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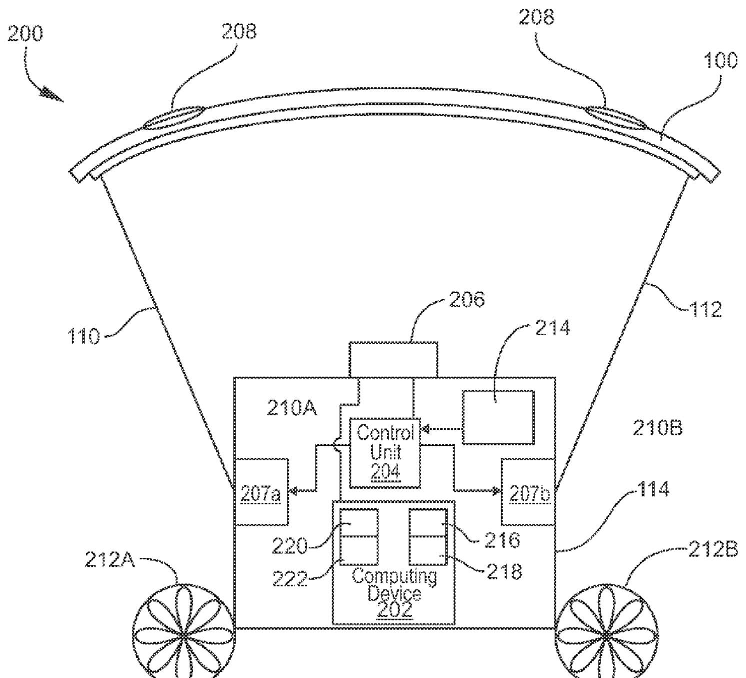

FIG. 2

(57) **Abstract**: Disclosed herein are systems and methods for using computer vision for parafoil flight control. According to an aspect, a method includes capturing an image of a parafoil including multiple indicator points distributed thereon. The method further includes determining positioning of the indicator points based on the captured image. The method further includes determining a condition of the parafoil based on the positioning of the indicator points. The method further includes controlling flight inputs based on the condition of the parafoil.

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SYSTEMS AND METHODS FOR USING COMPUTER VISION FOR PARAFOIL FLIGHT CONTROL

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application No. 61/836,236, filed on June 18, 2013 and titled PARAFOIL FLIGHT CONTROL IMPROVEMENT USING COMPUTER VISION, the content of which is hereby incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present subject matter relates to parafoil flight control, and more specifically, to systems and methods for using computer vision for parafoil flight control.

BACKGROUND

[0003] The parafoil is a wing shaped parachute capable of steerable, controlled descent. Essentially, the parachute aspect of the parafoil causes the parafoil to exhibit a gradual descent, while the wing aspect of the parafoil permits the parafoil to have a guided flight path. The flight path of the parafoil can be controlled by tugging and/or releasing lines coupled to the left trailing edge and right trailing edge of the parafoil. Specifically, the parafoil can be made to turn to the left if the left trailing edge line is tugged or pulled. Similarly, the parafoil can be made to turn to the right if the right trailing edge line is tugged or pulled. The parafoil can even be made to momentarily rise, or at least change its pitch upward if both the left and right trailing edge lines are tugged or pulled.

[0004] Because of the ability to control the flight path of the parafoil, parafoils have been used for guided drops of a payload. In order to successfully land the parafoil at or near some target, however, an individual or a guided electronic flight control system is needed to control the trailing edge lines so as to guide the parafoil with the requisite accuracy. Controlling the trailing edge lines is performed on the parafoil based on the location of the target, the altitude of the parafoil, the forward and transverse speeds of the parafoil, the roll, roll rate, yaw, yaw rate, pitch and pitch rate of the parafoil and the presence of winds. This is a complex task which can result in a complex system with frequent system and parafoil failures.

[0005] Previous flight control systems have been used to control the parafoil. Control of the parafoil is based on sensor data from multiple sensors on the payload (gondola) and may also be supplemented by sensor data from the parafoil as well. Previous flight control systems have used numerous small, wireless accelerometers installed on the parafoil or the payload to acquire this data. These approaches tend to require complex systems that have a high failure rate, causing difficulties in operation. In addition, the present technologies are both expensive in terms of equipment cost and payload damage upon system failure that may include mid-flight parafoil collapse.

[0006] For at least the foregoing reasons, there is a need for improved systems and methods for parafoil flight control.

SUMMARY

[0007] Disclosed herein are systems and methods for using computer vision for parafoil flight control. According to an aspect, a method comprising capturing an image of a parafoil. The method further includes determining positioning of multiple indicator points on the parafoil based on the captured image. The method further includes determining a condition of the parafoil based on the positioning of the indicator points. The method further includes controlling flight inputs based on the condition of the parafoil.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The foregoing summary, as well as the following detailed description of various embodiments, is better understood when read in conjunction with the appended drawings. For the purposes of illustration, there is shown in the drawings exemplary embodiments; however, the presently disclosed subject matter is not limited to the specific methods and instrumentalities disclosed. In the drawings:

[0009] FIG. 1A is a perspective view of an example parafoil in flight;

[0010] FIG. 1B is a perspective view of the parafoil of FIG. 1A in a left turn during flight;

[0011] FIG. 1C is a perspective view of the parafoil of FIG. 1A in a right turn during flight;

[0012] FIG. 1D is a cross-sectional view of an example parafoil and payload system using an eight (8) degree-of-freedom (DOF) model;

[0013] FIG. 1E is a rear view of an example parafoil and payload system using differential pitch and differential yaw of the parafoil in an eight (8) DOF model;

[0014] FIG. 2 illustrates a schematic diagram of an example flight control system for controlling the flight of a parafoil and payload according to embodiments of the present subject matter;

[0015] FIG. 3 is a flowchart of an example method of controlling the flight of a parafoil and payload using a flight control system according to embodiments of the present subject matter;

[0016] FIG. 4 is a flowchart of an example method of controlling the flight of the parafoil and payload using a flight control system in accordance with embodiments of the present subject matter;

[0017] FIG. 5A is a front view of an example flight control system in accordance with embodiments of the present subject matter;

[0018] FIG. 5B is a side view of the system shown in FIG. 5A;

[0019] FIG. 6A is a perspective view showing an example of a flight control system determining differential yaw in accordance with embodiments of the present subject matter ;

[0020] FIG. 6B is a perspective showing an example of the flight control system determining differential pitch; and

[0021] FIG. 6C is a perspective view showing an example of the flight control system determining parafoil deformation.

DETAILED DESCRIPTION

[0022] The presently disclosed subject matter is described with specificity to meet statutory requirements. However, the description itself is not intended to limit the scope of this patent. Rather, the inventors have contemplated that the claimed subject matter might also be embodied in other ways, to include different steps or elements similar to the ones described in this document, in conjunction with other present or future technologies. Moreover, although the term “step” may be used herein to connote different aspects of methods employed, the term should not be interpreted as implying any particular order among or between various steps herein disclosed unless and except when the order of individual steps is explicitly described.

[0023] As referred to herein, the term “computing device” should be broadly construed. It can include any type of device including hardware, software, firmware, the like, and combinations thereof. A computing device may include one or more processors and memory or other suitable non-transitory, computer readable storage medium having computer readable program code for implementing methods in accordance with embodiments of the present subject matter. A computing device may be, for example, a processing circuit for the detection of a change in voltage level or change in measured capacitance across a circuit. In another example, a computing device may be a server or other computer located within a commercial, residential or outdoor environment and communicatively connected to other computing devices for using computer vision for parafoil flight control. In another example, a computing device may be a mobile computing device such as, for example, but not limited to, a smart phone, a cell phone, a pager, a personal digital assistant (PDA), a mobile computer with a smart phone client, or the like. In another example, a computing device may be any type of wearable computer, such as a computer with a head-mounted display (HMD). A computing device can also include any type of conventional computer, for example, a laptop computer or a tablet computer. A typical mobile computing device is a wireless data access-enabled device (e.g., an iPHONE® smart phone, a BLACKBERRY® smart phone, a NEXUS ONE™ smart phone, an iPAD® device, or the like) that is capable of sending and receiving data in a wireless manner using protocols like the Internet Protocol, or IP, and the wireless application protocol, or WAP. This allows users to access information via wireless devices, such as smart phones, mobile phones, pagers, two-way radios, communicators, and the like. Wireless data access is supported by many wireless networks, including, but not limited to, CDPD, CDMA, GSM, PDC, PHS, TDMA, FLEX, ReFLEX, iDEN, TETRA, DECT, DataTAC, Mobitex, EDGE and other 2G, 3G, 4G and LTE technologies, and it operates with many handheld device operating systems, such as PalmOS, EPOC, Windows CE, FLEXOS, OS/9, JavaOS, iOS and Android. Typically, these devices use graphical displays and can access the Internet (or other communications network) on so-called mini- or micro-browsers, which are web browsers with small file sizes that can accommodate the reduced memory constraints of wireless networks. In a representative embodiment, the mobile device is a cellular telephone or smart phone that operates over GPRS (General Packet Radio Services), which is a data technology for GSM networks. In addition to a conventional voice communication, a given mobile device can communicate with another such device via many different types of message transfer techniques, including SMS (short message service), enhanced SMS (EMS), multi-media message (MMS), email WAP, paging, or other known or later-developed wireless data formats. Although many of the examples provided herein are implemented on smart phone, the examples may similarly be implemented on any suitable computing device, such as a computer.

[0024] To illustrate the operation of parafoils, FIG. 1A-1E are provided. FIG. 1A is a perspective view showing an example of a parafoil **100** in flight. The parafoil **100** is a wing shaped parachute capable of steerable, controlled descent. Essentially, the parachute aspect of the parafoil **100** causes the parafoil **100** to exhibit a gradual descent, generally in the direction indicated by arrow **102**, while the wing aspect of the parafoil **100** permits the parafoil **100** to have a guided flight path, generally indicated by arrow **104**. The flight path **104** of the parafoil **100** can be controlled by tugging/releasing lines coupled to the left trailing edge **106** and the right trailing edge **108** of the parafoil **100**. Specifically, as observed in FIG. lB, the parafoil **100** can be made to turn to the left if the left trailing edge line **110** is tugged or pulled. Likewise, referring to FIG. lC, the parafoil **100** can be made to turn to the right if the right trailing edge line **112** is tugged/pulled. The parafoil **100** can even be made to momentarily rise, or at least change its pitch upward if both the left and right trailing edge lines **110**, **112** are tugged or pulled.

[0025] Parafoils **100** have been used for guided drops as a consequence of the ability to control their flight path. In order to successfully land the parafoil **100** at or near some target, however, an individual or a guided electronic flight control system may need to control the trailing edge lines **110**, **112** so as to guide the parafoil **100** with the requisite accuracy. Controlling the trailing edge lines **110**, **112** is performed on the parafoil **100** based on the location of the target, the altitude of the parafoil **100**, the forward and transverse speeds of the parafoil **100**, the roll, roll rate, yaw, yaw rate, pitch and pitch rate of the parafoil **100** and the presence of winds.

[0026] With regard to FIG. 1D illustrates a cross-sectional view showing another example parafoil **100** and a payload system **114** using an eight (8) degree-of-freedom (DOF) model. The combined system of the parafoil **100** and the payload **114** is modeled with eight (8) DOF in FIG. 1D, including three inertial position rate components of the total system mass center as well as the three Euler orientation angles, plus differential pitch, and differential yaw relative to the payload. With the exception of movable parafoil brakes **116**, the parafoil **100** may be considered to be a substantially fixed shape once it has completely inflated. A body frame is fixed at the system mass center **118** with I_B forward and aligned with the top of the payload **114**. Orientation of the parafoil **100** with respect to the payload **114** may be defined as the incidence angle **120** and may be considered a control variable. Rotation of the parafoil **100** about point C **122** allows tilting of the parafoil lift and drag vectors resulting in changes in the equilibrium glide slope. The parafoil rotation point C **122** is in line with the rear suspension lines so that by shortening the front lines and lengthening the brake lines, a pure canopy rotation can be achieved. The aerodynamic center is defined as P **124**. FIG. 1E illustrates a rear view of the parafoil **100** shown in FIG. 1D.

[0027] In accordance with embodiments of the present subject matter, FIG. 2 illustrates a schematic diagram of an example flight control system **200** for controlling the flight of the parafoil **100** and payload **114**. Referring to FIG. 2, the flight control system **200** includes a computing device **202**, a control unit **204**, one or more digital imaging devices **206**. The flight control system **200** also includes multiple indicator points **208** attached to the parafoil **114** as markers. Although only two indicators points are shown in FIG. 2, it should be understood that the system **200** may include any number of indicator points distributed on the parafoil. As a non-limiting example, the indicator points **208** may be reflective markers, patterns, or other identifiable features that may be recognized in an image captured by the digital imaging device(s) **206**. Additionally, infrared or visible light may be used in combination with the indicator points **208**.

[0028] With continued reference to FIG. 2, the flight control system may use an eight (8) degrees-of-freedom (8-DOF) simulation the same or similar to the simulation discussed in Slegers, Nathan, "Use of Variable Incidence Angle for Glide Slope Control of Autonomous Parafoils," Journal of Guidance, Control, and Dynamics, Vol. 31, No. 3, May-June 2008. The 8-DOF includes 3 angles and 3 rates for the parafoil **100**, body mass center, and the payload **114**. The 8-DOF also includes differential pitch and differential yaw of the parafoil **100**, as measured relative to the payload (e.g., gondola) **114**. These 8-DOF can be used to model the physical system.

[0029] With continued reference to FIG. 2, the digital imaging device **206** may be coupled via wired or wireless electronic coupling to the computing device **202**. The computing device **202** may be configured to receive captured, digital images from the digital imaging device **206**. The digital image devices may be situated such that images of all or a portion of the parafoil **100** can be captured. The captured images may include one or more of the indicator points **208**. The computing device **202** may also be configured to control the type, resolution or rate of imaging of the digital imaging device(s) **206**. The digital imaging device(s) **206** may be configured to capture individual images or a continuous set of images during operation of the system **200**. The continuous set of images may be recorded at any frame rate, including high speed video of 60 fps, as an example. The frame rate may vary to accommodate processing limitations or other sampling requirements of the computing device **202**. The computing device **202** may identify the indicator points **208** in the captured digital images via image processing instructions executed by the computing device **202**. The recorded digital images are processed to determine relative positioning of the indicator points **208**. As will be described in greater detail herein (e.g., FIGs. 6A, 6B, and 6C), the relative positioning of the indicator points **208** may be measured relative to the digital image frame or the payload **114**. By determining the relative positioning of the indicator points **208** both differential yaw and differential pitch may be determined, as described in further detail herein such as the description of FIGs. 6A, 6B, and 6C. The computing device **208** may also be configured to determine the differential yaw and differential pitch over a period of time, thus determining the differential yaw rate and the differential pitch rate. In this manner, the computing device **202** may control the parafoil **100** using the control unit **204** and a plurality of actuators **210A**, **210B**, wherein the control unit **204** can control actuators **210A**, **210B**.

[0030] With continued reference to FIG. 2, the actuators **210A**, **210B** may be configured to alter the positioning of the left trailing edge line **110** and the right trailing edge line **112** in order to control the configuration of the parafoil **114** and subsequent flight path of the flight control system **200** and payload **114**. The flight control system **200** may process the received digital images in a control loop from 0.1 Hz to 300 Hz. The control loop may include the receiving of the digital image from the digital imaging device **206**, determination of differential yaw and/or differential pitch as calculated by the computing device **202** and subsequent processing of a control request by the control unit **204** and the plurality of actuators **210A**, **210B**. Alternatively, the control loop may include the control unit **204** controlling one or more propulsion units **212A, 212B** mounted on either the payload **114** or parafoil **100**. Propulsion of the system **100** may be made by an electric or fueled fan motor, as an example. Any other suitable propulsion may be utilized, including a jet/rocket or other propulsion means using a combustible or alternative fuel. A propulsion unit **212A, 212B** may be controlled independently of another source of propulsion in the case there are propulsion units **212A, 212B**. In this manner, greater control of the parafoil **100** and payload **114** flight path may be achieved. Additionally, the system **200** may be configured to control the actuators **210A**, **210B** or the propulsion units **212A, 212B** independently of each other. It is noted that the computing device **202** may be configured to control the plurality of actuators **210A**, **210B**, wherein no propulsion is used. In the example that no propulsion is used, the parafoil **100** may be guided by the actuators **210A**, **210B**.

[0031] With continued reference to FIG. 2, the flight control system **200** may be configured to determine the rigidity of the parafoil **100**. It may be desired to determine the rigidity of the parafoil **100** such that proper inflation and/or guided flight may be maintained. The proper inflation and/or guided flight path may be maintained via the computing device **202** and the control unit **204** based on the determination of the rigidity of the parafoil **100**. The rigidity of the parafoil **100** may be determined by the computing device **208** by processing the received digital images from the digital imaging device **206**. The processing of the received digital images may be performed by the computing device **208** by determining the positioning of the indicator points **208** on the parafoil **100**. Alternatively, or in addition to the positioning of the indicator points **208**, the rigidity of the parafoil **100** may be determined by the shape of the parafoil **100**. For example, a captured image of all or a portion of the parafoil **100** may be used to determine rigidity. Additionally, the flight control system **200** may also include one or more sensors **214** used for determination of the payload **114** orientation. The sensor(s) **214** may be, for example, an accelerometer, gyroscope, or other suitable sensor.

[0032] With continued regard to FIG. 2, the computing device **202** may include hardware, software, firmware, or combinations thereof. For example, the computing device **202** may include a processor **216** and memory **218** for implementing the functionality disclosed herein. The processor **216** may be used to make the necessary calculations for determining the flight path, differential pitch, differential yaw, and any other necessary calculation to maintain proper rigidity and control of the parafoil **100**. The computing device **202** may also include a wireless communications unit **220** for transmitting or receiving captured image data, telemetry data or other flight, parafoil **100** or payload **114** data for monitoring and controlling the flight control system **200**. The computing device **202** may also receive program instructions via the wired or wireless connection. The computing device **202** may also comprise storage **222** (e.g., memory) for storing flight data, including captured image data, telemetry data or other flight, parafoil or payload data. The computing device **202** may be configured to transmit any of the capture image data, telemetry data or other flight, parafoil **100** or payload **114** data. Additionally, the computing device **202** may be configured to receive control instructions via a wired or wireless connection. In this manner, the flight control system **200** may be controlled remotely.

[0033] With continued reference to FIG. 2, the lift-to-drag ratio, or L/D ratio, is the amount of lift generated by a wing or vehicle, divided by the drag it creates by moving through the air. A higher or more favorable L/D ratio is typically one of the major goals in any parafoil **100** design. Since the required lift of the parafoil **100** is set by the weight of the parafoil **100** and the payload **114**, delivering that lift with lower drag leads directly to better fuel economy, climb performance, and glide ratio. The L/D is calculated for any particular airspeed by measuring the lift generated, then dividing by the drag at that speed. L/D ratios may also be calculated using the measured or determined differential pitch and/or differential pitch rate. Based on the calculated L/D ratio, the flight control system **200** may control the flight inputs for an optimal L/D ratio. Further, a combination of the determined differential yaw and a measured ground track direction may be used by the flight control system **200** to determine wind direction. Based on the determination of wind direction, the flight control system **200** may be configured to control the flight inputs. As example, the flight control system **200** may be configured to provide the flight inputs to the actuators **210A**, **210B** for achieving an optimal L/D ratio or in controlling the parafoil **100** for an optimal flight path based on the determined wind direction.

[0034] FIG. 3 illustrates a flowchart of an example method **300** of controlling the flight of a parafoil **100** and payload **114** using a flight control system **200** according to embodiments of the present subject matter. In this example, reference is made to the parafoil **100**, payload **114** and flight control system **200** depicted in FIG. 2, although it should be understood that the method may alternatively be applied to any suitable parafoil, payload, and flight control system.

[0035] Referring to FIG. 3, the method includes capturing **302** a digital image of the parafoil **100** by the digital imaging device **206**. The digital image may be of the parafoil **100** as viewed from the perspective of the payload **114**, as an example. The method may include determining **304** the position of the plurality of indicator points **208** on the parafoil **100** based on the captured digital image. The position of the indicator points **208**, as described below, may be determined by a digital image processor (not shown) in the computing device **202**. The method may further include determining **306** a condition of the parafoil **100** based on the positioning of the plurality of indicator points **208**. The condition of the parafoil **100** may be of the parafoil **100** itself, such as, a partial collapse of the parafoil **100** as an example. The condition may also be of a position of the indicator points **208** mounted on the parafoil **100** as indicative of the position of the parafoil **100** relative to the digital image frame of the digital image device **206**. The method includes controlling **308** flight inputs based on the condition of the parafoil **100**. The flight inputs are used to control the flight path of the parafoil **100** and the payload **114** and may be provided to the plurality of actuators **210A**, **210B**, as an example.

[0036] FIG. 4 illustrates a flowchart of an example method **400** of controlling the flight of the parafoil **100** and payload **114** using a flight control system **200** in accordance with embodiments of the present subject matter. In this example, reference is made to the parafoil **100**, payload **114** and flight control system **200** depicted in FIG. 2, although it should be understood that the method may alternatively be applied to any suitable parafoil, payload, and flight control system. Controlling the flight of the parafoil **100** and payload **114** using a flight control system **200**, may be performed by determining differential pitch and differential yaw according to embodiments of the present subject matter.

[0037] Referring to FIG. 4, in a similar fashion to FIG. 3, the method includes capturing **302** an image of the parafoil **100**. The image may be of the parafoil **100** as viewed from the perspective of the payload **114**, as an example. Alternatively, the image may be of the payload **114** from the perspective of the parafoil **100**, as an additional example. The method may include determining **304** the position of a plurality of indicator points **208** on the parafoil **100** based on the captured image. The method may further include determining **306** a condition of the parafoil **100** based on the positioning of the plurality of indicator points **208**. The method includes controlling **308** flight inputs based on the condition of the parafoil **100**. The flight inputs may be provided to actuators **210A**, **210B**.

[0038] With continued reference to FIG. 4, the method may also include determining **402** the rigidity of the parafoil **100** based on the positioning of the indicator points **208**. In aerodynamics, a flight envelope or performance envelope of the parafoil **100** refers to the capabilities of a particular design or the flight control specifications in terms of airspeed, load factor, and/or turning capabilities. Additionally, the flight envelope refers to other measurements such as maneuverability, stall speed, and the like. Expanding the flight envelope or pushing the parafoil **100** beyond the intended or designed performance of the parafoil **100** may increase the likelihood that the parafoil **100** will collapse. The collapse of the parafoil **100** may be due to a leading edge fold overs or stalling, as an example. Feedback to the flight control system **200** regarding the state or status of the parafoil **100** may indicate to the flight control system **200** that control inputs should be adjusted when disturbances to the parafoil **100** are detected. By monitoring the state or status of the parafoil **100** and adjusting the control inputs accordingly will allow the flight control system **200** to reduce the margin in the flight envelope that must be maintained when no indication of parafoil **100** failure is detected, thus increasing potential flight envelope performance.

[0039] With continued reference to FIG. 4, the method includes determining the rigidity of the parafoil **100** based on the positioning of the indicator points **208**. If it is determined the current rigidity of the parafoil **100** requires correction to avoid failure, the flight control system **200** may be configured to make the necessary adjustments. The necessary adjustments may include adjusting or controlling the actuators **210A**, **210B** or the at least one propulsion means **212A, 212B**

independently of each other as appropriate. The method also includes determining **404** the positioning of the plurality of the indicator points over time. In this manner, the flight control system **200** may determine differential data over time. The differential data may include differential pitch and differential yaw. Yaw is the rotation or movement around the yaw axis of a rigid or semi-rigid body that changes the direction or heading of the rigid or semi-rigid body, such as the parafoil **100** or payload **114**. A differential yaw is the angular difference between the heading of the parafoil **100** and the payload **114** as indicated by the digital imaging device **206**. The method may also include calculating **406** a differential yaw either in a singular image or continuously over time determining the differential yaw rate based on the changing positioning of the plurality of indicator points over time. As an example, the flight control system 200 may be configured to maintain the differential yaw within a pre-determined value from between zero (0) to ten (10) degrees, as an example. The flight control system **200** may also be reprogrammed to adjust the pre-determined differential yaw range, as a non-limiting example, to twenty-five (25) degrees where conditions or equipment allow. It should be noted that the upper limit may be any appropriate limit as either conditions or equipment allow. The differential yaw range may also be changed in flight, in contrast to the pre-determined differential yaw range. Determining the differential yaw and the differential yaw rate may be used to damp out yaw perturbations, especially those caused at take-off and hard turns. Additionally, differential thrust adjustments by the flight control system **200** may be especially effective to control yaw perturbations.

[0040] Pitch is the rotation about the pitch axis of a rigid or semi-rigid body that changes the direction of the climb angle of the rigid or semi-rigid body. A differential pitch is the angular difference between the pitch of the parafoil **100** and the digital imaging device **206**. The method may also include calculating **408** a differential pitch either in a singular image or continuously over time determining the differential pitch rate based on the positioning of the plurality of indicator points over time. As an example, the flight control system 200 may be configured to maintain the pre-determined differential pitch from between zero (0) to twenty (20) degrees, as an example. The flight control system **200** may also be reprogrammed to adjust the differential pitch range, as a non-limiting example, to twenty-five (25) degrees where conditions or equipment allow. It should be noted that the upper limit may be any appropriate limit as either conditions or equipment allow. The differential pitch range may also be changed in flight, in contrast to the pre-determined differential pitch range. Determining the differential pitch and differential pitch rate improves the altitude control of the flight control system **200**, by decreasing the oscillations due to control input latency or perturbations. Additionally, time-varying thrust adjustments by the flight control system **200** may be especially effective to control or mitigate pitch perturbations. This method of pitch differential measurement may also be used to record measurement data for determining the lift-to-drag of the parafoil **100** and may be used where an intentional morphing of the parafoil **100** is desired. The intentional morphing of the parafoil **100** may be used to change the aerodynamic properties of the parafoil **100**. As an example, intentional morphing of the parafoil **100** may be used to change the performance of the parafoil **100** using varying flight speeds.

[0041] FIG. 5A illustrates a front view of an example flight control system in accordance with embodiments of the present subject matter. Referring to FIG. 5A, the figure shows a front view angle **500** of the digital imaging device **206**. The digital imaging device **206** may capture images of the parafoil **100** according to embodiments of the present subject matter. The digital imaging device **206** of the flight control system **200** may be mounted on the top of the payload **114** and configured to capture images of the parafoil **100**. FIG. 5A also shows the front viewing angle **500** from the front perspective of the payload **114**. In this manner, the digital imaging device **206** is able to view the indicator points **208** mounted on the parafoil **100** and determine the corresponding shape, the rigidity, the differential yaw, and the differential pitch.

[0042] FIG. 5B illustrates a side view of the system shown in FIG. 5A. Referring to FIG. 5B, the figure shows a side view angle **502** of the digital imaging device **206**. In this manner, the digital imaging device **206** may be able to view the parafoil **100** and determine the corresponding the shape, the rigidity, the differential yaw and the differential pitch.

[0043] FIG. 6A is a perspective view showing an example of the flight control system **200** determining differential yaw in accordance with embodiments of the present subject matter. In this example illustration, a differential yaw **600** as measured between the yaw angle of the parafoil **100** and the digital imaging device **206** as indicated by the indicator points **208** is -11.6 degrees. Based on this determination, the flight control system **200** may adjust the control inputs to reduce or increase the differential yaw **600** as appropriate for the current or anticipated flight conditions. It should be noted that based on the calculation of the differential yaw rate of change, the flight control system **200** may make adjustments to the control inputs based on anticipated flight conditions.

[0044] FIG. 6B is a perspective showing an example of the flight control system **200** determining differential pitch by imaging the parafoil **100** as viewed from the perspective of the payload (gondola). In this example illustration, a differential pitch **602** between the pitch angle of the parafoil **100** and the frame of the image captured by the digital imaging device **206** as indicated by the indicator points **208** is -10.5 degrees. As an example, the differential pitch **602** may be measured based on the angular distance from the digital image frame edge of the digital image device **206** and a center point on a virtual line imaged based on the indicator points **208**. Based on this determination, the flight control system **200** may adjust the control inputs to reduce or increase the differential pitch **602** as appropriate for the current or anticipated flight conditions. It should be noted that based on the calculation of the differential pitch rate the flight control system **200** may make adjustments to the control inputs based on anticipated flight conditions.

[0045] FIG. 6C is a perspective view showing an example of the flight control system **200** determining parafoil deformation. As an example, parafoil deformation may be determined by the flight control system **200** as a loss of rigidity of the parafoil **100**. In response to the determined loss of rigidity of the parafoil **100**, the flight control system **200** may be configured to adjust the propulsion means **212A, 212B** to increase air flow, thus reinflating the parafoil **100** and reestablishing rigidity, as an example. The flight control system **200** may also be configured to adjust the actuators **210A**, **210B** such that a turning radius of the parafoil **100** is decreased or increased, as a further example. It should be noted that based on the calculation of the parafoil **100** deformation the flight control system **200** may make adjustments to the control inputs based on anticipated flight conditions. Tracking the shape of the parafoil **100** over time may allow for increased turn rates, improving lateral control. Additionally, tracking the shape of the parafoil **100** over time may be used as parafoil **100** speed is increased.

[0046] The present subject matter may be implemented as a system, a method, and/or a computer program product. The computer program product may include a computer readable storage medium (or media) having computer readable program instructions thereon for causing a processor to carry out aspects of the present subject matter.

[0047] The computer readable storage medium can be a tangible device that can retain and store instructions for use by an instruction execution device. The computer readable storage medium may be, for example, but is not limited to, an electronic storage device, a magnetic storage device, an optical storage device, an electromagnetic storage device, a semiconductor storage device, or any suitable combination of the foregoing. A non-exhaustive list of more specific examples of the computer readable storage medium includes the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a static random access memory

(SRAM), a portable compact disc read-only memory (CD-ROM), a digital versatile disk (DVD), a memory stick, a floppy disk, a mechanically encoded device such as punch-cards or raised structures in a groove having instructions recorded thereon, and any suitable combination of the foregoing. A computer readable storage medium, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmission media (e.g., light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire.

[0048] Computer readable program instructions described herein can be downloaded to respective computing/processing devices from a computer readable storage medium or to an external computer or external storage device via a network, for example, the Internet, a local area network, a wide area network and/or a wireless network. The network may comprise copper transmission cables, optical transmission fibers, wireless transmission, routers, firewalls, switches, gateway computers and/or edge servers. A network adapter card or network interface in each computing/processing device receives computer readable program instructions from the network and forwards the computer readable program instructions for storage in a computer readable storage medium within the respective computing/processing device.

[0049] Computer readable program instructions for carrying out operations of the present subject matter may be assembler instructions, instruction-set-architecture (ISA) instructions, machine instructions, machine dependent instructions, microcode, firmware instructions, state-setting data, or either source code or object code written in any combination of one or more programming languages, including an object oriented programming language such as Java, Smalltalk, C++ or the like, and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The computer readable program instructions may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider). In some embodiments, electronic circuitry including, for example, programmable logic circuitry, field-programmable gate arrays (FPGA), or programmable logic arrays (PLA) may execute the computer readable program instructions by utilizing state information of the computer readable program instructions to personalize the electronic circuitry, in order to perform aspects of the present subject matter.

[0050] Aspects of the present subject matter are described herein with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to embodiments of the subject matter. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer readable program instructions.

[0051] These computer readable program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. These computer readable program instructions may also be stored in a computer readable storage medium that can direct a computer, a programmable data processing apparatus, and/or other devices to function in a particular manner, such that the computer readable storage medium having instructions stored therein comprises an article of manufacture including instructions which implement aspects of the function/act specified in the flowchart and/or block diagram block or blocks.

[0052] The computer readable program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other device to cause a series of operational steps to be performed on the computer, other programmable apparatus or other device to produce a computer implemented process, such that the instructions which execute on the computer, other programmable apparatus, or other device implement the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0053] The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various embodiments of the present subject matter. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of instructions, which comprises one or more executable instructions for implementing the specified logical function(s). In some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

[0054] While the embodiments have been described in connection with the various embodiments of the various figures, it is to be understood that other similar embodiments may be used or modifications and additions may be made to the described embodiment for performing the same function without deviating therefrom. Therefore, the disclosed embodiments should not be limited to any single embodiment, but rather should be construed in breadth and scope in accordance with the appended claims.

CLAIMS

What is claimed:

1. A method comprising:

capturing an image of a parafoil including a plurality of indicator points distributed thereon;

determining positioning of the indicator points based on the captured image;

determining a condition of the parafoil based on the positioning of the indicator points; and

controlling flight inputs based on the condition of the parafoil.

2. The method of claim 1, further comprising determining the rigidity of the parafoil based on the positioning of the indicator points.

3. The method of claim 1, further comprising:

determining the positioning of the indicator points over a predetermined period of time; and

calculating a differential yaw rate based on the positioning of the indicator points over the predetermined period of time.

4. The method of claim 1, further comprising calculating a differential yaw based on the positioning of the indicator points.

5. The method of claim 4, further comprising determining wind direction based on the calculated differential yaw and a ground track direction.

6. The method of claim 5, further comprising controlling flight inputs based on the determined wind direction.

7. The method of claim 1, further comprising:

determining the positioning of the indicator points over a predetermined period of time; and calculating a differential pitch rate based on the positioning of the indicator points over the predetermined period of time.

8. The method of claim 1, further comprising calculating a differential pitch based on the positioning of the indicator points.

9. The method of claim 8, further comprising calculating the lift-to-drag ratio based on the calculated the differential pitch.

10. The method of claim 8, further comprising controlling flight inputs based on the calculated differential pitch.

11. The method of claim 1, further comprising positioning an imaging device substantially near the center of a gondola for capturing the image of the parafoil.

12. The method of claim 1, further comprising determining whether a differential yaw is greater than a predetermined value.

13. The method of claim 12, wherein controlling the flight inputs based on the condition of the parafoil comprises controlling a turning rate of the parafoil in response to determining that the differential yaw is greater than the predetermined value.

14. The method of claim 12, wherein controlling the flight inputs based on the condition of the parafoil comprises controlling a propulsion force for adjusting the turning rate of a coupled gondola in response to determining that the differential yaw is greater than the predetermined value.

15. The method of claim 1, wherein controlling the flight inputs comprises creating a drag force on a first side of the parafoil.

16. The method of claim 4, wherein controlling the differential yaw comprises adjusting a plurality of propulsion forces.

17. The method of claim 6, wherein controlling the differential pitch comprises adjusting at least one propulsion force

18. The method of claim 14, wherein controlling the propulsion force for adjusting the turning rate comprises using a first fan and a second fan for propulsion of the parafoil, and

wherein controlling the flight inputs comprises controlling either the first fan or the second fan.

19. A system comprising:

a parafoil including a plurality of indicator points distributed thereon;

a digital imaging device configured to capture an image of the indicator points;

a computing device comprising at least one processor and memory configured to:

determine positioning of the indicator points based on the captured image;

determine a condition of the parafoil based on the positioning of the indicator points; and

control flight inputs based on the condition of the parafoil.

20. The system of claim 19, wherein the computing device is further configured to determine the rigidity of the parafoil based on the positioning of the indicator points.

21. The system of claim 19, wherein the computing device is further configured to:

determine the positioning of the indicator points over a predetermined period of time; and

calculate a differential yaw rate based on the positioning of the indicator points over the predetermined period of time.

22. The system of claim 19, wherein the computing device is further configured to:

calculate a differential yaw based on the positioning of the indicator points.

23. The system of claim 22, wherein the computing device is further configured to determine wind direction based on the calculated differential yaw and a ground track direction.

24. The system of claim 23, wherein the computing device is further configured to control flight inputs based on the determined wind direction.

25. The system of claim 19, wherein the computing device is further configured to:

determine the positioning of the plurality of indicator points over a predetermined period of time; and

calculate a differential pitch rate based on the positioning of the indicator points over the predetermined period of time.

26. The system of claim 19, wherein the computing device is further configured to:

calculate a differential pitch based on the positioning of the indicator points.

27. The system of claim 26, wherein the computing device is further configured to use the calculated differential pitch to calculate the lift-to-drag ratio.

28. The system of claim 26, wherein the computing device is further configured to control flight inputs based on the calculated differential pitch.

29. The system of claim 19, wherein the digital imaging device is positioned substantially near the center of a gondola.

30. The system of claim 19, wherein the computing device is further configured to determine whether a differential yaw is greater than a predetermined value.

31. The system of claim 30, wherein the computing device is further configured to control a turning rate of the parafoil in response to determining that the differential yaw is greater than the predetermined value.

32. The system of claim 31, further comprising:

at least one fan for propulsion of the parafoil, and

wherein the computing device is further configured to control a plurality of propulsion forces for adjusting the differential yaw.

33. The system of claim 31, further comprising:

at least one propulsion force for propulsion of the parafoil, and

wherein the computing device is further configured to control the at least one propulsion force for adjusting the differential pitch rate.

34. The system of claim 19, wherein the computing device is configured to control the flight inputs to create a drag force on a first side of the parafoil.

35. The system of claim 19, further comprising at least one fan for propulsion of the parafoil.

36. The system of claim 19, further comprising:

a first fan and a second fan for propulsion of the parafoil, and

wherein the computing device is configured to control the flight inputs by controlling either the first fan or the second fan.

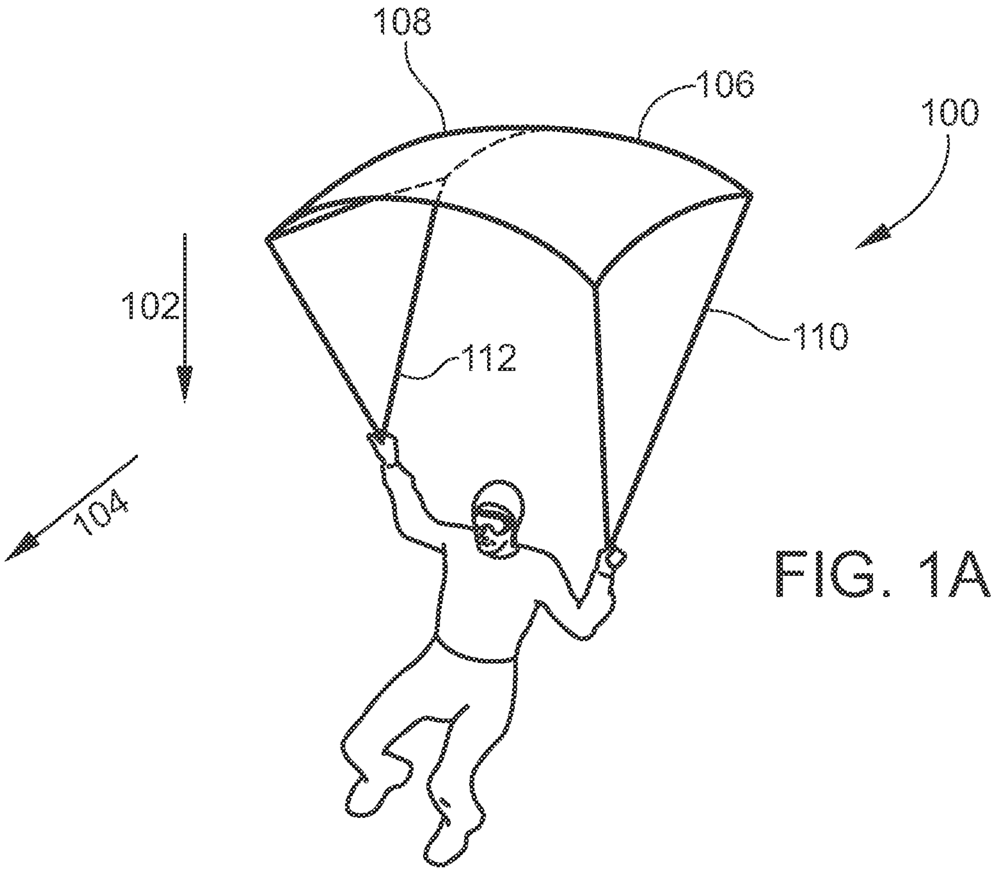
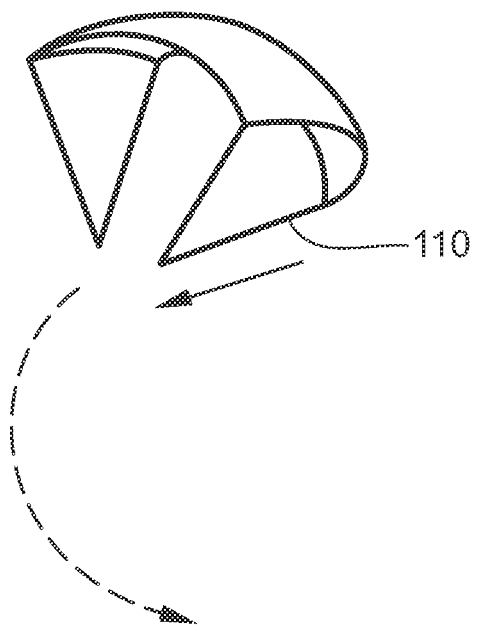


FIG. 1A



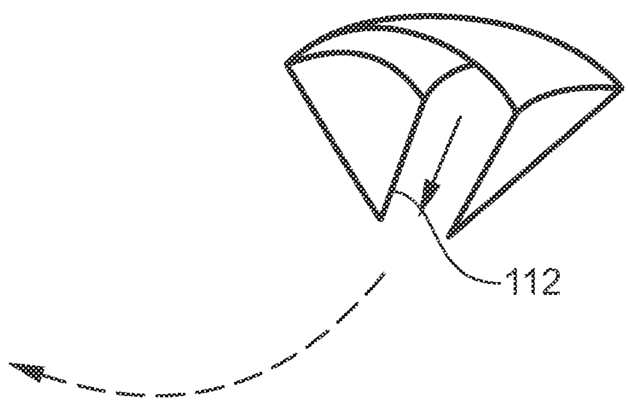


FIG. 1C

FIG. 1B

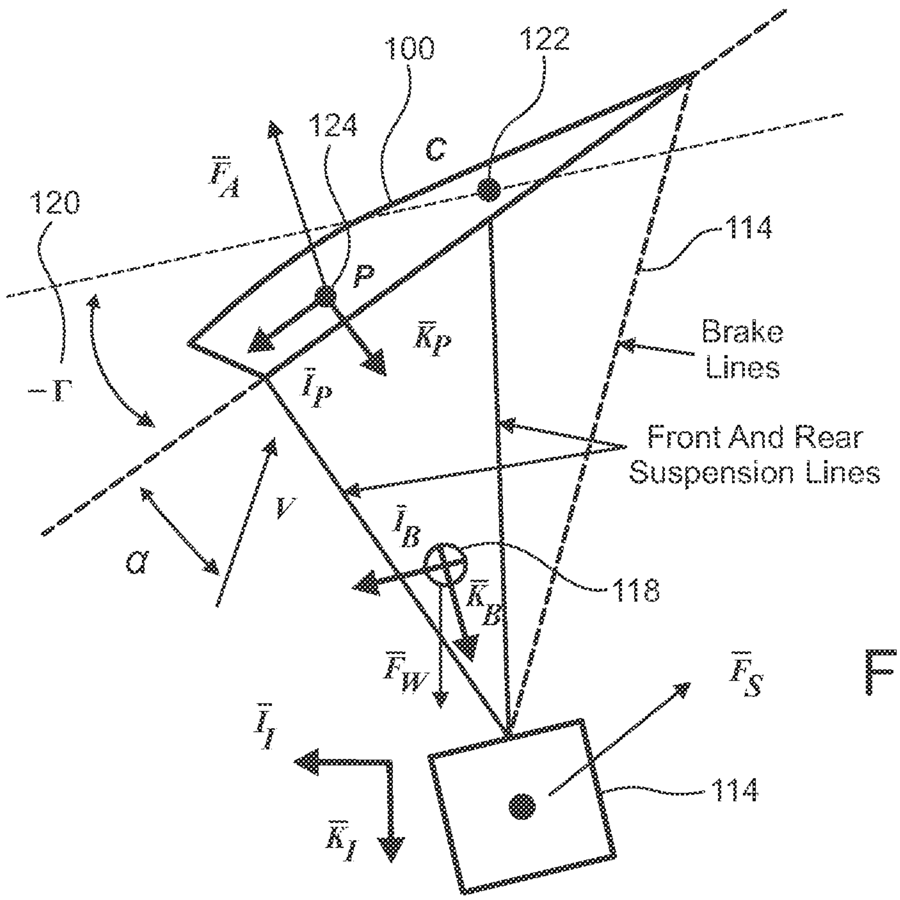

100
122
124
C
$\bar{F}_A$
120
114
P
$\bar{K}_P$
Brake
Lines
$-\Gamma$
$\bar{I}_P$
Front And Rear
Suspension Lines
V
$\bar{I}_B$
α
118
$\bar{K}_B$
$\bar{F}_W$
$\bar{F}_S$
$\bar{I}_I$
114
$\bar{K}_I$

FIG. 1D

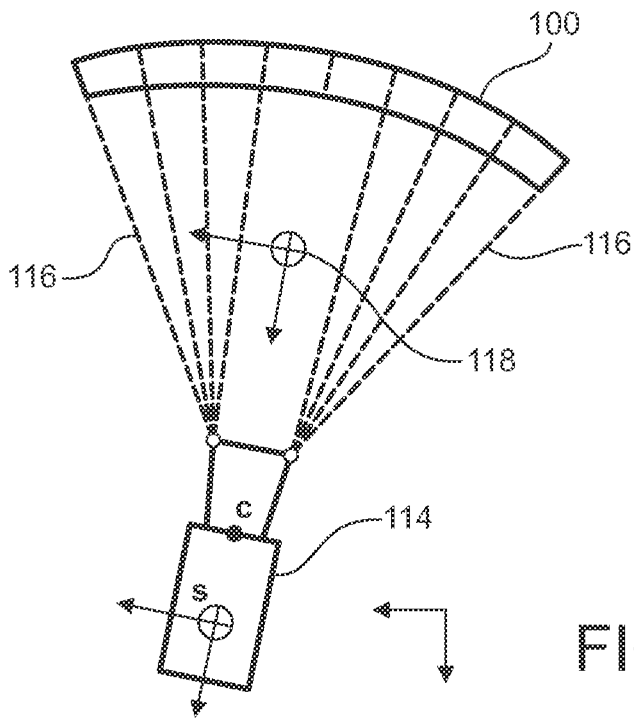

100
116
116
118
c
114
s

FIG. 1E

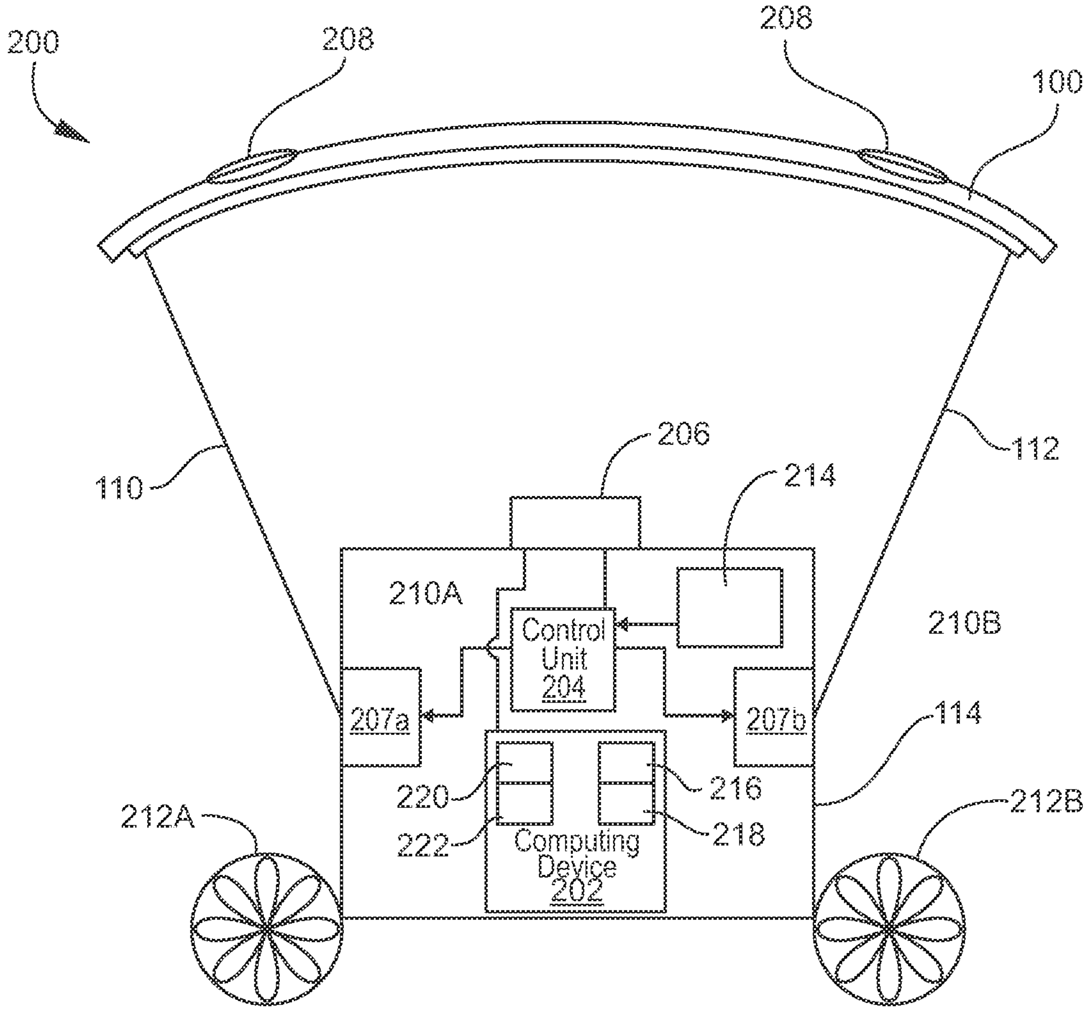

200
208
208
100
110
112
206
214
210A
210B
Control Unit 204
207a
207b
114
220
222
216
218
Computing Device 202
212A
212B

FIG. 2

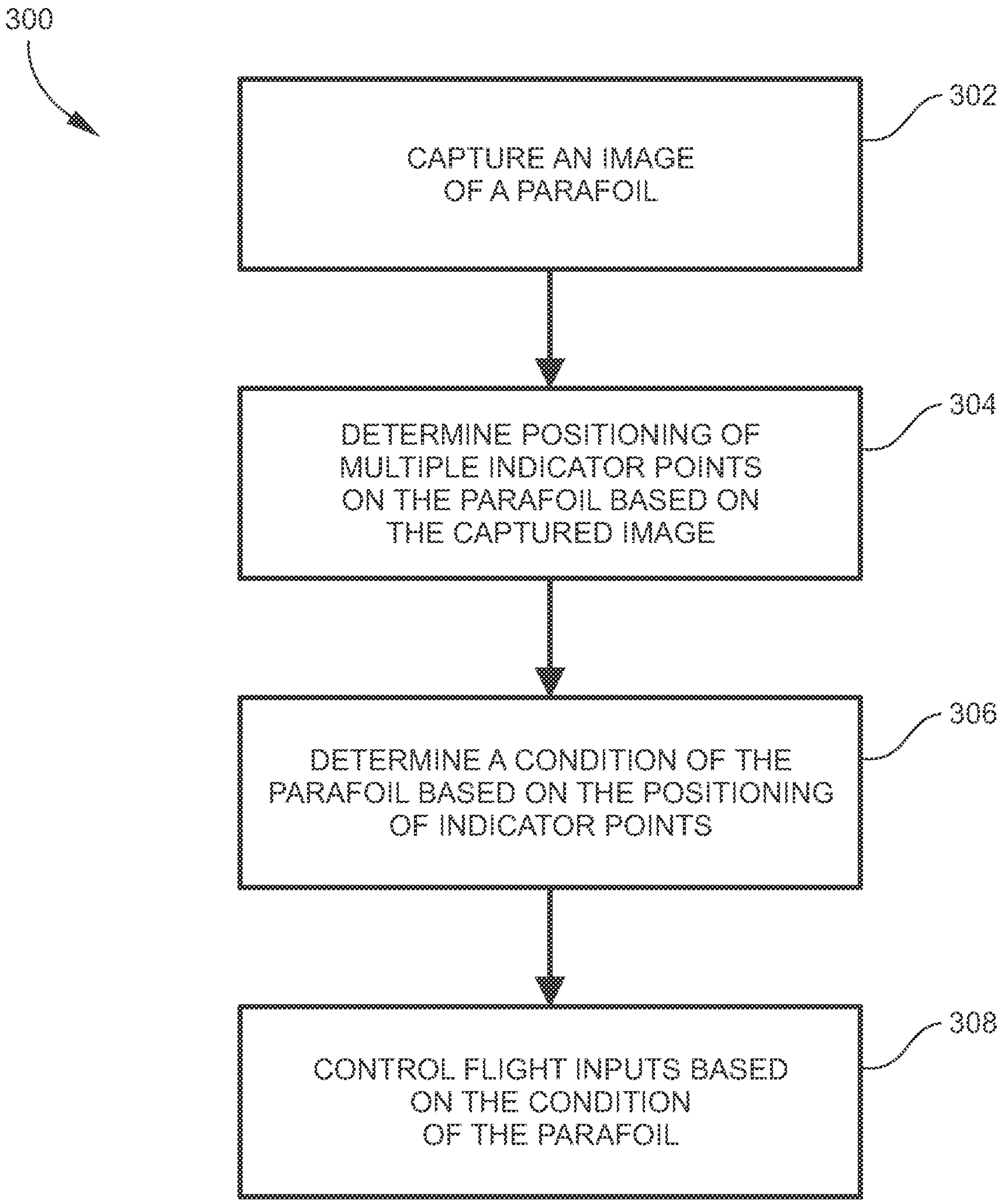

300
CAPTURE AN IMAGE OF A PARAFOIL
302
DETERMINE POSITIONING OF MULTIPLE INDICATOR POINTS ON THE PARAFOIL BASED ON THE CAPTURED IMAGE
304
DETERMINE A CONDITION OF THE PARAFOIL BASED ON THE POSITIONING OF INDICATOR POINTS
306
CONTROL FLIGHT INPUTS BASED ON THE CONDITION OF THE PARAFOIL
308

FIG. 3

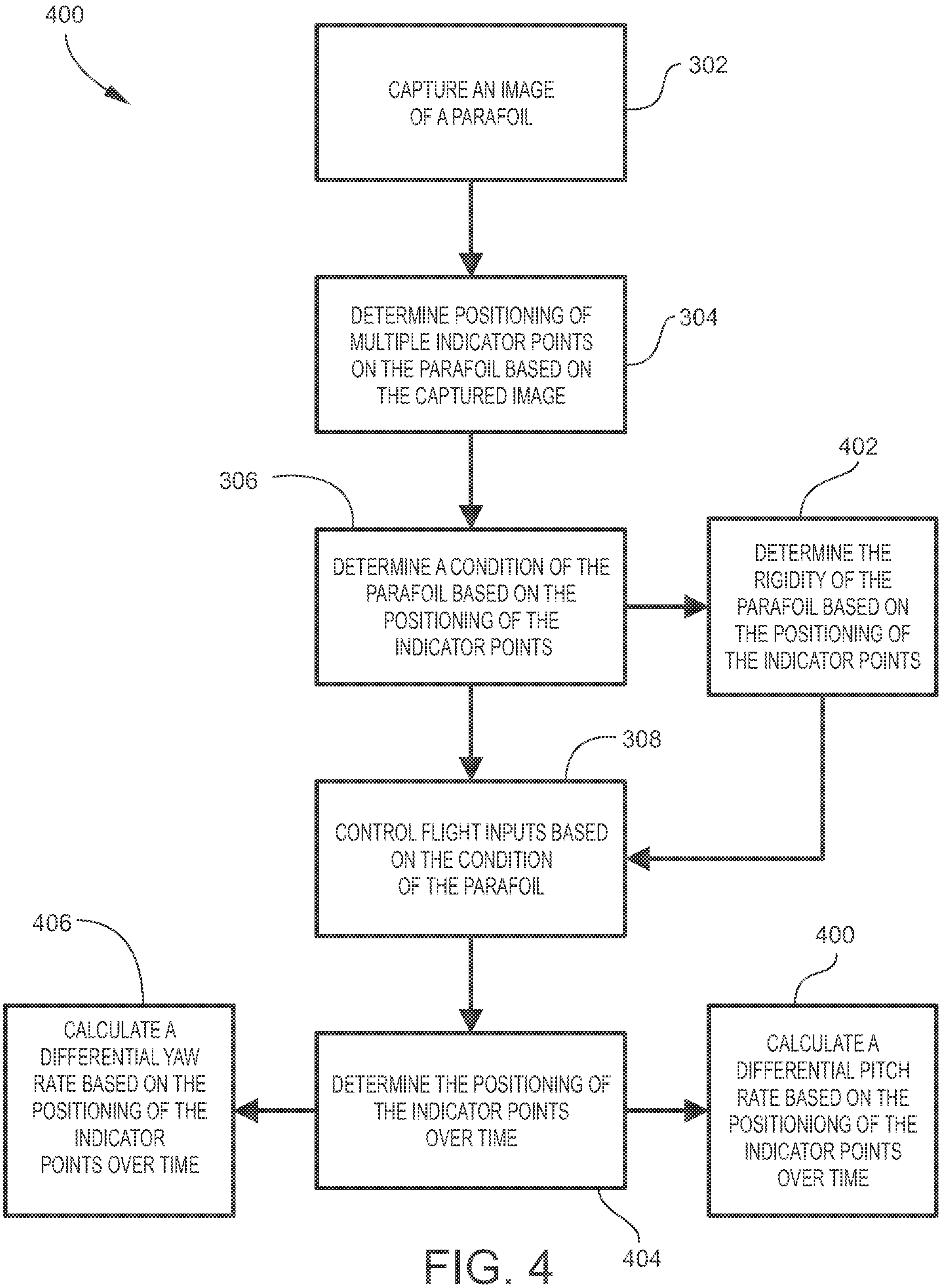

400
CAPTURE AN IMAGE OF A PARAFOIL
302
DETERMINE POSITIONING OF MULTIPLE INDICATOR POINTS ON THE PARAFOIL BASED ON THE CAPTURED IMAGE
304
306
DETERMINE A CONDITION OF THE PARAFOIL BASED ON THE POSITIONING OF THE INDICATOR POINTS
402
DETERMINE THE RIGIDITY OF THE PARAFOIL BASED ON THE POSITIONING OF THE INDICATOR POINTS
308
CONTROL FLIGHT INPUTS BASED ON THE CONDITION OF THE PARAFOIL
406
CALCULATE A DIFFERENTIAL YAW RATE BASED ON THE POSITIONING OF THE INDICATOR POINTS OVER TIME
DETERMINE THE POSITIONING OF THE INDICATOR POINTS OVER TIME
400
CALCULATE A DIFFERENTIAL PITCH RATE BASED ON THE POSITIONIONG OF THE INDICATOR POINTS OVER TIME
404

FIG. 4

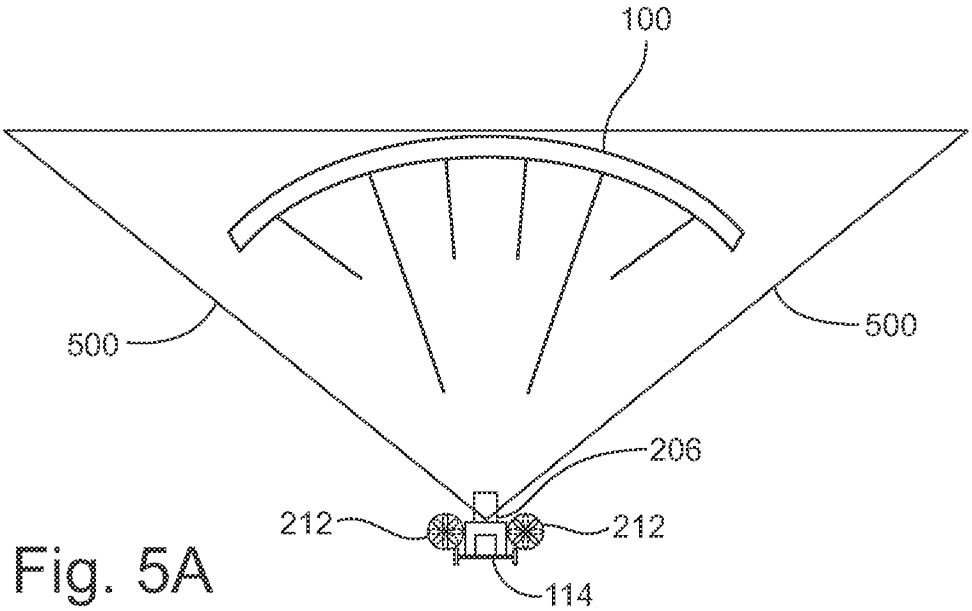


Fig. 5A

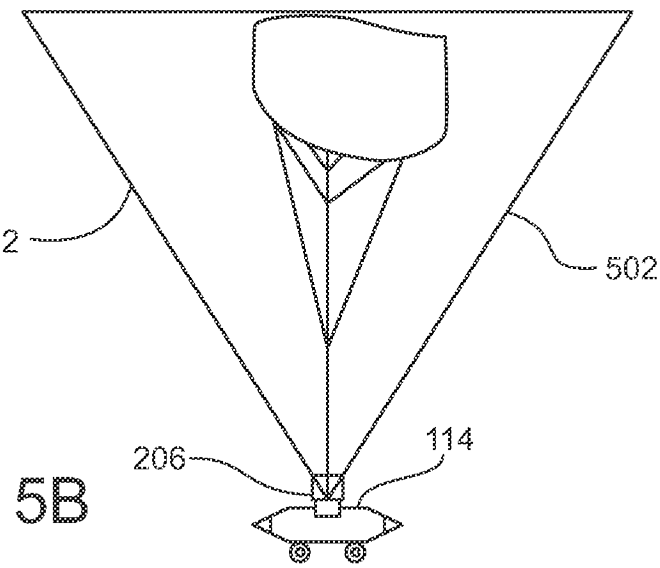


FIG. 5B

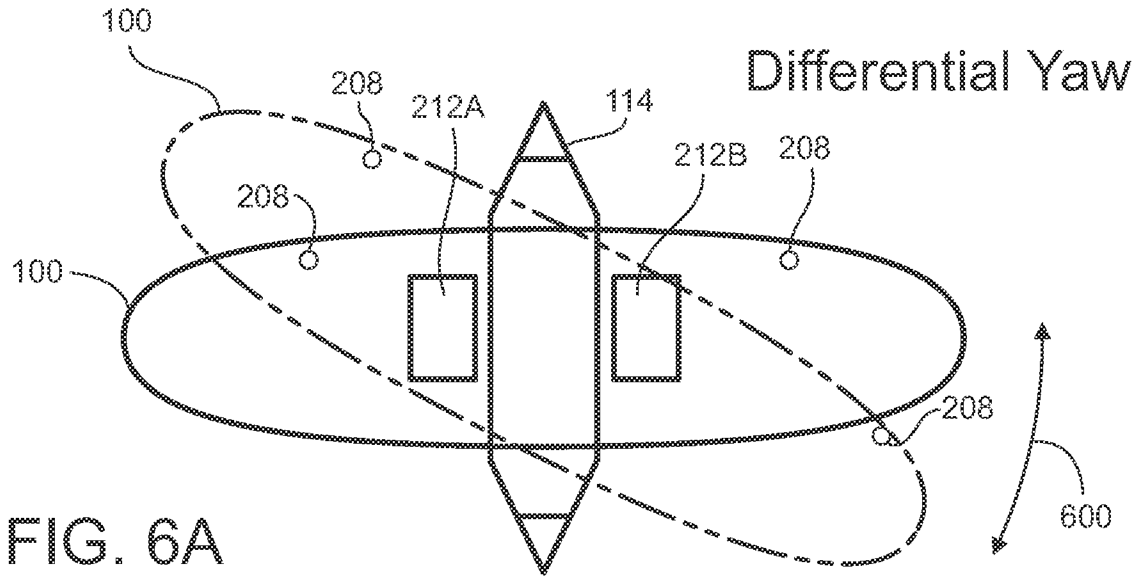


FIG. 6A

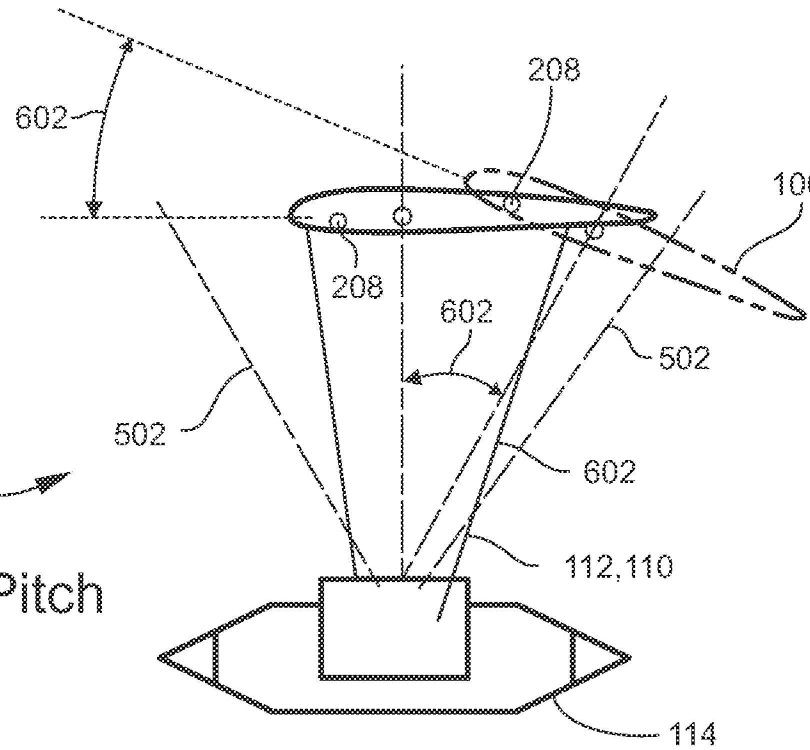


FIG. 6B

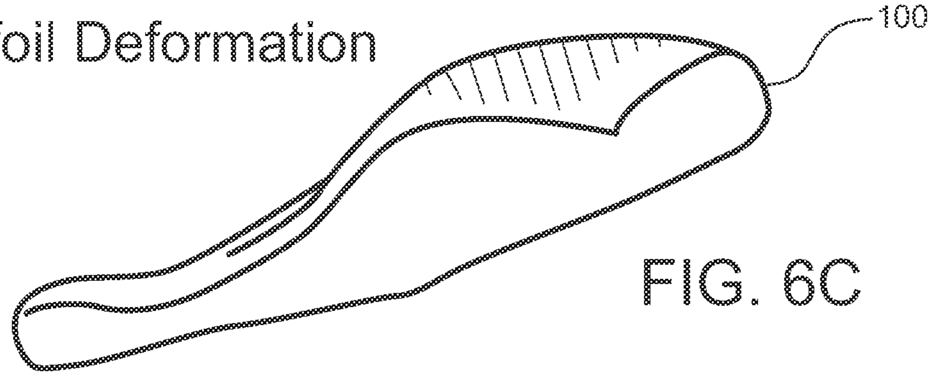


FIG. 6C