

HYBRID SOFT-RIGID GRIPPER WITH VARIABLE STIFFNESS

FIELD OF THE INVENTION

[0001] The present disclosure relates to a gripper, and more particularly to a hybrid soft-rigid gripper with variable stiffness for enhancing the adaptability and precision in object manipulation.

BACKGROUND OF THE INVENTION

[0002] Robotic grippers are end-effectors, which enable robots to execute grasping functionalities. The performance of these robotic end-effectors is critical across numerous applications pertaining to food industry, healthcare, smart factory and human-robot interactions. As a result, a diverse range of robotic grippers has been invented over the past few decades. In general, existing robotic grippers can be classified under two distinct categories: (i) the rigid and (ii) the soft grippers.

[0003] In general, the rigid grippers are created via a combination of rigid joints and links. These grippers realize their grasping functionalities through the force closure principle. Based on this principle, the grippers can grasp any object as long as they can exert sufficient contact forces on the object to balance its weight under static equilibrium conditions. As the rigid grippers have higher stiffness than the soft grippers, they can generally achieve higher payload and precision. Furthermore, since rigid grippers operate under the force closure principle, they are less susceptible to objects with wet, rough and dirty surface conditions compared to the soft grippers. However, as the rigid grippers have finite number of joints, their degrees-of-freedom are limited too. Hence, they are unable to establish force closure on objects with complex geometry because they cannot conform to the geometry of such objects well. Similarly, it is challenging for the rigid grippers to establish force closure on objects which are soft and deformable

since the grippers cannot conform well to the geometries of such objects too. Although it is desirable to increase the degrees-of-freedom of rigid grippers, the grippers would require more actuators to remain fully actuated when they have higher degrees-of-freedom motions. Due to the space and weight constraints of rigid grippers, these grippers can only carry a finite number of actuators, thus limiting their achievable degrees-of-freedom.

[0004] In contrast to the rigid grippers, the soft grippers are made of smart soft materials that can generate deformations upon actuation. By having such actuation methods, the soft grippers theoretically have infinite degrees-of-freedom motions. Hence, they can use their soft bodies to easily conform to the geometry of the objects which they wish to grasp, allowing them to overcome the challenges of rigid grippers. Similarly, the soft grippers are also shown to be highly effective in manipulating objects that are soft and deformable. Due to the advantages of soft grippers, such grippers are much more robust than the rigid ones as they can potentially grasp a much wider range of objects. Seeing the potential of soft grippers, scientists and engineers have therefore created a diverse range of soft grippers, which use different grasping mechanisms, over the past decade. For example, there exist soft grippers that utilize granular-jamming (mechanical-locking), adhesive and vacuum principles to grasp objects. While the soft grippers show great promise, their soft bodies may also result in reduced precision and repeatability in grasping tasks compared to their rigid counterparts. Furthermore, each type of soft grippers has their corresponding weaknesses, and they are unable to grip certain class(es) of objects.

[0005] Therefore, there is a need of providing a hybrid soft-rigid gripper with variable stiffness, to enhance the adaptability and precision in object manipulation, and obviate the drawbacks encountered from the prior arts.

SUMMARY OF THE INVENTION

[0006] It is an object of the present disclosure to provide a hybrid soft-rigid gripper with variable stiffness for enhancing the adaptability and precision in object manipulation.

[0007] It is another object of the present disclosure to provide a hybrid soft-rigid gripper with variable stiffness. The hybrid soft-rigid gripper is allowed to reprogram its stiffness upon command. The proposed gripper has an architecture that comprises several fingers (three to seven fingers). Each finger is made of a rigid, hyper-redundant endoskeleton that has many more degrees-of-freedom than those required by the manipulation task. In this way, the fingers of the hybrid soft-rigid gripper of the present disclosure can conform to the shape of objects with complex geometries, emulating the benefits of soft grippers. The rigid endoskeleton of the hybrid soft-rigid gripper of the present disclosure is allowed to generate the necessary stiffness to achieve high precision and payload during the grasping operation. The hybrid soft-rigid gripper of the present disclosure therefore inherit the benefits of both rigid and soft grippers. The hybrid soft-rigid gripper of the present disclosure has great potential to manipulate a much wider range of objects than existing robotic grippers would. On the other hand, the heavy and bulky actuators are placed at the base of the gripper while allowing them to remotely control the hybrid soft-rigid gripper via light cables (i.e., the primary actuation cable (L1) and/or the secondary actuation cable (L2)) , so that the space and weight constraints imposed by the actuators are overcome. Furthermore, the design of the hybrid soft-rigid gripper also accounts for the integration of tactile sensors that can provide force/slip feedback during the grasping operations.

[0008] It is a further object of the present disclosure to provide a hybrid soft-rigid gripper with variable stiffness. The stiffness of the hybrid soft-rigid

gripper can be reprogrammed by controlling the tensions of the actuation cables thereof. At the beginning of the grasping operation, the actuation cable tensions are programmed to be low so that the tension of the actuation cable is lower, and the hybrid soft-rigid gripper is compliant, so it can easily and properly conform to the geometry of the targeted object. Because the fingers of the hybrid soft-rigid gripper have a hyper-redundant endoskeleton, the gripper of the present disclosure has higher degrees-of-freedom than existing rigid grippers, potentially allowing it to grip a much wider range of objects that have complicated geometries and soft consistency. Upon establishing a good contact of the fingers with the targeted object, the hybrid soft-rigid gripper's cable tensions can be increased so that the gripper can assume a stiff configuration that is essential for executing force closure on the targeted object successfully. In the stiff configuration, the hybrid soft-rigid gripper has much higher stiffness than the conventional soft grippers, allowing it to achieve higher precision and payload during the grasping operations. Since the hybrid soft-rigid gripper of the present disclosure is using force closure principles to grasp the targeted objects, it is also much less susceptible to objects with varying surface properties than the conventional soft grippers. In other words, the unique advantages of the hybrid grasping mechanism of the present disclosure allow the hybrid soft-rigid gripper to have the potential to manipulate a much wider range of objects with varying stiffness, surface properties and geometries compared to the conventional grippers. In addition, the hybrid soft-rigid gripper is covered by protective skins made of soft material so that it can handle objects with vulnerable or sensitive surface without causing harm or damage. Sensors can be disposed on the protective skins so as to feedback pressure endured by the hybrid soft-rigid gripper and thus gripping force can be adjusted. Certainly, the present disclosure is not limited thereto.

[0009] In accordance with an aspect of the present disclosure, a hybrid soft-rigid gripper with variable stiffness is disclosed and includes a base and a plurality of fingers. The plurality of fingers are connected to the base. Each of the plurality of fingers includes a plurality of finger segments, a driving module and a primary actuation cable. The plurality of finger segments (FS) are pivotally connected in sequence from the base downward to a fingertip. Each of the plurality of finger segments includes a body portion, an inner cavity, a first pivot hole, an extruding portion, a second pivot hole and at least one cable hole. The body portion is spatially corresponding to the fingertip and includes a top surface and a bottom surface opposite to each other, and a first side and a second side opposite to each other, wherein the top surface and the bottom surface are connected through the first side and the second side, respectively. The inner cavity is recessed from the bottom surface of the body portion toward the top surface and located between the first side and the second side. The first pivot hole passes through the first side and the second side and is in communication with the inner cavity. The extruding portion is disposed on the top surface, located between the first side and the second side, and spatially corresponding to the inner cavity. The second pivot hole passes through the protruding portion and parallel to the first pivot hole. The at least one cable hole passes through the top surface and the bottom surface, and is misaligned with the extruding portion, the inner cavity and the first pivot hole. The extruding portion of a former one close to the fingertip is accommodated in the inner cavity of a latter one close to the base of each adjacent two of the plurality of finger segments, and the second pivot hole of the former one is aligned with the first pivot hole of the latter one and pivotally connected via a pivot shaft, allowing the latter one to swing relative to the former one. The driving module is disposed on the base. The primary actuation cable is connected to the driving module, and

connected from the base to the fingertip through the at least one cable hole of the plurality of finger segments in sequence, and then connected from the fingertip to the driving module through the at least one cable hole in sequence, wherein the driving module controls a tension of the primary actuation cable to control a posture and stiffness of a corresponding one of the plurality of fingers.

[0010] In an embodiment, each of the plurality of finger segments includes a protective skin, the protective skin having an upper opening and a lower opening, and the body portion is arranged on an outer periphery of the body portion through the upper opening and the lower opening.

[0011] In an embodiment, the protective skin includes a stopper, which is respectively arranged adjacent to a periphery of the upper opening and a periphery of the lower opening, protruding from outside to inside, and abutting against the top surface and the bottom surface to fix the protective skin to the outer periphery of the body portion.

[0012] In an embodiment, each of the fingertips of the plurality of finger segments includes a protective skin having an upper opening, the body portion passes through the upper opening so that the protective skin is arranged on an outer surface of the body portion.

[0013] In an embodiment, the protective skin includes a stopper, which is disposed adjacent to a periphery of the upper opening, protrudes from outside to inside, and abuts against the top surface to fix the protective skin to the outer surface of the body portion.

[0014] In an embodiment, the extruding portion is located between the first side and the second side to divide the top surface into a first-side top surface and a second-side top surface, wherein the first-side top surface is connected between the extruding portion and the first side, the second-side top surface is connected between the extruding portion and the second side,

and the at least one cable hole is arranged on the first-side top surface or the second-side top surface.

[0015] In an embodiment, the first-side top surface includes a first sub-slope surface and a second sub-slope surface, and the first sub-slope surface and the second sub-slope surface are respectively located on two opposite sides of the first pivot hole, wherein the second side top surface includes a third sub-slope surface and a fourth sub-slope surface, and the third sub-slope surface and the fourth sub-slope surface are respectively located on two opposite sides the first pivot hole, wherein the first sub-slope surface and the third sub-slope surface are located on the same side of the first pivot hole, and the at least one cable hole includes a first cable hole, a second cable hole, a third cable hole and a fourth cable hole arranged on the first sub-slope surface, the second sub-slope surface, the third sub-slope surface and the fourth sub-slope surface, respectively.

[0016] In an embodiment, the plurality of fingers are configured to grasp an object, the first sub-slope surface and the third sub-slope surface of the plurality of finger segments are close to the object, the primary actuation cable is connected from the base to the fingertip through the first cable hole or the third cable hole in the plurality of finger segments, and then connected from the fingertip to the driving module through the second cable hole or the fourth cable hole in sequence.

[0017] In an embodiment, the hybrid soft-rigid gripper further includes a secondary actuation cable which selectively pass through all or part of the plurality of finger segments from the base to achieve segmented control.

[0018] In an embodiment, the secondary actuation cable selectively passes through the first cable hole, the second cable hole, the third cable hole or the fourth cable hole of the plurality of finger segments from the base to achieve segmented control.

[0019] In an embodiment, each adjacent two of the plurality of finger segments have the former one close to the fingertip and the latter one close to the base, the former one close to the fingertip is allowed to swing within an angle range relative to the latter one close to the base, and the angle range is between 120 degrees and -120 degrees.

[0020] In an embodiment, each of the plurality of finger segments further includes a hollow structure penetrating the first side and the second side, and arranged parallel to the first pivot hole.

[0021] In an embodiment, each of the plurality of fingers includes at least one tactile sensor disposed at the fingertip and configured to sense pressure or sliding information of the plurality of fingers in contact with an object.

[0022] In an embodiment, the hybrid soft-rigid gripper further includes a controller, which is connected to the driving module (M) and the at least one tactile sensor and configured to receive a signal input from the tactile sensor and dynamically adjust the tension of the primary actuation cable according to the signal input.

[0023] In an embodiment, the driving module drives the primary actuation cable to change the tension through rotation.

[0024] In an embodiment, the plurality of fingers grasp an object by perform form closure and/or force closure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] The above contents of the present disclosure will become more readily apparent to those ordinarily skilled in the art after reviewing the following detailed description and accompanying drawings, in which:

[0026] FIG. 1A is schematic structural view illustrating a hybrid soft-rigid gripper with variable stiffness according to an embodiment of the present disclosure;

[0027] FIG. 1B is a structural exploded view illustrating the hybrid soft-rigid gripper with variable stiffness according to the embodiment of the present disclosure;

[0028] FIG. 2A and FIG. 2B are schematic structural views illustrating one single finger segment according to the embodiment of the present disclosure from different perspective;

[0029] FIG. 3 schematically shows two adjacent finger segment sequentially pivoted and the connection of the actuation cables according to the embodiment of the present disclosure;

[0030] FIG. 4A schematically shows the finger of the hybrid soft-rigid gripper with variable stiffness moving inwardly close to an object according to the embodiment of the present disclosure;

[0031] FIG. 4B schematically shows the fingers of the hybrid soft-rigid gripper with variable stiffness moving outwardly away from the object in the embodiment of the present disclosure;

[0032] FIG. 5A is a schematic structural view illustrating the protective skin according to the embodiment of the present disclosure; and

[0033] FIG. 5B is a side view illustrating the protective skin according to the embodiment of the present disclosure.

[0034] Persons skilled in the art will appreciate that elements in the figures are illustrated for simplicity and clarity and may have not been drawn to scale. For example, the dimensions of some of the elements in the figures may be exaggerated relative to the other elements to help to improve understanding of various exemplary embodiments of the present disclosure. Throughout the drawings, it should be noted that reference signs are used to depict the same or similar elements, features, and structures.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0035] The present disclosure will now be described more specifically with reference to the following embodiments. It is to be noted that the following descriptions of preferred embodiments of this disclosure are presented herein for purpose of illustration and description only. It is not intended to be exhaustive or to be limited to the precise form disclosed. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed. Further, spatially relative terms, such as “top,” “bottom,” “front,” “rear,” “left,” “right,” and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly. When an element is referred to as being “connected,” or “coupled,” to another element, it can be directly connected or coupled to the other element or intervening elements may be present. Although the wide numerical ranges and parameters of the present disclosure are approximations, numerical values are set forth in the specific examples as precisely as possible. In addition, although the “first,” “second” and the like terms in the claims be used to describe the various elements can be appreciated, these elements should not be limited by these terms, and these elements are described in the respective

embodiments are used to express the different reference numerals, these terms are only used to distinguish one element from another element. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of example embodiments. Besides, "and / or" and the like may be used herein for including any or all combinations of one or more of the associated listed items.

[0036] FIG. 1A is schematic structural view illustrating a hybrid soft-rigid gripper with variable stiffness according to an embodiment of the present disclosure. FIG. 1B is a structural exploded view illustrating the hybrid soft-rigid gripper with variable stiffness according to the embodiment of the present disclosure. FIG. 2A and FIG. 2B are schematic structural views illustrating one single finger segment according to the embodiment of the present disclosure from different perspective. FIG. 3 schematically shows two adjacent finger segment sequentially pivoted and the connection of the actuation cables according to the embodiment of the present disclosure. In the embodiment, a hybrid soft-rigid gripper (1) with variable stiffness is provided, and includes a base (10) and a plurality of fingers (F). The plurality of fingers (F) are connected to the base (10). In the embodiment, the hybrid soft-rigid gripper (1) has four fingers (F), each of four fingers (F) is embedded in a hyper-redundant endoskeleton that has multiple degrees of freedom. Each of the plurality of fingers (F) includes a plurality of finger segments (FS) and is respectively connected to a set of driving modules (M) and a primary actuation cable (L1) to perform the movement of the finger (F). In the embodiment, each of the plurality of fingers (F) includes a plurality of finger segments (FS), and the plurality of finger segments (FS) of each finger (F) are sequentially connected and pivotally connected from the base (10) downward to the fingertip (FF). In the embodiment, each

finger has eight finger segments (FS), and each of the eight finger segments (FS) includes a body portion (F10), an inner cavity (F20), a first pivot hole (F30), an extruding portion (F40), a second pivot hole (F50) and at least one cable hole (F60). The body portion (F10) is spatially corresponding to the fingertip (FF) and has a top surface (S1) and a bottom surface (S2) opposite to each other, and a first side (S3) and a second side (S4) opposite to each other. The top surface (S1) and the bottom surface (S2) are connected to each other through the first side (S3) and the second side (S4), respectively. The top surface (S1) faces the base (10), and the bottom surface (S2) faces the fingertip (FF). The inner cavity (F20) is recessed from the bottom surface (S2) of the body portion (F10) toward the top surface (S1), and is located between the first side (S3) and the second side (S4). The first pivot hole (F30) passes through the first side (S3) and the second side (S4), and is in communication with the inner cavity (F20). The extruding portion (F40) is disposed on the top surface (S1), arranged between the first side (S3) and the second side (S4), and spatially corresponding to the inner cavity (F20). In the embodiment, the size and the shape of the inner cavity (F20) and the protrusion (F40) are matched with each other. That is, the size and the shape of the inner cavity (F20) is corresponding to the size and the shape of the extruding portion (F40). The vertical cross-sections of the body portion (F10) and the extruding portion (F40) are polygonal. The second pivot hole (F50) passes through the protruding portion (F40) and is parallel to the first pivot hole (F30). The at least one cable hole (F60) passes through the top surface (S1) and the bottom surface (S2), and is misaligned with the protruding portion (F40), the inner cavity (F20) and the first pivot hole (F30) in view of a vertical direction. In the embodiment, the extruding portion (F40) of a former one (FS1) close to the fingertip (FF) is accommodated in the inner cavity (F20) of a latter one (FS2) close to the base (10) of each

adjacent two of the plurality of finger segments (FS), and the second pivot hole (F50) of the former one (FS1) is aligned with the first pivot hole (F30) of the latter one (FS2) and pivotally connected via a pivot shaft (F70), allowing the latter one (FS2) to swing relative to the former one (FS1). Certainly, in other embodiments, the connection of multiple fingers (FS) are implemented through different types of connectors. Furthermore, in the embodiment, the driving module (M) is disposed on the base (10). The primary actuation cable (L1) is connected to the driving module (M), and connected from the base (10) to the fingertip (FF) through at least one cable hole (F60) of the plurality of finger segments (FS) in sequence, and then connected from the fingertip (FF) to the driving module (M) in sequence through at least one cable hole (F60). In the embodiment, the driving module (M) controls a tension of the primary actuation cable (L1) to control a posture and stiffness of corresponding fingers (F).

[0037] In the embodiment, the driving module (M) of the hybrid soft-rigid gripper (1) is installed on the base (10). Each driving module (M) can remotely control the corresponding finger (F) through the primary actuation cable (L1). The driving module (M) and the finger (F) are located at opposite upper and lower sides of the base (10). Preferably but not exclusively, the hybrid soft-rigid gripper (1) is connected to an UR 10 robot via the robot arm connector of the base (10). The robot arm connector is a connector compatible with the UR 10 robot. The robot arm connector has a plurality of fixture legs (12) and a connecting plate (11). One end of the fixture leg (12) is disposed on the connecting plate (11), and the other end is connected to the gripper plate (13). A controller holder (C1) is disposed on the top connecting plate (11) for accommodating a controller (C2). The connection end (FB) of each finger (F) is detachably connected to the gripper plate (13). In the embodiment, the driving module (M) is, for example, a

DC servo motor. In other embodiments, other types of actuators are used. Each finger (F) is driven by at least one primary actuation cable (L1) and a plurality of secondary actuation cables (L2). Each primary actuation cable (L1) or secondary actuation cable (L2) is connected to an actuator of the driving module (M).

[0038] In the embodiment, each finger segment (FS) has a front-to-back and left-to-right symmetrical structure. The extruding portion (F40) is located between the first side (S3) and the second side (S4), and configured to divide the top surface (S1) into a first-side top surface (S13) and a second-side top surface (S14). The first-side top surface (S13) is connected between the extruding portion (F40) and the first side (S3), and the second-side top surface (S14) is connected between the extruding portion (F40) and the second side (S4). The least one cable hole (F60) is arranged on the first-side top surface (S13) or the second-side top surface (S14) for the primary actuation cable (L1) and the secondary actuation cable (L2) to pass through and realize tension control. In the embodiment, the first-side top surface (S13) includes a first sub-slope surface (S131) and a second sub-slope surface (S132), and the first sub-slope surface (S131) and the second sub-slope surface (S132) are respectively located on two opposite sides of the first pivot hole (F30). The second side top surface (S14) includes a third sub-slope surface (S141) and a fourth sub-slope surface (S142), and the third sub-slope surface (S141) and the fourth sub-slope surface (S142) are respectively located on two opposite sides the first pivot hole (F30). The first sub-slope surface (S131) and the third sub-slope surface (S141) are located on the same side of the first pivot hole (F30), and the at least one cable hole (F60) includes a first cable hole (F61), a second cable hole (F62), a third cable hole (F63) and a fourth cable hole (F64) arranged on the first sub-slope surface (S131), the second sub-slope surface (S132), the third sub-

slope surface (S141) and the fourth sub-slope surface (S142), respectively. The numbers of the first cable hole (F61), the second cable hole (F62), the third cable hole (F63) and the fourth cable hole (F64) are adjustable according to the practical requirements. In the embodiment, the numbers of the first cable hole (F61), the second cable hole (F62), the third cable hole (F63) and the fourth cable hole (F64) are all two and arranged front to back, allowing four actuation cables to pass through.

[0039] FIG. 4A schematically shows the finger of the hybrid soft-rigid gripper with variable stiffness moving inwardly close to an object according to the embodiment of the present disclosure. FIG. 4B schematically shows the fingers of the hybrid soft-rigid gripper with variable stiffness moving outwardly away from the object in the embodiment of the present disclosure. Please refer to FIG. 1A to FIG. 4B. In the embodiment, each finger (F) is configured to clamp an object (OB), the first sub-slope surfaces (S131) of the plurality of finger segments (FS) are close to the object (OB), and the primary actuation cable (L1) is connected from the base (10) to the fingertip (FF) in sequence through the first cable holes (F611) in the plurality of finger segments (FS), and then from the fingertip (FF) to the finger actuator in sequence through the second cable holes (F621). In the embodiment, each finger (F) is driven by the primary actuation cable (L1) passing through the all finger segments (FS) of the finger (F). Preferably but not exclusively, the actuator of the driving module (M) includes a cable wheel for rotating the actuation cable, and the rotation causes the primary actuation cable (L1) to change tension, thereby moving the finger inward or outward. In the embodiment, when the actuator of the driving module (M) controls the primary actuation cable (L1) to be tightened and shortened relative to the first sub-slope surfaces (S131) (i.e., the left side), and the tension of the primary actuation cable (L1) relative to the second sub-slope surfaces (S132)

(i.e., the right side) is released, so that the finger (F) is bent inward toward the object (OB). When the actuator of the driving module (M) controls the primary actuation cable (L1) to be tightened and shortened relative to the second sub-slope surfaces (S132) (i.e. the right side), and the tension of the primary actuation cable (L1) relative to the first sub-slope surfaces (S131) (i.e. the left side) is released, so that the finger (F) is bent outward away from the object (OB).

[0040] In the embodiment, the movement of one single finger (F) is controlled by the primary actuation cable (L1) in conjunction with a secondary actuation cable (L2). The first-side top surface (S13) of each finger segment (FS) includes four cable holes (F60). Namely, two first cable holes (F61) are located on the first sub-slope surface (S131), and two second cable holes (F62) are located on the second sub-slope surface (S132). The second-side top surface (S14) of each finger segment (FS) includes four cable holes (F60). Namely, two third cable holes (F63) are located on the third sub-slope surface (S141), and two fourth through holes (F64) are located on the fourth slope surface (S132). FIG. 3 illustrates the arrangement of the primary actuation cable (L1) and the secondary actuation cable (L2) through the cable hole (F60) on the first-side top surface (S13), but the present disclosure is not limited thereto.

[0041] In the embodiment, the primary actuation cable (L1) passes through the first cable hole (F611) at the corresponding position, turns back at the fingertip (FF), passes through the second cable hole (F621), and is controlled by the driving module (M). Preferably but not exclusively, the actuator of the driving module (M) includes a cable wheel for rotating the actuation cable, and the rotation causes the primary actuation cable (L1) to change tension, thereby moving the finger inward or outward. In the embodiment, the secondary actuator cable (L2) is selectively connected from

the base (10) to a specific finger segment (FS), not limited to the fingertip (FF), through the first cable hole (F612) in the plurality of finger segment (FS), and then connected to the driving module (M) in sequence from the specific finger segment through the second cable hole (F622). By selectively passing the secondary actuation cable (L2) through all or part of the plurality of finger segments (FS), a segmented control of the finger (F) can be achieved. Certainly, in other embodiments, different secondary actuator cables (L2) can selectively pass through the first hole (F61), the second cable hole (F62), the third cable hole (F63) or the fourth cable hole (F64) of the plurality of finger segments (FS) from the base (10) to achieve segmented control for more control degree of freedom.

[0042] In the embodiment, the primary actuation cable (L1) and one single actuator of the driving module (M) can provide bidirectional control of the finger (F), namely, the inward movement (as shown in FIG. 4A) and the outward movement (as shown in FIG. 4B) of the finger (F). In other embodiments, the movement of the finger (F) is controlled by three or more actuation cables, and some actuation cables do not pass through all the finger segments (FS) of the finger (F). For example, three actuation cables are provided to control the movement of the finger. The actuation cable passes through all the fingers (FS) as the primary actuation cable (L1), controlling the inward and outward movements respectively. Another actuation cable served as the secondary actuation cable (L2) passes through only a few adjacent segments (FS) at the lower or upper part of the finger (F) to enhance the inward movement of the finger (F).

[0043] Notably, the number and the position of the cable holes (F60) are adjustable according to the practical requirements. When N actuation cables are used to control the movement of a finger (F), N or 2N cable holes (F60) are provided on the first sub-slope surface (S131), the second sub-

slope surface (S132), the third sub-slope surface (S141) and the fourth sub-slope surface (S142) of the top surface (S1). The size or the dimension of the cable hole (F60) is determined by the actuation cables selected and the number of actuation cables passing through the cable hole (F60). The actuation cables are made of light-weight materials and the tensile or tension strength should be strong enough for handling required payload ranges.

[0044] On the other hand, in the embodiment, the plurality of finger segments are assembled together to form one single finger. In the embodiment, there are eight finger segments connected together to form a signal finger, and the hybrid soft-rigid gripper (1) includes four fingers (F). In other embodiments, the hybrid soft-rigid gripper (1) includes another number of fingers, such as three or five, and each finger (F) includes another number of finger segments (FS). The numbers of fingers (F) and finger segments (FS) can be determined according to the application, the tasks to be performed, or the user's demand. In another embodiment, the fingers (F) of the hybrid soft-rigid gripper (1) has different lengths, i.e., different numbers of finger segments (FS). For example, a hybrid soft-rigid gripper (1) has four fingers (F), in which two fingers having longer lengths than the other two fingers (F), and the fingers (F) are interleaved by long-short length. In addition, for example, the hybrid soft-rigid gripper (1) has six fingers (F), wherein three fingers (F) are shorter than the other three fingers (F), and the fingers (F) of the same length are arranged neighboring to each other or at the same side.

[0045] When the plurality of finger segments (FS) are assembled together, each finger segment (FS) is capable to rotate around the shaft. The maximum rotation range between two-connected adjacent finger segments (FS) may be determined by the design of the extruding portion (F40) and the inner cavity (F20), and is typically designed to be of the same

rotation range in the inward and outward directions. In the embodiment, for each two adjacent ones of the plurality of finger segments (FS), the former one (FS1) close to the fingertip (FF) is allowed to swing within an angle range relative to the latter one (FS2) close to the base (10), and the angle range is between 120 degrees and -120 degrees. Certainly, the total rotation range of the finger (F) may be greater than the rotation range of two-connected finger segment (FS), and different segments (FS) may rotate in different angles and directions. In this way, the hybrid soft-rigid gripper (1) with the plurality of fingers (F) is capable to grip objects of various geometry.

[0046] In the embodiment, each of the plurality of finger segments (FS) further includes a hollow structure (F90) penetrating the first side (S3) and the second side (S4), in communication with the inner cavity (F20), and arranged parallel to the first pivot hole (F30). The hollow design of the hollow structure (F90) can reduce the weight of the finger segments (FS) and reduce the material cost. In the embodiment, each finger segment (FS) can be manufactured by 3D printing, injection molding or other manufacturing processes. Taking 3D printing as an example, the hollow structure (F90) on the body portion (F10) can reduce the weight of the finger segments (FS).

[0047] FIG. 5A is a schematic structural view illustrating the protective skin according to the embodiment of the present disclosure. FIG. 5B is a side view illustrating the protective skin according to the embodiment of the present disclosure. Please refer to FIG. 1A to FIG. 5B. In the embodiment, each of the plurality of finger segments (FS) includes a protective skin (F80). The protective skin (F80) includes an upper opening (F81) and a lower opening (F82), and the body portion (F10) is arranged on an outer periphery of the body portion (F10) through the upper opening (F81) and the lower opening (F82). In the embodiment, the protective skin (F80) includes stoppers (F83, F84), which are respectively arranged adjacent to a

periphery of the upper opening (F81) and a periphery of the lower opening (F82), protruding from the outside to the inside, and abutting against the top surface (S1) and the bottom surface (S2) to fix the protective skin (F80) to the outer periphery of the body portion (F10). The stoppers (F83, F84) are not limited to corresponding arrangements or offset arrangements. In addition, a protective skin (F85) is provided for the fingertip (FF) of the plurality of finger segments (FS). The protective skin (F85) includes an upper opening (F86). The body portion (F10) passes through the upper opening (F86) so that the protective skin (F85) is arranged on an outer surface of the body portion (F10). Similarly, the protective skin (F85) includes a stopper (F87) which is disposed adjacent to a periphery of the upper opening (F86), protrudes from the outside to the inside, and abuts against the top surface (S1) to fix the protective skin (F85) to the outer surface of the body portion (F10). The protective skins (F80, F85) are made of soft materials and can be easily assembled with the finger segments (FS). The size, the shape and the dimensions of the protective skins (F80, F85) generally conform with the body portion (F10) of the finger segments (FS) so that the protective skins (F80, F85) can be properly and firmly attached with the finger segments (FS). In the embodiment, the inner surface of the protective skins (F80, F85) can be configured to have coarse texture or anti-slip design to enhance the attachment of the protective skins (F80, F85) and the finger segments (FS).

[0048] In the embodiment, each of the plurality fingers (F) includes at least one tactile sensor (T1), which is arranged on the fingertip (FF) or the outer surface or inner wall of the protective skin (F85), and configured to sense the pressure or sliding information of the contact between the plurality of fingers (F) and the object (OB). Preferably but not exclusively, in the embodiment, the tactile sensor (T1) can be disposed on the outer surface of

the protective skin (F85), or the tactile sensor (T1) is disposed on the contact side of the protective skin (F85) and the object (OB) to sense the force or pressure acting on the finger segments (FS). In other embodiments, the shape of the protective skin (F85) may also be adjusted according to the practical requirements, and the present disclosure is not limited thereto. In addition, in the embodiment, the controller (C2) is connected to the driving module (M) and at least one tactile sensor (T1) and configured to receive a signal input from the tactile sensor (T1) and dynamically adjust the tension of the primary actuation cable (L1) according to the signal input to provide force/slip feedback during the grasping operations. In the embodiment, the tactile sensor (T1) may be, for example, a force sensitive resistor (FSR), a pressure sensor or other appropriate sensors. In other embodiments, the sensor may be configured to detect external parameters such as pressure, vibration, texture, temperature, stiffness, shape, and/or size. The selection of sensor may depend on sensitivity requirements, task demand or user's choice. The sensor signals may be processed and utilized for control of the hybrid soft-rigid gripper (1) to adjust the gripping force and/or gripping gesture. Certainly, the present disclosure is not limited thereto.

[0049] In the embodiment, the hybrid soft-rigid gripper (1) can be attached to a robotic arm. By using the above grasping mechanism, the hybrid soft-rigid gripper (1) can grasp a wide range of objects with force closure and/or form closure principles. In the various embodiments, the hybrid soft-rigid gripper (1) is capable to perform grasping task with multiple fingers or a single finger. For example, the hybrid soft-rigid gripper (1) can pick up a bag or press a button with just one finger. Furthermore, the hybrid soft-rigid gripper (1) can grasp or hold objects using multiple fingers. The hybrid soft-rigid gripper (1) is also capable to grasp or grip objects in various shapes, sizes, dimensions and/or stiffness or softness. For example, the

hybrid soft-rigid gripper (1) is capable to pick up and hold a flower, which is small, soft and without solid exterior shape.

[0050] Notably, the hybrid soft-rigid gripper (1) of the present disclosure can utilize force closure and/or form closure when performing grasp tasks. The key difference between force closure and form closure principles is that the latter does not require frictional forces between the object and the gripper while the former does. Form closure is applicable when the object has simpler geometries where the hybrid soft-rigid gripper (1) can establish good contact with the bottom flat surface of the container. Similarly, the hybrid soft-rigid gripper (1) can also establish form closure when it acts like a hook to support the loop handle of an object. If form closure is possible, the gripper can carry heavier load. For other scenarios, the hybrid soft-rigid gripper (1) of the present disclosure can perform force closure on different objects. As an example, it can establish force closure on a roll of adhesive tape by establishing good contact with the tape's exterior surfaces. The hybrid soft-rigid gripper (1) can also implement force closure principle by establishing good contact with the internal surfaces of an object.

[0051] In general, the hybrid soft-rigid gripper (1) of the present disclosure can successfully grasp several objects with varying weight (2g to 5000g), geometry (convex, concave), surface conditions (rough, smooth) and stiffness (rigid, soft). Unlike existing rigid grippers, the hybrid soft-rigid gripper (1) of the present disclosure can grasp a vast range of objects with complex geometries, and it can also handle wet, soft and deformable objects like tofu. Likewise, the hybrid soft-rigid gripper (1) of the present disclosure can also handle fragile objects like flowers. The hybrid soft-rigid gripper (1) of the present disclosure can also handle rough and dirty surfaces. The hybrid soft-rigid gripper (1) of the present disclosure can also

execute other manipulation tasks such as pressing an emergency button when one of its fingers is in its stiff configuration. These preliminary results indicate that the hybrid soft-rigid gripper (1) of the present disclosure is indeed promising, and it has great potential to achieve unprecedented grasping performance. Certainly, the applications of the hybrid soft-rigid gripper (1) of the present disclosure are not limited thereto and not redundantly described hereafter.

[0052] In summary, the present disclosure provides a hybrid soft-rigid gripper with variable stiffness for enhancing the adaptability and precision in object manipulation. The hybrid soft-rigid gripper is allowed to reprogram its stiffness upon command. The proposed gripper has an architecture that comprises several fingers (three to seven fingers). Each finger is made of a rigid, hyper-redundant endoskeleton that has many more degrees-of-freedom than those required by the manipulation task. In this way, the fingers of the hybrid soft-rigid gripper of the present disclosure can conform to the shape of objects with complex geometries, emulating the benefits of soft grippers. The rigid endoskeleton of the hybrid soft-rigid gripper of the present disclosure is allowed to generate the necessary stiffness to achieve high precision and payload during the grasping operation. The hybrid soft-rigid gripper of the present disclosure therefore inherit the benefits of both rigid and soft grippers. The hybrid soft-rigid gripper of the present disclosure has great potential to manipulate a much wider range of objects than existing robotic grippers would. On the other hand, the heavy and bulky actuators are placed at the base of the gripper while allowing them to remotely control the hybrid soft-rigid gripper via light cables, so that the space and weight constraints imposed by the actuators are overcome. Furthermore, the design of the hybrid soft-rigid gripper also accounts for the integration of tactile sensors that can provide force/slip feedback during the

grasping operations. The stiffness of the hybrid soft-rigid gripper can be reprogrammed by controlling the tensions of the actuation cables thereof. At the beginning of the grasping operation, the actuation cable tensions are programmed to be low so that the tension of the actuation cable is lower, and the hybrid soft-rigid gripper is compliant, so it can easily and properly conform to the geometry of the targeted object. Because the fingers of the hybrid soft-rigid gripper have a hyper-redundant endoskeleton, the gripper of the present disclosure has higher degrees-of-freedom than existing rigid grippers, potentially allowing it to grip a much wider range of objects that have complicated geometries and soft consistency. Upon establishing a good contact of the fingers with the targeted object, the hybrid soft-rigid gripper's cable tensions can be increased so that the gripper can assume a stiff configuration that is essential for executing force closure on the targeted object successfully. In the stiff configuration, the hybrid soft-rigid gripper has much higher stiffness than the conventional soft grippers, allowing it to achieve higher precision and payload during the grasping operations. Since the hybrid soft-rigid gripper of the present disclosure is using force closure principles to grasp the targeted objects, it is also much less susceptible to objects with varying surface properties than the conventional soft grippers. In other words, the unique advantages of the hybrid grasping mechanism of the present disclosure allow the hybrid soft-rigid gripper to have the potential to manipulate a much wider range of objects with varying stiffness, surface properties and geometries compared to the conventional grippers. In addition, the hybrid soft-rigid gripper is covered by protective skins made of soft material so that it can handle objects with vulnerable or sensitive surface without causing harm or damage. Sensors can be disposed on the protective skins so as to feedback pressure endured by the hybrid soft-rigid

gripper and thus gripping force can be adjusted. Certainly, the present disclosure is not limited thereto.

[0053] It will also be apparent to a skilled person that the embodiments described above are specific examples of a single broader invention, which may have greater scope than any of the singular descriptions taught. There may be many alterations made in the description without departing from the scope of the invention. While embodiments of the invention have been described, it is not intended that the invention be limited to said configuration disclosed thereto, as it is intended that the invention be as broad in scope as the art will allow and that the specification be read likewise not restrictive to the terminology described herein above. Any discussion of embodiments included in this specification is solely for the purpose of providing a context for the disclosure. It is not to be taken as an admission that any or all these matters form a part of the prior art base or were common general knowledge in the field relevant to the disclosure as it existed anywhere before the priority date of this application.

[0054] While the disclosure has been described in terms of what is presently considered to be the most practical and preferred embodiments, it is to be understood that the disclosure needs not be limited to the disclosed embodiment. On the contrary, it is intended to cover various modifications and similar arrangements included within the spirit and scope of the appended claims which are to be accorded with the broadest interpretation so as to encompass all such modifications and similar structures.

WHAT IS CLAIMED IS:

1. A hybrid soft-rigid gripper with variable stiffness, comprising:

a base; and

a plurality of fingers connected to the base, wherein each of the plurality of fingers comprises:

a plurality of finger segments, wherein the plurality of finger segments are pivotally connected in sequence from the base downward to a fingertip, wherein each of the plurality of finger segments comprises:

a body portion spatially corresponding to the fingertip and comprising a top surface and a bottom surface opposite to each other, and a first side and a second side opposite to each other, wherein the top surface and the bottom surface are connected through the first side and the second side, respectively;

an inner cavity recessed from the bottom surface of the body portion toward the top surface and located between the first side and the second side;

a first pivot hole passing through the first side and the second side and in communication with the inner cavity;

an extruding portion disposed on the top surface, located between the first side and the second side, and spatially corresponding to the inner cavity;

a second pivot hole passing through the protruding portion and parallel to the first pivot hole; and

at least one cable hole passing through the top surface and the bottom surface, and misaligned with the extruding portion, the inner cavity and the first pivot hole;

wherein the extruding portion of a former one close to the fingertip is accommodated in the inner cavity of a latter one close to the base of each adjacent two of the plurality of finger segments, and the second pivot hole of the former one is aligned with the first pivot hole of the latter one and pivotally connected via a pivot shaft, allowing the latter one to swing relative

to the former one;

a driving module disposed on the base; and

a primary actuation cable connected to the driving module, and connected from the base to the fingertip through the at least one cable hole of the plurality of finger segments in sequence, and then connected from the fingertip to the driving module through the at least one cable hole in sequence, wherein the driving module controls a tension of the primary actuation cable to control a posture and stiffness of a corresponding one of the plurality of fingers.

2. The hybrid soft-rigid gripper with variable stiffness according to claim 1, wherein each of the plurality of finger segments comprises a protective skin, the protective skin having an upper opening and a lower opening, and the body portion is arranged on an outer periphery of the body portion through the upper opening and the lower opening.

3. The hybrid soft-rigid gripper with variable stiffness according to claim 2, wherein the protective skin comprises a stopper, which is respectively arranged adjacent to a periphery of the upper opening and a periphery of the lower opening, protruding from outside to inside, and abutting against the top surface and the bottom surface to fix the protective skin to the outer periphery of the body portion.

4. The hybrid soft-rigid gripper with variable stiffness according to claim 1, wherein each of the fingertips of the plurality of finger segments comprises a protective skin having an upper opening, the body portion passes through the upper opening so that the protective skin is arranged on an outer surface of the body portion.

5. The hybrid soft-rigid gripper with variable stiffness according to claim 4, wherein the protective skin includes a stopper, which is disposed adjacent to a periphery of the upper opening, protrudes from outside to inside, and

abuts against the top surface to fix the protective skin to the outer surface of the body portion.

6. The hybrid soft-rigid gripper with variable stiffness according to claim 1, wherein the extruding portion is located between the first side and the second side to divide the top surface into a first-side top surface and a second-side top surface, wherein the first-side top surface is connected between the extruding portion and the first side, the second-side top surface is connected between the extruding portion and the second side, and the at least one cable hole is arranged on the first-side top surface or the second-side top surface.

7. The hybrid soft-rigid gripper with variable stiffness according to claim 6, wherein the first-side top surface comprises a first sub-slope surface and a second sub-slope surface, and the first sub-slope surface and the second sub-slope surface are respectively located on two opposite sides of the first pivot hole, wherein the second side top surface comprises a third sub-slope surface and a fourth sub-slope surface, and the third sub-slope surface and the fourth sub-slope surface are respectively located on two opposite sides the first pivot hole, wherein the first sub-slope surface and the third sub-slope surface are located on the same side of the first pivot hole, and the at least one cable hole comprises a first cable hole, a second cable hole, a third cable hole and a fourth cable hole arranged on the first sub-slope surface, the second sub-slope surface, the third sub-slope surface and the fourth sub-slope surface, respectively.

8. The hybrid soft-rigid gripper with variable stiffness according to claim 6, wherein the plurality of fingers are configured to grasp an object, the first sub-slope surface and the third sub-slope surface of the plurality of finger segments are close to the object, the primary actuation cable is connected from the base to the fingertip through the first cable hole or the third cable

hole in the plurality of finger segments, and then connected from the fingertip to the driving module through the second cable hole or the fourth cable hole in sequence.

9. The hybrid soft-rigid gripper with variable stiffness according to claim 1, further comprising a secondary actuation cable which selectively pass through all or part of the plurality of finger segments from the base to achieve segmented control.

10. The hybrid soft-rigid gripper with variable stiffness according to claim 9, wherein the secondary actuation cable selectively passes through the first cable hole, the second cable hole, the third cable hole or the fourth cable hole of the plurality of finger segments from the base to achieve segmented control.

11. The hybrid soft-rigid gripper with variable stiffness according to claim 1, wherein each adjacent two of the plurality of finger segments have the former one close to the fingertip and the latter one close to the base, the former one close to the fingertip is allowed to swing within an angle range relative to the latter one close to the base, and the angle range is between 120 degrees and -120 degrees.

12. The hybrid soft-rigid gripper with variable stiffness according to claim 1, wherein each of the plurality of finger segments further comprises a hollow structure penetrating the first side and the second side, and arranged parallel to the first pivot hole.

13. The hybrid soft-rigid gripper with variable stiffness according to claim 1, wherein each of the plurality of fingers comprises at least one tactile sensor disposed at the fingertip and configured to sense pressure or sliding information of the plurality of fingers in contact with an object.

14. The hybrid soft-rigid gripper with variable stiffness according to claim 13, further comprising a controller, which is connected to the driving module

and the at least one tactile sensor and configured to receive a signal input from the tactile sensor and dynamically adjust the tension of the primary actuation cable according to the signal input.

15. The hybrid soft-rigid gripper with variable stiffness according to claim 13, wherein the driving module drives the primary actuation cable to change the tension through rotation.

16. The hybrid soft-rigid gripper with variable stiffness according to claim 1, wherein the plurality of fingers grasp an object by perform form closure and/or force closure.