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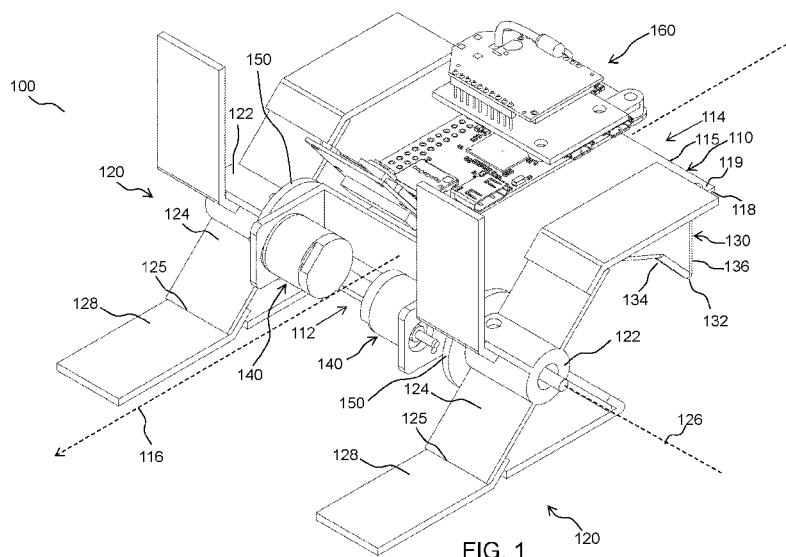


FIG. 1

(57) Abstract: A climbing robot including a chassis having a front portion and a rear portion, wherein the front portion and the rear portion are opposite end portions of the chassis along a forward movement axis of the chassis; at least one multi-legged rotary component including a hub rotatably coupled to the front portion of the chassis in an orientation with a rotational axis of the hub being transverse to the forward movement axis of the chassis, a plurality of rigid elongate leg members extending outwards from the hub with respect to the rotational axis, and a plurality of flexible adhesive flaps extending respectively from corresponding free-ends of the plurality of rigid elongate leg members; and a tail appendage component at the rear portion of the chassis and protruding perpendicularly away from an underside of the chassis.



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CLIMBING ROBOT

Cross-reference to Related Applications

[0001] The present application claims the benefit of the Singapore patent application No. 10201903500S filed on 18 April 2019, the entire contents of which are incorporated herein by reference for all purposes.

Technical Field

[0002] Various embodiments generally relate to a climbing robot.

Background

[0003] Climbing robots have many benefits such as a highly expanded workspace and the ability to reach or accomplish otherwise impossible spots or tasks for ground robots. When climbing robots are used collaboratively with unmanned ground vehicles (UGV) for indoor autonomous intelligence, surveillance and reconnaissance (ISR) missions, they can be a powerful swarm that collectively completes tasks such as mapping, detection, monitoring and tracking. Specifically, the climbing robot can be used to provide an overall image of the area and as a bridge for communication for robots on different floors. To complete such tasks, the robot may be required to climb obstacles and transition from one plane to another, both internally (concave angle) and externally (convex angle).

[0004] Preferably, the attachment means of a climbing robot should be lightweight, operationally quiet, and energy efficient. It has been observed from nature that the mechanism for attachment to the surface in climbing animals generally provides strong adhesion instantaneously during attachment while minimal effort is needed for contact release during detachment. For miniature climbing robots, designing bulky legged mechanism to fulfil this is undesirable. On the other hand, a track-based vehicle is unable to produce this locomotion.

[0005] Most of the existing miniature climbing robots are only capable of flat surface climbing, and either have no or limited internal plane-to-plane transition capabilities. Those that are capable of performing external transitions usually need additional active tail or body joint, to support the robot while it transits to make contact with the adjacent surface before

pulling the rest of its body. These then require additional actuators and/or body segments which increase the size and mass of the robot significantly.

[0006] Accordingly, there is a need for a simpler and effective climbing robot so as to address the above issues.

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Summary

[0007] According to various embodiments, there is provided a climbing robot. The climbing robot may include a chassis having a front portion and a rear portion, wherein the front portion and the rear portion may be opposite end portions of the chassis along a forward movement axis of the chassis. The climbing robot may include at least one multi-legged rotary component. The at least one multi-legged rotary component may include a hub rotatably coupled to the front portion of the chassis in an orientation with a rotational axis of the hub being transverse to the forward movement axis of the chassis. The at least one multi-legged rotary component may include a plurality of rigid elongate leg members extending outwards from the hub with respect to the rotational axis. The at least one multi-legged rotary component may include a plurality of flexible adhesive flaps extending respectively from corresponding free-ends of the plurality of rigid elongate leg members. The climbing robot may further include a tail appendage component at the rear portion of the chassis and protruding perpendicularly away from an underside of the chassis.

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Brief description of the drawings

[0008] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments are described with reference to the following drawings, in which:

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FIG. 1 shows a climbing robot according to various embodiments;

FIG. 2 shows a photograph of a prototype climbing robot according to various embodiments;

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FIG. 3 shows a schematic side view of a mechanism model of the climbing robot according to various embodiments;

FIG. 4(a) shows a free body diagram of the climbing robot according to various embodiments during external transition;

FIG. 4(b) shows a free body diagram of a climbing robot without a tail appendage component for comparison with FIG. 4(a).

5 FIG. 5(a) shows a mechanism model of a climbing robot without a tail appendage component for the flat-surface climbing analysis;

FIG. 5(b) shows a mechanism model of the climbing robot according to various embodiments for the flat-surface climbing analysis;

10 FIG. 5(c) shows a separate mechanism model for the tail appendage component of the climbing robot according to various embodiments;

FIG. 6(a) shows a schematic illustrations of the 4-way external transitions achieved by the climbing robot according to various embodiments;

FIG. 6(b) shows an adhesive moment requirement for the transitions at various approach distances from the intersection corner;

15 FIG. 6(c) shows an adhesive normal force requirement for the transitions at various approach distances from the intersection corner;

FIG. 6(d) shows a motor torque requirement for the transitions at various approach distances from the intersection corner; and

FIG. 7(a) to (h) show snapshots of actual experiment during transitions.

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Detailed description

[0009] Embodiments described below in the context of the apparatus are analogously valid for the respective methods, and vice versa. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment
25 may be combined with a part of another embodiment.

[00010] It should be understood that the terms “on”, “over”, “top”, “bottom”, “down”, “side”, “back”, “left”, “right”, “front”, “lateral”, “side”, “up”, “down” etc., when used in the following description are used for convenience and to aid understanding of relative positions or directions, and not intended to limit the orientation of any device, or structure or any part

of any device or structure. In addition, the singular terms “a”, “an”, and “the” include plural references unless context clearly indicates otherwise. Similarly, the word “or” is intended to include “and” unless the context clearly indicates otherwise.

[00011] Various embodiments generally relate to a climbing robot. The climbing robot
5 may include miniature climbing robot. According to various embodiments, the climbing robot may be configured to climb obstacle as well as to transition from one plane to another, both internally (concave angle) and externally (convex angle). According to various embodiments, the climbing robot may be provided with attachment means based on the general principle of an entire-surface attachment and a peeling-like detachment such that
10 strong adhesion is instantaneously generated while minimal effort is needed for contact release. According to various embodiments, the climbing robot may employ multi-legged rotary component, e.g. whegs (or wheel-legs) mechanism, for locomotion with compliant adhesive to passively achieve the required motion.

[00012] Various embodiments may provide a climbing robot which may be capable to
15 perform plane-to-plane transitioning robustly. According to various embodiments, the climbing robot may be configured to achieve external transitions based on analyzing the requirements for successful external transitions. According to various embodiments, the outcome of the analysis may provide a basis and configuration to achieve the climbing robot with robust transitioning capabilities without requiring additional active actuator or body
20 joint in a manner so as to keep the robot scaled-down or to allow the climbing robot to be miniaturized.

[00013] According to various embodiments, the climbing robot may include at least one multi-legged rotary component (or whleg) and at least one passive tail appendage component (or a tail component) which may enable robust transitioning capabilities. As an example,
25 the climbing robot may include two multi-legged rotary components (or whegs) and one passive tail appendage component. According to various embodiments, such configuration may allow the climbing robot to be minimally actuated and may also allow the climbing robot to be significantly scaled down, for example to meso-scale (i.e. millimeters to centimeters range). According to various embodiments, each multi-legged rotary
30 component (or whleg) may include multiple flexible adhesive flaps (for example, made of compliant dry adhesive). As an example, each multi-legged rotary component (whleg) may include four flaps. Further, the climbing robot may be equipped with electronics including, but not limited to, a controller (e.g. a microcontroller), an inertial measurement unit (IMU),

a single board computing device (e.g. a Raspberry Pi Zero single board computer), a camera module, and a wireless communication module (e.g. a XBee communication module).

[00014] FIG. 1 shows a climbing robot 100 according to various embodiments. According to various embodiments, the climbing robot 100 may include a chassis 110. According to
5 various embodiments, the chassis 110 may include a base or a base frame or a framework to which a drive mechanism or locomotive mechanism may be mounted. According to various embodiments, the chassis 110 may provide the skeletal structure for supporting the climbing robot 100 such that the body of the climbing robot 100 may be mounted thereto. According to various embodiments, the chassis 110 may have a front portion 112 and a rear
10 portion 114. The front portion 112 and the rear portion 114 may be opposite end portions of the chassis 110 along a forward movement axis 116 of the chassis 110. According to various embodiments, the climbing robot 100 may be configured to be capable of forward movement. Accordingly, a leading portion of the chassis 110, which is the foremost or forward portion of the chassis 110 in the direction of the forward movement, is the front
15 portion 112 of the chassis 110. Hence, a trailing portion of the chassis 110, which is the rearmost or aft portion of the chassis 110 in the direction of the forward movement, is the rear portion 114 of the chassis 110.

[00015] According to various embodiments, the climbing robot 100 may include at least one multi-legged rotary component 120. According to various embodiments, the at least
20 one multi-legged rotary component 120 may include a wheel-legs (or whleg) or a rimless wheel having only spokes serving as legs. Accordingly, the at least one multi-legged rotary component 120 may provide a locomotion that combines a rotation of a wheel with advantages of legs for climbing terrains and obstacles.

[00016] According to various embodiments, the at least one multi-legged rotary
25 component 120 may include a hub 122. The hub 122 may be rotatably coupled to the front portion 112 of the chassis 110. Accordingly, the hub 122 may be located at the front portion 112 of the chassis 110 and may be capable of being rotated relative to the chassis 110. According to various embodiments, the hub 122 may be in an orientation with a rotational axis 126 of the hub 122 being transverse to the forward movement axis 112 of the chassis
30 110. Accordingly, the rotational axis 126 of the hub 122 may extend across the forward movement axis 112 of the chassis 110 in a perpendicular or orthogonal manner such that hub 122 may be rotated in a forward direction for forward movement of the chassis 110.

[00017] According to various embodiments, the at least one multi-legged rotary component 120 may include a plurality of rigid elongate leg members 124. The plurality of

rigid elongate leg members 124 may be extending outwards from the hub 122 with respect to the rotational axis 126. Accordingly, the plurality of rigid elongate leg members 124 may extend or spread from the hub 122 in a fan out manner such that each rigid elongate leg members 124 extend in a different direction from the hub 122 along a same plane. Thus, 5 the plurality of rigid elongate leg members 124 may be extending substantially radially outwards or radiating from the hub 122 along the plane perpendicular to the rotational axis 126. According to various embodiments, the plurality of rigid elongate leg members 124 may be equally distributed circumferentially around the hub 122. According to various embodiments, each of the rigid elongate leg members 124 may include, but not limited to, 10 a spoke, a rod, a bar, or a pole, or a long panel, etc.

[00018] According to various embodiments, the at least one multi-legged rotary component 120 may include a plurality of flexible adhesive flaps 128. The plurality of flexible adhesive flaps 128 may be extending respectively from corresponding free-ends 125 of the plurality of rigid elongate leg members 124. Accordingly, one flexible adhesive 15 flap 128 may extend from a free-end of one corresponding rigid elongate leg member 124. Hence, each of the flexible adhesive flap 128 may be a flexible extension of the corresponding rigid elongate leg member 124. According to various embodiments, each of the flexible adhesive flap 128 may be attached at one side only to the corresponding free-end of the corresponding rigid elongate leg member 124. Accordingly, each of the flexible 20 adhesive flap 128 may hang from the corresponding free-end of the corresponding rigid elongate leg member 124. According to various embodiments, since the elongate leg member 124 is rigid and the adhesive flap 128 is flexible, each of the flexible adhesive flap 128 may swing or sway or flip loosely with respect to the corresponding rigid elongate leg member 124. According to various embodiments, each of the flexible adhesive flap 128 25 may be compliant or pliant or adaptable to a movement of the corresponding rigid elongate leg member 124 interacting with an external surface such that the flexible adhesive flap 128 may be brought to engage the external surface instantaneously during attachment and to disengage the external surface in a peeling manner during detachment.

[00019] According to various embodiments, the climbing robot 100 may include a tail 30 appendage component 130. The tail appendage component 130 may be at the rear portion 114 of the chassis 110 and protruding perpendicularly away from an underside 118 of the chassis 110. Further, the tail appendage component 130 may be protruding in a manner such that a tip 132 of the tail appendage component 130 may be below the rear portion 114 of the chassis 110. Accordingly, the tail appendage component 130 may be located at a

portion of the chassis 110 away or opposite from the front portion 112 of the chassis 110 which the at least one multi-legged rotary component 120 is located. Further, the tail appendage component 130 may be protruding vertically downwards from the underside 118 of the chassis 110 with the tip 132 of the tail appendage component 130 disposed or situated or peaked or terminated perpendicularly away from the rear portion 114 of the chassis 110. Hence, the tip 132 of the tail appendage component 130 may be disposed or situated or peaked or terminated in a direction projecting away and along a normal vector with respect to the underside 118 of the chassis 110 at the rear portion 114 of the chassis 110. Thus, the tail appendage component 130 may be an auxiliary part additional to a main structure of the chassis 110 and which may extend in a tail-like manner from under the rear portion 114 of the chassis 110, whereby the tail appendage component 130 may be an upright structure with respect to the underside 118 of the chassis 110 with the tip 132 of the tail appendage component 130 vertically disposed away from the underside 118 of the chassis 110 at the rear portion 114 of the chassis 110.

[00020] According to various embodiments, the tail appendage component 130 may be laterally bounded corresponding to a perimeter of the chassis 110. For example, within a lateral boundary or border corresponding to the perimeter of the chassis 110. Accordingly, the tail appendage component 130 may be extending from the underside 118 of the chassis 110 into a space underneath the chassis 110 which is horizontally limited or bounded by a boundary or border corresponding to the perimeter of the chassis 110. Hence, the tail appendage component 130 may not extend beyond or outside the boundary or border corresponding to the perimeter of the chassis 110. According to various embodiments, the tip 132 of the tail appendage component 130 may be within the perimeter of the chassis 110. Accordingly, the tip 132 of the tail appendage component 130 may be within the space underneath the chassis 110 laterally bounded corresponding to the perimeter of the chassis 110. Hence the tip 132 of the tail appendage component 130 may not lie beyond or outside the perimeter of the chassis 110.

[00021] According to various embodiments, the tail appendage component 130 may be fixed to the chassis 110 in a manner such that the tail appendage component 130 is immovable relative to the chassis 110. Accordingly, the tail appendage component 130 may be a passive structure additional to the main structure of the chassis 110 and so fixed as to be not movable with respect to the chassis 110. According to various embodiments, the tail appendage component 130 may be integrally connected to, joined to, molded with, or formed with the chassis 110 so as to be a single structural unit. Accordingly, the tail

appendage component 130 and the chassis 110 together may be a single complete piece or unit incapable of relative movements between the tail appendage component 130 and the chassis 110.

5 [00022] According to various embodiments, a height of the tail appendage component 130 measured from the underside 118 of the chassis 110 to a tip 132 of the tail appendage component 132 may be determined by optimizing the height of the tail appendage component 130 based on analyzing the effect of the height of the tail appendage component 130 on an adhesive requirement (e.g. normal adhesive force and/or adhesive moment) of the flexible adhesive flap 128 and a driving torque requirement of the at least one multi-legged
10 rotary component 120 during transition of the mobile robot 100 between two perpendicular surfaces. For example, the height of the tail appendage component 130 may be optimized to minimize the adhesive requirement and the driving torque requirement. Further details regarding the analysis of the effect of the height of the tail appendage component 130 is provided later with reference to the prototype climbing robot 200 as shown in FIG. 2.

15 [00023] According to various embodiments, the tail appendage component 130 may include a forward facing sloped portion 134. The forward facing sloped portion 134 may slope away from the underside 118 of the chassis 110 in a protrusion direction of the tail appendage component 130. Further, the forward facing sloped portion 134 may slope from the underside 118 of the chassis 110 to the tip 132 of the tail appendage component 130.
20 Accordingly, the forward facing sloped portion 134 may incline or slant towards the tip 132 of the tail appendage component 130. According to various embodiments, the forward facing sloped portion 134 may include a sloped edge or a sloped surface. The sloped edge or the sloped surface may be directed forward of the chassis 110 with respect to the forward movement axis 116 of the chassis 110. Accordingly, the sloped edge or sloped surface may
25 be facing the forward direction corresponding to the forward movement of the chassis 110. According to various embodiments, the forward facing sloped portion 134 may have a concave slope profile. Accordingly, the forward facing sloped portion 134 may have a gentler slope towards the underside 118 of the chassis 110 and a steeper slope towards the tip 132 of the tail appendage component 130. Hence, the concave slope profile of the
30 forward facing sloped portion 134 may be sunken inwards or curved inwards.

[00024] According to various embodiments, the tail appendage component 130 may include a straight portion 136. The straight portion 136 may extend perpendicularly from the underside 118 of the chassis 110 to the tip 132 of the tail appendage component 130. According to various embodiments, the straight portion 136 of the tail appendage

component 130 may extend from a rear end 115 of the chassis 110 to the tip 132 of the tail appendage component 130. Accordingly, the straight portion 136 may form a right angle relative to the underside 118 of the chassis 110 at the rear end 115 of the chassis 110 and the tip 132 of the tail appendage component 130 may be aligned to the rear end 115 of the chassis 110. According to various embodiments, the straight portion 136 may be directed rearward of the chassis 110 with respect to the forward movement axis 116 of the chassis 110. Accordingly, the straight portion 136 may be facing the backward direction with respect to the forward movement axis 116 of the chassis 110.

[00025] According to various embodiments, each of the flexible adhesive flaps 128 of the at least one multi-legged rotary component 120 may include three layers, namely a micro-suction surface layer, a resilient intermediate layer and an elastic backing layer. According to various embodiments, the resilient intermediate layer may be sandwiched between the micro-suction surface layer and the elastic backing layer. According to various embodiments, the micro-suction surface layer may include a plurality of microscopic air pockets across an exposed surface of the micro-suction surface layer. The plurality of microscopic air pockets may create partial vacuum between the exposed surface of the micro-suction surface layer and the target surface for attachment to the target surface. According to various embodiments, the resilient intermediate layer may help the compliant micro-suction surface layer to return to its original flat shape to encourage maximum contact between the micro-suction surface layer and the target surface. According to various embodiments, the elastic backing layer may provide a different elastic behavior creating a gradient in the viscoelastic property which may enhance the adhesive force of the flexible adhesive flap 128. According to various embodiments, the micro-suction surface layer may be a micro-suction tape (e.g. AirStick™ Microsuction tape), the resilient intermediate layer may be a plastic sheet and the elastic backing layer may be an acrylic foam tape (e.g. 3M very high bonding VHB tape).

[00026] According to various embodiments, the flexible adhesive flap 128 may be oriented with respect to the corresponding rigid elongate leg member 124 in a manner such that the micro-suction surface layer is a leading-layer and the elastic backing layer is a trailing-layer with respect to a driven rotation (or rotation in a forward direction) of the at least one multi-legged rotary component 120 for forward movement of the chassis 110. Accordingly, the micro-suction surface layer of the flexible adhesive flap 128 may be rotated to engage with the target surface when the at least one multi-legged rotary component 120 is rotated in a forward direction to move the chassis 110 forward. Hence,

the micro-suction surface layer of the flexible adhesive flap 128 may be the first layer in the direction of the driven rotation of the at least one multi-legged rotary component 120.

[00027] According to various embodiments, a length of the flexible adhesive flap 128 extending from the free-end 125 of the rigid elongate leg member 124 may be equal or less than a direct distance between the free-ends 125 of two adjacent rigid elongate leg members 124. Accordingly, when the flexible adhesive flap 128 of one rigid elongate leg member 124 is fully engaged to a target surface, the flexible adhesive flap 128 may not overlap onto the flexible adhesive flap 128 of the adjacent rigid elongate leg member 124.

[00028] According to various embodiments, the flexible adhesive flap 128 may form an angle between 0° and 180° with respect to the corresponding rigid elongate leg member 124. According to various embodiments, the angle between the flexible adhesive flap 128 and the corresponding rigid elongate leg member 124 may be varied depending on the number of rigid elongate leg members 124 in the at least one multi-legged rotary components 120. According to various embodiments, the angle between the flexible adhesive flap 128 and the corresponding rigid elongate leg member 124 may correspond to an obtuse angle between the corresponding rigid elongate leg member 124 and the target surface when the corresponding rigid elongate leg member 124 first strikes the target surface such that the entire flexible adhesive flap 128 may also contact the target surface simultaneously.

[00029] According to various embodiments, the at least one multi-legged rotary components 120 may include four rigid elongate leg members 124 extending outwards from the hub 122 and equally distributed circumferentially around the hub 122. Accordingly, the four rigid elongate leg members 124 may be distributed 90° apart from the hub 122. According to various embodiments, when there are four rigid elongate leg members 124, the flexible adhesive flap 128 may form an angle of about 135° with respect to the corresponding rigid elongate leg member 124.

[00030] According to various embodiments, the climbing robot 100 may include at least one motor 140 mounted to the chassis 110. According to various embodiments, the at least one multi-legged rotary component 120 may be coupled to the at least one motor 140 so as to be driven by the at least one motor 140. According to various embodiments, the at least one motor 140 may be mounted to the forward portion 112 of the chassis 110. According to various embodiments, the hub 122 of the at least one multi-legged rotary component 120 may be coupled to a driving shaft of the at least one motor 140.

[00031] According to various embodiments, the climbing robot 100 may include a reduction gear arrangement 150 interconnecting the at least one motor 140 and the at least

one multi-legged rotary component 120. Accordingly, the reduction gear arrangement 150 may be connected between the at least one motor 140 and the at least one multi-legged rotary component 120. Hence, a rotation of the driving shaft of the at least one motor 140 may be transferred to the reduction gear arrangement 150 which in turn is transferred to the at least one multi-legged rotary component 120.

[00032] According to various embodiments, the climbing robot 100 may include two coaxial multi-legged rotary components 120 laterally spaced apart at the front portion 112 of the chassis 110. Accordingly, the two multi-legged rotary components 120 may be aligned along the common rotational axis 126 so as to be rotatable about the common rotational axis 126. The two multi-legged rotary components 120 may be at the front portion 112 of the chassis 110 and may be spaced apart along the common rotational axis 126 so as to be on two opposite sides of the chassis 110.

[00033] According to various embodiments, the tail appendage component 130 may be located at a lateral center of the rear portion 114 of the chassis 110. Accordingly, the tail appendage component 130 may be at the center of a transverse direction across the rear portion 114 of the chassis 110 between two opposite sides of the chassis 110.

[00034] According to various embodiments, the climbing robot 100 may include an electronic module 160. According to various embodiments, the electronic module 160 may include, but not limited to, a controller (e.g. a microcontroller), an inertial measurement unit (IMU), a single board computing device (e.g. a Raspberry Pi Zero single board computer), a camera module, and a wireless communication module (e.g. a XBee communication module). According to various embodiments, the electronic module 160 may be configured to control the climbing robot 100. According to various embodiments, the electronic module 160 may be carried on a topside 119 of the chassis 110. Accordingly, the electronic module 160 may be on top of the chassis 110 and the tail appendage component 130 may be under the chassis 110.

[00035] FIG. 2 shows a photograph of a prototype climbing robot 200 according to various embodiments.

[00036] Shown in FIG. 2, according to various embodiments, the architecture of the developed prototype climbing robot 200 may be categorized into three main parts: the multi-legged rotary component 220 (or the whegs), the chassis 210, and the tail appendage component 230 (or the passive vertical tail). The chassis 210 may house the electronic module 260 required for intelligence, surveillance and reconnaissance (ISR) task, and two motors 240 (e.g. DC motors) each driving a multi-legged rotary component 220 (or a whég)

with four flexible adhesive flaps 228 (or “flaps” equipped with compliant adhesive tape). According to various embodiments, there may be a 4:1 gear reduction between the motor 240 and the multi-legged rotary component 220 (or the whegs). The climbing robot 200 may differ from conventional climbing robot in the addition of the tail appendage component 230 (or the passive vertical tail) that helps a lot in accomplishing robust external transitions based on the analysis which will be discussed in more detail later. As an example, the dimensions of the prototype climbing robot 200 are 100 mm x 82 mm x 64 mm and the mass is 137.5 g. According to various embodiments, the flexible adhesive flaps 228 used in the climbing robot 200 may include three layers: a micro-suction surface layer 228a (for example, a 0.8 mm AirStick™ Microsuction tape by Sewell), a resilient intermediate layer 228b (for example, a 0.18 mm plastic sheet), and an elastic backing layer 228c (for example, 3M VHB tape). According to various embodiments, the surface of the micro-suction surface layer 228a may include or may consists of thousands of microscopic air pockets which can create partial vacuums between the surface of the micro-suction surface layer 228a and the target surface. The thinness of the micro-suction surface layer 228a may typically make it susceptible to deformation. However, according to various embodiments, the additional resilient intermediate layer 228b in the form of a flexible plastic sheet may help the compliant micro-suction surface layer to return to its original flat shape to encourage maximum contact between the micro-suction surface layer 228a of the flexible adhesive flaps 228 and the target surface. Further, the elastic backing layer 228c (or the unstructured backing layer of polymer in the form of 3M VHB tape) of different elastic behavior may create a gradient in the viscoelastic property, which may enhance the adhesive force of flexible adhesive flaps 228 according to various embodiments.

[00037] According to various embodiments, the climbing robot 200 may, similar to the climbing robot 100 of FIG. 1, include the chassis 210 having a front portion 212 and a rear portion 214, wherein the front portion 212 and the rear portion 214 may be opposite end portions of the chassis 210 along a forward movement axis of the chassis 210. The climbing robot 200 may, similar to the climbing robot 100 of FIG. 1, include at least one multi-legged rotary component 220. The at least one multi-legged rotary component 220, may similar to the at least one multi-legged rotary component 120 of the climbing robot 100 of FIG. 1, include a hub 222 rotatably coupled to the front portion 212 of the chassis 210 in an orientation with a rotational axis of the hub 222 being transverse to the forward movement axis of the chassis 210. The at least one multi-legged rotary component 220, may similar to the at least one multi-legged rotary component 120 of the climbing robot 100 of FIG. 1,

include a plurality of rigid elongate leg members 224 extending outwards from the hub 222 with respect to the rotational axis. The at least one multi-legged rotary component 220, may similar to the at least one multi-legged rotary component 120 of the climbing robot 100 of FIG. 1, include a plurality of flexible adhesive flaps 228 extending respectively from
5 corresponding free-ends 225 of the plurality of rigid elongate leg members 224. Further, the climbing robot 200 may, similar to the climbing robot 100 of FIG. 1, include a tail appendage component 230 at the rear portion of the chassis 210 and protruding perpendicularly away from an underside 218 of the chassis 210.

[00038] According to various embodiments, the tail appendage component 230 may,
10 similar to the tail appendage component 130 of the climbing robot 100 of FIG. 1, be laterally bounded corresponding to a perimeter of the chassis 210. Further, the tip 232 of the tail appendage component 130 may, similar to that of the tail appendage component 130 of the climbing robot 100 of FIG. 1, be within the perimeter of the chassis 210. According to various embodiments, the tail appendage component 230 may, similar to the tail appendage
15 component 130 of the climbing robot 100 of FIG. 1, be fixed to the chassis 210 in a manner such that the tail appendage component 230 is immovable relative to the chassis 210.

[00039] According to various embodiments, the climbing robot 200 may, similar to the climbing robot 100 of FIG. 1, include that a height of the tail appendage component 230 measured from the underside 218 of the chassis 210 to a tip 232 of the tail appendage
20 component 230 may be determined by optimizing the height of the tail appendage component 230 based on analyzing the effect of the height of the tail appendage component 230 on an adhesive requirement of the flexible adhesive flap 228 and a driving torque requirement of the at least one multi-legged rotary component 220 during transition of the mobile robot 200 between two perpendicular surfaces.

[00040] According to various embodiments, the tail appendage component 230 may,
25 similar to the tail appendage component 130 of the climbing robot 100 of FIG. 1, include a forward facing sloped portion 234 that slopes away from the underside 218 of the chassis 210 in a protrusion direction of the tail appendage component 230 towards the tip 232 of the tail appendage component 230. According to various embodiments, the forward facing
30 sloped portion 234, may similar to that of the tail appendage component 130 of the climbing robot 100 of FIG. 1, include a sloped edge or a sloped surface directed forward with respect to the forward movement axis of the chassis 210. Further, the forward facing sloped portion 234, may similar to that of the tail appendage component 130 of the climbing robot 100 of FIG. 1, include a concave slope profile.

[00041] According to various embodiments, the tail appendage component 230 may, similar to the tail appendage component 130 of the climbing robot 100 of FIG. 1, include a straight portion 236 extending perpendicularly from the underside 218 of the chassis 210 to the tip 232 of the tail appendage component 230. According to various embodiments, the straight portion 236 may, similar to that of the tail appendage component 130 of the climbing robot 100 of FIG. 1, extend from a rear end 215 of the chassis 210 to the tip 232 of the tail appendage component 230. According to various embodiments, the straight portion 236 may, similar to that of the tail appendage component 130 of the climbing robot 100 of FIG. 1, be directed rearward of the chassis 210 with respect to the forward movement axis of the chassis 210.

[00042] According to various embodiments, each flexible adhesive flap 228 may, similar to the flexible adhesive flap 128 of the climbing robot 100 of FIG. 1, include three layers, the micro-suction surface layer 228a, the resilient intermediate layer 228b and the elastic backing layer 228c. Similarly, the resilient intermediate layer 228b may be sandwiched between the micro-suction surface layer 228a and the elastic backing layer 228c. The micro-suction surface layer 228a may be a micro-suction tape, the resilient intermediate layer 228b may be a plastic sheet and the elastic backing layer 228c may be an acrylic foam tape. Further, each flexible adhesive flap 228 may, similar to the flexible adhesive flap 128 of the climbing robot 100 of FIG. 1, be oriented with respect to the corresponding rigid elongate leg member 224 in a manner such that the micro-suction surface layer 228a may be a leading-layer and the elastic backing layer 228c may be a trailing-layer with respect to a driven rotation of the at least one multi-legged rotary component 220.

[00043] According to various embodiments, similar to the flexible adhesive flap 128 of the climbing robot 100 of FIG. 1, a length of the flexible adhesive flap 228 extending from the free-end 225 of the rigid elongate leg member 224 may be equal or less than a direct distance between the free-ends 225 of two adjacent rigid elongate leg members 224. Further, according to various embodiments, similar to the flexible adhesive flap 128 of the climbing robot 100 of FIG. 1, the angle between the flexible adhesive flap 228 and the corresponding rigid elongate leg member 224 may correspond to an obtuse angle between the corresponding rigid elongate leg member 224 and the target surface when the corresponding rigid elongate leg member 224 first strikes the target surface such that the entire flexible adhesive flap 228 may also contact the target surface simultaneously.

[00044] According to various embodiments, as shown, the at least one multi-legged rotary components 220 may include four rigid elongate leg members 224 extending outwards from

the hub 222 and equally distributed circumferentially around the hub 222. Accordingly, the four rigid elongate leg members 224 may be distributed 90° apart from the hub 222. According to various embodiments, when there are four rigid elongate leg members 224, the flexible adhesive flap 228 may form an angle of about 135° with respect to the
5 corresponding rigid elongate leg member 224.

[00045] According to various embodiments, the climbing robot 200 may, similar to the climbing robot 100 of FIG. 1, include at least one motor 240 mounted to the chassis 210, wherein the at least one multi-legged rotary component 220 may be coupled to the at least one motor 240 so as to be driven by the at least one motor 240.

10 **[00046]** According to various embodiments, the climbing robot 200 may, similar to the climbing robot 100 of FIG. 1, include a reduction gear arrangement 250 interconnecting the at least one motor 240 and the at least one multi-legged rotary component 220.

[00047] According to various embodiments, as shown, the climbing robot 200 may include two coaxial multi-legged rotary components 220 laterally spaced apart at the front
15 portion 212 of the chassis 210. Accordingly, the two multi-legged rotary components 220 may be aligned along the common rotational axis so as to be rotatable about the common rotational axis. The two multi-legged rotary components 220 may be at the front portion 212 of the chassis 210 and may be spaced apart along the common rotational axis 226 so as to be on two opposite sides of the chassis 210.

20 **[00048]** According to various embodiments, as shown, the tail appendage component 230 may be located at a lateral center of the rear portion 214 of the chassis 210. Accordingly, the tail appendage component 230 may be at the center of a transverse direction across the rear portion 214 of the chassis 210 between two opposite sides of the chassis 210.

[00049] According to various embodiments, the climbing robot 200 may, similar to the
25 climbing robot 100 of FIG. 1, include an electronic module 260. According to various embodiments, the electronic module 260 may include, but not limited to, a controller (e.g. a microcontroller), an inertial measurement unit (IMU), a single board computing device (e.g. a Raspberry Pi Zero single board computer), a camera module, and a wireless communication module (e.g. a XBee communication module). According to various
30 embodiments, the electronic module 260 may be configured to control the climbing robot 200. According to various embodiments, the electronic module 260 may be carried on a topside of the chassis 210.

[00050] The following provides a robot modeling and force analysis to analyses failure and success conditions for external transitioning of the climbing robot 200 according to

various embodiments. The robot modeling and force analysis may include external transition modeling, external transition analysis, tail appendage component 230 (or vertical tail) analysis, and tail appendage component 230 (or vertical tail) modeling.

[00051] In external transition modeling, the climbing robot 200 may first be modeled as a chain of linkages to obtain its configuration at different possible instances when transiting externally. FIG. 3 shows the mechanism model of the robot 200 during the external transition (-90° convex angle between the first and second surface). The robot's adhesive pivot P can make contact with the second surface at different distance q from the intersecting corner U of the surfaces, with $q \leq r - J_d$, r is the multi-legged rotary component's 220 (or whleg's) radius and J_d is the distance between the rotational axis of the hub 222 and the chassis 210.

[00052] At the initial contact with the second surface, the robot's configuration may be such that the chassis 210 is in contact with the intersecting corner point U and the robot's tail point B_e (or the tip 232 of the tail appendage component) is in contact with the first surface, as depicted in FIG. 3. Hence, the following coordinate transformations relative to the origin frame at point O_e can be obtained:

$$\begin{aligned} \begin{Bmatrix} \mathbf{U} \\ 1 \end{Bmatrix} &= Z(\sigma)X(r)Z(\lambda + 90^\circ)X(J_d)Z(-90^\circ)X(U_d) \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix} \\ &= \begin{Bmatrix} r \cos \sigma + U_d \cos(\sigma + \lambda) - J_d \sin(\sigma + \lambda) \\ r \sin \sigma + U_d \sin(\sigma + \lambda) + J_d \cos(\sigma + \lambda) \\ 1 \end{Bmatrix} \equiv \begin{Bmatrix} q \\ e \\ 1 \end{Bmatrix} \end{aligned} \quad (1)$$

$$\begin{aligned} \begin{Bmatrix} \mathbf{B}_e \\ 1 \end{Bmatrix} &= \begin{Bmatrix} r \cos \sigma + L_e \cos(\sigma + \lambda) - (J_d + H) \sin(\sigma + \lambda) \\ r \sin \sigma + L_e \sin(\sigma + \lambda) + (J_d + H) \cos(\sigma + \lambda) \\ 1 \end{Bmatrix} \\ &\equiv \begin{Bmatrix} q \\ |\mathbf{B}_e - \mathbf{U}| \\ 1 \end{Bmatrix} \end{aligned} \quad (2)$$

where $Z(a)$ is a rotation of angle a about the Z-axis, $X(l)$ is a translation of distance l along the X-axis, σ is the angle between the flexible adhesive flap 228 and the corresponding rigid elongate leg member 224 (or whleg spoke), λ is the angle between the corresponding rigid elongate leg member 224 and the robot's chassis 210, U_d is the distance between the rotational axis of the hub 222 (or whleg's shaft) and the corner U along the robot's chassis

210, e is the flexible adhesive flap's 228 thickness, and H is the height of the tail appendage component 230 (or the vertical tail).

[00053] Solving Eq. (1) and (2) gives the values of σ , λ and U_d for different q values, which gives the robot configuration as it contacts the second surface at variable distances from the intersecting corner U. These robot configurations may be useful for analyzing extensively the robot equilibrium at different instances that the robot 200 contacts the second surface, as will be discussed in the following.

[00054] In external transition analysis, the free body diagram of the climbing robot 200, as shown in FIG. 4(a), is used to analyze the success and failure conditions for robust external transitioning. The forces acting on the robot 200 are the weight component of the robot (W) acting at the robot's center of gravity (CG), an equivalent normal force (F_{Rne}), shear force (F_{Rye}) and moment (M_{Re}) acting on the adhesive pivot P , and a normal reaction force (F_u) acting on the intersection between the robot's chassis 210 and the corner U in the direction perpendicular to the chassis 210.

[00055] The system of equations for equilibrium during external transitioning is then obtained as

$$\sum F_x = 0 = F_U \sin \beta - W \sin \theta + F_{Rne} \quad (3)$$

$$\sum F_y = 0 = F_U \cos \beta - W \cos \theta - F_{Rye} \quad (4)$$

$$\sum M_P = 0 = F_U L_{yue} \sin \beta - W L_{ycge} \sin \theta - W L_{xcge} \cos \theta - M_{Re} \quad (5)$$

where θ is the slope angle of the first surface, $\beta = 270^\circ - \sigma - \lambda$ is the acute angle between the direction of F_u and the second surface, L_{xcge} is the distance between the robot's CG and the second surface, and L_{ycge} and $L_{yue} = q$ are the distances of the pivot P from the CG and the first surface respectively.

[00056] There are two distinct cases of the force analysis: (I) when $F_u > 0$ and the chassis 210 is in contact with the surface, and (II) when $F_u \leq 0$ and the chassis 210 loses contact with the surface. Case II can happen, e.g., when the robot 200 transits from a vertically-down to a horizontally-inverted orientation ($\theta = 270^\circ$). In case I, the reaction force on the chassis 210 provides the moment to counteract the weight component and there is no moment required on the flexible adhesive flap 228 ($M_{Re} = 0$). In case II, F_u needs to be set to zero as the chassis 210 loses contact with the surface and the flexible adhesive flap 228 needs to provide the moment to counteract the weight component. In summary

Case I Chassis is in contact with the surface ($F_u > 0$)

$$\begin{aligned}
 F_U &= \frac{W}{q \sin \beta} (L_{ycge} \sin \theta + L_{xcge} \cos \theta) \\
 M_{Re} &= 0
 \end{aligned} \tag{6}$$

Case II Chassis loses contact with the surface ($F_u = 0$)

$$\begin{aligned}
 F_U &= 0 \\
 M_{Re} &= -W(L_{ycge} \sin \theta + L_{xcge} \cos \theta)
 \end{aligned} \tag{7}$$

[00057] The forces acting on the flexible adhesive flap 228 can then be obtained as

$$F_{Rne} = W \sin \theta - F_U \sin \beta \tag{8}$$

5

$$F_{Rye} = F_U \cos \beta - W \cos \theta \tag{9}$$

[00058] The motor torque requirement can be obtained by decoupling the free body diagram into the multi-legged rotary component 220 (or whleg) and the chassis 210. Then from the equilibrium equations, the motor torque requirement can be obtained as

$$T_{Se} = M_{Re} + F_{Rne} L_{yse} + F_{Rye} L_{xse} \tag{10}$$

10 where L_{yse} and L_{xse} are the perpendicular distances of the rotational axis of the hub 222 from the first and second surface respectively.

[00059] In tail appendage component 230 (or vertical tail) analysis, the theoretical ground behind the tail appendage component 230 for accomplishing external transitions with only two multi-legged rotary component 220 (or whlegs) can be derived from the force analysis
15 discussed above.

[00060] Consider the robot 201 without the tail appendage component 230 (or vertical tail), i.e. $H = 0$ and $\beta = 0$, as shown in FIG. 4(b). This particular robot configuration actually creates another distinct case of the force analysis where the forces acting on the robot 200 is given by

20 **Case III** Tail appendage component 230 (or vertical tail component) is absent ($\beta = 0$)

$$\begin{aligned}
 F_U &= \infty \\
 M_{Re} &= -W(L_{ycge} \sin \theta + L_{xcge} \cos \theta) \\
 F_{Rne} &= W \sin \theta \\
 F_{Rye} &= F_U - W \cos \theta
 \end{aligned} \tag{11}$$

[00061] From Eq. (10), the motor torque requirement for case III can then be obtained as

$$T_{Se} = F_U L_{xse} - W [\sin \theta (L_{ycge} - L_{yse}) + \cos \theta (L_{xcge} + L_{xse})] \tag{12}$$

[00062] As can be seen from these derived equations, the reaction force on the chassis 210
25 F_u is infinity for this particular case when the robot does not have the tail appendage component 230 (or vertical tail component). This robot configuration is bound to fail

because of either slip due to the high shear force on the flexible adhesive flap 228 or motor 240 stall due to the high torque requirement, as there is F_u component in these two requirements. This occurrence is observed and verified in the experiments, where the robot without tail appendage component 230 (or vertical tail component) is unable to perform the external transitions due to either slip or motor stall. Adding the simple tail appendage component 230 (or vertical tail component) in the various embodiments results in $\beta > 0$, which breaks the robot from the case III failure and hence the success of the external transitions now depends on the fulfilment of the adhesive requirement of the flexible adhesive flap 228 and motor torque requirement.

5 [00063] Based on this analysis, the tail appendage component 230 (or vertical tail component) is found to enable the climbing robot 200 to be able to perform external transitions. By changing the value of H in Eq. (2), the effect of the height of the tail appendage component 230 (or vertical tail component) on the adhesive requirement of the flexible adhesive flap 228 and motor torque requirement can also be analyzed.

15 [00064] In tail appendage component 230 (or vertical tail) modeling, to complete the climbing robot analysis, the additional tail appendage component 230 (or vertical tail component) needs to be incorporated into the flat-surface-climbing analysis. FIG. 5(a) shows the slider-crank model of the climbing robot 201 without tail appendage component 230 (or vertical tail component) and FIG. 5(b) shows the slider-crank model of the climbing robot 200 with tail appendage component 230 (or vertical tail component). As shown in FIG. 5(b), as the tail appendage component 230 (or vertical tail component) is added, the robot 200 will have a new $L_v(H)$ and $\alpha_v(H)$ values to replace the L and α values in the original analysis for the robot in FIG. 5(a).

25 [00065] To incorporate the additional component easily into the original analysis, the tail appendage component 230 (or vertical tail component) is modeled as a separate mechanism as shown in FIG. 5(c). From the model, the following coordinate transformations relative to the origin frame at point O can be obtained:

$$\begin{aligned} \begin{Bmatrix} \mathbf{B}_v \\ 1 \end{Bmatrix} &= Z(\eta)X(L)Z(180^\circ - \mu)X(H) \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix} \\ &= \begin{Bmatrix} L \cos \eta - H \cos(\eta - \mu) \\ L \sin \eta - H \sin(\eta - \mu) \\ 1 \end{Bmatrix} \equiv \begin{Bmatrix} k \\ L_{ys} \\ 1 \end{Bmatrix} \quad (13) \end{aligned}$$

[00066] where $L_{ys} = \frac{r}{\sqrt{2}} - e$. Solving Eq. (13) gives the value of η for different H values, and the new L and α values for variable H values can be obtained as

$$L_v(H) = |\mathbf{B}_v| \quad (14)$$

$$\alpha_v(H) = \sin^{-1} \frac{H \sin \mu}{L_v(H)} + \alpha \quad (15)$$

[00067] Using these variable L_v and α_v values, the effect of the height of the tail appendage component 230 (or vertical tail component) on the adhesive requirement of the flexible adhesive flap 228 and motor torque requirement for flat surface climbing can be easily incorporated and studied.

[00068] In the following, the theoretical results in terms of the robot requirements and its expected performance based on the above analysis are presented and discussed. Results of experiments conducted to verify the theoretical prediction are also presented.

[00069] In order to obtain the robot requirements and its expected performance for robust external transitioning, the analytical results are generated for all four cases of external transitions: vertical up to horizontal ($VU \rightarrow H, \theta = 90^\circ$), horizontal to vertical down ($H \rightarrow VD, \theta = 0^\circ$), vertical down to horizontal inverted ($VD \rightarrow HI, \theta = 270^\circ$), and horizontal inverted to vertical up ($HI \rightarrow VU, \theta = 180^\circ$), as depicted in FIG. 6(a). As the flexible adhesive flap 228 generally have high shear adhesion strength, the results discussed will be in terms of the adhesive moment, normal adhesive force, and motor torque requirement, as plotted in FIG. 6(b), FIG. 6(c), and FIG. 6(d) respectively, for the different instances of approach distance q and the four different external transitions. As representatives and for clarity reason, only the plots for two different H values are generated: $H = 0$ mm, i.e. robot without tail appendage component 230 (or vertical tail component), and $H = L_{ys} = 19.8$ mm. Nevertheless, the results discussed here are generally applicable to any height H values for the tail appendage component 230 (or vertical tail component), with difference only in the requirement values. For FIG. 6(c) and FIG. 6(d), only the results for the robot with the tail appendage component 230 (or vertical tail component) can be seen as the robot without the tail appendage component 230 (or vertical tail component) gives infinite values for the normal adhesive force and motor torque.

[00070] Inferred from FIG. 6(b), for a robot with a tail appendage component 230 (or vertical tail component) having a height of 19.8 mm, the flexible adhesive flap 228 must be able to withstand a minimum moment of 35 mNm for complete robust external transitions at any instances of distance q . Interestingly, when looking at the results for the normal

adhesive force (FIG. 6(c)) and required motor torque (FIG. 6(d)), as they can demand as high as 20 N force and 200 mNm torque respectively for the HI $\rightarrow$ VU transition at the instances of small q values, i.e. the robot's multi-legged rotary component 220 (or whleg) contacts the second surface very near to the intersecting corner. This is because, as can be inferred from Eq. (6), F_u is inversely proportional to q , which then directly affects F_{Rne} (Eq. (8)) and T_{Se} (Eq. (10)). This effect is not prevalent for the H $\rightarrow$ VD and VD $\rightarrow$ HI transitions because they fall into case II where the chassis 210 loses contact with the surface and $F_u = 0$. It also does not affect VU $\rightarrow$ H transition much because of the fact that at $\theta = 90^\circ$, the robot dimension that affects F_u is L_{ycge} and it decreases as q decreases, which dampens the effect of small q . For the case of HI $\rightarrow$ VU, the robot dimension that affect F_u is L_{xcge} , which increases as q decreases and thus further magnifies F_u at small q .

[00071] Based on the analytical results, the climbing robot 200 with the tail appendage component 230 (or vertical tail component) is thus expected to have no difficulties performing VU $\rightarrow$ H, H $\rightarrow$ VD, and VD $\rightarrow$ HI transitions as long as the normal adhesive force, adhesive moment, and motor torque are above 2 N, 35 mNm, and 10 mNm respectively. Further, it will also be able to perform HI $\rightarrow$ VU transition when the multi-legged rotary component 220 (or whleg) approach distance from the intersecting corner is adequate to meet the high normal adhesive force and motor torque requirements. The following results from experiments on the physical prototype climbing robot 200 verified this performance prediction based on the theoretical analysis.

[00072] In the experiment, to maximize the possibility of HI $\rightarrow$ VU success, the maximum possible torque of 15 mNm provided by the motor were used for the experimental tests. At this torque value, it was empirically found that the maximum adhesive dimension that the torque is able to peel off is 45 mm x 15 mm, which were used for the experimental tests. Based on the tail appendage component 230 (or vertical tail) modeling above and the adhesive characterization of the tri-layer flexible adhesive flap 228, it was estimated that this dimension provides a normal adhesive force and adhesive moment of 3 N and 40 mNm respectively. With these specifications for the climbing robot 200, it is expected that with tail appendage component 230 (or vertical tail component) having a height of 19.8 mm is able to robustly perform VU $\rightarrow$ H, H $\rightarrow$ VD, and VD $\rightarrow$ HI transitions as well as to perform HI $\rightarrow$ VU when approach distance is adequate.

[00073] As predicted by the analysis, FIG. 7(a) to FIG. 7(d) show the photo snapshots of the prototype climbing robot 200 with the tail appendage component 230 (or vertical tail

component) performing the 4-way external transitions. In the experimental tests, the climbing robot 200 can perform $VU \rightarrow H$ (FIG. 7(a)) and $H \rightarrow VD$ (FIG. 7(b)) transitions robustly independent of the distance of the initial contact of the multi-legged rotary component 220 (or the wheg) with the second surface from the intersecting corner. For the

5 $HI \rightarrow VU$ (FIG. 7(d)), the climbing robot 200 is also able to complete the transition when the multi-legged rotary component 220 (or the wheg) approaches the second surface at a sufficient distance from the intersection corner, as also predicted by the analysis. For the $VD \rightarrow HI$ (FIG. 7(c)), the climbing robot 200 is also able to complete the transition when the last multi-legged rotary component 220 (or the wheg) is at a position of a sufficient

10 distance from the intersecting corner such that adequate adhesive area is in contact with the first surface to support the climbing robot 200 before the next multi-legged rotary component 220 (or the wheg) contacts the second surface. Further, as demonstrated in FIG. 7(e) to FIG. 7(h), the climbing robot 200 is also able to perform 4-way internal transitions.

[00074] According to various embodiments, the climbing robot may be scaled and

15 dimensioned to various size and configuration, and the climbing robot would be able to perform all the climbing and transitioning when the adhesive and motor are provided or configured to meet the requirements obtained from the above analysis. According to various embodiments, the dimension of the climbing robot may be optimized based on the analysis results obtained so as to minimize the adhesive and the motor torque requirements to achieve

20 a robust climbing robot.

[00075] Various embodiments have provided a climbing robot capable of climbing any slope angles, 4-way internal transitions, and 4-way external transitions. Various embodiments have provided a climbing robot with a configuration having two multi-legged rotary components (or two whegs) that is capable of climbing any slope angles, 4-way

25 internal transitions, and 4-way external transitions, which has not been able to be achieved in the past and was thought to be impossible. Various embodiments have provided a climbing robot including a passive tail appendage component (or vertical tail) which enables achieving external transitions with the climbing robot having a two multi-legged rotary components (or two whegs).

30 [00076] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes, modification, variation in form and detail may be made therein without departing from the scope of the invention as defined by the appended claims. The scope of the

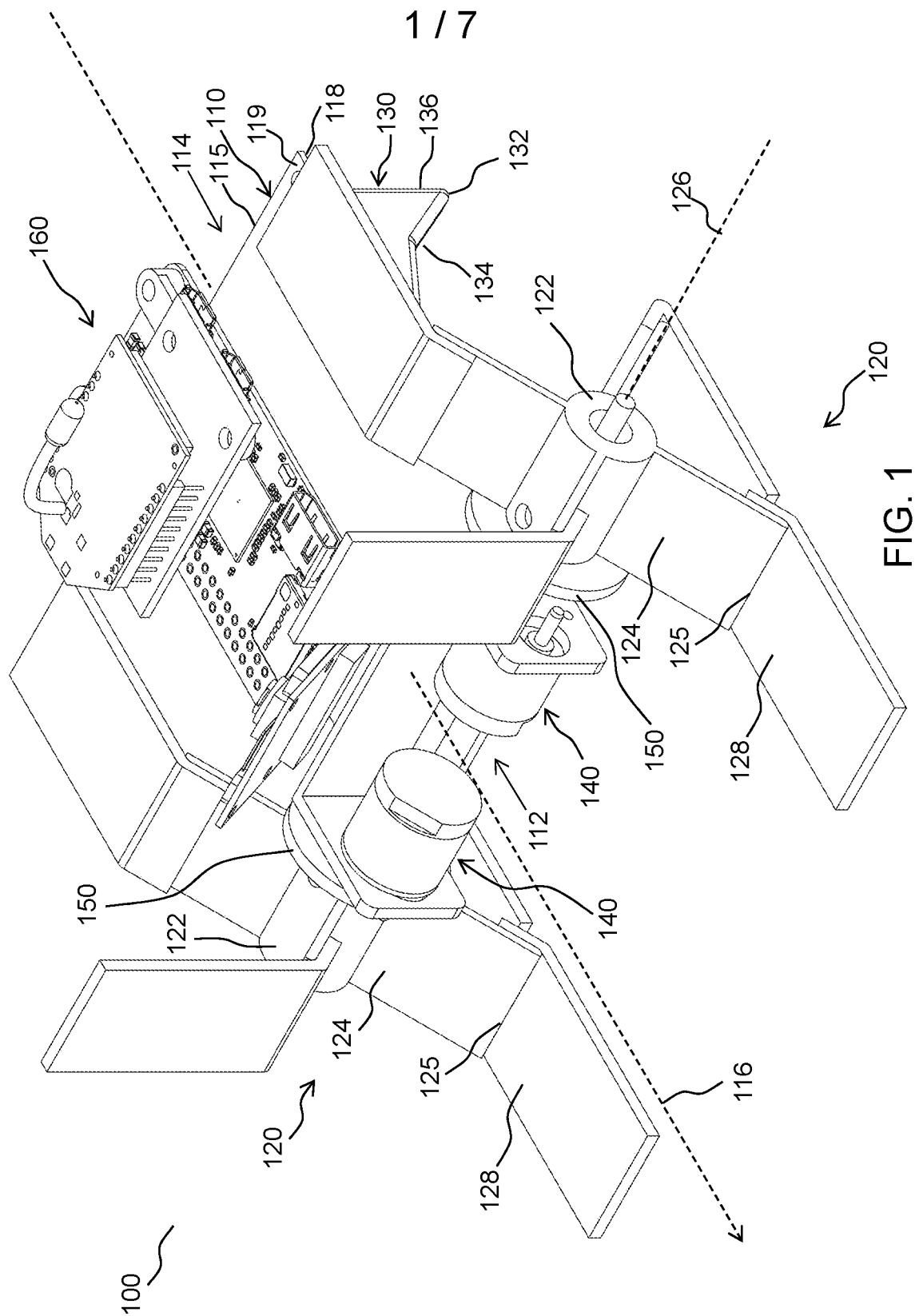
invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

Claims

1. A climbing robot comprising
a chassis having a front portion and a rear portion, wherein the front portion and the rear portion are opposite end portions of the chassis along a forward movement axis of the chassis;
at least one multi-legged rotary component comprising
a hub rotatably coupled to the front portion of the chassis in an orientation with a rotational axis of the hub being transverse to the forward movement axis of the chassis;
a plurality of rigid elongate leg members extending outwards from the hub with respect to the rotational axis, and
a plurality of flexible adhesive flaps extending respectively from corresponding free-ends of the plurality of rigid elongate leg members; and
a tail appendage component at the rear portion of the chassis and protruding perpendicularly away from an underside of the chassis.
2. The robot as claimed in claim 1, wherein a height of the tail appendage component measured from the underside of the chassis to a tip of the tail appendage component is determined by optimizing the height of the tail appendage component based on analyzing the effect of the height of the tail appendage component on an adhesive requirement of the flexible adhesive flap and a driving torque requirement of the at least one multi-legged rotary component during transition of the mobile robot between two perpendicular surfaces.
3. The robot as claimed in claim 1 or 2, wherein the tail appendage component is laterally bounded corresponding to a perimeter of the chassis.
4. The robot as claimed in any one of claims 1 to 3, wherein each flexible adhesive flap comprises three layers, a micro-suction surface layer, a resilient intermediate layer and an elastic backing layer.

5. The robot as claimed in claim 4, wherein the resilient intermediate layer is sandwiched between the micro-suction surface layer and the elastic backing layer.
6. The robot as claimed in claim 4 or 5, wherein the micro-suction surface layer is a leading-layer and the elastic backing layer is a trailing-layer with respect to a driven rotation of the at least one multi-legged rotary component.
7. The robot as claimed in any one of claims 4 to 6, wherein the micro-suction surface layer is a micro-suction tape, the resilient intermediate layer is a plastic sheet and the elastic backing layer is an acrylic foam tape.
8. The robot as claimed in any one of claims 1 to 7, wherein the tail appendage component comprises a forward facing sloped portion that slopes away from the underside of the chassis in a protrusion direction of the tail appendage component.
9. The robot as claimed in claim 8, wherein the forward facing sloped portion has a concave slope profile.
10. The robot as claimed in claim 8 or 9, wherein the forward facing sloped portion comprises a sloped edge or a sloped surface directed forward with respect to the forward movement axis of the chassis.
11. The robot as claimed in any one of claims 1 to 10, wherein the at least one multi-legged rotary components comprises four rigid elongate leg members extending outwards from the hub and equally distributed circumferentially around the hub.
12. The robot as claimed in any one of claims 1 to 11, wherein each flexible adhesive flap forms an angle between 0° and 180° with respect to each corresponding rigid elongate leg member.
13. The robot as claimed in any one of claims 1 to 12, further comprising at least one motor mounted to the chassis, wherein the at least one multi-legged rotary component is coupled to the at least one motor so as to be driven by the at least one motor.

14. The robot as claimed in claim 13, further comprising a reduction gear arrangement interconnecting the at least one motor and the at least one multi-legged rotary component.
15. The robot as claimed in any one of claims 1 to 14, comprising two coaxial multi-legged rotary components laterally spaced apart at the front portion of the chassis.
16. The robot as claimed in claim 15, wherein the tail appendage component is located at a lateral center of the rear portion of underside of the chassis.
17. The robot as claimed in any one of claims 1 to 16, wherein an electronic module is carried on a topside of the chassis.



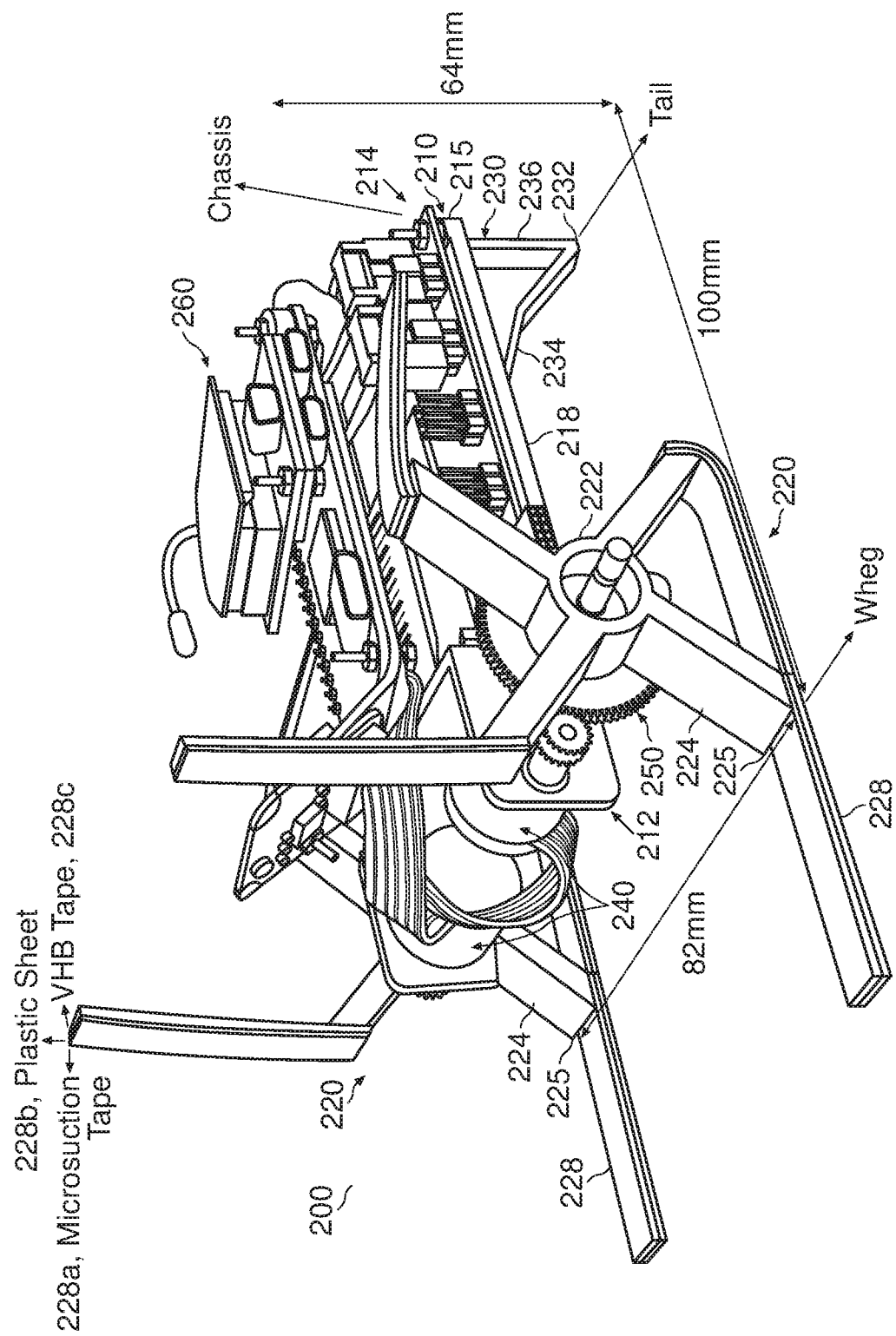


FIG. 2

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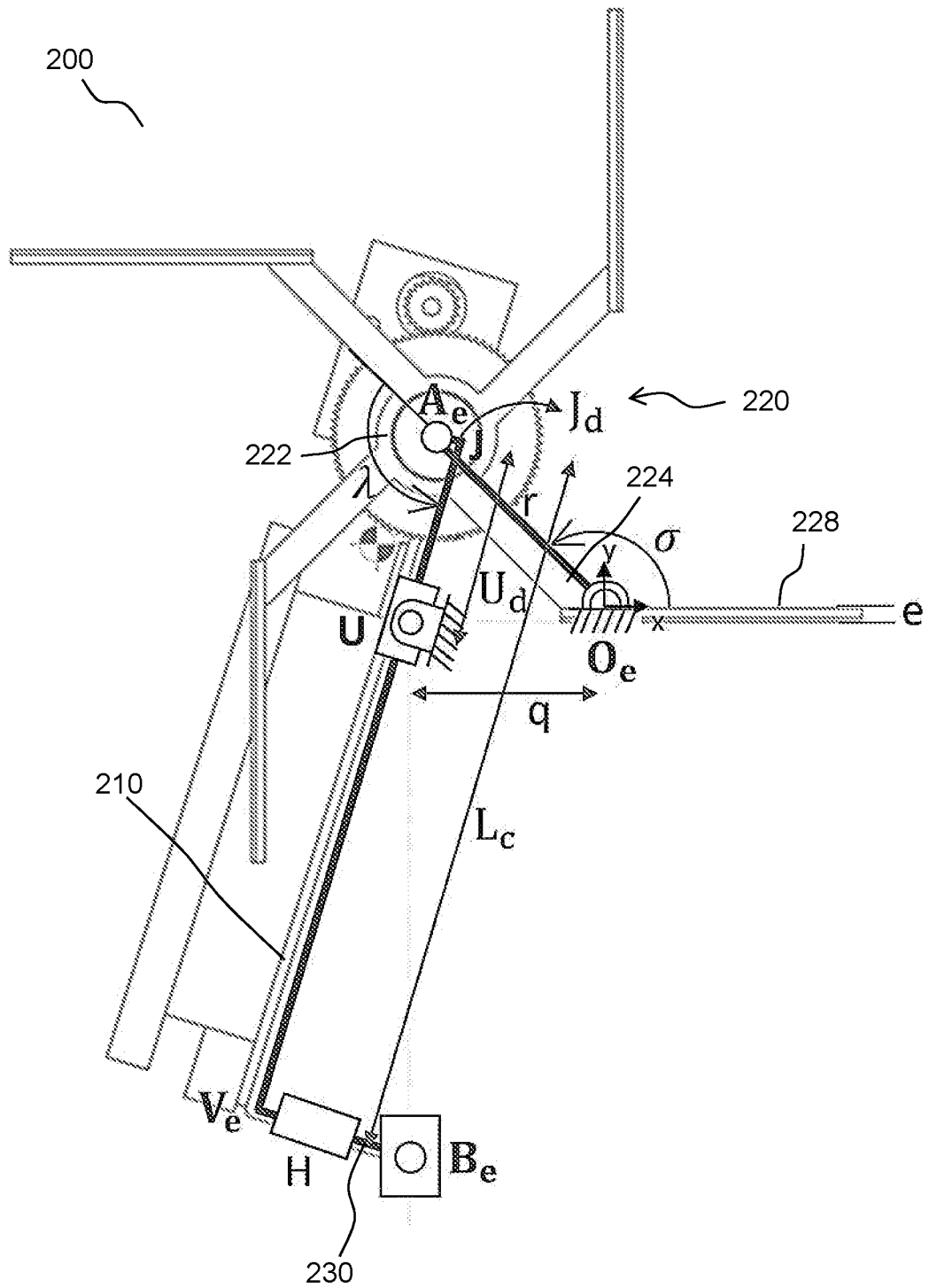


FIG. 3

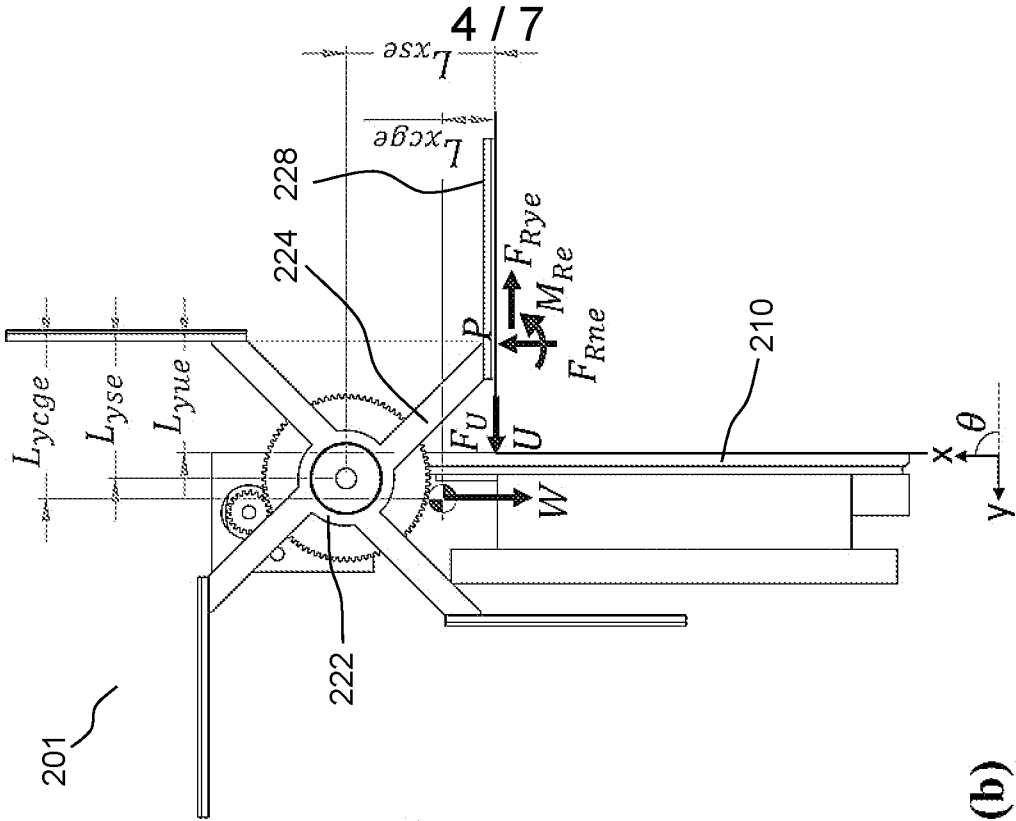


FIG. 4(b)

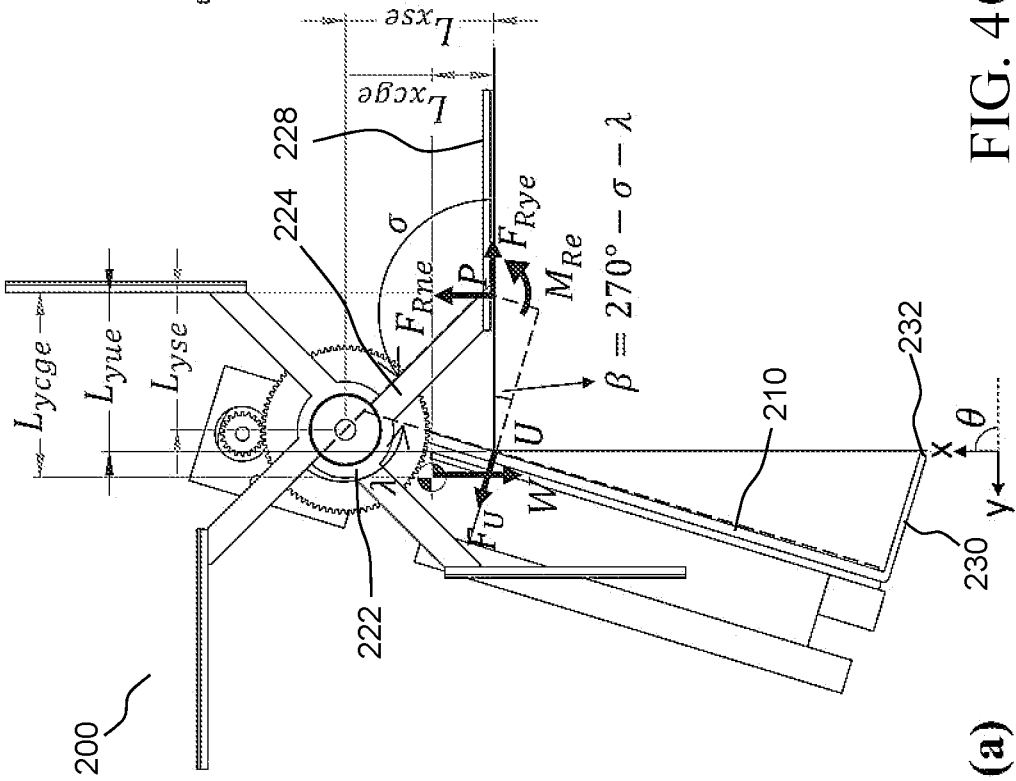


FIG. 4(a)

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FIG. 5(a)

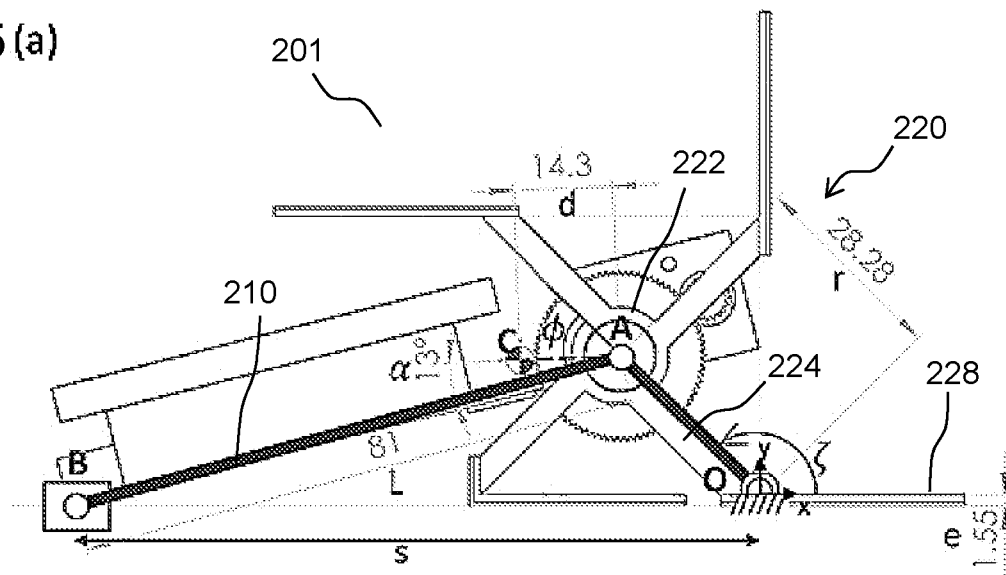


FIG. 5(b)

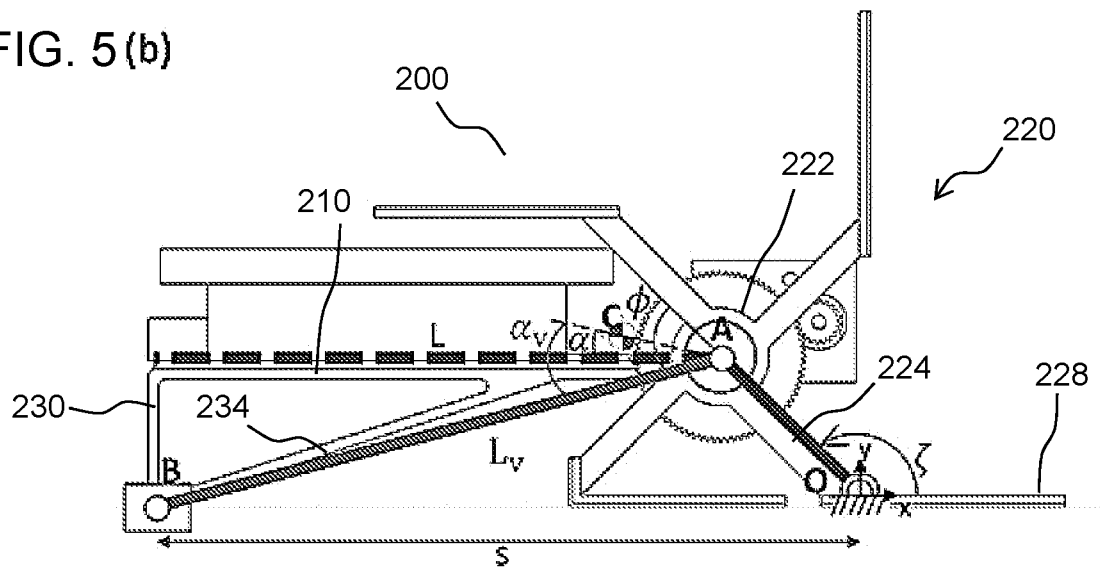
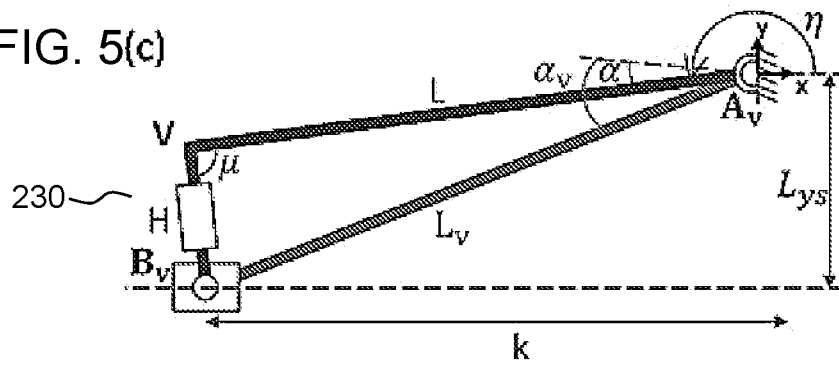


FIG. 5(c)



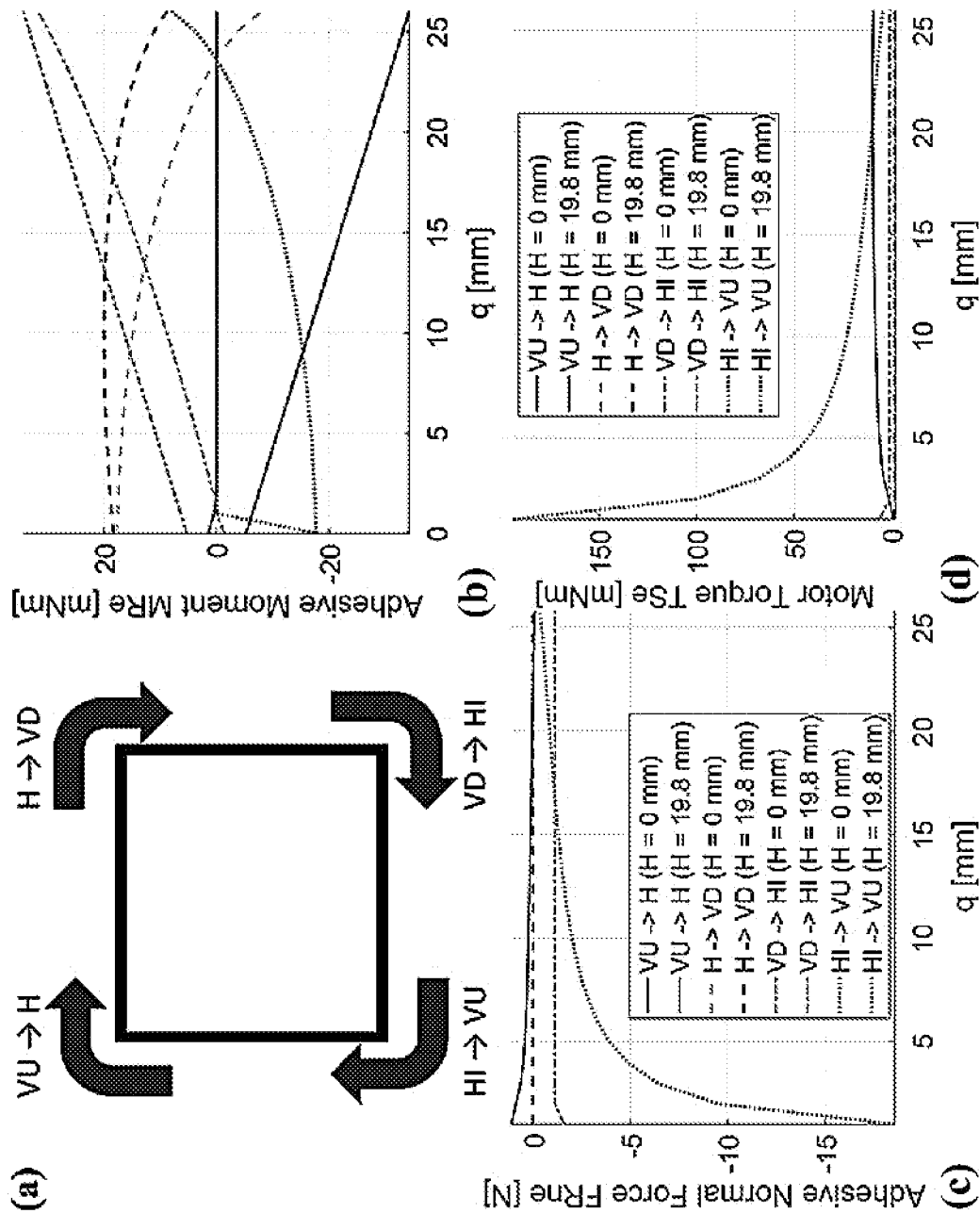


FIG. 6

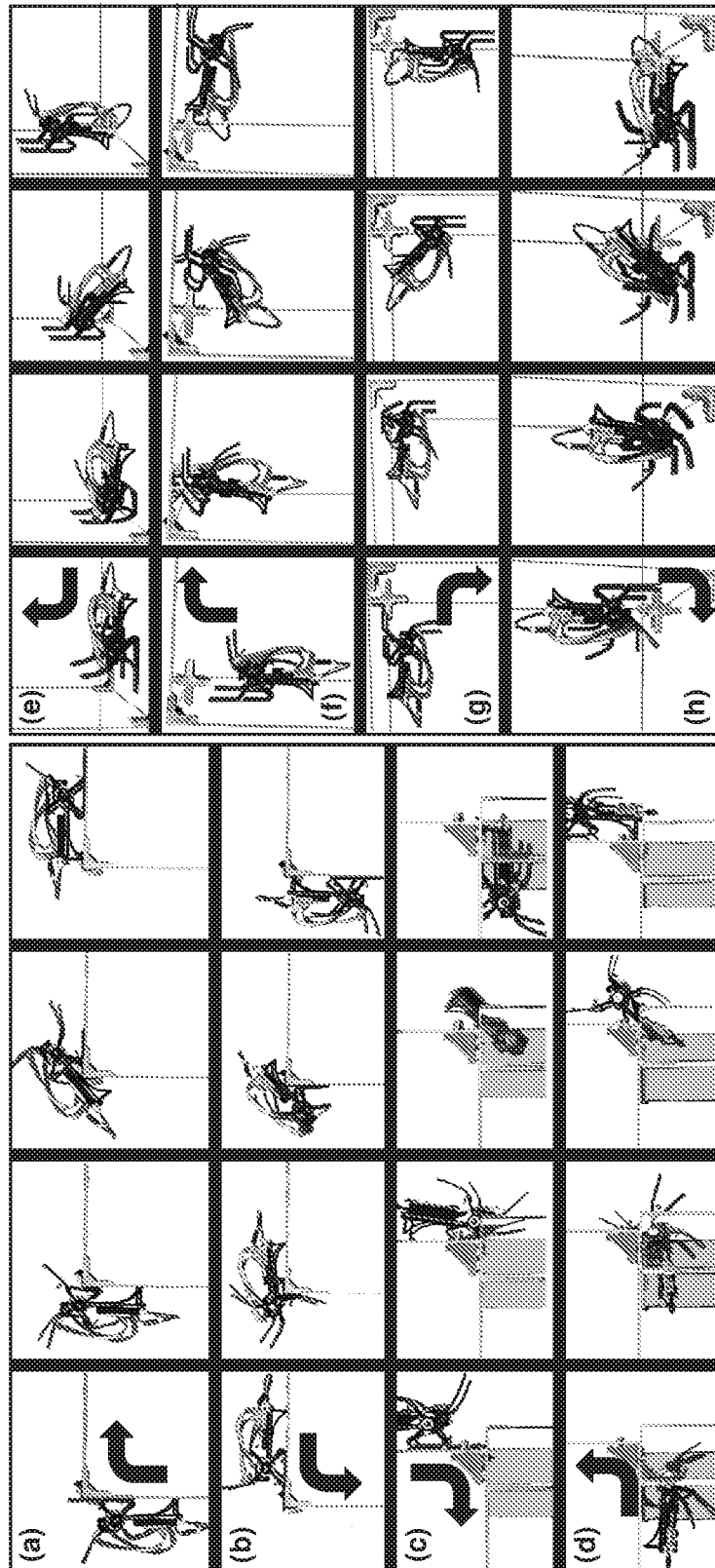


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2020/050242

A. CLASSIFICATION OF SUBJECT MATTER

B62D 57/02 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B62D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Database: FAMPAT

Keywords: Climbing, ceiling, wall, wheg, appendage, leg, adhesive, suction, tail, transition, 爬, 爬, 爬, 吸, 尾, 过渡 and related terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 1035231 09 A (UNIVERSITY OF TIANJIN) 22 January 2014	1, 3-17
Y	Para[0002], [0029], [0034] and Fig. 1-2 of the machine translation	2
Y	US 2014/0203623 A1 (PARNESS A. ET AL.) 24 July 2014 Para[0003], [0140] and Fig. 16	2
A	CN 109018051 A (UNIVERSITY OF NANJING AERONAUTICS & ASTRONAUTICS) 18 December 2018 Whole document of the machine translation	

EI Further documents are listed in the continuation of Box C.

E See patent family annex.

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2020/050242**C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 1071 6 1232 A (SONG TIANYU) 15 September 2017 Whole document of the machine translation	
A	DALTORIO K. A. ET AL., Passive Foot Design and Contact Area Analysis for Climbing Mini-Whegs. <i>Proceedings 2007 IEEE International Conference on Robotics and Automation</i> , 21 May 2007, pages 1274-1 279 [Retrieved on 2020-09-08] <DOI: 10.1109/ROBOT.2007.3631 60> Whole document	

INTERNATIONAL SEARCH REPORT

Information on patent family members

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Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 1035231 09 A	22/01/201 4	NONE	
US 201 4/0203623 A 1	24/07/201 4	NONE	
CN 10901 8051 A	18/12/201 8	NONE	
CN 1071 6 1232 A	15/09/201 7	NONE	