motion of the sleeve has stopped and the sleeve is next to the target object, the object width 2406 is used to set the radius of the growing finger body. In an example, the radius may be set as 1.2 times the width from the sensor value. The extensions of the elongated member and the finger body 2407 begin until the desired angle of wrap is reached 2408. At this stage, the gripper is near to enveloping the object. The elongated member is then slowly retracted 2409 until the tension in the elongated member reaches the grasping requirement 2410, whereby a signal is sent to the controller or external sources to signify the completion of grasping 2411. The gripper then waits for a release signal 2412 to continue, where the elongated member would be released to fully straighten the gripper 2413. When the elongated member has reached goal 2414, the object is released and the sleeve, finger body, and elongated member are retracted to the original position 2415. Once the positions of the sleeve, finger body, and elongated member are reached 2416, a release complete signal is sent 2417.

[00172] FIG. 52 is a functional diagram describing the operations of the gripper on determining the amount of movement and whether the goal is achieved. To begin actuation 2501, the various distances of the finger body 2502, elongated member or tendon 2503, and sleeve 2504 are used to convert the linear distance to encoder steps 2505. The steps are then normalized against the largest value 2506 which is used to set the motor velocity ratio 2507, ensuring that the positions of the gripper, finger body, sleeve, and tendon are in the right position in time. By using the current encoder position 2508, the goal position is calculated by

adding the number of steps required 2509. Thereafter the motor is moved towards the goal position 2510 and stops if goal position 2511 is within error tolerance against the encoder position 2512 and motor movement is complete 2513.

[00173] Next referring to FIG. 53, for the grasping operation 2600, a signal is used to for the beginning of grasping 2601, and an input force array 2602 is used to determine if the grasping force is sufficient. The maximum force of the array 2603 is used to check if the grasping force has exceeded the crushing threshold 2604, which is the force whereby the gripper might damage objects. If the force is greater, the gripper releases on the elongated member slightly 2605 and the process is repeated till the maximum force is lower than the crushing threshold. Thereafter, the force array is compared with a grasping threshold criterion 2606, where a minimum number of sensors reached a baseline force value that applies sufficient pressure for grasping. If the criterion is met, grasping is completed 2607, and a signal is sent.

[00174] In various embodiments, the proposed sensor-integrated gripper may be configured to perform sorting of objects. Referring to FIG. 54, a deep learning network may be used to perform classification tasks. The input layer 2701 may include various input data are used to feed the model. Hidden layers 2702 and 2703 may be modified to increase the learning performance, and the output layer 2704 may be used to feedback items that are grabbed. The number of hidden layers can also be modified to improve performance. Additionally, together with a vision sensor mounted with the gripper housing or in the environment, the proposed smart gripping system may provide data collection for other machine learning operations such as for Q-reinforcement learning, determination of the freshness of vegetables using images and capacitance values etc. A relevant overview of the signal flow 2800 is illustrated in FIG. 55.

[00175] In various embodiments, as shown in FIGs. 56 and 57, the single-finger gripper 2900 has two basic operations: to extend the finger body and to vary or control the elongated member length. The combinations of the two operations at pre-defined speeds lead to different gripping

modes or forms. As exemplary embodiments, two operating modes of the gripper 2900 include: grow-then-twine (FIG.56) and grow-and-twine (FIG.57). In the grow-then-twine mode, the finger body is initially extended out to a desired working length and elongated member is released at a similar speed simultaneously. Thereafter, the elongated member is tensioned or pulled gradually, to deform the finger body achieving a suitable radius. Hence, it may be appreciated that the extension of the finger body is performed sequentially with the pulling of the elongated member towards the sleeve.

[00176] In the "grow-and-twine" mode, the finger body is extended outward concurrent with the pulling of the elongated member. The elongated member may be pulled at a controlled speed to maintain the desired radius of the finger throughout the finger body extension process. Hence, it may be appreciated that the extension of the finger body is performed concurrently with the pulling of the elongated member towards the sleeve.

[00177] In other embodiments, the gripper 3000 comprising sectional springs may also realize the basic operations of finger body extension and elongated member length control. The grow-and-twine gripping motion of the spring-type finger is illustrated as an example in FIG. 58. Through the control of the finger body extension and elongated member length, the helical/spiral shape of the finger may be finely adjusted and manipulated according to requirements. This enables the gripper to achieve various desired configurations, enhancing the adaptability to handle objects of different shapes and sizes with precision.

[00178] According to another aspect of the disclosure, as illustrated in FIG. 59, disclosed herein a method of gripping 7000 according to various embodiments. The method of gripping 7000 may include, in step 7100, applying a pulling force on the elongated member towards the housing to form a helical shape with the selected first ones of the plurality of actuating members about a first gripping axis. In various embodiments, the method of gripping 7000 may also include in step 7200, moving the finger body along the finger axis relative to the housing to

vary a working length of the finger body protruding from the housing, wherein the working length corresponds to a diameter of the helical shape. In various embodiments, the method of gripping 7000 may include: concurrently applying the pulling force on the elongated member towards the housing and moving the finger body along the finger axis away from the housing.

[00179] Various embodiments of the proposed gripper system disclose a compact integration of a soft finger body, flexible rack, and dual-sleeve configuration which provides the gripper with the functions to extend, grow, and twine around objects. The introduction of a flexible finger augments adaptability, providing special grasping motions and a tailored workspace. In addition, the seamless incorporation of sensors improves the gripper's gripping capabilities, enabling delicate handling and facilitating integration with sensor fusion and IoT applications. The combinations of different extending/retracting and twining motions of the finger body allow various movement patterns and workspaces of the gripper, facilitating the gripping and/or manipulating of objects spanning a spectrum of shapes and sizes.

[00180] According to various embodiments, the proposed gripper includes a cable-driven (or tendon-driven) multi-phalanx finger which is coupled to a flexible rack (FIG. 30) housed inside a sleeve. The cable-driven multi-phalanx finger is able to bend and conform to a customized predetermined 3D shape. In addition, the flexible rack empowers the finger to move linearly in relative to the sleeve, leading to an effective growth and twining grasping motion often seen in vine plants.

[00181] In various embodiments, if the object has a diameter smaller than the gripper's defined grip/helical diameter and has a contour graspable by the finger body, the finger body may twine around the contour of the object, squeezing the phalanx members towards each other. The finger body may form a helical closed surface and as long as the elongated member length is constant, the finger body is able to hold the helical shape, achieving high payload-to-self-weight ratio. In various embodiments, if the object has a diameter larger than the gripper's

defined grip/helical diameter, the finger body may twine around the object with the contact surface of the phalanx touching/biting onto the object. As the elongated member is tightened, the forces are redirected to the top of the phalanx member, pressing into the object and providing a robust grip.

[00182] As the flexible multi-phalanx finger body is able to form a helical shape or able to twine, in comparison to conventional pinching grippers, the proposed gripper has an increase contact points and total contact area, which in turn decreases the contact pressure, allowing a gentle and efficient grasping.

[00183] In various embodiments, super-elastic or shape-memory materials may be embedded inside the flexible finger body and racks. The flexible finger body with embedded material provides an improved elasticity, culminating in an exceptional ability to maintain a stable arc formation when a tension is provided to the elongated member to actuate the finger body twining. This allows a symmetrical and evenly distributed application of contact forces, ensuring a secure and efficient grasp across an array of object shapes and sizes.

[00184] With an increase in elasticity, the flexible rack forms a versatile structural element, with the capability to bear a longitudinal load akin to a beam while retaining the flexibility to coil within the motor housing for save saving. The elasticity adjustment empowers controlled buckling under substantial external loads. With the flexible rack's elasticity, the rack may function as a beam to extend the finger linearly while being able to deform to spool/roll in the motor housing. The elasticity in the rack may be adjusted or fine-tuned to allow buckling under large external load. Together with the soft material used to make the finger body and rack, the risk of inflicting sharp damage on delicate objects is minimized, preventing object damage during gripping.

[00185] In various embodiments, the shape memory material may be activated in sections on demand, i.e. when the finger body is required to be straightened, the extended portion of the

finger may be heat activated to straighten while the rest of the embedded nitinol remains soft. This reduces the torque requirement to drive the finger body as torque/tension is not needed to overcome the critical load separating stability and instability, whereby as the finger body has to buckle before the force can be transmitted to further bend the finger body during grasping.

[00186] In various embodiments, as an alternative to the multi-phalanx finger body configuration, the finger body may be in a continuum form. Deviating from conventional design methods for continuum robotic fingers, the proposed finger body comprises a solitary elongated member with a non-linear routing along segmented springs and disks. The configuration enables the finger to perform three-dimensional bending or twisting motions. Given that the stiffness changes (e.g. decreases) progressively along the segmental springs from the base of the finger body to the tip, the finger body initiates the bend/twist from the tip when the non-linearly routed elongated member is pulled. In similar fashion, with the stiffness increasing progressively from the base to the tip of the finger body, the bend/twist may be initiated from the base.

[00187] In various embodiments, the growth/retraction motion of the spring-type finger may be achieved by adding a pair of symmetrically linear-routed tendons. Given that the stiffness decreases progressively along the segmental springs from the finger's base to its tip, the finger starts to grow or retract from the tip when the pair of tendons are released or pulled. Alternatively, the growth/retraction motion of the spring-type finger may be achieved by a built-in feature such as a stopper provided inside the sleeve. A rolling/rotating motion of the sleeve (rotor) may be transformed into the linear motion of the finger, with a stator connecting the base spring.

[00188] In various embodiments, flexible racks and fingers enables an extendable outer sleeve and a long finger, facilitating a compact motor box, allowing access to constricted areas

with ease. The extension of the outer sleeve introduces an additional degree of freedom to the gripper, enabling dynamic adjustments in the grasping location.

[00189] In various embodiments, to address the challenge of accurately monitoring the force and shape of the proposed gripper during operation, various sensors are coupled to or embedded in the finger body to enhance sensing capabilities. For example, an on/off sensor and contact sensor array may be embedded in the finger body, without altering the finger body structure in terms of size and functionality. The incorporation of the contact sensor array enhances the gripper's capability to detect finger body extension and determine contact status, allowing improved precision in motion control and informed decision-making, such as sorting based on calculated object size derived from elongated member retraction length. With the integrable diverse range of sensor types, the proposed gripper allows a comprehensive measurement and understanding of the gripper's interaction with the environment and/or object, enabling accurate measurement and monitoring of forces and shape changes.

[00190] In view of the various limitations in conventional sensors, such as sensing sensitivity/resolution, repeatability, intricate design and fabrication difficulty, and constrained measurement range, in various embodiments, with the provision of channel(s) or path(s) along the finger body, enables integration of high-sensitivity flexible FBG-based sensors during the fabrication process. In addition, it was demonstrated that the integrated sensor has good repeatability and offers an extended measurement range, such as up to 8 N for contact force at each phalanx member, which may be adjusted by modifying the size of the uvula and cavity inside each phalanx member. Further, multiple channels or paths may be formed, each embedded with one or more FBG sensor array. This allows the detection of contact force and 2D/3D bending curvature along the finger body.

[00191] The proposed gripper offers several significant advantages over conventional solutions:

[00192] 1. Outstanding payload-to-self-weight ratio. The finger body achieved a 690% payload-to-self-weight ratio, a performance surpassing the capabilities of conventional grippers. With the significantly enhanced payload-to-self-weight ratio, the proposed gripper allows industries to perform tasks that demand both error-margin and efficiency with high levels of performance and productivity.

[00193] 2. Wide adaptivity: Through the integration of the multi-phalanx finger body configuration and the flexible rack, the proposed gripper may grip or handle objects of varying sizes and shapes. The objects may be of different sizes, intricate contours, irregular forms, single pieces and multiple/clustered pieces, etc.

[00194] 3. Soft touch. The finger and flexible rack may be constructed from soft, high-quality materials such as TPU (Shore hardness: 90A). The choice of materials enables a gentle and tactile interaction with objects, preserving the structural integrity of the objects. Further, the inherent flexibility of the soft finger and rack allows a natural adjustment and buckling under load. This mitigates the risk of inflicting sharp damage on delicate objects, offering protection to the objects. With the unique 'Soft Touch' feature, the proposed gripper provides both finesse and reliability, suitable for applications where object preservation is valued.

[00195] 4. Ability to access constricted areas. The proposed gripper provides the capability to access confined spaces. The gripper's slender profile and small cross-sectional area enables reach and access to narrow and restricted areas. This enhances the versatility of the gripper ideal for tasks that require access to constricted spaces that would otherwise be challenging for bulkier alternatives.

[00196] 5. Compact size. Leveraging on the flexible rack and pinion design, a balance of compactness and functionality is achieved by the proposed gripper. This approach allows a compact size while concurrently providing a long extension distance through the elongated and adaptable finger, achieving space-efficient form factor.

[00197] 6. Large contact area. In contrast to conventional grippers characterized by limited contact areas and heightened contact forces, the proposed gripper provides an increased contact surface by way of twining around the objects. In addition to maximizing the area of contact/interaction, the contact forces are reduced, resulting in a gentler and more effective grasp.

[00198] 7. Evenly distributed contact force. In comparison to conventional grippers, the proposed gripper leverages on embedded materials to vary the elasticity of the finger body, resulting in a more evenly distributed contact force when interacting with the object. This effectively decreases and disperses contact forces, resulting in a secure and efficient grasp.

[00199] 8. Durability. The proposed gripper may be made of engineered plastic (ABS, TPU, etc), metal structure, and stainless multi-strand wires with Teflon coating. The combination provides for durability, increasing the gripper's longevity and continued robust performance.

[00200] 9. Modularity. The proposed gripper may include multiple finger bodies collaborating to execute pinch or envelope grasps. Further, diverse tools, such as cutters, may be integrated with the gripper for a wide spectrum of operations/applications.

[00201] 10. Diverse Sensor Modalities. A variety of sensor types, including on/off sensors, capacitive contact sensor arrays, and fiber optics sensors, may be integrated with the proposed gripper/finger body to provide contact status, force, and shape sensing. The diversity in sensor modalities allows for a comprehensive measurement of the gripper's interaction with the object and environment, enabling accurate measurement and monitoring of forces and shape changes.

[00202] 11. Enhanced Situational Awareness. With the integration of sensors in the proposed finger body, a higher level of situational awareness is provided during robotic operation. This is particularly useful in tasks requiring delicate and precise interactions, as well as for safety and performance optimization.

[00203] 12. Improved Control and Adaptability. The incorporation of sensors enables real-time feedback and data-driven control strategies for the proposed gripper, enabling improved adaptability, responsiveness, and overall performance in various applications.

[00204] All examples described herein, whether of 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 gripper, comprising:

a housing;

a finger body movable relative to the housing along a finger axis, the finger body

comprising:

a plurality of actuating members, each of the plurality of actuating members

defining: a pair of contact surfaces disposed opposing each other and a

path formed passing through the pair of contact surfaces;

a plurality of connecting members, each of the plurality of connecting

members movably coupled between a respective pair of the plurality of

actuating members; and

an elongated member passing through the respective path of selected ones of

the plurality of actuating members to define a respective first axis, the

elongated member being fixedly coupled to a distal one of the plurality

of actuating member,

wherein for each of a selected first ones of the plurality of actuating members,

at least one of the pair of contact surfaces forms a first tilt in relative to the

respective first axis, the first tilt being characterized by: in relative to the

respective first axis, forming a first oblique angle about a respective second

axis and forming a second oblique angle about a respective third axis,

wherein the respective first axis, the respective second axis, and the respective

third axis are orthogonal to each other.

2. The gripper as recited in claim 1, wherein the selected first ones of the plurality of actuating members collectively form a helical shape about a first gripping axis responsive to a pulling force applied to the elongated member towards the housing.
3. The gripper as recited in claim 2, wherein for each of a selected second ones of the plurality of actuating members, at least one of the pair of contact surfaces forms a second tilt in relative to the respective first axis, the second tilt being characterized solely by the first oblique angle about the respective second axis in relative to the first axis.
4. The gripper as recited in claim 3, wherein the selected second ones of the plurality of actuating members collectively form a circular shape about a second gripping axis responsive to the pulling force applied to the elongated member towards the housing, the second gripping axis oblique to the first gripping axis.
5. The gripper as recited in any one of the above claims, wherein each of the pair of contact surfaces defines a respective pair of openings, wherein each of the path passes through the respective pair of openings.
6. The gripper as recited in any one of the above claims, wherein ones of the respective first axis of the plurality of actuating members are non-coaxial from one another.
7. The gripper as recited in any one of the above claims, wherein the finger body further comprising: at least one sensor detachably coupleable to the finger body, the at least one sensor being at least one of: a force sensor, a pressure sensor, and a bending sensor.

8. The gripper as recited in any one of claims 1 to 7, wherein the plurality of actuating members comprises a plurality of phalanx members, each of the plurality of phalanx members comprising: a gripping surface and a base surface opposing the gripping surface, the gripping surface and the base surface being disposed between the pair of contact surfaces, and wherein the base surface is coupled to at least one of the plurality of connecting members.
9. The gripper as recited in claim 8, wherein the plurality of connecting members comprises a plurality of elastic flaps, wherein each of the plurality of elastic flaps extends between and couples a respective pair of base surfaces.
10. The gripper as recited in claim 9, wherein the finger body further comprises: a first sensor path formed extending through the plurality of elastic flaps; and a bending sensor disposed in the first sensor path.
11. The gripper as recited in any of claims 8 to 10, wherein ones of the plurality of phalanx members define a second sensor path formed passing through the pair of contact surfaces; and wherein the finger body further comprises: a contact sensor disposed pass through the second sensor paths.
12. The gripper as recited in any one of claims 8 to 11, wherein each of the plurality of phalanx members further comprises a side-wing member, the side-wing member extending parallelly from a respective base surface to end at a narrowed tip portion.

13. The gripper as recited in claim 12, further comprising a second elongated member operably coupled to each of the narrowed tip portions, wherein each of the narrowed tip portions moves towards each other, responsive to the second elongated member pulling on each of the narrowed tip portions.
14. The gripper as recited in any one of claims 8 to 11, each of the plurality of phalanx members further comprises a cutting member, the cutting member extending parallelly from a respective base surface to end at a cutting edge.
15. The gripper as recited in any one of claims 1 to 7, wherein the plurality of connecting members comprises a plurality of spring members, each of the plurality of spring members defining a pair of opposing ends, each of the pair of opposing ends coupled to a respective one of the plurality of actuating members.
16. The gripper as recited in claim 15, wherein the plurality of actuating members comprises a plurality of plate members, each of the plurality of plate members comprising a plurality of through-openings, wherein the elongated member passes through each of the plurality of plate members via one of the plurality of through-openings along the respective first axis.
17. The gripper as recited in claim 16, wherein each of the plurality of plate members define a thickness axis, wherein the plurality of through openings are disposed rotational symmetrical about the thickness axis.

18. The gripper as recited in any one of claims 15 to 17, wherein each of the plurality of spring members has a different spring stiffness.
19. The gripper as recited in any one of claims 15 to 18, wherein the plurality of spring members forms a reducing diameter along the finger axis.
20. The gripper as recited in any one of claims 15 to 19, wherein the housing further comprises a stopper, wherein responsive to rotating the finger body about the finger axis along a first rotational direction, a distal end of the finger body translates along the finger axis away from the housing, wherein responsive to rotating the finger body about the finger axis along a second rotational direction, the distal end of the finger body translates along the finger axis towards from the housing.
21. The gripper as recited in any one of the above claims, wherein the housing further comprises a base and a sleeve extending from the base, and wherein the finger body is disposed movable relative to the sleeve along the finger axis.
22. The gripper as recited in claim 21, wherein at least a distal portion of the sleeve is movable relative to the base.
23. The gripper as recited in claim 22, wherein at least a distal portion of the sleeve is controllably bendable relative to the base.
24. The gripper as recited in any one of the above claims, wherein the elongated member is an elastic member in tension.

25. The gripper as recited in any one of the above claims, further comprising a finger actuator coupled to the finger body, wherein the finger actuator is configured to move the finger body relative to the housing along the finger axis.
26. The gripper as recited in claim 25, wherein the finger actuator comprises a flexible rack, the flexible rack deformably spooled within the housing.
27. The gripper as recited in any one of the above claims, further comprising an elongated member actuator coupled to the elongated member, wherein the elongated member actuator is configured to apply a pulling force on the elongated member towards the housing.
28. A gripping system, comprising:
the gripper as recited in any one of the above claims; and
a controller in signal communication with the gripper, the controller being configured to perform a method of gripping, the method comprising:
applying a pulling force on the elongated member towards the housing
to form a helical shape with the selected first ones of the plurality of actuating members about a first gripping axis.
29. The gripper system as recited in claim 28, further comprising a robotic arm coupled to the gripper, the robotic arm in signal communication with the controller.

- 30.** The gripper system as recited in any one of claims 28 to 29, wherein the method further comprising: moving the finger body along the finger axis relative to the housing to vary a working length of the finger body protruding from the housing, wherein the working length corresponds to a diameter of the helical shape.
- 31.** The gripper system as recited in any one of claims 28 to 29, wherein the method further comprising: concurrently applying the pulling force on the elongated member towards the housing and moving the finger body along the finger axis away from the housing.