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(54) **Title:** ROBOTIC SYSTEMS AND METHODS EMPLOYING ACTUATED MOBILE EFFECTOR MOUNTS AND PASSIVE FLEXIBLE ARMS

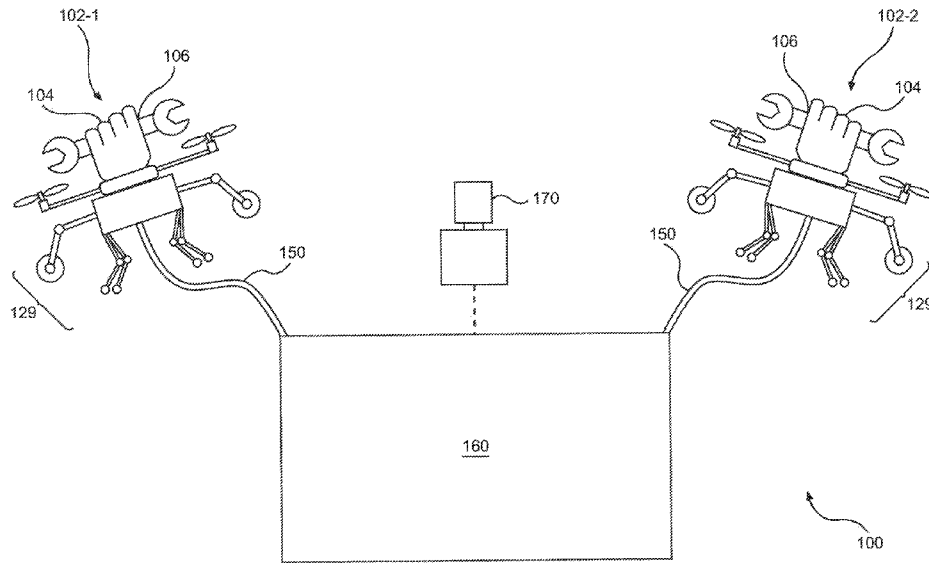


FIG. 1A

(57) **Abstract:** A robotic limb includes a non-articulated passive flexible arm that does not have powered movement, and an actuated mobile hand (e.g., effector mount) to hold a tool (e.g., effector). The mobile hand has a propulsion system and the flexible arm carries a control signal to the propulsion system to control the mobility of the mobile hand. A robotic limb controller autonomously determines a location of the mobile hand, autonomously determines a trajectory of the mobile hand based on its location, and generates the control signal for the propulsion system. In various examples, the tool held by the mobile hand facilitates contact with an object (e.g., to facilitate repair, painting, cleaning, or other surface treatment, or crop harvesting). The propulsion system of the mobile hand may include multiple thrusters to facilitate mobility in air or water, and/or wheels or motorized/articulated legs to facilitate mobility on a surface.



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**ROBOTIC SYSTEMS AND METHODS EMPLOYING ACTUATED MOBILE EFFECTOR  
MOUNTS AND PASSIVE FLEXIBLE ARMS**

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] This application claims the priority benefit, under 35 U.S.C. 119(e), of U.S. Application No. 63/569,519, filed March 25, 2024 and entitled, “DISTRIBUTED ROBOTIC SYSTEMS AND METHODS EMPLOYING AERIAL END EFFECTORS AND FLEXIBLE ARMS,” and U.S. Application No. 63/507,735, filed June 12, 2023 and entitled, “DISTRIBUTED ROBOTIC SYSTEMS AND METHODS EMPLOYING AERIAL END EFFECTORS AND FLEXIBLE ARMS.” Each of the aforementioned applications is incorporated herein by reference in its entirety.

BACKGROUND

[0002] A robot is a machine designed to perform one or more tasks (also referred to herein as an “operation”) in an automated manner with little to no human guidance. Robots are often deployed in controlled environments to perform repetitive tasks, such as fabricating parts for a product, fulfilling orders for goods, or preparing certain foods or drinks. The use of robots in these settings typically results in greater productivity, lower manufacturing and/or operating costs, and greater worker safety. More recent advances in robotics have also led to the deployment of robots in less controlled, more real-world environments. In these environments, robots are generally required to adapt to different and, in some instances, changing environments. Examples of these robots include robotic vacuum cleaners, lawnmowers, and automated construction equipment.

SUMMARY

[0003] The Inventor has recognized and appreciated continued advancements in robotics have provided greater automation of tasks traditionally performed by humans. However, the Inventor has also recognized certain tasks that involve the use of a tool (also referred to herein as an “effector”) to interact with objects or structures in hard-to-reach locations, such as elevated vertical or inclined surfaces remain challenging for robots to perform let alone automate. These tasks include, for example, cleaning the windows of a structure (e.g., a house, a multi-story building, a skyscraper), painting a structure (e.g., bridges, ships, building exteriors and interiors), harvesting a crop (e.g., picking a fruit from a tree), removing weeds, or other types of contact and/or near contact treatments for surfaces (e.g., scrubbing, sanding, polishing, applying various coatings, etc.). As a result, human workers still perform these tasks manually,

which is time consuming, expensive, and in some instances exposes the workers to dangerous conditions.

[0004] To address some of the foregoing challenges, the Inventor has previously invented systems with aerobots configured to perform one or more operations on an elevated or inclined surface. Specifically, the aerobot includes an effector that physically contacts the surface. The aerobot may further be coupled to a base station via an umbilical cord, which provides, for example, electrical power and/or fluidic connections to the aerobot. The system may further include an umbilical support system to carry and suspend the umbilical cord above the aerobot. Further details of these systems may be found in International Application No. PCT/US2024/028198 (hereafter referred to as the ‘198 application), filed on May 7, 2024, entitled “SYSTEMS, APPARATUS, AND METHODS FOR TREATMENT OF OUTDOOR AND INDOOR VERTICAL OR INCLINED SURFACES VIA AERIAL VEHICLES,” which is incorporated by reference herein in its entirety.

[0005] Following the Inventor’s conception of the inventive systems disclosed in the ‘198 application, the Inventor further recognized an alternative inventive implementation to more generally address limitations of conventional robotic systems in applications that involve interactions with objects and/or surfaces in hard-to-reach locations.

[0006] One limitation of conventional robots is their limited range of operation, which makes it challenging for conventional robots to access hard-to-reach locations. The vast majority of conventional robots typically include “articulated” arms. A typical articulated arm includes one or more rigid structural segments connected together by respective joints. An effector (also referred to as an “end-arm effector” and an “end effector”) is often attached to the end of the arm. The articulated arm is also used to provide structural support for digital communication and power cables and/or fluid lines to facilitate actuation of the effector.

[0007] The articulated arm can move the effector in three-dimensional space by rotating respective joints via integrated actuators. Specifically, the actuation of the joints causes one or more rigid segments to move, which, in turn, leads to movement of the effector. Thus, an articulated robot can be characterized as having one or more arms with actuated segments and a passive effector mount at the end of the arms to which an effector is attached. The range of operation of a conventional robot with an articulated arm is limited by the length of the arm. In order for the robot to physically interact with an object, it should be positioned within an arm’s length of that object.

**[0008]** Another limitation of conventional robots is their limited perception of the environment when positioned near an object or structure. Conventional robots typically include onboard sensors and/or imaging systems to obtain sensory information of its surroundings to facilitate localization and trajectory planning. However, when a conventional robot is positioned near a target surface to perform an operation on that surface, the robot's perception may only be able to obtain sensory information near that surface resulting in appreciably reduced perception of its surroundings. Limitations on the perception of the robot can make it challenging to accurately and precisely locate the robot in the environment, which, in turn, makes it challenging to determine a trajectory for the robot to follow as it performs operations.

**[0009]** Yet another limitation of some conventional robots relates to a degradation of performance and increased costs associated with the tendency to incorporate onboard components that provide all the necessary functionality for the robot to execute a particular task. For example, conventional aerobots often include an onboard power source (e.g., a battery), fluid storage and pumps (e.g., fluid(s) for treating surfaces such as cleaning fluid, paint, surfactants, etc.), sensors and/or imaging systems, and a flight controller. The weight of these various components may appreciably reduce its power-to-weight ratio (e.g., affecting the ability of the aerobot to perform rapid, complex maneuvers) and reduce the robot's payload capacity (e.g., its ability to carry consumables). Moreover, the integration of these components for every aerobot may appreciably increase the cost of a system that deploys multiple aerobots.

**[0010]** In view of the foregoing, the present disclosure is generally directed to robotic systems (also sometimes referred to herein as a "distributed robotic system") that include one or more end effector systems with an appreciably greater range of operation than conventional articulated arms. Additionally, components that are conventionally found onboard conventional autonomous vehicles are moved offboard from the end effector systems disclosed herein and onto other components and subassemblies of the robotic system, thus appreciably reducing the size, weight, and complexity of a mobile component of the robotic system and, hence, increasing the payload capacity and the power-to-weight ratio. The robotic system may further include a perception and localization system that provides appreciably greater perception for each end effector system and its surroundings, which may provide improved localization and trajectory planning. This may be achieved, in part, by the perception and localization system being positioned at a sufficient distance from the robotic system's primary area of operation (e.g., a target surface, wherein the perception and localization system is

positioned at a distance greater than the distance between the end effector system and the target surface).

**[0011]** The robotic system may include, for example, a robotic controller operably coupled to the effector systems where the robotic controller is physically separate from the effector systems. Each effector system includes an actuated effector mount and an effector (e.g., a contact tool). The actuated effector mount includes an onboard propulsion system to facilitate movement over one or more axes of motion. Thus, the actuated effector mount provides a way to position and orient the effector to interact with the environment.

**[0012]** In one aspect, the robotic systems disclosed herein may generally incorporate one or more flexible arms (also referred to herein as a “flex arm”) with passive, or non-actuated segments (i.e., non-articulated), with an effector system disposed at one end of the flexible arm. Specifically, the effector system may include an actuated effector mount (also referred to herein as a “mobile hand”) coupled to the flexible arm and an effector (also referred to herein as a “tool”) supported by the actuated effector mount. The actuated effector mount may include a propulsion system (e.g., one or more actuators, one or more thrusters) to facilitate movement of the effector system. Thus, in some implementations, the robotic controller may control the propulsion system to direct movement of the effector system in three-dimensional space rather than relying on actuators and/or a propulsion system integrated into the flexible arm. The flexible arm may instead be a passive component that generally provides various connections between the actuated effector mount and the remainder of the robotic system, such as a digital communications link, a power connection, and fluid lines as needed. In some implementations, the flexible arm may incorporate these various connections into a single, flexible cable that may be coiled and/or wound when retracted to occupy a relatively compact space. When deployed, the flexible arm may allow the effector system to have an appreciably greater reach compared to conventional robots with articulated arms. In the present disclosure, the robotic systems disclosed herein that have non-articulated passive flexible arms and actuated effector mounts (e.g., a mobile hand with a propulsion system) are sometimes referred to as a “flex-arm” robot.

**[0013]** In another aspect, the actuated effector mounts are capable of moving substantially independently or, in some instances, independently in the environment. Said another way, the actuated effector mount may be capable of movement in an environment that is not appreciably constrained by any other component or subassembly of the robotic system. As described above, the actuated effector mounts may be coupled to a flex arm that provides electrical power,

communication, fluids, and the like. The flex arm may be a mechanically passive and compliant component configured to impart little to no mechanical loads onto the effector system during operation. Thus, the effector system has the ability to provide all desired movement via the actuated effector mount to complete any task independent of the flexible arm.

**[0014]** In yet another aspect, the actuated effector mounts disclosed herein are not capable of generating control signals to facilitate movement of the actuated effector mount or the effector through an environment. Instead, the actuated effector mounts rely exclusively on external control signals (e.g., from the robotic controller) for movement. Thus, the actuated effector mount functions as an appendage (e.g., a hand) of the controller in the robotic system where the actuated effector mount is unable to operate independently, but instead is dependent on the controller during operation.

**[0015]** In yet another aspect, operation of the actuated effector mounts may be dependent on sensory data acquired, at least in part, by a physically separate location tracking system operably coupled to the controller. The sensory data includes location information that may be used by the controller to determine respective locations of the effector systems in the environment during operation.

**[0016]** In one example implementation, the effector system may be capable of flight and, hence, referred to herein as an “aerial effector” (also referred to as an “aerial end effector”). As described above, the aerial effector of a robotic system is unable to navigate an environment on its own or determine its location within that environment on its own. Instead, in example implementations, the aerial effector relies on one or more physically separate components of a robotic system to perform these functions.

**[0017]** Accordingly, the present disclosure discloses, in part, various inventive implementations of a robotic system that includes one or more aerial effectors configured to perform one or more operations on a vertical or inclined surface with a contact tool, and various methods of using the system to perform the operation(s). The operation(s) performed by the system include, but are not limited to, applying a cleaning fluid to a window, removing a waste fluid (e.g., a mixture of cleaning fluid and detritus) from the window, and painting a structure. In particular, an operation may involve moving an aerial effector equipped with a contact tool along a vertical or inclined surface with the contact tool in continuous physical contact with the surface. Additionally, the effector may be configured to apply a fluid to a surface (e.g., a cleaning fluid, paint) or remove a fluid from the surface (e.g., waste fluid). It should be

appreciated that, in some implementations, ground-based effectors with motorized wheels and/or articulated legs may be used in some applications.

**[0018]** Compared to conventional aerobots, the aerial effectors disclosed herein may be appreciably smaller, lighter, and simpler in design. In particular, multiple components onboard the previously disclosed aerobot may instead be disposed in one or more other components that, for example, may be less sensitive to payload considerations (e.g., the umbilical support system). More generally, the Inventor contemplates an alternative inventive implementation in which multiple components onboard the previously disclosed aerobot related to power management, fluidic control, localization sensing (e.g., to determine the location of the aerobot in the environment), and even flight control may be moved offboard to another component of a robotic system. In this manner, the size, weight, and complexity of a flying or aerial component of the robotic system may be appreciably reduced and the payload capacity and the power-to-weight ratio of the flying/aerial component may be appreciably increased. These improvements allow the flying/aerial component to more readily perform complex maneuvers (particularly when it is in physical contact with a surface) and/or more readily compensate for any external forces and/or torques applied to the flying/aerial component.

**[0019]** In one non-limiting implementation, a robotic window cleaning system includes one or more aerial effector(s) to perform various cleaning-related operations to a window of a structure. For example, the system may include an aerial effector with an applicator contact tool (also referred to as “an applicator aerial effector”) to apply a cleaning fluid to the window and an aerial effector with a squeegee contact tool (also referred to as a “squeegee aerial effector”) to remove waste fluid from the window. The applicator aerial effector and the squeegee aerial effector each include thrusters and are thus capable of flight. This allows multiple operations to be performed on different portions of the window simultaneously. For example, the applicator aerial effector may apply a cleaning fluid to one portion of the window and the squeegee aerial effector may simultaneously remove waste fluid from another portion of the same window or a different window. The squeegee aerial effector may further be capable of removing waste fluid using vacuum suction.

**[0020]** The applicator aerial effector and the squeegee aerial effector may be coupled to a support system via respective flexible arms (also referred to herein as “flex arms”). The support system provides, via the flex arms, electrical power, communication, and/or fluidic connections to the aerial effectors (e.g., to supply cleaning fluid, to remove waste fluid). Each flex arm may be a flexible, compliant cable that allows the aerial effector to readily move with respect to the

support system so long as the flex arm is not pulled taut (i.e., tensioned). The support system may include a localization system (also referred to herein as a “location tracking system,” or “perception and localization module”) to monitor the locations of the applicator aerial effector and the squeegee aerial effector in the environment. The support system may further include a controller to control the applicator aerial effector and the squeegee aerial effector. For example, the controller provides flight control signals to an aerial effector (e.g., signals to respective thrusters of the aerial effector) to facilitate movement of the aerial effector to a desired location within the environment and/or along a predetermined trajectory using the location data acquired by the localization system. In this manner, a robotic system including the support system, flex arms, and one or more aerial effectors is capable of performing at least some operations and/or processes in an autonomous or semi-autonomous manner, where the one or more aerial effectors effectively provide end-of-arm tooling.

[0021] The support system may further be coupled to a base station via an umbilical cord. The base station may be deployed on the ground or a roof of the structure. The base station may provide the support system cleaning fluid, electrical power, and/or communication via the umbilical cord. In some implementations, the base station may also retrieve waste fluid collected by the support system via the squeegee effector for storage. A central control system communicatively coupled to the base station and the support system to retrieve various sensory data and/or transmit commands to the base station and/or the support system to perform an action (e.g., clean a different window). The central control system may also provide an access point for a human operator to interface and control the system. For example, the central control system may include a portable computing device (e.g., a laptop, a phone, a tablet). The computing device may further include an application that provides a user interface to a human operator to monitor operation of the system and/or to input new commands for the system to execute. The central control system may further include a server and/or another computing device to facilitate, for example, analysis of data acquired by the robotic system (e.g., to compute and/or update a trajectory for an aerial effector).

[0022] In one aspect, each aerial effector may be operably coupled to a support system or a base station via a flex arm. In robotic systems where the aerial effectors are operably coupled to the base station via respective flex arms, the base station may perform the same function as the support system and thus may also be referred to as the support system. The flex arm may be a wired connection, such as in the above example implementation. Thus, the aerial effector may include a port as a flex arm interface to physically couple the flex arm to the aerial effector.

However, it should be appreciated that, in some implementations, the flex arm may provide a wireless connection (e.g., a wireless communication link). In other words, the aerial effector may be communicatively coupled to a support system and/or a base station wirelessly. For example, the aerial effector may be communicatively coupled to a support system or a base station via a radio frequency (RF) signal. Thus, the aerial effector may include an RF transceiver as a flex arm interface. The support system and/or the base station may also include an RF transceiver.

[0023] In another aspect, the aerial effectors disclosed herein may be appreciably lighter weight than conventional aerobots. This may be accomplished, as described above, by moving components that are typically onboard a conventional aerobot offboard onto another portion of the system. For example, the aerial effector may only include a frame, an effector coupled to the frame (e.g., a tool), one or more thrusters coupled to the frame, and a flex arm interface. In some implementations, the aerial effector may also include one or more sensors (e.g., a contact pressure sensor, a camera) to improve the use of the effector. Other components related to power management (e.g., a battery, power electronics), fluidic control (e.g., a valve, fluid storage), localization sensing (e.g., a camera, sonar, a LiDAR imager), and flight control (e.g., a flight controller) may be moved to the support system or the base station.

[0024] By reducing the weight of the aerial effectors, the payload capacity and/or the power-to-weight ratio may appreciably increase. This, in turn, may allow the aerial effector to be more agile. For example, the aerial effector may change its attitude at a higher rate compared to conventional aerobots. The higher power-to-weight ratio may also allow the aerial effector to more readily compensate for any undesirable forces and/or torques applied to the aerial effector, thus obviating the need for any separate device or mechanism to reduce the transmission of these forces and/or torques to the aerial effector. For example, in implementations where the flex arm is a cable, the weight of the flex arm and/or any forces acting on the flex arm (e.g., a wind force) may be transmitted as a force and/or a torque to the aerial effector. However, the higher power-to-weight ratio of the aerial effector may readily compensate for these forces and/or torques. Thus, the aerial effectors disclosed herein may carry at least a portion of the flex arm. Additionally, the operation of the support system and the base station is less affected by additional payload compared to the aerial effector. For example, the support system and the base station do not have to be agile. Thus, moving the components described above to the support system and/or the base station may not require any appreciable alterations to their respective designs to compensate for the higher payload. In yet

another aspect, the aerial effectors disclosed herein may be relatively less expensive to manufacture and maintain.

**[0025]** It should be appreciated that, in some implementations, the aerial effectors disclosed herein may include additional components for some applications. For example, in some applications, an aerial effector may navigate a confined space, such as the inspection and/or maintenance of a pipe. For these applications, a flex arm with a cable may get caught on environmental obstacles. Thus, it may be preferable to use a flex arm that provides a wireless connection, as described above. Additionally, the aerial effector may include a battery to provide an onboard power source. In some applications, the aerial effector may also dispense a fluid (e.g., dispensing a sealant on the surface of the pipe to seal a crack). Thus, the aerial effector may also include an onboard pump and/or an onboard tank containing the fluid.

**[0026]** The robotic systems contemplated herein may generally support various support systems. In one example, the base station may be deployed on a roof of a structure and include a boom arm. The support system may be suspended from the boom arm via a cable and an end pulley. During operation, the support system may move to a particular window (e.g., by adjusting the length of the cable, moving the base station) and the aerial effectors may perform one or more operations on that window. In another example, the support system may include one or more thrusters to provide sustained flight. In other words, the support system may be an aerobot. During operation, the support system may fly to a particular window (e.g., by adjusting the thrust generated by each thruster) and the aerial effectors may perform one or more operations on that window. It should also be appreciated that, in some implementations, the base station can function as a support system. For example, the aerial effectors may be directly coupled to the base station via respective flex arms. This system may be deployed, for example, to clean the windows of a one or two-story building.

**[0027]** It should also be appreciated that at least some of the concepts described above may be implemented in a robotic system with an aerial effector configured to perform other surface-related operations in other applications. For example, a robotic painting system may include an aerial effector with a paint roller to apply paint to a surface. The aerial effector may be connected to a base station via a flex arm that supplies the paint to the aerial effector. A support system separate from the base station may also be included to facilitate deployment of multiple aerial effectors near the surface (e.g., to paint multiple nearby surfaces simultaneously, to paint different coatings on the same surface).

[0028] In another example, a robotic crop harvesting system may include an aerial effector with a crop harvesting tool (e.g., a fruit picker basket) to collect crops from various plants. In particular, the aerial effector may readily harvest crops from relatively tall plants (e.g., a fruit tree) that typically are only accessible to human workers with a ladder. The aerial effector may include an onboard storage unit (e.g., a container, a basket) to store collected crops and may periodically transfer the crops from the onboard storage unit to an offboard storage unit (e.g., a larger container onboard the base station). The aerial effector may be connected to a base station via a flex arm that provides electrical power and communication. A support system separate from the base station may also be included to facilitate deployment of multiple aerial effectors to harvest crops simultaneously.

[0029] It should be appreciated that all combinations of the foregoing concepts and additional concepts discussed in greater detail below (provided such concepts are not mutually inconsistent) are contemplated as being part of the inventive subject matter disclosed herein. In particular, all combinations of claimed subject matter appearing at the end of this disclosure are contemplated as being part of the inventive subject matter disclosed herein. It should also be appreciated that terminology explicitly employed herein that also may appear in any disclosure incorporated by reference should be accorded a meaning most consistent with the particular concepts disclosed herein.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0030] The skilled artisan will understand that the drawings primarily are for illustrative purposes and are not intended to limit the scope of the inventive subject matter described herein. The drawings are not necessarily to scale; in some instances, various aspects of the inventive subject matter disclosed herein may be shown exaggerated or enlarged in the drawings to facilitate an understanding of different features. In the drawings, like reference characters generally refer to like features (e.g., functionally similar and/or structurally similar elements).

[0031] FIG. 1A shows an example of a robotic system.

[0032] FIG. 1B shows a diagram of the robotic system of FIG. 1A with arrows indicating the flow of sensory data and control signals between an effector system and a controller.

[0033] FIG. 1C shows an example of a robotic system that includes one or more aerial effectors with multiple degrees of freedom to perform various work tasks by utilizing a plurality of thrusters.

[0034] FIG. 2 shows an example window cleaning system that includes a base station with a boom arm deployed on a roof of a structure, a support system with a location tracking system suspended from the boom arm, and multiple aerial effectors to clean a window of the structure. In this example, the base station only supplies a cleaning fluid.

[0035] FIG. 3 shows another example window cleaning system that includes a base station with a boom arm deployed on a roof of a structure, a support system with a location tracking system suspended from the boom arm, and multiple aerial effectors to clean a window of the structure. In this example, the base station supplies a cleaning fluid and retrieves waste fluid.

[0036] FIG. 4 shows another example window cleaning system that includes a base station with a boom arm deployed on a roof of a structure, a support system suspended from the boom arm, and multiple aerial effectors to clean a window of the structure. In this example, the base station the base station only supplies a cleaning fluid and an aerial effector includes a location tracking system.

[0037] FIG. 5 shows another example window cleaning system that includes a base station deployed on the ground, a support system with thrusters for sustained flight and a location tracking system, and multiple aerial effectors to clean a window of the structure.

[0038] FIG. 6 shows another example window cleaning system that includes a base station deployed on the ground, a support system with thrusters for sustained flight, and multiple aerial effectors to clean a window of the structure. In this example, an aerial effector includes a location tracking system.

[0039] FIG. 7 shows another example window cleaning system that includes a base station deployed on the ground and multiple aerial effectors to clean a window of the structure. In this example, the base station is a support system and an aerial effector includes a location tracking system.

[0040] FIG. 8 shows another example window cleaning system that includes a base station deployed on the ground and multiple aerial effectors to clean a window of the structure. In this example, the base station is a support system and includes a mounting arm to support a location tracking system.

[0041] FIG. 9 shows another example window cleaning system that includes a base station deployed on the ground and multiple aerial effectors to clean a window of the structure. In this example, a support system is mounted onto the base station via a telescoping mast and supports multiple aerial effectors.

[0042] FIG. 10 shows a block diagram of an example window cleaning system that includes a support system with a robotic controller to control the support system and an aerial effector and a base station with a base station controller to control the base station.

[0043] FIG. 11 shows a block diagram of another example window cleaning system that includes a support system with a robotic controller to control the support system, an aerial effector, and a base station.

[0044] FIG. 12 shows a block diagram of another example another window cleaning system that includes a support system and a base station with a base station controller to control the support system, the base station, and an aerial effector.

[0045] FIG. 13 shows a block diagram of another example another window cleaning system that includes a base station with a base station controller to control the base station and an aerial effector.

[0046] FIG. 14A shows another example window cleaning system that includes a base station, a support system mounted to the base station via a telescoping mast, and multiple aerial effectors supported by the support system. In this figure, the window cleaning system includes multiple legs in a retracted position.

[0047] FIG. 14B shows the window cleaning system of FIG. 14A with the legs in a deployed position.

[0048] FIG. 14C shows the window cleaning system of FIG. 14B where the support system is rotated to partially face a building.

[0049] FIG. 14D shows the window cleaning system of FIG. 14C where the support system is rotated to face the building.

[0050] FIG. 14E shows multiple window cleaning systems of FIG. 14A deployed to clean different portions of a building. A first window cleaning system is shown with a support system at its lowest position. A second window cleaning system is shown already deployed and in operation.

[0051] FIG. 14F shows the first window cleaning system of FIG. 14E with the support system raised to an intermediate position by the telescoping mast.

[0052] FIG. 14G shows the first window cleaning system of FIG. 14F with the support system raised to its highest position by the telescoping mast.

[0053] FIG. 14H shows the first window cleaning system of FIG. 14G with landing pads moved from a storage position to a deployed position.

[0054] FIG. 14I shows the first window cleaning system of FIG. 14H with an applicator aerial effector deployed from the support system. The second window cleaning system is shown with its support system lowered to its lowest position.

[0055] FIG. 14J shows a front perspective view of the window cleaning system of FIG. 14A where the support system 200g and the base station 300g have a spotted pattern to give the window cleaning system a more animal-like appearance.

[0056] FIG. 14K shows a rear perspective view of the window cleaning system of FIG. 14J.

[0057] FIG. 15A shows the support system of the window cleaning system of FIG. 14A with the landing pads in a storage position.

[0058] FIG. 15B shows the support system of the window cleaning system of FIG. 14A with the landing pads in a deployed position.

[0059] FIG. 16A shows an applicator aerial effector in the window cleaning system of FIG. 14A.

[0060] FIG. 16B shows another view of the applicator aerial effector of FIG. 16A.

[0061] FIG. 17A shows a squeegee aerial effector in the window cleaning system of FIG. 14A.

[0062] FIG. 17B shows another view of the squeegee aerial effector of FIG. 17A.

[0063] FIG. 18A shows the window cleaning system of FIG. 14A with the support system being lowered to position the aerial effectors to begin respective tasks on different windows.

[0064] FIG. 18B shows the window cleaning system of FIG. 18A with a squeegee aerial effector beginning to remove waste fluid from a first window and an applicator aerial effector beginning to apply cleaning fluid to a second window. The paths followed by the squeegee and applicator aerial effectors are shown in dashed lines on respective windows.

[0065] FIG. 18C shows the window cleaning system of FIG. 18B with the squeegee and applicator aerial effectors progressing in their respective tasks.

[0066] FIG. 18D shows the window cleaning system of FIG. 18C with the squeegee and applicator aerial effectors progressing in their respective tasks.

[0067] FIG. 18E shows the window cleaning system of FIG. 18D with the squeegee and applicator aerial effectors progressing in their respective tasks.

[0068] FIG. 18F shows the window cleaning system of FIG. 18E with the squeegee and applicator aerial effectors progressing in their respective tasks.

[0069] FIG. 18G shows the window cleaning system of FIG. 18F with the squeegee and applicator aerial effectors progressing in their respective tasks.

[0070] FIG. 18H shows the window cleaning system of FIG. 18G with the squeegee and applicator aerial effectors completing their respective tasks.

[0071] FIG. 18I shows the window cleaning system of FIG. 18H with the support system being lowered to position the aerial effectors to begin respective tasks on different windows.

[0072] FIG. 19A shows the window cleaning system of FIG. 18A with the base station being moved horizontally to position the aerial effectors to begin respective tasks on different windows.

[0073] FIG. 19B shows the window cleaning system of FIG. 19A with the squeegee and applicator aerial effectors progressing in their respective tasks. As shown, the squeegee and applicator aerial effectors may perform tasks on windows that are not adjacent to each other.

[0074] FIG. 19C shows the window cleaning system of FIG. 19B with the squeegee and applicator aerial effectors progressing in their respective tasks.

[0075] FIGS. 20A-20J show additional views of the cleaning system of FIG. 19A. The cleaning system is shown as a shaded model.

[0076] FIGS. 21A-21J show additional views of the cleaning system of FIG. 19A. The cleaning system is shown as a wireframe model.

[0077] FIGS. 22A-22G show additional views of the support system in the cleaning system of FIG. 19A. The support system is shown as a shaded model.

[0078] FIGS. 23A-23G show additional views of the support system in the cleaning system of FIG. 19A. The support system is shown as a wireframe model.

[0079] FIGS. 24A-24C show views of an example squeegee aerial effector for the cleaning system of FIG. 19A.

[0080] FIGS. 25A-25C show views of an example applicator aerial effector for the cleaning system of FIG. 19A.

## DETAILED DESCRIPTION

**[0081]** Following below are more detailed descriptions of various concepts related to, and implementations of, robotic systems and methods for using the robotic system to facilitate interactions with an environment via one or more effector systems. In one non-limiting example, a robotic system may facilitate contact treatment of outdoor and indoor vertical or inclined surfaces (which may be elevated surfaces) via one or more effector systems configured to operate as aerial effectors. Examples of contact treatment contemplated by the present disclosure include, but are not limited to, cleaning (e.g., including application of a cleaning fluid, agitating/scrubbing of the surface, removal of waste fluid, and/or drying), coating (e.g., with a surfactant), painting, sanding, polishing, and crop harvesting. It should be appreciated that various concepts introduced above and discussed in greater detail below may be implemented in multiple ways. Examples of specific implementations and applications are provided primarily for illustrative purposes so as to enable those skilled in the art to practice the implementations and alternatives apparent to those skilled in the art.

**[0082]** The figures and example implementations described below are not meant to limit the scope of the present implementations to a single embodiment. Other implementations are possible by way of interchange of some or all of the described or illustrated elements. Moreover, where certain elements of the disclosed example implementations may be partially or fully implemented using known components, in some instances only those portions of such known components that are necessary for an understanding of the present implementations are described, and detailed descriptions of other portions of such known components are omitted so as not to obscure the present implementations.

**[0083]** In the discussion below, various examples of a robotic system with effector systems (e.g., an aerial effector to perform at least one operation on a vertical or inclined surface) are provided, wherein a given example or set of examples showcases one or more features of an actuated effector mount, an effector, a base station, a support system, a central control system, a controller, and one or more control systems to generate and execute a trajectory or method of performing an operation. It should be appreciated that one or more features discussed in connection with a given example of a robotic system may be employed in other examples of robotic systems according to the present disclosure, such that the various features disclosed herein may be readily combined in a given robotic system according to the present disclosure (provided that respective features are not mutually inconsistent).

[0084] Certain dimensions and features of the robotic system and its subassemblies, components and/or subsystems are described herein using the terms “approximately,” “about,” “substantially,” and/or “similar.” As used herein, the terms “approximately,” “about,” “substantially,” and/or “similar” indicates that each of the described dimensions or features is not a strict boundary or parameter and does not exclude functionally similar variations therefrom. Unless context or the description indicates otherwise, the use of the terms “approximately,” “about,” “substantially,” and/or “similar” in connection with a numerical parameter indicates that the numerical parameter includes variations that, using mathematical and industrial principles accepted in the art (e.g., rounding, measurement or other systematic errors, manufacturing tolerances, etc.), would not vary the least significant digit.

#### [0085] 1. An Example Robotic System

[0086] Herein, a robotic system may include multiple, physically separate subassemblies that operate together to perform one or more operations. Thus, the robotic systems disclosed herein may be viewed as a single robot with distributed subassemblies and not multiple, distributed robots. A subassembly refers to an assembly of components that are physically coupled together such that they move together during operation. For example, a subassembly may include an onboard propulsion system (e.g., motorized wheels, legs, thrusters, and the like) to collectively move an assembly of components together as a single body. Each subassembly of the robot may be communicatively coupled to other subassemblies via a wired or wireless connection.

[0087] FIGS. 1A and 1B show an example of a robotic system 100. As shown, the robotic system 100 may include a robotic controller 160 (also referred to herein as a “controller 160,” and a “robotic limb controller 160”) operatively coupled to a pair of effector systems 102-1 and 102-2 (referred to herein generally as an “effector system 102”) via respective flexible arms 150 (also referred to herein as a “flexible robotic arm 150” or a “flex arm 150”). In one non-limiting example, the flex arm 150 may be a cable that provides one or more conduits to carry, for example, electrical power, communication signals (e.g., data, control signals), and/or fluids to and/or from the effector system 102 (e.g., cleaning fluid for cleaning windows, waste fluid from the windows). Each respective pair of the effector system 102 and its corresponding flex arm 150 constitute a robotic limb of the robotic system 100 through which the system 100 interacts with the environment. The robotic system 100 may further include a location tracking system 170 (also referred to herein as a “localization system 170,” and a “perception and

localization module 170”) to monitor the locations of the effector systems 102-1 and 102-2 in the environment during operation.

[0088] In this example, the effector systems 102-1 and 102-2 each constitute a subassembly. The controller 160 and the location tracking system 170 may form part of the same subassembly or different subassemblies. FIG. 1B shows the system 100 may further include one or more sensor(s) 171, which may be disposed on the same subassembly as the controller 160 and/or the location tracking system 170 or a different subassembly. It should be appreciated that the system 100 depicted in FIGS. 1A and 1B omits certain components for the sake of clarity. More generally, the system 100 may include other components that may form one or more subassemblies including, but not limited to, a power management subsystem (e.g., to supply and regulate electrical power to various subassemblies of the robotic system 100), a fluid management subsystem (e.g., to supply and regulate the flow of various fluids used by the robotic system 100), propulsion systems to facilitate movement of other subassemblies, and actuation mechanisms for other subassemblies (e.g., a pair of subassemblies may be mechanically coupled together via one or more actuators, such as the stage 220, the boom arm 222, and the cable winch 228 in FIG. 2).

[0089] Each effector system 102 may include an actuated mobile effector mount 104 (also referred to herein as a “actuated effector mount,” and an “actuated mobile hand”) and an effector 106 (also referred to herein as a “tool 106”) supported (e.g., held) by the actuated effector mount 104. The actuated effector mount 104 may provide movement over one or more axes of motion (e.g., translation and/or rotation) via an onboard propulsion system 129. Said another way, the actuated effector mount 104 may be configured for at least one of translational or rotational motion with multiple degrees of freedom. The propulsion system 129 may facilitate mobility of the actuated effector mount 104. Thus, the actuated effector mount 104 may position and orient the effector 106 to interact with the environment, e.g., a structure or an object in the environment. The effector 106 is a device used to perform one or more operations associated with the structure or object (e.g., apply cleaning fluid to a window, remove waste fluid from the window, harvest crops from a tree, acquire imagery and/or sensory data, and the like). In some implementations, the effector 106 may be a passive device that is manipulated solely by the actuated effector mount 104 via the propulsion system 129. In some implementations, the effector 106 may be an active device that includes one or more actuator(s) 132 (e.g., an articulated arm) to provide another mechanism for manipulation in addition to manipulation by the actuated effector mount 104.

**[0090]** In some implementations, the effector 106 may perform one or more operations that involve the effector 106 physically contacting a surface of an object or structure. For example, the effector 106 may be an applicator (e.g., see the applicator effector 106a) used to apply a cleaning fluid to a surface of a window. In another example, the effector 106 may be a squeegee (e.g., see the squeegee effector 106b) used to remove waste fluid from a window. In some implementations, the effector 106 may perform one or more operations that do not involve the effector 106 physically contacting a surface. For example, the effector 106 may itself be a location tracking system that acquires imagery and/or other sensory data that is processed (e.g., by the controller 160) to determine the location of other effector systems 102 operating in the environment.

**[0091]** In some implementations, the robotic system 100 may operate autonomously. In other words, the robotic system 100 may operate (e.g., perform an operation) without any human intervention once the robotic system 100 is deployed and activated. For example, a human operator may move the robotic system 100 to a worksite and, once deployed, the robotic system 100 may thereafter execute a workplan (e.g., clean multiple windows of a building) without requiring any further input from a human operator. Example operations that the robotic system 100 can perform autonomously include, but are not limited to, the controller 160 autonomously determining a location of the actuated mobile hand 104, the controller 160 autonomously determining a trajectory of the mobility of the actuated mobile hand 104 based at least in part on the location of the actuated mobile hand 104, and the controller 160 generating the at least one control signal for the propulsion system 129 of the actuated mobile hand 104 based at least in part on the determined trajectory of the mobility of the actuated mobile hand 104.

**[0092]** In some implementations, the robotic system 100 may operate semi-autonomously. In other words, the robotic system 100 may operate (e.g., perform an operation) with some human intervention and/or oversight. For example, the robotic system 100 may execute a workplan that requires the human operator to occasionally intervene during operation. Example operations that the robotic system 100 can perform semi-autonomously include, but are not limited to, the system 100 cleaning a first subset of windows on a building and thereafter having a human operator move the system 100 to another location near the building to clean a second subset of windows.

**[0093]** It should be appreciated that the robotic system 100 shown in FIG. 1A is a non-limiting example and that, more generally, the robotic systems 100 disclosed herein may include one or more effector systems 102. For example, the system 100 may only include a single effector

system 102. In another example, the system 100 may include three or more effector systems 102 (see, for example, the window cleaning system 100d in FIG. 4). Additionally, the robotic systems 100 disclosed herein may include multiple, different effector systems 102. For example, the robotic system 100 may include multiple effector systems 102 configured to operate as aerial effectors (e.g., capable of flying through air) where respective effector systems 102 include different effectors 106 to perform different operations (e.g., an applicator effector to apply a cleaning fluid to a window and a squeegee effector to remove waste fluid from the window).

**[0094]** In one aspect, the effector systems 102 disclosed herein may be capable of moving in a substantially independent or, in some instances, independent manner with respect to other subassemblies or components of the robotic system 100. This may be accomplished, in part, by the actuated effector mount 104 providing active actuation while the flex arm 150 remains mechanically passive. In contrast, a conventional articulated robot typically includes an actively actuated articulated arm to facilitate movement of a mechanically passive effector.

**[0095]** Herein, each actuated effector mount 104 is considered to be “actuated.” In other words, the position and/or orientation of the actuated effector mount 104 may be actively controlled via powered movement through use of one or more actuators (e.g., motors, hydraulic systems, pneumatic systems, or other mechanisms) to move the actuated effector mount 104. Moreover, the movement of the actuated effector mount 104 may then cause movement of other components in the system 100. For example, as the actuated effector mount 104 actively moves, it may displace the attached flex arm 150. For example, the actuated effector mount 104 may include an onboard propulsion system 129 to generate a propulsive force to move the actuated effector mount 104 and the effector 106 with multiple degrees of freedom. Thus, the effector system 102 may not rely on any propulsion system or actuator external to the actuated effector mount 104 and the effector 106 for movement.

**[0096]** In some implementations, the flex arm 150 may be a cable that physically couples the effector system 102 to another subassembly of the robotic system 100 (e.g., the controller 160). The flex arm 150, however, may be mechanically “passive.” In other words, the position and/or orientation of the flex arm 150 may not be actively controlled. Said another way, the flex arm 150 does not have any powered movement, e.g., the flex arm 150 does not include any propulsion system or actuation mechanism to facilitate movement of the flex arm 150. Said in yet another way, the flex arm 150 is not an articulated arm. Thus, the flex arm 150 may also be referred to as a non-articulated passive flexible arm 150. The flex arm 150 relies upon an

externally applied force for movement. The external force may come from various sources including, but not limited to, gravity acting on the center of mass of the flex arm 150, and movement of one or more other actuated components (e.g., the actuated effector mount 104).

[0097] Additionally, the effector system 102 may be capable of movement through an environment without any appreciable physical constraints imposed by other subassemblies or components of the robotic system 100. The flex arm 150, for example, may be designed such that no appreciable loads (e.g., forces, torques) are transferred from the flex arm 150 to the effector system 102 during operation. For example, the flex arm 150 may be formed from a lightweight material (e.g., plastic, rubber, fluoropolymer), thus reducing the weight of the flex arm 150. In another example, the robotic system 100 may maintain sufficient slack in the flex arm 150 during operation to appreciably reduce or, in some instances, eliminate tension in the flex arm 150.

[0098] It should also be appreciated that, in some implementations, the effector systems 102 may not be physically coupled to another subassembly in the robotic system 100. For example, the effector system 102 may be communicatively coupled to the controller 160 via a wireless transceiver. Further, the effector system 102 may retain an onboard power source (e.g., a battery) and/or components to store, dispense, and/or retrieve a fluid (e.g., a pump, a tank). Thus, the flex arm 150 in this configuration may only include a wireless communication link.

[0099] The propulsion system 129 may provide propulsion in various ways. In some implementations, the propulsion system 129 may include one or more thrusters that produce thrust by displacing a fluid (e.g., air, water). For example, the thruster(s) may each include a motorized rotor to displace air (see, for example, the thrusters 130 in FIG. 1C). Multiple thrusters may be incorporated onto the actuated effector mount 104 and arranged to facilitate movement over multiple degrees of freedom. For example, the thrusters may position and orient the effector system 102 over six degrees of freedom (e.g., three translational degrees of freedom and three rotational degrees of freedom).

[0100] Although the example implementations disclosed in the present application are generally directed to motorized rotors that displace air, one of ordinary skill in the art should readily appreciate that the architecture of the robotic systems 100 disclosed herein may be readily adapted for operation in aquatic environments. For example, the robotic system 100 may include multiple effector systems 102 configured to operate along the surface of a body

of water or under water. The effector system 102 may include, for example, one or more thrusters that displace water instead of air.

**[0101]** In some implementations, the propulsion system 129 may provide a way for the actuated effector mount 104 to move on the ground. For example, the propulsion system 129 may include one or more motorized wheels or tracks. In another example, the propulsion system 129 may include one or more motorized articulated legs and/or feet. For instance, the propulsion system 129 may be a quadruped with four motorized articulated legs.

**[0102]** It should be appreciated that the propulsion system 129 may generally include any combination of the foregoing propulsion mechanisms described above. For example, FIG. 1A shows the propulsion system 129 for each effector system 102 may include multiple rotor(s), motorized wheel(s), and articulated legs and feet. These different propulsion mechanisms may be used to facilitate movement in the air, the water, and/or on the ground.

**[0103]** In another aspect, the actuated effector mounts 104 disclosed herein rely exclusively on external control signals from a physically separate device or system (e.g., the controller 160, a central control system) to facilitate movement of the actuated effector mount 104 and, by extension, the effector 106. The external control signals may facilitate, for example, navigation through an environment and/or interactions with various objects and structures in the environment via movement of the actuated effector mount 104 (e.g., maneuvering the actuated effector mount 104 into physical contact with an object or to acquire imagery of objects and structures). Although conventional autonomous vehicles also receive external control signals during operation, the actuated effector mounts 104 disclosed herein are distinguished over conventional autonomous vehicles, in part, because conventional autonomous vehicles generally retain the ability to generate control signals (i.e., internal control signals) to facilitate movement of the vehicle.

**[0104]** Herein, a control signal is considered to be generated by processing one or more inputs of data. This may involve applying one or more operations to the input(s) to obtain the control signal. These operations may include, but are not limited to, addition, subtraction, multiplication, scaling, differentiation, integration, and the like. For example, a conventional aerobot often includes a rotor-based thruster with a speed controller. The control signal for the speed controller is generated by processing sensory data as inputs, such as the attitude of the aerobot, the position of the aerobot in the environment, and the desired trajectory of the aerobot. However, a control signal is not considered to be generated if the control signal is merely

converted between different forms. For example, a control signal is not considered to be generated when the control signal is converted from a first communication protocol to a second communication protocol.

**[0105]** As an illustrative example, it is not uncommon for a conventional aerobot to receive a control signal from a remote device (e.g., a phone, a computer) operated by a human operator with instructions to move from its current location to a new location. As the aerobot executes the instructions, a flight controller onboard the aerobot actively adjusts the thrust generated by each thruster to direct the aerobot towards the new location along a desired trajectory. The adjustments made by the flight controller often involve processing sensory data and generating control signals for each thruster based on the sensory data. The sensory data typically includes location data on the aerobot acquired by an onboard location tracking system.

**[0106]** In contrast, the effector system 102 and, in particular, the actuated effector mount 104 disclosed herein do not generate any internal control signals to facilitate movement of the actuated effector mount 104. Said another way, no component of the actuated effector mount 104 is able to apply an operation to one or multiple inputs for the purposes of obtaining a control signal based on those input(s) for the propulsion system 129. For example, the actuated effector mount 104 is unable to receive sensory data as an input and generate a control signal for the propulsion system 129 based on the sensory data. Instead, the actuated effector mount 104 relies exclusively on external control signals during operation. The control signals may generally originate from any device or system that is physically separate from the effector system 102. This approach of making the actuated effector mount 104 dependent on external control signal(s) for movement may reduce the payload and cost of the effector system 102. For example, the actuated effector mount 104 of each effector system 102 in the robotic system 100 may not include an onboard flight controller, thus reducing the weight and cost of each effector system 102.

**[0107]** In some implementations, the external control signals may be provided exclusively by the controller 160. From a control architecture standpoint, the actuated effector mount 104 thus functions as an appendage (e.g., a hand) of the controller 160 in the robotic system 100 instead of a standalone autonomous vehicle. Said another way, the actuated effector mount 104 is an instrument used, in part, to manipulate the effector 106, but is not capable of independent operation. Instead, the actuated effector mount 104 is dependent on the controller 160 during operation.

**[0108]** In some non-limiting implementations, the effector system 102 may be unable to generate internal control signals for any onboard components of the actuated effector mount 104 and the effector 106. Thus, the external control signal(s) provided to the actuated effector mounts 104 may facilitate operation of all components in the effector system 102. These components may include, but are not limited to, the propulsion system 129 of the actuated effector mount 104, and the actuator(s) 132 of the effector 106. Accordingly, the external control signal(s) may include, but are not limited to, electrical signals to adjust the operation of a propulsion system 129 onboard the actuated effector mount 104 to facilitate movement of the effector system 102 through an environment, electrical signals to adjust the operation of one or more actuator(s) 132 of the effector 106 (e.g., a motor to perform a scrubbing motion with an applicator effector, a motor to rotate a squeegee effector to provide a continuous sweeping motion), and the like.

**[0109]** Although the effector system 102 may rely on external control signal(s) from a separate device or system during operation, it should be appreciated that the effector system 102 may still retain some onboard processing capability. For example, the effector system 102 may include onboard electronic circuitry, such as a processor. The electronic circuitry, however, may be limited in terms of the functions it performs during operation, e.g., it cannot generate any control signals. In some implementations, the electronic circuitry may only facilitate the transmission of signals and/or the conditioning of electrical power.

**[0110]** As an illustrative example, FIG. 1B shows several components of the subassemblies in the robotic system 100 and the manner in which signals (e.g., sensory data, control signals) may flow to and from the effector system 102 and the controller 160. As shown, the actuated effector mount 104 may include a processor 140 to execute a limited set of processes described below and memory 141 to store, at least, instructions to facilitate execution of the limited set of processes. The processor 140 may be operatively coupled to other various onboard components of the effector system 102 including, but not limited to, the propulsion system 129, the actuator(s) 132 of the effector 106, one or more sensor(s) 142 onboard the actuated effector mount 104, one or more sensor(s) 146 onboard the effector 106, and a flex arm interface 120a to facilitate mechanical and electrical connection to the flex arm 150. For example, the flex arm interface 120a may include a connector that allows the flex arm 150 to be removably coupled to the effector system 102. The flex arm interface 120a may be connected to various onboard components of the effector system 102 (e.g., the processor 140, the sensors 142 and 146, and so on).

[0111] The controller 160 may include a processor 161 to execute various processes and memory 162 to store, at least, instructions to facilitate execution of these processes. The processes executed by the controller 160 may include the generation of control signals for any component of the robotic system 100. The processor 140 may be operatively coupled to other various subassemblies of the robotic system 100 including, but not limited to, the location tracking system 170, sensor(s) 171 disposed on the same or different subassembly as the controller 160 of the robotic system 100, and a flex arm interface 120b to facilitate mechanical and electrical connection to the flex arm 150. The flex arm interface 120a may be connected to various components of the robotic system 100 (e.g., the controller 160, a power source).

[0112] FIG. 1B shows that during operation, the processor 140 may facilitate the transmission of sensory data from the sensors 142 and 146 onboard the effector system 102 to the controller 160. The processor 140 may also facilitate the transmission of control signals from the controller 160 to various components of the effector system 102, such as the propulsion system 129 and the actuator(s) 132.

[0113] Thus, an example process that may be executed by the processor 140 is the transmission of sensory data acquired by the sensor(s) 142 and/or 146 in the effector system 102 to the controller 160. In some implementations, the processor 140 may receive sensory data from the sensor(s) 142 and/or 146 as an analog signal or a digital signal and may transmit the sensory data to the controller 160 according to a desired communication protocol via the flex arm 150. However, the processor 140 may not process and/or otherwise utilize the sensory data to directly adjust any other onboard components (e.g., the propulsion system 129, the actuator(s) 132), but instead rely on the controller 160 to process the sensory data and generate control signals to adjust the onboard components of the effector system 102.

[0114] Another example process that may be executed by the processor 140 is the receipt of one or more control signals from the controller 160 and the subsequent transmission of the control signal(s) to one or more corresponding onboard components of the effector system 102. This process may involve the conversion of control signal(s) from a first communication protocol to a second communication protocol different from the first communication protocol. For example, the processor 140 may receive control signal(s) for the propulsion system 129 and/or the actuator(s) 132 with a communication protocol suitable for transmission over several meters (e.g., Controller Area Network (CAN)). The processor 140 may thereafter convert the control signal(s) into a form compatible with the propulsion system 129 and/or the actuator(s) 132 (e.g., using pulse width modulation (PWM)).

**[0115]** In FIG. 1B, the effector system 102 may transmit data to the controller 160 and/or transmit and receive control signal(s) from the controller 160 via a wired connection (e.g., the flex arm 150a and 150b). However, it should be appreciated that, in some implementations, the effector system 102 may communicate with the controller 160 using a flex arm that provides a wireless connection (e.g., via corresponding wireless transceivers coupled to the effector system 102 and the controller 160). It should also be appreciated that, even if the effector system 102 is communicatively coupled to the controller 160 wirelessly, the effector system 102 may still be coupled to the controller 160 or another subsystem of the robotic system 100 via a physical cable, e.g., to receive electrical power and/or fluids. Thus, in some implementations, the flex arm 150 may include both wired and wireless connections.

**[0116]** The effector system 102 may generally communicate with the controller 160 using various wired and/or wireless communication protocols including, but not limited to, CAN, RS-485, RS-422, Universal Asynchronous Receiver/Transmitter (UART), Universal Synchronous/Asynchronous Receiver/Transmitter (USART), Universal Serial Bus (USB), Serial Peripheral Interface (SPI), I2C, WiFi, Bluetooth, Zigbee, Z-wave, Radio Frequency Identification (RFID), Near Field Communication (NFC), and Long Range Wide Area Network (LoRaWAN).

**[0117]** In yet another example, the actuated effector mount 104 may include onboard electronic circuitry that provides power conditioning. The actuated effector mount 104 disclosed herein may receive electrical power from a physically separate power source via the flex arm 150. The electronic circuitry, in turn, may improve the quality of the electrical power supplied to the various onboard components of the effector system 102 (e.g., the propulsion system 129, the sensors 142 and 146, the processor 140). Herein, the quality of electrical power may be improved by reducing electrical noise and/or fluctuations (e.g., voltage fluctuations, current fluctuations), supplying electrical power at an appropriate voltage for respective onboard components, and the like. This may be accomplished, for example, by the electronic circuitry incorporating active power conditioning circuitry (e.g., transistors) and/or passive power conditioning circuitry (e.g., resistors, inductors, capacitors).

**[0118]** In yet another aspect, the operation of the effector systems 102 in the robotic system 100 may be dependent on sensory data acquired, at least in part, by a physically separate system in the robotic system 100. The sensory data is used by the controller 160 to determine a location of each effector system 102 within the environment. In some implementations, the location of each effector system 102 may be defined in relation to the environment. In some

implementations, the location of each effector system 102 may be defined in relation to other subassemblies of the robotic system 100 (e.g., other effector systems 102, the controller 160, and so on).

**[0119]** In one example, the robotic system 100 may include the location tracking system 170 to monitor the location of respective effector system(s) 102 in the robotic system 100 during operation. The location tracking system 170 may be physically separate from the effector system(s) 102 capable of monitoring the locations of two or more effector systems 102 simultaneously. The location tracking system 170 may include, but is not limited to, one or more sensors (e.g., a rangefinder, a global positioning system (GPS) receiver), imaging systems (e.g., a camera, a LiDAR imager), and the like.

**[0120]** In some implementations, the location tracking system 170 may provide a field of view suitable for visually identifying the effector systems 102 and/or physical features in the environment, including objects or structures that the effector systems 102 physically contact and/or otherwise interact with during operation (e.g., a window, a building façade). For example, the location tracking system 170 may acquire a physical 3D map of the environment suitable for determining a 3D coordinate location of the effector systems 102 in the environment. The 3D map may also be used to identify (e.g., by the controller 160) various objects and structures in the environment (e.g., a window of a building) that the effector systems 102 may interact with or avoid. In another example, the location tracking system 170 may acquire video imagery of the environment and the effector systems 102 in the environment suitable for object recognition and localization.

**[0121]** The field of view of the location tracking system 170 may be appreciably larger than the field of view attainable by a location tracking system incorporated onto any one effector system 102 of the robotic system 100. The relatively larger field of view of the location tracking system 170 may be used to monitor the location of each effector system 102 in the robotic system 100 that is deployed in the environment and the portion of the environment where each deployed effector system 102 is expected to travel while executing an operation, e.g., according to their respective trajectories. Thus, in some implementations, the field of view of the location tracking system 170 may cover two or more effector systems 102 simultaneously during operation.

**[0122]** This means the location tracking system 170 may provide location information for each actuated effector mount 104 in the system 100 (e.g., the actuated effector mounts 104 of the

effector systems 102-1 and 102-2). The controller 160, in turn, may generate at least one control signal for respective actuated effector mounts 104 based on the received location information associated with that actuated effector mount 104. For example, the controller 160 may receive, from the location tracking system 170, first location information for the actuated effector mount 104 of the effector system 102-1 and second location information for the actuated effector mount 104 of the effector system 102-2. The controller 160 may thereafter generate at least one first control signal based on the received first location information to control the mobility of the actuated effector mount 104 of the effector system 102-1, and generate at least one second control signal based on the received second location information to control the mobility of the actuated effector mount 104 of the effector system 102-2. By monitoring the current locations of each effector system 102 and their expected travel path, the controller 160 may better identify obstacles nearby each effector system 102 (e.g., portions of a nearby structure, other effector systems 102) and thus better direct each effector system 102 through the environment to avoid collisions.

**[0123]** In some implementations, the location tracking system 170 may maintain each effector system 102 within its field of view as the effector system(s) 102 performs operations in the environment. For example, the location tracking system 170 may be positioned in such a way that the effector systems 102 of the robotic system 100 remain within the field of view of the location tracking system 170 during operation while the location tracking system 170 remains stationary. In another example, the location tracking system 170 may itself move through the environment to maintain the effector system(s) 102 within its field of view as the effector system(s) 102 move through the environment. This may be accomplished, for example, by the location tracking system 170 being mounted to a support system or a base station of the robotic system 100 that is capable of movement (see, for example, the support systems 200a-200g and the base stations 300a-300g in Section 2).

**[0124]** It should be appreciated that, in some implementations, the effector system 102 may also incorporate sensor(s) and/or camera(s) that provide sensory data for determining the location of the effector system 102. However, the sensory data acquired by any onboard components in the effector system 102 may only supplement sensory data acquired by a physically separate system in the robotic system 100 (e.g., the location tracking system 170). For example, the actuated effector mount 104 of each effector system 102 may include a camera to acquire video imagery of its surroundings and/or a GPS receiver to obtain a coordinate location of the effector system 102 in the environment. This video imagery and/or coordinate

location may be used in combination with LiDAR data obtained by the location tracking system 170 to improve the location accuracy and/or precision of the effector systems 102. However, the controller 160 may not use the video imagery and/or the coordinate location of the effector system 102 on its own to determine the location of each effector system 102.

**[0125]** It should also be appreciated that the sensory data used to determine the locations of the effector systems 102 may not always be suitable to generate a physical map or perform object recognition. Said another way, the robotic system 100 may monitor the locations of the effector systems 102 without having sensors and/or imaging systems that provide a field of view to visually identify the effector systems 102 in the environment. For example, the robotic system 100 may operate in an environment where the effector systems 102 are visually obscured from other subassemblies of the system 100 by various structures in the environment (e.g., a wall). Thus, the robotic system 100 may rely on sensors and the like that don't require direct line of sight with the effector systems 102. For example, the location tracking system 170 may include a GPS receiver and each of the effector systems 102 may also include a GPS receiver. The coordinate locations obtained by the respective GPS receivers may be sufficient for determining the locations of the effector systems 102 in relation to the location tracking system 170 during operation.

**[0126]** In yet another aspect, the effector systems 102 disclosed herein may generally have reduced payloads compared to conventional autonomous vehicles. This may be accomplished, in part, by offloading various components traditionally incorporated onto a conventional autonomous vehicle from the effector system 102 to another subassembly of the robotic system 100.

**[0127]** In one example, the effector system 102 may not include onboard sensors and imaging systems (e.g., a camera, a LiDAR imager) to track the location of the effector system 102 within the environment during deployment. Instead, the location of the effector system 102 may be monitored exclusively by a physically separate system (e.g., the location tracking system 170). Although the location tracking system 170 may itself comprise one or more sensors, imaging systems, and the like, the robotic system 100 may generally include fewer components to track the locations of each subassembly, thus simplifying and, in some instances, reducing the cost of the robotic system 100.

**[0128]** In another example, the effector system 102 may not include an onboard controller. Instead, the effector system 102 may rely on the controller 160, which is physically separate

from the effector system 102 and connected to the effector system 102 via the flex arm 150. In yet another example, the effector system 102 may not include an onboard power source (e.g., a battery). In yet another example, the effector system 102 may not include fluid management components (e.g., a valve, a pump, a storage tank) in applications where the effector system 102 is used, for example, to dispense or retrieve a fluid. Instead, these foregoing components, if present, may be integrated into other subassemblies of the robotic system 100 (e.g., a base station, a support system). In some implementations, the flex arm 150 may provide respective electrical and fluidic conduits to carry electrical power and/or fluids, respectively, to and from the effector system 102.

**[0129]** By offloading at least some of these components from the effector system 102, the payload of the effector system 102 may be appreciably reduced. This, in turn, may appreciably increase the payload capacity and/or the power-to-weight ratio. A higher payload capacity allows the effector system 102 to carry more cargo. A higher power-to-weight ratio allows the effector system 102 to be more agile. For example, if the effector system 102 is an aerial effector (see, for example, the aerial effectors 102a in FIG. 1C), a higher power-to-weight ratio may allow the effector system 102 to change its attitude at a higher rate compared to conventional, heavier aerobots. Said another way, the effector system 102 may change its position and/or orientation more rapidly to counteract any undesirable forces and/or torques applied to the effector system 102 during operation. In implementations where the flex arm 150 is a cable, the weight of the flex arm 150 and/or any forces acting on the flex arm 150 (e.g., wind) may be transmitted as a force and/or a torque to the effector system 102. However, the higher power-to-weight ratio of the effector system 102 may readily compensate and counteract these externally applied dynamic forces and/or torques.

## **[0130] 2. An Example Robotic System with an Aerial End Effector**

**[0131]** Following the discussion on the inventive aspects of the robotic system 100 in Section 1, this section provides an example implementation where the end effector systems are capable of movement through air. Accordingly, the effector systems in this section are referred to as an “aerial effector.”

**[0132]** As described above, it is often a challenge for conventional robots to perform tasks that involve interactions with objects or structures in hard-to-reach locations, such as elevated vertical or inclined surfaces. In regard to elevated surfaces, the primary limitation of ground-based robots lies in their inability to access the elevated surfaces. Much like human workers,

ground-based robots generally require a separate support system to change their vertical position with respect to a structure. For example, a suspended platform is often used to support a ground-based robot configured to clean or paint a building. The suspended platform typically includes a cable attached to a set of anchor points on the roof of the building and a motorized pulley system to change the vertical position of the platform. Accordingly, this approach suffers from similar disadvantages as human workers performing these tasks.

[0133] Although the vertical position of the robot may be readily adjusted via the suspended platform, the horizontal position of the robot is typically fixed or at least limited to the width of the platform. In order for the robot to access other portions of the building, the platform and/or the robot would need to be detached from one set of anchor points and reattached to another set of anchor points, which is a time-consuming process that reduces the productivity of the robot. Additionally, buildings often provide a fixed set of anchor points to support a suspended platform, scaffolding, and/or the like, which limits the placement of the platform and, in some instances, prevent the robot from accessing all the surfaces of the building, particularly because the robot is fixed in position on the platform.

[0134] The challenge associated with accessing hard-to-reach locations, such as elevated surfaces or crawl spaces, may be mitigated, in part, by using an aerial robot capable of sustained flight (also referred to herein and in the art as an “aerobot,” a “drone,” or an “autonomous aerial vehicle”). Compared to ground-based robots, an aerobot has appreciably more freedom to navigate and interact with the environment. In principle, an aerobot equipped with an effector can fly quickly to a desired surface of a structure and perform an operation on the surface (e.g., cleaning, painting) while remaining airborne.

[0135] Despite their potential, the Inventor has recognized aerobots have yet to be widely adopted to automate tasks that involve interactions with elevated, inclined, and/or vertical surfaces. This is due, in part, to several challenges associated with the use of an aerobot with an effector (also referred to as a “tool”), particularly if the effector is in physical contact with the surface or in close proximity to the surface. More specifically, in the context of contact treatment (e.g., window cleaning) of an elevated, inclined and/or vertical surface (e.g., a window), the Inventor has recognized and appreciated that conventional aerobots with a fixed effector do not have the capability to perform translational and rotational movement with sufficient precision, while maintaining sufficient contact with the surface or maintaining the effector in close proximity to the surface, to effectively perform the treatment of the surface.

[0136] For instance, the translational and rotational movement of commonly employed conventional aerobots is unable to be controlled independently with six degrees of freedom (6-DOF). For example, one commonly employed aerobot is a quadcopter, which includes four rotors that are each capable of producing thrust. The rotors are often rigidly affixed to a frame and arranged to generate thrust in the same direction, thus limiting the number of degrees of freedom that are independently controlled. As a result, a quadcopter is typically unable to perform certain maneuvers, such as pitching or rolling without changing position or moving laterally without rotating. This, in turn, limits the capability of commonly employed conventional aerobots to maneuver an effector while performing an operation. Additionally, if the aerobot is subjected to environmental or other external disturbances, such as wind, conventional aerobots may have to change their attitude and/or position to compensate for these disturbances, further compromising the aerobot's ability to perform an operation with sufficient precision.

[0137] Commonly employed conventional aerobots are also typically less agile along certain degrees of freedom due to the arrangement of their thrusters. Referring again to the example of a quadcopter, the four rotors of the quadcopter are typically arranged to generate thrust along a vertical direction. This, in turn, allows the quadcopter to readily adjust its vertical position in response to external disturbances that act on the quadcopter vertically. However, the quadcopter is unable to generate a torque in an arbitrary direction, which significantly limits its range of possible translational and rotational motion; thus, it is incapable of performing more sophisticated movement patterns that may significantly facilitate various types of contact treatment of surfaces and is often unable to effectively compensate for external (and in some cases dynamic) disturbances (e.g., environmental conditions such as wind) acting upon the aerobot.

[0138] Additionally, an effector typically protrudes outward from the aerobot. Thus, any variability in the position and/or attitude of the aerobot is amplified at the effector particularly if the effector is a passive effector affixed to the aerobot. For example, if the distal end of the effector (e.g., the end that contacts the surface) is located 1 meter from the center of mass of the aerobot, an error in the attitude of the aerobot of  $\pm 1$  degree may result in a positioning error at the distal end of the effector of about  $\pm 2$  centimeters. This error is sufficient to hinder or even prevent the aerobot from performing certain tasks, such as cleaning the edges of a window or harvesting a crop (e.g., a fruit).

[0139] Moreover, if the effector protrudes laterally (e.g., to interact with a vertical surface of a building), the weight of the effector generally causes the aerobot to pitch or roll downwards. If the effector physically contacts a surface, any contact force applied to the effector (e.g., friction) also affects the attitude of the aerobot. These effects collectively result in a force and/or a torque being applied by the effector to the aerobot, which can affect precision and accuracy with which an aerobot is positioned and/or oriented.

[0140] Some conventional aerobots also have a limited ability to carry a significant payload (e.g., fluid(s) for treating surfaces such as cleaning fluid, paint, surfactants, etc.) due to the aforementioned incorporation of other various components (e.g., a power source, sensors and imaging systems, etc.). The limited payload of the aerobot can be addressed by connecting a cord to the aerobot that supplies any fluids required for the aerobot to perform a certain task. However, the attachment of a cord to the aerobot applies another external force and/or torque to the aerobot, thus affecting the aerobot's mobility. For example, the weight of the cord may pull the aerobot downwards. In another example, external forces applied to the cord may be directly transmitted to the aerobot. If the aerobot is operating in a windy outdoor environment, for instance, the wind can displace the cord and, in turn, the aerobot away from a desired position and/or attitude.

[0141] As a result of the above limitations, commonly employed conventional aerobots are limited in their ability to precisely maneuver and control an effector, particularly when the effector must be placed in physical contact with a surface. More specifically, commonly employed conventional aerobots equipped with an effector are notably limited in their ability to mimic the actions of a human worker using a tool to perform a task relating to contact treatment of a surface, and/or mimic the execution of a given task with the same performance result (in situations where this might be desirable). In particular, if a commonly-employed conventional aerobot equipped with an effector is used to clean a window, the foregoing limitations (including intermittent contact of the effector on the surface as the aerobot maneuvers around the window) may cause the aerobot to leave streaks on the window and/or miss portions of the window all together (e.g., near the edges of the window, which typically require more precise movement of the effector). In another example, if such an aerobot is used to paint a structure, the foregoing limitations may cause the aerobot to apply an uneven coating of paint on a surface, such as a surface with patches of paint that is too thick or too thin, which is aesthetically undesirable. In yet another example, if the aerobot is configured to harvest a

crop, the foregoing limitations may cause the aerobot to inefficiently pick the crop (e.g., the aerobot may damage the crop due to the lack of precision with picking).

[0142] In addition to the limitations of conventional aerobots, the Inventor recognized several challenges in deploying aerobots that utilize a consumable fluid (e.g., cleaning fluid, paint). For example, conventional aerobots can create a falling hazard if they lose power. Without adequate safety measures, the commercial deployment of aerobots is often limited to less populated areas where safety risks to people are appreciably less.

[0143] In view of the foregoing limitations of conventional aerobots, FIG. 1C shows a non-limiting example of a robotic system 100a that includes effector systems 102a configured for aerial flight (also referred to herein as “aerial effectors 102a”). It should be appreciated that the robotic system 100a may incorporate one or more features of the robotic system 100 described in Section 1. For brevity, a discussion of these features is not repeated below.

[0144] As shown, each aerial effector 102a may include one or more thrusters 130 where each thruster 130 includes a motor with a propeller and provides propulsion along at least one direction. In some implementations, the actuated effector mount 104 may facilitate motion over six degrees of freedom by incorporating six or more thrusters 130. However, it should be appreciated that, in some implementations, the actuated effector mount 104 may facilitate motion over less than six degrees of freedom, e.g., three degrees of freedom, four degrees of freedom, or five degrees of freedom.

[0145] The system 100a further includes the location tracking system 170 separate from the aerial effector(s) 102a to provide location information for the aerial effector(s) 102a to the controller 160 so that the controller 160 can generate one or more signals for transmission to at least some of the plurality of thrusters 130 to cause the aerial effector 102a to move along a predetermined trajectory.

[0146] Some advantages of the robotic system 100a are that unlike traditional fixed-length robotic arms, the robotic system 100a can easily perform tasks at a large range of heights and distances between the controller 160 and the aerial effector(s) 102a. Because of the aerial capability of the aerial effectors 102a, the aerial effectors 102a can quickly reach areas that would be impossible for traditional robots to reach. In addition, the aerial effectors 102a can move with a high degree of freedom allowing the robotic system 100a to perform a wide range of work tasks including, but not limited to, cleaning surfaces, treating surfaces, performing maintenance and/or repairs, and harvesting crops.

**[0147] 3. Example Robotic Window Cleaning Systems**

[0148] In some example implementations disclosed herein, a robotic system may be configured to perform one or more operations related to cleaning windows. The robotic system (also referred to herein as a “robotic window cleaning system,” or “window cleaning system”) may include one or more aerial effectors with effectors to clean one or more windows of a structure. Herein, a structure may refer to a building or any man-made structure with an opening fitted with glass or another transparent material. The process to clean a window may be accomplished by the aerial effectors performing one or more operations that involve physically contacting the surface of the window with an effector (e.g., a contact tool). For example, the system may include an applicator aerial effector (e.g., an aerial effector with an applicator effector) to apply a cleaning fluid and/or scrub the surface to agitate and release detritus (e.g., dust, dirt, water spots) from the surface of the window. In another example, the system may include a squeegee aerial effector (e.g., an aerial effector with a squeegee effector) to remove the resulting waste fluid (e.g., a mixture of the cleaning fluid and the detritus) from the surface of the window by either displacing the waste fluid (e.g., towards the bottom of the window) or removing the waste fluid using a vacuum.

[0149] Following below are several example implementations of a window cleaning system that includes one or more aerial effectors to clean an interior surface or an exterior surface of a window. It should be appreciated that multiple window cleaning systems may be deployed to clean multiple windows in parallel. The multiple window cleaning systems may further be controlled by a central control system.

[0150] It should also be appreciated that one or more components and/or subsystems of one window cleaning system may be readily combined or substituted with one or more components and/or subsystems of another window cleaning system provided the combination or substitution does not result in mutually inconsistent features. It should be further appreciated that one or more components and/or subsystems of the window cleaning systems disclosed herein alternatively may be used in other types of contact treatment of one or more surfaces that employs one or more aerial effectors to facilitate execution of the contact treatment. For example, a robotic painting system may be substantially similar or the same as the window cleaning system with the exception of the aerial effector(s) having a different effector to facilitate painting and being supplied with paint. In another example, a robotic crop harvesting system may include aerial effector(s) with crop harvesting tools to remove crops from plants.

In this example, the crop harvesting may be simpler than the window cleaning or painting systems since the aerial effectors may not apply or remove any fluids.

[0151] In some implementations, the aerial effector may support multiple types of effectors. The effectors may include, but are not limited to, an applicator effector, a squeegee effector, and the like. Additionally, the aerial effector may allow an effector to be readily removed and replaced with another effector. Thus, the aerial effector may be readily customized before and during deployment.

[0152] For example, when a window cleaning system is deployed to clean a first set of windows of a first structure, the system may include aerial effectors equipped with a first set of effectors to perform one or more first operations on the first set of windows. Here, each aerial effector of the window cleaning system supports one effector in the first set of effectors. Once the first operation(s) are complete, an operator may reconfigure the window cleaning system to perform one or more second operations on a second set of windows of the first structure. This may include replacing the first set of effectors with a second set of effectors that is different from the first set of effectors. Again, each aerial effector of the window cleaning system supports one effector in the second set of effectors. Upon completing all operations on the first structure, the window cleaning system may be subsequently deployed to clean a first set of windows of a second structure. Before deployment, the aerial effectors may be equipped with a third set of effectors. The third set of effectors may be the same or different than the first and second sets of effectors.

[0153] It should also be appreciated that the aerial effectors coupled to a support system may be readily removed and/or replaced with other aerial effectors. Thus, each window cleaning system contemplated herein may be readily customized with different combinations of aerial effectors. For example, a given window cleaning system may initially be equipped with a first set of aerial effectors to perform one or more first operations on a first set of windows. Upon completing the first operation(s), the first set of aerial effectors may be removed and replaced with a second set of aerial effectors to perform one or more second operations on a second set of windows.

### [0154] **3.1 Example Window Cleaning Systems with a Roof-Based Base Station and a Suspended Support System**

[0155] FIG. 2 shows an example window cleaning system 100b with a base station 300a deployed on the roof of a structure 10 and a support system 200a to support an applicator aerial

effector 102b and a squeegee aerial effector 102c. As shown, the support system 200a may be suspended from a boom arm 222 via an end pulley 224. The boom arm 222 is coupled to the base station 300a. The base station 300a may supply electrical power (e.g., via a power conduit 324 connected to a power source 322), cleaning fluid 332 (e.g., via a cleaning fluid conduit 333 that includes a cleaning fluid pump 334 and a cleaning fluid tank 331), and a communication channel (not shown) to the support system 200a via an umbilical cord 352a. The power source 322 on the base station 300a may be, for example, a battery, or an electric generator. For example, Inset A of FIG. 2 shows the umbilical cord 352a may include electrical conduits 357 and 358 for electrical power and communication, respectively, and a fluidic conduit 355 for the cleaning fluid 332. The support system 200a, in turn, provides electrical power, communication, and a fluidic connection to the applicator aerial effector 102b and the squeegee aerial effector 102c via respective flex arms 150a and 150b. In this example, the flex arms 150a and 150b are cables that provide a physical connection between the aerial effectors 102b and 102c and the support system 200a. Inset B of FIG. 2 shows the flex arm 150b for the squeegee aerial effector 102c includes electrical conduits 153 and 154 for electrical power and communication, respectively, and a fluidic conduit 152 for waste fluid. Inset C of FIG. 2 shows the flex arm 150a for the applicator aerial effector 102b includes electrical conduits 153 and 154 for electrical power and communication, respectively, and a fluidic conduit 151 for cleaning fluid 332. In this example, the aerial effectors 102b and 102c, the support system 200a, and the base station 300a may each constitute a subassembly of the window cleaning system 100b.

[0156] The support system 200a and the base station 300a may each include one or more sensors 171 and 363, respectively. The sensors 171 and 363 may monitor various operation and environmental parameters associated with the support system 200a and the base station 300a, respectively. The sensors 171 may measure, for example, various parameters associated with the operation of the support system 200a and/or the environmental conditions near the support system 200a and the aerial effectors 102b and 102c. These parameters include, but are not limited to, wind speed, air temperature, relative humidity, the position and/or attitude of the support system 200a, the velocity and/or acceleration of the support system 200a, input electrical power parameters (e.g., voltage and current) received from a power source, output electrical power parameters (e.g., voltage and current) transmitted to the aerial effectors 102b and 102c, communication parameters (e.g., bandwidth, data rate) associated between the support system 200a and, respectively, the aerial effectors 102b and 102c, the base station 300a,

and/or the central control system 108, flow rate parameters for the cleaning fluid 332 (e.g., flow rate from the base station 300a, flow rate to the aerial effector 102b), flow rate parameters for the waste fluid 341 (e.g., flow rate to the base station 300a, flow rate from the aerial effector 102c), and the like.

**[0157]** The sensors 363 may measure, for example, various parameters associated with the operation of the bases station 300a and/or the environmental conditions near the base station 300a. These parameters include, but are not limited to, wind speed, air temperature, relative humidity, the position and/or attitude of the base station 300a, the velocity and/or acceleration of the base station 300a, output electrical power parameters (e.g., voltage and current) transmitted to the support system 200a from the power source 322, communication parameters (e.g., bandwidth, data rate) associated between the base station 300a and, respectively, the aerial effectors 102b and 102c, the support system 200a, and/or the central control system 108, flow rate parameters for the cleaning fluid 332 (e.g., flow rate from the base station 300a, quantity of cleaning fluid 332 stored in the tank 331), flow rate parameters for the waste fluid 341 (e.g., flow rate to the base station 300a, quantity of waste fluid 341 stored in the tank 340 if present), operating parameters associated with the boom arm 222, the cable winch 228, and the stage 220 (e.g., operating status, position), operating parameters associated with the umbilical cord winch 354 (e.g., amount of umbilical cord 352 released and/or stored on the winch 354) and/or the winches 155 (e.g., amount of flex arm 150 released and/or stored on the winch 155).

**[0158]** Accordingly, the sensors 171 and 363 may generally include various sensors 146 including, but not limited to, an inertial measurement unit (IMU) (e.g., accelerometer(s), gyroscope(s), magnetometer(s)), a location tracker (e.g., a GNSS receiver, such as a global positioning system (GPS) receiver, an altimeter), one or more imaging systems (e.g., a camera, a LiDAR imager, an acoustic localization sensor), a temperature sensor, a relative humidity sensor, an anemometer, a flowmeter, an ammeter, a voltmeter, a network monitor, a level sensor (e.g., to measure a volume of liquid such as the cleaning fluid 332 or the waste fluid 341), an encoder (e.g., to provide position feedback for the boom arm 222, the cable winch 228, the stage 220, the cable winch 354, and the flex arm winches 155).

**[0159]** FIG. 2 shows the umbilical cord 352a may be coupled to a top portion of an enclosure 210 of the support system 200a and the flex arms 150a and 150b may be coupled to a front portion of the enclosure 210. It should be appreciated this arrangement is non-limiting and that the respective ports on the support system 200a that couple to the umbilical cord 352a and/or

the flex arms 150a and 150b may be disposed on any side of the enclosure 210 (e.g., the front, rear, right, left, top, or bottom sides of the enclosure 210 of the support system 200a).

**[0160]** The boom arm 222 is configured to change the position of the support system 200a, for example, to move the support system 200a near different windows 12 of a building 10 for cleaning. For example, the boom arm 222 may adjust the vertical position of the support system 200a along the *Y* axis by extending or retracting a cable 226 supporting the system 200a using a cable winch 228. The boom arm 222 may further be telescoping to adjust a horizontal position of the support system 200a along the *Z* axis (e.g., the distance the support system 200a is located from the side of the building 10). The boom arm 222 may further be mounted to the base station 300a via a stage 220 (e.g., a rotation stage, a linear stage), which may be used to adjust the horizontal position of the support system 200a at least along the *X* axis. In some implementations, the base station 300a may also include a base structure 310 with one or more motorized wheels 312. During operation, the base station 300a may move along the roof to change the position of the support system 200a, e.g., to another side of the building 10.

**[0161]** In this example, the support system 200a is shown equipped with an applicator aerial effector 102b to apply a cleaning fluid 332 to the window 12 and scrub the window 12 to remove and suspend surface contaminants (e.g., detritus) in the cleaning fluid 332. The support system 200a also includes a squeegee aerial effector 102c to remove the resulting waste fluid 341 (e.g., a mixture of cleaning fluid 332 and detritus from the window 12). Examples of applicator effectors 106a and squeegee effectors 106b that may be readily integrated into the applicator aerial effector 102b and the squeegee aerial effector 102c, respectively, may be found in the '198 application. In some implementations, the squeegee aerial effector 102c may provide vacuum suction to remove and capture waste fluid 341 as it is removed by a squeegee blade, thus reducing or, in some instances, eliminating run off of waste fluid 341. This, in turn, may eliminate a separate operation to clean a frame of the window 12, thus reducing cleaning time and costs and improving the quality of service. This may be accomplished, for example, by the support system 200a including a suction pump to remove waste fluid 341 from the squeegee aerial effector 102c via the flex arm 150b. As shown, the aerial effectors 102b and 102c of the system 100b are not required to carry A) any onboard tanks to store cleaning fluid 332 or waste fluid 341, B) any onboard pumps to generate a flow of cleaning fluid 332 or to suction waste fluid 341, or C) an onboard energy storage module, such as a battery, thus appreciably reducing the payload of the aerial effectors.

**[0162]** It should be appreciated that in other implementations, the support system 200a may support a different number and/or combination of aerial effectors 102a to perform a different set of operations. For example, the support system 200a may have multiple squeegee aerial effectors with different sized squeegee blades to remove waste fluid 341 from different portions of a window 12, e.g., a wide squeegee blade to remove waste fluid 341 from a center portion of the window 12 and a narrow squeegee blade to remove waste fluid 341 from an edge portion of the window 12.

**[0163]** In some implementations, the support system 200a may include a tank (not shown) to store the waste fluid 341. In some implementations, the support system 200a may dispense the waste fluid 341 as it is removed from the squeegee aerial effector 102c such that the waste fluid 341 falls onto the ground below. In some implementations, the captured waste fluid 341 may be recycled (e.g., continuously, or in a batch, using an in-line filtration system) to recover water that can be reused by the system 100b (e.g., while executing an operation, or for a later executed operation).

**[0164]** For example, FIG. 3 shows a window cleaning system 100c with a support system 200b and a base station 300b configured to transport waste fluid 341 from the squeegee aerial effector 102c to a waste fluid tank 340 via a waste fluid conduit 342 and a waste fluid pump 343 on the base station 300b. This may be accomplished, for example, using a suction pump in the support system 200b to suction the waste fluid 341 from the squeegee aerial effector 102c. Then, the support system 200b and/or the base station 300b may include one or more pumps to transport the waste fluid 341 from the support system 200b to the base station 300b. For example, Inset A of FIG. 3 shows the umbilical cord 352b may include fluidic conduits 355 and 356 for the cleaning fluid 332 and the waste fluid 341, respectively. The base station 300b may further include an in-line filtration system disposed between the waste fluid tank 340 and the cleaning fluid tank 331 to effectively recycle at least some, if not a substantial portion of, the waste fluid 341. By using the base station 300b to store the cleaning fluid 332 and the waste fluid 341, to recycle the waste fluid 341, and to supply electrical power to the support system 200b, the support system 200b and, by extension, the aerial effectors 102b and 102c may operate continuously without requiring resupply (e.g., refill of cleaning fluid 332, removal of waste fluid 341, or recharge of power). For example, the support system 200b may control one or more aerial effectors 102a to perform the operation of applying a cleaning fluid 332 to one or more windows 12 (e.g., via the applicator aerial effector 102b) without interruption until completion. In another example, the support system 200b may control one or more aerial

effectors 102a to perform the operation of removing waste fluid 341 from one or more windows 12 (e.g., via the squeegee aerial effector 102c) without interruption until completion.

[0165] Returning to the example window cleaning system 100b shown in FIG. 2, the aerial effectors 102b and 102c may be controlled by the support system 200a (e.g., via an onboard robotic controller 160) or the base station 300a (e.g., via an onboard base station controller 360). During operation, the aerial effectors 102b and 102c may be configured to operate near the support system 200a, for example, to maintain some slack in the flex arms 150a and 150b between the aerial effectors 102b and 102c and the support system 200a. Thus, as the support system 200a moves (e.g., to different windows 12), the aerial effectors 102b and 102c may follow the support system 200a. It should be appreciated that in implementations where the aerial effector 102a is communicatively coupled to a support system 200 or a base station 300 via a wireless connection provided by the flex arm (e.g., via a wireless transceiver), the aerial effector 102a may not be constrained to operate near the support system 200 or the base station 300. Instead, the aerial effector 102a may operate at longer distances provided the aerial effector 102a stays communicatively coupled to the support system 200 or the base station 300.

[0166] Generally, the system 100b may support multiple aerial effectors 102a to perform different operations on a window 12. In some implementations, the aerial effectors 102a may perform respective operations simultaneously, thus reducing the time to clean the window 12. For example, the system 100b may use the applicator aerial effector 102b to apply cleaning fluid 332 to one portion of the window 12 and the squeegee aerial effector 102c to remove waste fluid 341 from another portion of the window 12 (e.g., a portion that the applicator aerial effector 102b already applied cleaning fluid 332).

[0167] When multiple aerial effectors 102a are in operation simultaneously, there is a risk the respective flex arms 150 of the aerial effectors 102a may become entangled. In some implementations, the risk of entanglement may be appreciably reduced or, in some instances, mitigated by generating trajectories for each aerial effector 102a that takes into consideration the trajectories of other aerial effectors 102a operating in close proximity to that aerial effector 102a. For example, a predetermined trajectory for an aerial effector 102a may be generated with constraints that do not allow the flex arm 150 coupled to the aerial effector 102a to wrap around the flex arm 150 coupled to another aerial effector 102a. In another example, one aerial effector 102a may only be allowed to perform an operation on a window at a time. However, multiple aerial effectors 102a may operate on multiple, different windows simultaneously.

[0168] As described above, the aerial effectors 102a rely upon external control signals to perform an operation. The external control signals may come from the controller 160, which may be incorporated into the support system 200a or the base station 300a. In this manner, the aerial effectors 102a may function as end-of-arm tooling.

[0169] For example, the process of localizing the aerial effectors 102b and 102c (e.g., determining the location of the aerial effectors 102b and 102c within the environment) may be executed by the support system 200a. As shown in FIG. 2, the support system 200a may include a location tracking system 170 to monitor the locations of the aerial effectors 102b and 102c, for example, relative to the window 12 being cleaned, or relative to the system 200a. The location tracking system 170 may include various sensors and/or imaging systems including, but not limited to, an imaging sensor (e.g., a camera), a LiDAR imager, a sound navigation and ranging (SONAR) device, a satellite navigation device, and an acoustic localization sensor.

[0170] As shown, the support system 200a may be positioned such that the window 12 is approximately centered within the field of view of the location tracking system 170, which may provide a relatively clear view of the aerial effectors 102b and 102c performing operations on the window 12. However, it should be appreciated that the aerial effectors 102b and 102c may still be tracked by the support system 200a if the support system 200a is located at a different position relative to the window 12 (see, for example, the location tracking system 170 of the support system 200d in FIG. 5). For example, the location tracking system 170 may have a sufficiently large field of view such that the location tracking system 170 may be located any position relative to the window 12 so long as a substantial portion of the window 12 is within the field of view. In some implementations, the location tracking system 170 may have a sufficiently large field of view that multiple windows 12 may be monitored simultaneously. This, in turn, may facilitate location tracking of aerial effectors 102a performing operations on different windows 12 simultaneously.

[0171] In some implementations, a separate aerial effector 102a with a location tracking system 170 may be deployed. For example, FIG. 4 shows a window cleaning system 100d with a support system 200c that supports a location tracking aerial effector 102d. Inset A of FIG. 4 shows the flex arm 150c for the location tracking aerial effector 102d may only include electrical conduits 153 and 154 for electrical power and communication, respectively. The support system 200c may further include a separate location tracking system (not shown) to monitor the location of the location tracking aerial effector 102d. In this manner, each of the aerial effectors 102b-102d remains dependent on sensory data acquired by a location tracking

system that is physically separate from that aerial effector. For example, operation of the aerial effectors 102b and 102c is dependent on sensory data acquired by the location tracking system 170 of the aerial effector 102d. Additionally, operation of the aerial effector 102d is dependent on sensory data acquired by a location tracking system mounted to the support system 200c.

**[0172]** The location tracking aerial effector 102d may provide more freedom to monitor the locations of the other aerial effectors 102b and 102c from a more desirable field of view. Also, the support system 200c may only track the location of the location tracking aerial effector 102d rather than all the aerial effectors supported by the support system 200c. This may appreciably reduce the need to maintain the support system 200c within a particular position relative to the aerial effectors 102b-102d during operation. For example, the support system 200c may readily move during operation (e.g., due to external disturbance such as wind) without affecting the operation of the aerial effectors 102b-102d so long as sufficient slack is provided in the flex arms 150a-150c. Additionally, the location of the location tracking aerial effector 102d relative to the support system 200c may be used to adjust the position of the support system 200c during operation so that sufficient slack is maintained in the flex arms 150a-150c as the aerial effectors 102b-102d perform operations on different windows 12.

**[0173]** It should be appreciated that a separate location tracking system on the support system 200c is not generally required. In some implementations, the position of the support system 200c may be adjusted according to other sensory data. For example, the aerial effectors 102b-102d and/or the support system 200c may include sensor(s) (e.g., a load cell, an accelerometer, a strain gauge) to detect when a flex arm 150 is being pulled taut, which may be an indication the distance between the aerial effector 102a and the support system 200c is too large. Accordingly, the position of the support system 200c may be adjusted to reduce the force detected by the sensor(s).

**[0174]** The system 100b may also include an umbilical cord winch 354 mounted to the base station 300a to adjust the length of the umbilical cord 352a as the position of the support system 200a changes. The operation of the umbilical cord winch 354 may be synchronized with the operation of the support system 200a. For example, the umbilical cord winch 354 may release the umbilical cord 352a as the support system 200a moves away from the base station 300a to maintain slack in the umbilical cord 352a or prevent the umbilical cord 352a from being pulled taut. In another example, the umbilical cord winch 354 may retract the umbilical cord 352a, thus reducing the length of the umbilical cord 352a as the support system 200a moves closer to the base station 300a to prevent the umbilical cord 352a from touching the ground or

becoming entangled with any obstacles near the ground. The base station 300a may control the operation of the umbilical cord winch 354 (e.g., via a base station controller 360).

[0175] The window cleaning system 100b may further be communicatively coupled to a central control system 108. For example, the window cleaning system 100 may be communicatively coupled to the central control system 108 via a wireless transceiver 362 disposed on the base station 300a, as shown in FIG. 2. It should be appreciated that the central control system 108 may additionally or alternatively be communicatively coupled to the support system 200a, e.g. wirelessly via a wireless transceiver (not shown) on the support system 200c. It should also be appreciated that, in some implementations, the central control system 108 may be coupled to the window cleaning system 100b via a wired connection (e.g., an Ethernet cable, a universal serial bus (USB) cable). For example, the central control system 108 may be a portable computing device that is plugged directly into the base station 300a, e.g., via a communication port.

[0176] The central control system 108 may be used by an operator to manage the operation of the system 100b. For example, the central control system 108 may include a computing device with at least one software application 109 that provides a user interface for an operator to monitor the system 100b (e.g., operating status, sensor readings, error notifications) and/or to control the system 100b (e.g., input commands that are transmitted as one or more instructions for execution by the support system 200a and/or the base station 300a), as shown in FIG. 2. For example, the computing device may be a portable device, such as a tablet or a phone, carried by the operator during operation of the system 100b. In another example, the computing device may be a computer integrated into the base station 300a with one or more user input devices (e.g., a pointing device (a mouse), tactile buttons, a keyboard, a touchscreen) to facilitate control of the central control system 108.

[0177] The central control system 108 may facilitate execution of one or more operations to clean a set of windows of a structure. The set of windows may include a subset of the windows of the structure or, in some instances, all the windows of the structure. This may be accomplished, for example, by the software application generating a work plan for the system 100b to execute the one or more operations according to a predetermined schedule. The work plan may further be executed in an autonomous manner. For example, once the system 100b is deployed by an operator, the operator may activate the system 100b to execute the one or more operations. As the system 100b executes the one or more operations, no further input from the operator is required unless an error or problem occurs.

[0178] The work plan may specify, for example, one or more operations to be performed by the system 100b at each window in the set of windows. As described above, the operations may include, but are not limited to, applying a cleaning fluid 332 to a window, removing waste fluid 341 from the window, and acquiring imagery of the window. Each operation may specify a particular aerial effector 102a that should be used, thus informing the operator which aerial effectors 102a should be connected to the support system 200a before deployment. Additionally, the work plan may specify the order of the windows to be cleaned by the system 100b. For example, the order may correspond to the vertical position of the windows, where the topmost windows are cleaned first and the support system 200a progressively moves downwards to clean windows via the aerial effectors at a lower elevation with the bottommost windows being cleaned last. In another example, the order may correspond to the shortest overall path for the support system 200a to access each window in the set of windows.

[0179] The work plan may also specify to the operator where the base station 300a should be placed with respect to the structure to ensure the support system 200a can access each of the windows in the set of windows. For example, the work plan may indicate a particular area near a building where the operator should deploy the base station 300a. In some implementations, the base station 300a may move autonomously (e.g., via a set of motorized wheels 312) to different locations specified in the work plan as the support system 200a finishes cleaning windows in one location of the building. Thus, the operator may only deploy the base station 300a at or near a starting point of the work plan and the window cleaning system 100b may thereafter clean the set of windows without requiring further input from the operator. In other words, the window cleaning system 100b may operate autonomously.

[0180] In one non-limiting example, an operation may utilize the applicator aerial effector 102b to apply a cleaning fluid 332 to at least a portion of a particular window of the structure. The central control system 108 may transmit instructions to the support system 200a that include, for example, an indication of which aerial effector 102a to use for the operation (e.g., the applicator aerial effector 102b), a coordinate location of the window in the environment to facilitate navigation to that window and/or provide a starting point to begin the operation (e.g., a GPS coordinate and altitude corresponding to a corner or center point of the window), and a predetermined trajectory for the applicator aerial effector 102b to follow in order to apply the cleaning fluid 332 to the surface of that window. The support system 200a may thereafter transmit control signals to the applicator aerial effector 102b (e.g., from the controller 160) to move the applicator aerial effector 102b to the starting point and thereafter follow the

predetermined trajectory. The trajectory may be determined, in part, based on the geometry of the window, which may be obtained in a separate process (see, for example, Section 4 for further details). Additional examples of trajectories may be found in the '198 application.

**[0181]** In another example, an operation may utilize the squeegee aerial effector 102c to remove waste fluid 341 from at least a portion of a particular window of the structure. The central control system 108 may transmit instructions to the support system 200a that include, for example, an indication of which aerial effector 102a to use for the operation (e.g., the squeegee aerial effector 102c), a coordinate location of the window in the environment to facilitate navigation to that window and/or provide a starting point to begin the operation (e.g., a GPS coordinate and altitude corresponding to a corner or center point of the window), and a predetermined trajectory for the squeegee aerial effector 102c to follow in order to remove the waste fluid 341 from the surface of that window. The support system 200a may thereafter transmit control signals to the squeegee aerial effector 102c (e.g., from the controller 160) to move the squeegee aerial effector 102c to the starting point and thereafter follow the predetermined trajectory. The trajectory, as described above, may be determined, in part, based on the geometry of the window. It should be appreciated that the trajectories used to respectively apply cleaning fluid 332 and to remove waste fluid 341 may be different.

**[0182]** It should be appreciated that, in some implementations, multiple operations may be performed to apply cleaning fluid 332 and/or remove waste fluid 341 from different portions of a window. For example, the removal of waste fluid 341 may be performed using two operations: 1) an operation to remove waste fluid 341 from a center portion of the window where the squeegee aerial effector 102c is configured to move at a higher velocity at the expense of lower precision in the placement of the squeegee effector against the window; and 2) an operation to remove waste fluid 341 from an edge portion of the window where the squeegee aerial effector 102c is configured to move at a lower velocity in favor of achieving a higher precision in the placement of the squeegee effector 106b against the window. In some implementations, these multiple operations may be performed by one aerial effector 102a or multiple aerial effectors 102a simultaneously, as described above. For example, the system 100 may include a first squeegee aerial effector 102c equipped with a wider squeegee blade to remove waste fluid 341 from the center portion of the window and a second squeegee aerial effector 102c equipped with a narrow squeegee blade to remove waste fluid 341 from the edge portion of the window.

[0183] During operation, the base station 300a may be configured to provide a continuous supply of cleaning fluid 332 to the support system 200a (e.g., via the cleaning fluid pump 334). The support system 200a may also provide continuous suction to remove waste fluid 341 from the support system (e.g., via a waste fluid pump onboard the support system 200a). In some implementations, the base station may instead provide continuous suction to remove waste fluid 341 from the support system (see, for example, the system 100c of FIG. 3). To control the dispensing of cleaning fluid 332 and/or suction of waste fluid 341, the support system 200a may include one or more valves to regulate the application of cleaning fluid 332 and/or suction of waste fluid 341. For example, a valve for the cleaning fluid 332 may only be opened when the applicator aerial effector 102b is performing an operation on a window. In another example, a valve to provide suction of waste fluid 341 may only be opened when the squeegee aerial effector 102c is performing an operation on a window.

### [0184] 3.2 Example Window Cleaning Systems with a Ground-Based Base Station and a Support System with Thrusters

[0185] FIG. 5 shows another window cleaning system 100e that includes a base station 300c deployed on the ground and a flight-capable support system 200d. As shown, the support system 200d may include an enclosure 210, one or more thrusters 212 mounted to the enclosure 210, a location tracking system 170, and one or more sensor(s) 171. The support system 200d may further support an applicator aerial effector 102b and a squeegee aerial effector 102c. The system 100e may include several of the same features, components, and/or subsystems as the systems 100a-100d. The system 100e may further operate in a similar manner to the systems 100a-100d unless indicated otherwise. For brevity, repeated discussions of these features may not be provided below.

[0186] As shown, the support system 200d may be capable of sustained flight. This may be accomplished, for example, by coupling an umbilical cord 352b from the base station 300c to the support system 200d to provide a continuous source of electrical power to the thrusters 212 of the support system 200d (as well as the aerial effectors 102b and 102c). The support system 200d may include multiple thrusters 212 to allow the support system 200d to navigate and fly to different windows (e.g., the windows 12a and 12b) of a structure 10. In some implementations, the support system 200d may not require precise control over each of its six degrees of freedom provided the support system 200d is able to fly to any desired position within the environment. Thus, in some implementations, the support system 200d may only have independent control over three or four degrees of freedom. For example, the support

system 200d may be a tricopter or a quadcopter. The support system 200d may operate in a similar manner as the support systems 200a-200c in that the support system 200d may move to different windows 12 and control the aerial effectors 102b and 102c coupled to the support system 200d to perform one or more operations on the respective windows 12. In some implementations, the support system 200d may hover above the aerial effectors 102b and 102c so that the weight of the flex arms 150a and 150b are primarily carried by the support system 200d.

[0187] In some implementations, the support system 200d may include an onboard location tracking system 170 similar to the support system 200a. As shown in FIG. 5, the support system 200d may operate above the aerial effectors 102b and 102c and the location tracking system 170 may be disposed on a bottom portion of the support system 200d to track the location of the aerial effectors 102b and 102c. It should be appreciated that the support system 200d may be configured to operate closer to the window 12 similar to the support systems 200a-200c. For example, the location tracking system 170 and the flex arms 150a and 150b may be mounted to front portion of the support system 200d and the support system 200d may be aligned to the window 12 such that the window 12 is approximately centered within the field of view of the location tracking system 170 as shown in FIG. 2. It also should be appreciated that, in some implementations, a support system with thrusters may also support a location tracking aerial effector. For example, FIG. 6 shows window cleaning system 100f with a support system 200e supporting a location tracking aerial effector 102d along with a squeegee aerial effector 102c and an applicator aerial effector 102b.

[0188] FIG. 5 also shows the base station 300c is configured to transport and store waste fluid 341 collected by the support system 200d via the squeegee aerial effector 102c in a similar manner as the base station 300b described above. It should be appreciated that, in some implementations, the base station 300c may not include a waste fluid tank or the other components to facilitate transport of waste fluid 341 (e.g., a suction pump, a fluidic conduit to transport waste fluid). Instead, the waste fluid removed by the squeegee aerial effector 102c may be stored and/or dispensed by the support system 200d.

### [0189] 3.3 Example Window Cleaning Systems with a Ground-Based Base Station/Support System and Aerial Effectors Directly Coupled to the Base Station

[0190] In some implementations, the window cleaning systems disclosed herein may not include a separate support system. Instead, the components and functions of the support system

may be incorporated into the base station. Thus, the aerial effectors may be directly coupled to the base station via respective flex arms. For example, FIG. 7 shows another window cleaning system 100g that includes a base station 300d deployed on the ground and multiple aerial effectors 102a (e.g., an applicator aerial effector 102b, a squeegee aerial effector 102c, and a location tracking aerial effector 102d) directly coupled to the base station 300d via respective flex arms 150a, 150b, and 150c. The system 100g may include several of the same features, components, and/or subsystems as the systems 100a-100f. The system 100g may further operate in a similar manner to the systems 100a-100f unless indicated otherwise. For brevity, repeated discussions of these features may not be provided below.

**[0191]** The base station 300d may include several of the components in the support systems 200a-200e. For example, if the squeegee aerial effector 102c is configured to remove waste fluid 341 via vacuum suction, the base station 300d may include a waste fluid pump 343 and a waste fluid conduit 342 to provide the suction to the squeegee aerial effector 102c. In some implementations, the base station 300d may also include a waste fluid tank 340 to store the recovered waste fluid 341. In another example, the base station 300d may directly couple to multiple flex arms 150 (e.g., one flex arm 150 for each aerial effector 102). In some implementations, the flex arms 150 may be controllably extended and/or retracted using respective winches 155. For example, FIG. 7 shows the base station 300d may include flex arm winches 155a, 155b, and 155c for the flex arms 150a, 150b, and 150c, respectively. The operation of the flex arm winches 155 may be synchronized with the operation of the corresponding aerial effector 102a. For example, the flex arm winch 155 may release the flex arm 150 as the aerial effector 102a moves away from the base station 300d to maintain slack in the flex arm 150 or prevent the flex arm 150 from being pulled taut. In another example, the flex arm winch 155 may retract the flex arm 150, thus reducing the length of the flex arm 150 as the aerial effector 102a moves closer to the base station 300d to prevent the flex arm 150 from touching the ground or becoming entangled with any obstacles near the ground.

**[0192]** The elimination of the support system may appreciably simplify the system 100g compared to the systems 100b-100f. However, the aerial effectors 102a may carry relatively longer sections of flex arms 150 compared to the systems 100b-100f, thus increasing the payload. The high power-to-weight ratio of the aerial effectors 102a may allow the aerial effectors 102a to carry relatively longer sections of flex arms 150 without appreciably affecting its ability to perform different operations. Nevertheless, the system 100g may be more suited to

perform operations on surfaces closer to the base station 300d. For example, the system 100g may be used to clean the windows of a one or two-story building.

[0193] It should be appreciated that, in some implementations, a location tracking system 170 may be directly mounted to the base station 300d rather than an aerial effector 102a (e.g., the location tracking aerial effector 102d). For example, FIG. 8 shows a window cleaning system 100h that includes a base station 300e with a location tracking system 170 disposed on a mounting arm 230. The mounting arm 230 may provide, for example, a more mechanically stable support for the location tracking system 170 compared to the location tracking aerial effector 102d. In some implementations, the mounting arm 230 may further be telescoping and/or otherwise movable so that the location tracking system 170 can be positioned and/or aligned to different windows (e.g., different sized and/or shaped windows located at different heights relative to the base station 300d).

#### [0194] **3.4 Example Window Cleaning Systems with a Ground-Based Base Station and a Support System with Aerial Effectors Directly Coupled to the Support System**

[0195] FIG. 9 shows another example window cleaning system 100i. As shown, the system 100i may include a base station 300f, a support system 200f mounted to the base station 300f via a telescoping mast 232, and a pair of aerial effectors 102b and 102c coupled to the support system 200f via respective flex arms 150a and 150b. The system 100g may include several of the same features, components, and/or subsystems as the systems 100a-100h. The system 100i may further operate in a similar manner to the systems 100a-100h unless indicated otherwise. For brevity, repeated discussions of these features may not be provided below.

[0196] In some implementations, the window cleaning system 100i may be a single deployable package. For example, the window cleaning system 100i may not require any assembly or disassembly for operation and transport between worksites. Rather, the cleaning system 100i may be a self-contained system that includes the components and subsystems necessary to execute a work plan in an automated manner. For example, the base station 300f, the support system 200f, and the aerial effectors 102b and 102c may be integrated into a single system with the base station 300f supporting the support system 200f via the mast 232 and the support system 200f supporting the aerial effectors 102b and 102c.

[0197] In some implementations, the aerial effectors 102b and 102c may be collectively configured to provide a desired set of effectors 106 to execute the work plan. For example, FIG. 9 shows the system 200f may include a pair of aerial effectors 102b and 102c having

either an applicator effector 106a or a squeegee effector 106b. It should be appreciated that this is a non-limiting example and that the set of effectors 106 included in the system 100i may vary depending on the work plan. For example, the pair of aerial effectors 102a may both have applicator effectors 106a. In another example, the pair of aerial effectors 102a may both have squeegee effectors 106b. It should also be appreciated that while the system 200f may be configured to execute the work plan before deployment, the system 100i may nevertheless allow the operator to modify the system 100i during execution of a work plan as needed. For example, the system 100i may allow the operator to change the effectors 106 on each aerial effector 102a.

**[0198]** As shown in FIG. 9, the base station 300f may include one or more wheels 312 to facilitate transport of the window cleaning system 100i between work sites (e.g., loading and unloading from a truck) and positional adjustment of the system 100i during operation. Some or, in some instances, all the wheels 312 may be motorized. It should be appreciated that base station 300f is a non-limiting example and that other mechanisms may be incorporated to facilitate transport of the window cleaning system 100i. These mechanisms include, but are not limited to, a continuous track (e.g., a tank tread), a robotic leg (e.g., the base station 300f may be a bipedal or quadrupedal robot), and a robotic leg with a wheel to contact the ground (e.g., the wheel may further be motorized).

**[0199]** In this example, the base station 300f and the support system 200f may each have respective processors 161 and 364 that form part of a robotic controller 160 and a base station controller 360, respectively, to facilitate execution of their respective functions. In some implementations, the base station 300f and the support system 200f may each be configured to operate autonomously during operation. Said another way, the base station 300f and the support system 200f may each perform respective tasks without requiring any input from a human operator. For example, the support system 200f may control the operation of the aerial effectors 102a without any input from the base station 300f. In another example, the base station 300f may position the cleaning system 100i according to a predetermined work plan without any input from the support system 200f.

**[0200]** In some implementations, the base station 300f may control the support system 200f by transmitting one or more control signals (e.g., commands) to the support system 200f for execution by the support system 200f. Alternatively, the support system 200f may control the base station 300f by transmitting one or more control signals (e.g., commands) to the base station 300f for execution by the base station 300f. For example, the support system 200f may

transmit signals to the base station 300f to change its position and/or orientation so that the support system 200f is able to monitor a particular window via its location tracking system 170.

**[0201]** The base station 300f may include a power source 322 to supply electrical power to the various components of the system 100i, in part, via electrical conduits 324. The base station 300f may include a cleaning fluid tank 331 and a cleaning fluid pump 334 to supply cleaning fluid 332, for example, to an applicator aerial effector 102b. The base station 300f may include a waste fluid pump 343 and a waste fluid conduit 342 to provide vacuum suction to a squeegee aerial effector 102c. In this example, the waste fluid pump 343 may be directly coupled to a discharge port 359 located on the bottom of the base structure 310 of the base station 300f. Thus, during operation, waste fluid 341 collected by the squeegee aerial effector 102c may be discharged directly onto the ground. It should be appreciated that the placement of the waste fluid pump 343 is not limited to the base station 300f. In other implementations, the waste fluid pump 343 may be integrated into the support system 200f or the squeegee aerial effector 102c itself.

**[0202]** The telescoping mast 232 provides a way to adjust the vertical position of the support system 200f. During operation, the vertical position of the support system 200f may be changed to facilitate cleaning of windows located at different levels of a building (e.g., the windows 12a and 12b). For example, the vertical position of the support system 200f may be changed so that a field of view associated with a location tracking system 170 coupled to the support system 200f may cover one or more windows (e.g., the windows 12 and 12b) to be cleaned by the aerial effectors 102b and 102c. In another example, the vertical position of the support system 200f may be changed so that the aerial effectors 102b and 102c may be positioned closer to the windows to be cleaned while maintaining a relatively short length in the flex arms 150a and 150b supporting the aerial effectors 102b and 102c.

**[0203]** As shown in FIG. 9, the system 100i may include an umbilical cord 352a that connects the support system 200f to the base station 300f. The umbilical cord 352a may provide various fluidic and/or electrical connections to support the operation of the support system 200f and the aerial effectors 102b and 102c. In some implementations, the umbilical cord 352a may be disposed internally within the mast 232 (e.g., the mast 232 may be hollow). In some implementations, the umbilical cord 352a may be disposed outside the mast 232. The umbilical cord 352a may be coupled to a winch 354 disposed on or in the base station 300f. During operation, the winch 354 may be configured to release the umbilical cord 352a as the mast 232

is extended or retract the umbilical cord 352a as the mast 232 is retracted. In this manner, the umbilical cord 352a that extends between the base station 300f and the support system 200f may remain substantially straight or, in some instances, straight. The umbilical cord 352a may connect to a port on the support system 200f. Thereafter, the electrical and/or fluidic connections in the umbilical cord 352a may be routed to various components of the support system 200f and/or the aerial effectors 102b and 102c including, but not limited to, a processor 161 in the support system 200f, a location tracking system 170, a squeegee aerial effector 102c, and an applicator aerial effector 102b.

[0204] As described above, the location tracking system 170 may monitor one or more windows during operation to at least direct the movement of the aerial effectors 102b and 102c. As shown in FIG. 9, the field of view associated with the location tracking system 170 may cover multiple windows 12a and 12b to facilitate, for example, the aerial effectors 102b and 102c operating on different windows (e.g., the windows 12a and 12b) simultaneously. In some implementations, the location tracking system 170 may include a pair of cameras to acquire video imagery of the window(s). The pair of cameras may be separated from each other by a sufficient distance to provide parallax vision (e.g., the video imagery acquired may be used to ascertain the depth of objects or features in the imagery). The location tracking system 170 may further include other sensors and/or imaging systems including, but not limited to, a LiDAR imager and an acoustic localization sensor.

[0205] The aerial effectors 102b and 102c may be coupled to the support system 200f via respective flex arms 150a and 150b. As described above, each flex arm 150a and 150b may provide electrical and/or fluidic connections to the aerial effectors 102b and 102c, respectively. In some implementations, the support system 200f may include winches (not shown) for each flex arm 150 to controllably extend and retract the flex arm 150 as the aerial effector 102a connected to that flex arm 150 moves away from the support system 200f or towards the support system 200f, respectively. The operation of the flex arm winch may be synchronized with the operation of the corresponding aerial effector 102a. For example, the flex arm winch may release the flex arm 150 as the aerial effector 102a moves away from the base station 300f to maintain slack in the flex arm 150 or prevent the flex arm 150 from being pulled taut. In another example, the flex arm winch may retract the flex arm 150, thus reducing the length of the flex arm 150 as the aerial effector 102a moves closer to the base station 300f to prevent the flex arm 150 from touching the ground or becoming entangled with any obstacles near the ground.

**[0206]** In some implementations, the support system 200f may be movable with respect to the mast 232. For example, the support system 200f may rotate about a vertical rotation axis (see rotation axis 233 in FIG. 9) with respect to the mast 232. In another example, the support system 200f may rotate about a horizontal rotation axis (not shown) with respect to the mast 232. In yet another example, the support system 200f may rotate about both a vertical rotation axis and a horizontal rotation axis with respect to the mast 232 to change the azimuth and the elevation of the support system 200f, respectively. The ability to adjust the orientation of the support system 200f in the foregoing manner may provide a way to alter the field of view of the location tracking system 170 while allowing the base station 300f to remain fixed in position and/or orientation. In this manner, the support system 200f may emulate the movement of an anthropomorphic head or a zoomorphic head.

**[0207]** FIGS. 14A-14I show another example window cleaning system 100j. The system 100j may include several of the same features, components, and/or subsystems as the systems 100a-100i. The system 100j may further operate in a similar manner to the systems 100a-100i unless indicated otherwise. For brevity, repeated discussions of these features may not be provided below.

**[0208]** The window cleaning system 100j may be a single deployable package (i.e., a system that does not require any assembly or disassembly for operation and transport). In some implementations, the window cleaning systems disclosed herein may be designed to have an animal-like appearance (i.e., the window cleaning system is zoomorphic). As an example, FIG. 14A shows the window cleaning system 100j may be designed to have the appearance of a giraffe. For example, the system 100j may include a base station 300g that emulates the body of the giraffe, a mast 232 that emulates the neck of the giraffe, and a support system 200g that emulates the head of the giraffe. The support system 200g may support aerial effectors 102b and 102c and the base station 300g may support the support system 200g. In some implementations, the various components of the base station 300g and the support system 200g may have a spotted pattern to further give the system 100j the appearance of a giraffe (see, for example, FIGS. 14J and 14K).

**[0209]** FIGS. 14A and 14B further show the base station 300g may include a platform 313 with a body housing 311 mounted thereto. Together, the platform 313 and the body housing 311 may form the base structure 310 of the base station 300g. As shown, the base station 300g may include one or more deployable legs 314 mounted to the body housing 311. In this example, the leg(s) 314 may be fully retracted and nested into a body housing 311 of the base

station 300g during transport of the system 100j. The leg(s) 314, when deployed, may provide additional mechanical stability to the system 100j, particularly when the support system 200g is raised to an elevated position by the mast 232 (see FIGS. 14F and 14G). For example, the leg(s) 314 may reduce the likelihood of the system 100j tipping over when a sudden gust of wind blows against the support system 200g. During operation, the legs 314 may lift up off the ground without being fully retracted when the base station 300g changes position (e.g., when moving to a new location along a building as in FIG. 19A). In this manner, the time spent lifting and lowering the legs 314 may be reduced.

**[0210]** As shown the base station 300g may include multiple wheels 312 to facilitate automated movement of the system 100j during operation. One or more of the wheels 312 may be motorized. In some implementations, all the wheels 312 may be motorized. It should be appreciated that the wheels 312 are a non-limiting example and that any other ground-based propulsion mechanism may be used including, but not limited to, a continuous track (e.g., tank treads), a robotic leg (e.g., a biped robot, a quadruped robot), or a robotic leg with a wheel.

**[0211]** As described above, the mast 232 provides a mechanism to adjust the vertical position of the support system 200g during operation. For example, FIGS. 14E-14G show the mast 232 may be a telescoping arm. As shown in FIG. 14G, the mast 232 may extend an appreciable distance to facilitate cleaning of a multi-story building. In this non-limiting example, the window cleaning system 100j may elevate the support system 200g to reach the top floor of a four-story building. More generally, the vertical position of the support system 200g may be varied, via the mast 232, to range from about ground level (e.g., where the base station 300g is located) to about 56 feet (e.g., approximately four stories), including all sub-ranges and values in between.

**[0212]** By adjusting the vertical position of the support system 200g, the aerial effectors 102b and 102c may remain near windows that are designated for cleaning, thus avoiding the need for the flex arms 150a and 150b to span excessive distances. During operation, the mast 232 may change the vertical position of the support system 200g as the aerial effectors 102b and 102c clean windows on different floors of the building.

**[0213]** The support system 200g may further be rotatable about the mast 232 via one or more motorized actuators (e.g., a hollow shaft rotary actuator), thus providing greater flexibility to controllably position and/or orient the support system 200g during operation while the position and/or orientation of the base station 300g remains fixed. The ability to change the position

and/or orientation of the support system 200g may provide, for instance, a way to adjust the field of view of a location tracking system 170 incorporated into the support system 200g during operation (e.g., to follow the aerial effectors 102b and 102c as they move in the environment).

[0214] For example, FIGS. 14C and 14D show an enclosure 210 of the support system 200g may rotate about a vertical axis relative to the mast 232, for example, to orient the location tracking system 170 of the support system 200g to face the building. In this example, the support system 200g may rotate approximately 90 degrees about a polar axis to orient the location tracking system 170 so that it faces the building to be cleaned. In some implementations, there may be no limit to the rotational range of motion of the support system 200g (e.g., the support system 200g may rotate 360 degrees about the polar axis). In some implementations, the support system 200g may be rotatable about one or more axes, e.g., to change the azimuth and/or elevation of the support system 200g with respect to the mast 232.

[0215] FIGS. 14H and 14I show that once the support system 200g is positioned near a window, landing pads 240 on the support system 200g supporting the aerial effectors 102b and 102c may be moved from a “storage” position to a “deployed” position (see, for example, FIG. 15B). Thereafter, the aerial effectors 102b and/or 102c may lift off from the landing pads 240 and begin performing operations, e.g., applying a cleaning fluid to the window, removing the cleaning fluid via a squeegee (see, for example, FIGS. 16A-18K).

[0216] During operation, the system 100j may also collect waste fluid via the aerial effector 102c. The waste fluid may be transported from the squeegee aerial effector 102c to the support system 200g via the flex arm 150b. The waste fluid may then be transported to the base station 300g (e.g., via an umbilical cord in the mast 232). Thereafter, FIG. 14E shows the waste fluid may be discharged from the base station 300g directly onto the ground where it can then drain into gutters/storm drains.

[0217] FIGS. 14E-14I also show multiple window cleaning systems 100j may be deployed simultaneously and managed by a single operator. As discussed above, the systems 100j may be deployed in different locations around the building. For example, the façade of the building may be divided into multiple sections that are then assigned to different systems 100j for cleaning.

[0218] FIGS. 15A and 15B show magnified views of the support system 200g of the window cleaning system 100j. The support system 200g may include an enclosure 210 shaped like the

head of a giraffe. The support system 200g may further include landing pads 240 to mechanically support respective aerial effectors 102b and 102c. As shown, the landing pads 240 may be disposed onto the enclosure 210 to have the appearance of ears. Each landing pad 240 may move between a “storage” position (see FIG. 15A) and a “deployed” position (see FIG. 15B). This may be accomplished, for example, by each landing pad 240 being mechanically coupled to the enclosure 210 via a motorized hinge or, more generally, a rotary joint with an actuator to transition the landing pad 240 from the storage position to the deployed position and/or from the deployed position to the storage position. The actuator may be, for example, an electrical actuator or a hydraulic actuator.

**[0219]** In the storage position, the landing pad 240 may lie against a side of the enclosure 210 so that the space occupied by the landing pad 240 and the aerial effectors 102b and 102c may be reduced. The storage position may be used, for example, when the window cleaning system 100j is stored in a confined space (e.g., a warehouse) or transported by a vehicle (e.g., a truck). In the deployed position, the landing pad 240 may extend from the support system and provide a horizontal platform from which an aerial effector 102a may take off and/or land. Accordingly, the deployed position may be used when the aerial effectors 102b and 102c are commanded to perform an operation.

**[0220]** As shown, the aerial effectors 102b and 102c may be supported by respective flex arms 150a and 150b mounted to the support system 200g. In this example, the flex arms 150a and 150b may provide at least a fluid conduit to either carry cleaning fluid or waste fluid. In some implementations, the flex arms 150a and 150b supporting the aerial effectors 102b and 102d, respectively, may be routed through an opening 242 on the landing pad 240 as the flex arms 150a and 150b are extended or retracted from the support system 200g. The opening 242 may guide the flex arm 150a and 150b, thus reducing the likelihood of the flex arms 150a and 150b getting caught and/or entangled with another portion of the window cleaning system 100j.

**[0221]** During operation, the cleaning fluid 332 may be supplied after the applicator aerial effector 102b lifts off the landing pad 240. In some implementations, the cleaning fluid 332 may be supplied immediately after the applicator aerial effector 102b lifts off from the landing pad 240 (e.g., before the applicator aerial effector 102b comes into contact with a window). In some implementations, the cleaning fluid 332 may be supplied only after the applicator aerial effector 102b physically contacts with the window. Similarly, vacuum suction may be supplied after the squeegee aerial effector 102c lifts off the landing pad 240. In some implementations, vacuum suction may be provided immediately after liftoff and before the squeegee aerial

effector 102c contacts a window. In some implementations, vacuum suction may be provided only after the squeegee aerial effector 102c physically contacts with the window.

[0222] FIG. 15A further shows the location tracking system 170 may include a pair of cameras 173 and a LiDAR imager 172. In this example, the cameras 173 may be arranged to appear as eyes and the LiDAR imager 172 is arranged to appear as a nose. The cameras 173 may be separated by a distance,  $w_c$ , which is chosen to be sufficiently large (e.g., about 2 feet) to provide parallax vision of the building and, in particular, the windows.

[0223] FIGS. 16A and 16B show several views of the applicator aerial effector 102b. The applicator effector 106a may be fluidically coupled to the flex arm 150a such that cleaning fluid may be dispersed along the applicator effector 106a when applying the cleaning fluid to the window. In some implementations, the applicator effector 106a may include one or more sensors (e.g., sensor(s) 146) to detect a contact force with the window and/or the presence of detritus on the window. In some implementations, the applicator effector 106a may be rotatable with respect to the inner frame 111 of the aerial effector 102b, e.g., via a rotary actuator (not shown). The applicator effector 106a may be rotated to provide a scrubbing motion during operation to remove detritus attached to the window. It should be appreciated that the aerial effector 102b may further incorporate various components described, for example, in Section 3.1.

[0224] FIGS. 17A and 17B show several views of the squeegee aerial effector 102c. The squeegee effector 106b may include vacuum suction to remove waste fluid as the squeegee effector 106b is moved across a window. The squeegee effector 106b may include one or more sensors (e.g., sensor(s) 146) to monitor contact between different portions of the squeegee effector 106b and the surface of the window. The squeegee effector 106b may be rotatable with respect to the inner frame 111 of the aerial effector 102c, e.g., via a rotary actuator (not shown), to provide an additional degree of freedom to position/orient the squeegee effector 106b as the squeegee aerial effector 102c moves along different portions of the window. This may provide a way to more precisely position and orient the squeegee effector 106b. It should be appreciated that the aerial effector 102b may further incorporate various components described, for example, in Section 3.1.

[0225] FIGS. 18A-18I and FIGS. 19A-19C show example operations performed by the window cleaning system 100j to clean the windows of a building. In some implementations, the applicator and squeegee aerial effectors 102b and 102c may be configured to perform tasks

on different windows to reduce the likelihood of their respective flex arms 150a and 150b becoming entangled. For example, the applicator aerial effector 102b may apply cleaning fluid 332 to one window and the squeegee aerial effector 102c may remove waste fluid 341 from another window. This may be facilitated, in part, by the support system 200g being positioned such that the field of view of the location tracking system 170 covers multiple windows. For example, the support system 200g may be positioned between two windows so that the field of view of the location tracking system 170 covers both windows as the aerial effectors 102b and 102c perform operations on those respective windows. It should be appreciated that, in some implementations, the applicator and squeegee aerial effectors 102b and 102c may perform operations on the same window simultaneously (see, for example, FIG. 2).

[0226] As the window cleaning system 100j cleans windows of the building, the aerial effectors 102b and 102c, the support system 200g, and the base station 300g may each move so that the aerial effectors 102b and 102c are generally positioned near the windows being cleaned. In some implementations, the aerial effectors 102b and 102c, the support system 200g, and/or the base station 300g may move simultaneously. For example, FIG. 18A shows the support system 200 being lowered while the applicator and squeegee aerial effectors 102b and 102c move into position to perform respective operations on different windows.

[0227] FIG. 18B shows the applicator aerial effector 102b and the squeegee aerial effector 102c may follow different paths along their respective windows. As shown, the applicator aerial effector 102b may move along a serpentine path 190a with long vertical strokes that span the height of the window. The path 190a provides a way to reduce the travel distance and, thus, the time required for the applicator aerial effector 102b to apply cleaning fluid to a window. In some implementations, the applicator aerial effector 102b may stop along the path 190a and scrub a particular area of the window (e.g., by rotating the applicator effector 106a) to remove detritus before progressing further along the path.

[0228] The squeegee aerial effector 102c may follow a spiral path 190b that begins at the periphery of the window (e.g., the edges and corners of the window) and progressively moves towards the center of the window. Thus, the squeegee aerial effector 102c may first remove waste fluid from a peripheral portion of the window (e.g., portions adjoining a window frame) and then remove waste fluid from a center portion of the window. As the squeegee aerial effector 102c travels along the path 190b, the squeegee aerial effector 102c may move relatively slower and more carefully along the periphery of the window near the window frame to ensure waste fluid 341 is more carefully removed along the outer edges and corners of the

window (see FIG. 18C). Once the waste fluid 341 is removed from the periphery of the window, the squeegee aerial effector 102c may move relatively quicker to remove the remaining waste fluid 341. This may be accomplished by the squeegee aerial effector 102c moving in such a way that a portion of the squeegee effector 106b always passing over a portion of the window where the waste fluid 341 was previously removed, i.e., overlapping a previously squeegeed portion of the window (see FIG. 18E).

**[0229]** In some implementations, the applicator aerial effector 102b and the squeegee aerial effector 102c may be configured to apply cleaning fluid 332 and remove waste fluid 341, respectively, within a similar amount of time. However, it should be appreciated that the time taken for the applicator aerial effector 102b and the squeegee aerial effector 102c to perform their respective tasks may be different. Once the applicator aerial effector 102b and the squeegee aerial effector 102c complete their respective tasks on a particular window, the system 100j may be configured to reposition the support system 200g and/or the base station 300g so that the applicator aerial effector 102b and the squeegee aerial effector 102c may begin performing new tasks on different windows. In some implementations, movement of the support system 200g and/or the base station 300g may only occur when all the aerial effectors 102a are no longer in physical contact with a surface (e.g., a window). For example, FIG. 18I shows the support system 200g being lowered together with the applicator and squeegee aerial effectors 102b and 102c after the aerial effectors 102b and 102c completed their respective operations on the previous windows. In another example, FIG. 19A shows the base station 300g moving horizontally together with the support system 200g and the applicator and squeegee aerial effectors 102b and 102c after the aerial effectors 102b and 102c completed their respective operations on the previous windows.

**[0230]** The applicator and squeegee aerial effectors 102b and 102c may be configured to perform tasks on adjacent windows (e.g., a pair of windows disposed above one another or side by side), such as in FIGS. 18A-18I. However, it should be appreciated that this is a non-limiting example. More generally, the applicator and squeegee aerial effectors 102b and 102c may operate on different windows that may not be adjacent. For example, FIGS. 19B and 19C show the applicator and squeegee aerial effectors 102b and 102c performing tasks on windows that are not adjacent to one another.

**[0231]** FIGS. 20A-20J show additional views of the cleaning system 100j of FIG. 19A. The cleaning system 100j is shown as a shaded model.

[0232] FIGS. 21A-21J show additional views of the cleaning system 100j of FIG. 19A. The cleaning system 100j is shown as a wireframe model.

[0233] FIGS. 22A-22G show additional views of the support system 200g in the cleaning system 100j of FIG. 19A. The support system 200g is shown as a shaded model.

[0234] FIGS. 23A-23G show additional views of the support system 200g in the cleaning system 100j of FIG. 19A. The support system 200g is shown as a wireframe model.

### [0235] 3.5 Other Example Window Cleaning Systems with Support Systems

[0236] It should be appreciated that the window cleaning systems 100b-100j described above in Sections 2.1-2.4 are non-limiting examples. Other window cleaning systems with different base stations and/or support systems are also contemplated herein.

[0237] For example, a window cleaning system may include a base station 300 deployed on the ground with a boom arm that raises a suspended support system 200 to different heights to facilitate cleaning of windows at different levels above the ground level of a structure. Examples of a ground-based base station with a boom arm may be found in the '198 application. The umbilical cord 352 may further be routed up to the support system 200 from the base station 300 and the aerial effectors 102a may be coupled to the support system 200 via respective flex arms 150.

[0238] In another example, a window cleaning system may include a base station 300 deployed on the ground and a boom arm deployed on the roof of a structure to support a suspended support system 200 from the roof. The boom arm may be coupled to the roof via a roof anchor. Examples of a ground-based base station and a boom arm supported by a roof anchor may be found in the '198 application. The umbilical cord 352 may further be routed up to the support system 200 from the base station 300 and the aerial effectors 102a may be coupled to the support system 200 via respective flex arms 150.

[0239] In yet another example, a window cleaning system may include a base station 300 deployed on the ground and a support system 200 with an aerostat to provide lift to the support system 200. Examples of a ground-based base station with an aerostat may be found in the '198 application. The umbilical cord 352 may further be routed up to the support system 200 from the base station 300 and the aerial effectors 102a may be coupled to the support system 200 via respective flex arms 150.

### [0240] 4. Example Components of the Window Cleaning System

[0241] This section provides additional discussion on respective components and subsystems of the window cleaning systems 100b-100h described in Section 2. It should be appreciated that one or more features of the components and/or subsystems described in this section may be readily combined or substituted with other features of other components and/or subsystems provided the combination or substitution does not result in mutually inconsistent features. Moreover, several example components disclosed in the '198 application may be incorporated into the aerial effectors disclosed in this section.

#### [0242] 4.1 Example Aerial Effectors for Window Cleaning Systems

[0243] The aerial effectors 102a disclosed herein may be appreciably lighter weight, simpler, and, in some instances, smaller than conventional aerobots. This may be accomplished, in part, by offloading components typically disposed onboard an aerobot to another device or component of the window cleaning system, such as the support system 200 or the base station 300. For example, some or, in some instances, all the components related to power management (e.g., power electronics, a battery), fluidic control (e.g., pumps, valves), localization sensing, and flight control may be offloaded from the aerial effector 102a to the support system 200 and/or the base station 300. In doing so, the aerial effectors 102a may have a higher payload capacity and/or a higher power-to-weight ratio. This may allow, for example, the aerial effectors 102a to maintain continuous physical contact with a surface even in the presence of one or more external disturbances (e.g., forces/torques from the flex arm 150, wind forces acting on the aerial effector 102a).

[0244] In some implementations, the aerial effector 102a may only include a frame 105, one effector 106, one or more thrusters 130 to control a desired set of degrees of freedom of the aerial effector 102a to perform an operation using the effector 106, and a flex arm interface 120a. Herein, the frame 105, the thrusters 130, and the flex arm interface 120a may form the actuated effector mount 104. Thus, the aerial effector 102a may not include a flight controller. In some implementations, the aerial effector 102a may not include any electronics to manage the operation of the aerial effector 102a. Instead, the aerial effector 102a may receive control signals (e.g., signals to adjust the thrust produced by each thruster 130) via the flex arm 150 coupled to the flex arm interface 120a. It should be appreciated that, in some implementations, the aerial effector 102a may retain some onboard electronic circuitry (e.g., see the processor 140 and the memory 141) to perform some limited functions as described in Section 1. The aerial effector 102a may also receive electrical power and/or be fluidically coupled to a fluidic

circuit (e.g., to supply cleaning fluid, to remove waste fluid) via the flex arm 150 depending on the type of effector used (e.g., an applicator effector 106a, a squeegee effector 106b).

[0245] The control signals, the electrical power, and/or the fluidic circuit may be incorporated into the support system 200 and/or the base station 300. In particular, the support system 200 and/or the base station 300 may include a controller (e.g., the robotic controller 160, the base station controller 360 shown in FIGS. 10-13) to manage the operation of various components and/or subsystems associated with the aerial effector 102a using the flex arm 150 coupled to the flex arm interface 120a of the aerial effector 102a. For example, the controller 160 may facilitate transmission of sensory data from the aerial effector 102a to the central control system 108 (see discussion on sensors below). In another example, the controller 160 may facilitate execution of an operation, e.g., by transmitting one or more control signals to the aerial effector 102a to adjust the respective electric motors of each thruster 130 to produce different thrusts so that the aerial effector 102a moves along a desired trajectory. In yet another example, the controller 160 may open or close a fluidic circuit that supplies a flow of cleaning fluid to the aerial effector 102a (e.g., via an applicator effector 106a) or removes waste fluid from the aerial effector 102a (e.g., via a squeegee effector 106b). In yet another example, the controller 160 may perform localization of the aerial effectors 102a. In FIGS. 10-13, a location tracking subsystem 170 is shown incorporated into either the support system 200 or the base station 300. It should be appreciated that a separate aerial effector 102a carrying a location tracking system 170 may also be used and communicatively coupled to the support system 200 or the base station 300 as shown in FIGS. 4, 6, and 7.

[0246] The frame 105 of the aerial effector 102a may provide structural support and mounting points for the effector 106, the thrusters 130, and the flex arm interface 120a. In some implementations, the frame 105 may be an assembly of lightweight struts arranged to form a mechanically rigid structure sufficient to support the foregoing components. In one aspect, the frame 105 may be constructed in such a way that the thrusters 130 are positioned and oriented to facilitate movement over multiple degrees of freedom (e.g., six degrees of freedom).

[0247] As an illustrative example, FIGS. 24A-24C and 25A-25C show several views of an example frame 105, which is used in both the squeegee aerial effector 102c and the applicator aerial effector 102b in the window cleaning system 100j. As shown, the frame 105 may include an inner frame 111 and an outer frame 110 coupled to the inner frame 111 via multiple struts 112 and 114. The inner frame 111 may support the effector 106 and the flex arm interface 120a, e.g., the inner frame 111 may include a port to connect to the flex arm 150. The struts 112 may

support the thrusters 130. The outer frame 110 connects the struts 112 and 114 together to form a more mechanically rigid structure. Additionally, the outer frame 110 may provide a physical barrier to protect the components mounted to the inner frame 111 and/or the strut(s) 112 and 114 (e.g., against collisions with the environment).

**[0248]** As shown, the inner frame 111 may support the effector 106 via a mount 124. Specifically, the effector 106 may include a rod 107 coupled, for example, to an applicator or a squeegee. The rod 107 may be directly coupled to the mount 124. In some implementations, the mount 124 may incorporate one or more motorized actuators 132 to move and/or orient the effector 106 relative to the frame 105. For example, the mount 124 in FIGS. 25A-25C may be configured to rotate the squeegee effector 106b about an axis that is collinear with the centerline axis of the rod 107.

**[0249]** In some implementations, the inner frame 111 may further support a housing to enclose various onboard components of the actuated effector mount 104. For example, the housing may support and/or enclose various sensors 146 and/or electronic circuitry, if present. The housing may be coupled to the inner frame 111 via, for example, one or more screw fasteners, bolt fasteners, an adhesive, welding, and the like.

**[0250]** The struts 112 and 114 may be directly coupled to the inner frame 111 and oriented to protrude outwards from the inner frame 111 as shown in FIGS. 24A-25C. As described above, the struts 112 may each support one thruster 130. This may be accomplished, for example, by a joint 122 that directly clamps onto the strut 112 and supports the motor and speed controller of the thruster 130. Thus, each strut 112 directly supports the weight of one thruster 130 and is further subject to any forces generated by the thruster 130 during operation. To accommodate these loads, the struts 112 may be relatively larger in size (e.g., diameter/width) compared to the struts 114. Additionally, adjacent struts 112 may be connected together via a strut 113, which provides additional mechanical support to reduce or, in some instances, mitigate undesirable mechanical deflections along the struts 112 during operation.

**[0251]** The outer frame 110 is an assembly formed from struts 115 and 116 connected together via corner joints 121a, 121b, 121c, and 121d. The corner joints 121a, 121b, 121c, and 121d may further facilitate connection to the struts 112 and 114. The outer frame 110 may also include a support bracket 123 that mechanically supports another portion of the rod 107 of the effector 106. As shown, the bracket 123 may be coupled to corner joints 121a and 121c via struts 117. In this manner, the rod 107 may be supported at two different locations, thus

appreciably reducing any undesirable bending deflections, i.e., the rod 107 is not cantilevered off from the inner frame 111.

[0252] FIGS. 24A-25C show the frame 105 may be shaped as a hexagonal prism. However, it should be appreciated that this is a non-limiting example. More generally, the frame 105 may be constructed to have various three-dimensional geometries including, but not limited to, a polyhedron (e.g., a cube, a hexagonal prism), a sphere, an ellipsoid, or any combination of the foregoing.

[0253] The components of the frame 105 may be formed of lightweight materials including, but not limited to, a carbon fiber composite, fiber glass, Kevlar, and plastic (e.g., acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyethylene terephthalate glycol (PETG), nylon, thermoplastic polyurethane (TPU), polyvinyl alcohol (PVA), high impact polystyrene (HIPS)).

[0254] The thrusters 130 may generally control the position and/or attitude of the aerial effector 102a along one or more degrees of freedom. The number and orientation of the thrusters 130 in the aerial effector 102a may vary based on the type of the effector 106 used and the degrees of freedom over which independent control is sought to manipulate the effector 106. For example, an aerial effector 102a with an applicator effector 106a or a squeegee effector 106b may have relatively more thrusters 130 to independently control more degrees of freedom so that the applicator effector 106a or the squeegee effector 106b may be more precisely moved along a desired trajectory across a surface.

[0255] In some implementations, the aerial effector 102a may include six or more thrusters to independently control each of its six degrees of freedom (i.e., three orthogonal translational degrees of freedom, three orthogonal rotational degrees of freedom). In other words, the aerial effector 102a may be an omnidirectional aerial effector. Example arrangements of thrusters 130 that provide omnidirectional control of an aerial vehicle, which may be incorporated in the aerial effectors 102a disclosed herein, may be found in the '198 application. However, it should be appreciated that, in some implementations, control over fewer degrees of freedom may be sufficient to manipulate the applicator effector 106a, the squeegee effector 106b, or another effector 106. For example, the aerial effector 102a may provide independent control over three, four, or five degrees of freedom. In another example, an aerial effector 102a with a location tracking effector (e.g., a location tracking system 170) may have relatively fewer thrusters to independently control fewer degrees of freedom since the location tracking effector may not

require precise movement or movement along a complex trajectory. For example, the aerial effector 102a may have independent control over four or less degrees of freedom.

**[0256]** In some implementations, the aerial effector 102a may include different thrusters 130 capable of producing a different amount of thrust and/or the thrusters 130 may be arranged in a manner that provides more precise control, a higher rate of change along one (or more) degree of freedom over at least one other degree of freedom, and/or more thrust along one (or more) degree of freedom over at least one other degree of freedom. For example, an aerial effector 102a with an effector 106 that physically contacts a surface may be configured to generate more thrust along the direction in which the effector 106 makes physical contact with the surface (e.g., the normal axis of the surface, such as a horizontal direction for a vertical surface), thus increasing the contact pressure between the effector 106 and the surface.

**[0257]** In some implementations, the thrusters 130 of the aerial effector 102a may each include a DC brushless electric motor with a rotor, which rotates at variable speeds to generate a variable amount of thrust. The motor may include an electronic speed controller (ESC) to receive control signals and adjust the speed of the rotor based on the control signals. The thrusters 130 may be fixed-pitch rotors where the thruster 130 switches between positive and negative thrust by reversing the direction of rotation of the rotor. The thrusters 130 may be variable-pitch rotors where the thruster 130 switches between positive and negative thrust by using an actuator to adjust the angle of attack of the rotors between positive to negative. In some implementations, the thrusters 130 may have different handedness. For example, for an aerial effector 102a with an even number of thrusters 130 (e.g., four thrusters, six thrusters, eight thrusters), half of the thrusters 130 may have one handedness (e.g., rotate clockwise) and the remaining half of the thrusters 130 may have another handedness (e.g., rotate counterclockwise).

**[0258]** In some implementations, the thrusters 130 may be statically mounted to the frame 105 as described above. In other words, the orientation of the thrusters 130 with respect to the frame 105 may be fixed. In some implementations, the thrusters 130 may be mounted to the frame 105 via one or more rotary joints. The rotary joints may provide a way to independently change the orientation of the thruster 130, thus allowing independent control over multiple degrees of freedom using relatively fewer thrusters. Examples of statically mounted thrusters and thrusters mounted with one or more rotary joints that may be implemented in the aerial effectors 102a disclosed herein may be found in the '198 application.

[0259] The flex arm interface 120a may take various forms depending, in part, on whether the aerial effector 102a is communicatively coupled to the support system 200 or the base station 300 via a wired connection (e.g., a cable) or a wireless connection. For example, if the aerial effector 102a is connected to the support system 200 or the base station 300 via one of the flex arms 150a-150c, the flex arm interface 120a may include a port to physically couple the flex arm 150a, 150b, or 150c to the aerial effector 102a. The support system 200 and/or the base station 300 may also include a corresponding port (i.e., a flex arm interface 120b) to couple to the other end of the flex arm 150a, 150b, or 150c. In some implementations, the port may provide various connections to the aerial effector 102a including, but not limited to, electrical power, communication, and a fluidic connection (e.g., to supply cleaning fluid to the aerial effector 102a, to receive waste fluid from the aerial effector 102a). If the aerial effector 102a is communicatively coupled to the support system 200 or the base station 300 wirelessly, the flex arm interface 120a may include a wireless transceiver and the flex arm interface 120b of the support system 200 or the base station 300 may include a corresponding wireless transceiver. In some implementations, the wireless transceiver may operate in the radio frequency (RF) band.

[0260] The aerial effector 102a may also include one or more sensors (e.g., sensors 142 and 146) to acquire, for example, sensory data near or on a surface that may otherwise be difficult to obtain using sensors disposed elsewhere in the window cleaning system (e.g., on the support system 200, the base station 300). The flex arm 150 may thus provide additional channels to facilitate transmission of sensory data from the sensors onboard the aerial effector 102a. For example, the sensors 146 of the aerial effector 102a may include one or more pressure sensors disposed within the effector 106 to measure the contact pressure between the effector 106a and a surface. Additional examples of effectors 106 with sensors 146 and their use to measure contact pressure may be found in the '198 application and may be readily incorporated in the aerial effectors 102a described above. In another example, the sensors 142 of the aerial effector 102a may include a camera to acquire imagery of the surface in contact with the aerial effector 102a. The imagery may be used, for example, to evaluate whether the surface of a window is sufficiently clean or if another cleaning operation should be performed. The aerial effector 102a may generally include various sensors 146 including, but not limited to, an inertial measurement unit (IMU) (e.g., accelerometer(s), gyroscope(s), magnetometer(s)), a location tracker (e.g., a GNSS receiver, such as a global positioning system (GPS) receiver, an

altimeter), one or more imaging systems (e.g., a camera, a LiDAR imager, an acoustic localization sensor), a temperature sensor, a relative humidity sensor, and an anemometer.

**[0261]** It should be appreciated, however, that it may be preferable to offload any sensors from the aerial effector 102a if the operation of the aerial effector 102a is not appreciably affected. For example, localization sensing used to determine the location of the aerial effector 102a within the environment may be offloaded to the support system 200 and/or the base station 300. Specifically, a camera, an acoustic localization sensor, and/or a LiDAR imager (collectively forming a location tracking system 170) disposed on the support system 200 and/or the base station 300 may track the location of the aerial effector 102a relative to, for example, an object in the environment (e.g., a particular window) or the support system 200 and/or the base station 300 itself. The support system 200 and/or the base station 300 may further include a location tracker to determine its own location within the environment. The data obtained by the camera, LiDAR imager, acoustic localization sensor, and/or the location tracker may be sufficient to determine the location of the aerial effector 102a within the environment. In another example, some environmental conditions near the aerial effector 102a, the support system 200, and/or the base station 300 may be substantially similar or, in some instances, the same. Thus, sensors measuring these environmental conditions (e.g., a temperature sensor, a relative humidity sensor, an anemometer) may be disposed on the support system 200 and/or the base station 300 instead of the aerial effector 102a. In some implementations, the aerial effector 102a may not include any onboard sensors. Instead, any sensory data used to operate the aerial effector 102a may be acquired by sensors onboard the support system 200 and/or the base station 300.

**[0262]** It should also be appreciated that while the aerial effectors 102a disclosed herein may be designed to have fewer components compared to conventional aerobots, it may be preferable to retain certain components on the aerial effector 102a for some applications. For example, in applications that require the aerial effector 102a to navigate a confined environment where the flex arm 150 is likely to get caught on a structure or object in the environment, it may be preferable for the aerial effector 102a to forego any physical connection with a support system 200 and/or a base station 300. Thus, the aerial effector 102a may be communicatively coupled to the support system 200 and/or the base station 300 via a flex arm that provides a wireless communication link. Additionally, the aerial effector 102a may include a battery to provide electrical power. In some implementations, the aerial effector 102a may also include a pump and/or a tank to supply a fluid (e.g., a sealant).

**[0263] 4.1.1 Example Controller Architectures of the Window Cleaning Systems**

[0264] The operation of the window cleaning systems disclosed herein may be facilitated, in part, by one or more controllers. The controller(s) may be responsible, for example, for operating one or more subsystems of the window cleaning system, and/or executing instructions received by another device (e.g., a work plan from the central control system, as discussed in Section 4). The following discussion provides multiple non-limiting examples of controller architectures that may be implemented in the window cleaning systems disclosed herein.

[0265] In some implementations, the window cleaning system may include multiple controllers that are each responsible for operating different subsystems. For example, FIG. 10 shows a block diagram of an example window cleaning system that includes a support system 200 with a robotic controller 160 to control the support system 200 and an aerial effector 102a and a base station 300 with a base station controller 360 to control the base station 300. As shown, the base station controller 360 may control a fluid supply subsystem 303 (e.g., to supply cleaning fluid 332), a power supply subsystem 301 (e.g., to provide electrical power from an onboard power source), and a communication subsystem 302 (e.g., to facilitate communication with the support system 200 via the umbilical cord 352 and/or the central control system 108). The robotic controller 160 may control a fluid management system 203 (e.g., to dispense fluids to retrieve fluids from one or more aerial effectors 102a), a power management subsystem 201 (e.g., to supply electrical power to one or more aerial effectors), a location tracking system 170, and a communication subsystem 202 (e.g., to facilitate communication with one or more aerial effectors 102a, the base station 300 via the umbilical cord 352, and/or the central control system 108). The robotic controller 160 may also control the aerial effector 102a via a flex arm 150. For example, the robotic controller 160 may control one or more thrusters 130 of the aerial effector 102a and, in some implementations, receive sensory data from one or more sensors 142 and 146 onboard the aerial effector 102a. In this example, the robotic controller 160 may further control the base station controller 360. For instance, the robotic controller 160 may be responsible for executing an operation and, in doing so, may transmit commands to the base station controller 360. The base station controller 360 may execute the commands received from the robotic controller 160.

[0266] In some implementations, the window cleaning system may include a single controller to manage the operation of all the subsystems of the window cleaning system. For example, FIG. 11 shows a block diagram of a window cleaning system that includes a support system

200 with a robotic controller 160 that controls the support system 200, an aerial effector 102a, and a base station 300. In another example, FIG. 12 shows a block diagram of another window cleaning system that includes a support system 200 and a base station 300 with a robotic controller 160 that controls the support system 200, the base station 300, and an aerial effector 102a. For window cleaning systems that include a base station 300 that also functions as a support system 200 (see FIGS. 7 and 8), the base station controller 360 may manage the operation of all the subsystems of the window cleaning system, as shown in FIG. 13. Here, the base station controller 360, in effect, functions as the robotic controller 160.

#### **[0267] 4.1.2 Example Effectors**

**[0268]** The support system 200 and/or the base station 300 may support multiple aerial effectors 102a. This may be facilitated, in part, by the support system 200 and/or the base station 300 having multiple flex arm ports (i.e., flex arm interfaces 120b) to couple to respective flex arms 150 for the aerial effectors 102a. In some implementations, the flex arm ports may be identical and/or standardized to accommodate different types of aerial effectors 102a. In some implementations, the ports may provide quick connect interface to facilitate easy removal and attachment of the aerial effectors 102a. In some implementations, a subset of the flex arm ports may be used for one type of operation. For example, the support system 200 and/or the base station 300 may include a first set of flex arm ports fluidically coupled to a fluidic circuit supplying cleaning fluid 332. Accordingly, applicator aerial effectors 102b may be coupled to a flex arm port in the first set of flex arm ports. In another example, the support system 200 and/or the base station 300 may include a second set of flex arm ports fluidically coupled to a fluidic circuit to retrieve waste fluid 341. Accordingly, a squeegee aerial effector 102c may be coupled to a flex arm port in the second set of flex arm ports.

**[0269]** Generally, the aerial effectors 102a may be readily swapped out and/or replaced with other aerial effectors 102a depending on the operations to be performed at a particular work site. For example, a first set of aerial effectors 102a may be attached to a support system 200 or base station 300 to perform a first set of operations. Thereafter, the first set of aerial effectors 102a may be replaced with a second set of aerial effectors 102a to perform a second set of operations. Therefore, the operator may customize the window cleaning system to include different sets of aerial effectors 102a according to the demands of an operation or work plan. This may be accomplished, for example, by the human operator disconnecting an aerial effector 102a from a flex arm 150 or disconnecting the aerial effector 102a and the flex arm 150 from the support system 200 and/or the base station 300. For example, the window cleaning system

may include an equal number of applicator aerial effectors 102b and squeegee aerial effectors 102c. In another example, the window cleaning system may include more applicator aerial effectors 102b than squeegee aerial effectors 102c. In yet another example, the window cleaning system may include fewer applicator aerial effectors 102b than squeegee aerial effectors 102c.

**[0270]** The aerial effectors 102a disclosed herein may each include one or more effectors 106 to perform one or more operations on a surface. In some implementations, the aerial effector 102a may include only one effector 106. This may be preferable, for example, to reduce the weight of the aerial effector 102a by limiting the aerial effector 102a to perform one type of operation (e.g., applying a cleaning fluid 332 to a window, removing waste fluid 341 from the window). In some implementations, the aerial effector 102a may include two or more effectors 106 capable of performing multiple types of operations, thus improving the productivity of each aerial effector 102a. For example, an aerial effector 102a may include a combined applicator effector 106a and squeegee effector 106b to simultaneously apply cleaning fluid 332 and remove waste fluid 341.

**[0271]** The aerial effectors 102a disclosed herein may further include passive or active effectors 106. A passive effector 106 relies on the thrusters 130 of the aerial effector 102a to position and/or orient the effector 106. An active effector 106 may include one or more motors and one or more joints actuated by the motor(s) (collectively actuators 132) to adjust the position and/or attitude of the effector 106 relative to the actuated effector mount 104 of the aerial effector 102a. In some implementations, an active effector 106 may be preferable in situations where controlling the position and/or orientation of the effector 106 with greater precision is desired. For example, the edges of a window may require greater precision to apply cleaning fluid 332 or remove waste fluid 341.

**[0272]** Example effectors 106 that may be incorporated in the aerial effectors 102a disclosed herein include various contact tools and non-contact tools including, but not limited to, a passive applicator effector with a sponge, a brush, or a roller, a passive squeegee effector with wide or narrow squeegee blades, a combined applicator and squeegee effector, an active squeegee effector with one or more rotary joints arranged in a serial or parallel configuration, a location tracking system (e.g., a camera, a LiDAR imager, an acoustic localization sensor), a passive or active paint roller effector, a passive or active fruit picker effector, a passive or active screwdriver, and a passive or active drill. Additional details and examples of at least some of the foregoing effectors 106 may be found in the '198 application.

**[0273] 4.2 Example Central Control System**

**[0274]** As described above, the central control system 108 may facilitate the execution of one or more operations by the window cleaning systems 100b-100h. This may be accomplished, in part, via a software application 109 on the central control system 108. The software application 109 provides a user interface to display information on the window cleaning system (e.g., operating status, sensor readings, error notifications) to an operator and facilitates receipt of instructions from the operator. Generally, the central control system 108 may be communicatively coupled to one or more window cleaning systems. For example, multiple window cleaning systems 100b may be deployed at a particular work site to clean several windows in parallel. Each of the window cleaning systems 100b may be managed by the central control system 108. The central control system 108 may also assist the operator in performing other functions, such as mapping a worksite to obtain data on the set of windows to be cleaned, or generating a quote for customers regarding the cost of cleaning the set of windows.

**[0275]** The central control system 108 may include one or more computing devices including, but not limited to, a desktop computer, a laptop, a tablet, and a phone. The central control system 108 may be communicatively coupled directly to at least one of the support system 200a (e.g., the robotic controller 160 via a communication subsystem 202 on the support system 200a), or the base station 300a (e.g., the base station controller 360 via a communication subsystem 302 on the base station 300a). Communication between the central control system 108 and the respective communication subsystems 202 and 302 of the support system 200a and/or the base station 300a may be accomplished via a wired connection (e.g., an Ethernet cable, a Universal Serial Bus (USB) cable, and/or the like) and/or a wireless communication (e.g., LoRaWAN, WiSun, Zigbee, Bluetooth, 3G, 4G, 5G, and/or the like). In some implementations, the central control system 108 may maintain a persistent connection with the window cleaning system 100b.

**[0276]** In some implementations, the central control system 108 may include one or more servers (e.g., cloud servers), which may provide several functions including, but not limited to, remote backup storage of data related to the work plan, and data analysis (e.g., analyzing image maps of the work site to facilitate generation of a work plan or trajectories for the aerial effectors 102a to follow when cleaning different windows of a structure).

**[0277] 4.3 Example Computer Components**

**[0278]** The robotic controller 160, the base station controller 360, and the central control

system 108 may each include one or more processors and memory. For example, the robotic controller 160 may include a processor 161 and memory 162. In another example, the base station controller 360 may include a processor 364 and memory 365. Additionally, in some implementations, the aerial effector 102a may retain some onboard electronic circuitry (e.g., the processor 140 and the memory 141). The processors may be any suitable processing device configured to run and/or execute a set of instructions or code. Each processor may be, for example, a general-purpose processor, a Field Programmable Gate Array (FPGA), an Application Specific Integrated Circuit (ASIC), a Digital Signal Processor (DSP), and/or the like. The memory may encompass, for example, a random-access memory (RAM), a memory buffer, a hard drive, a database, an erasable programmable read-only memory (EPROM), an electrically erasable read-only memory (EEPROM), a read-only memory (ROM), Flash memory, and/or so forth. The memory may store instructions to cause the one or more processors, respectively, to execute processes and/or functions associated with the execution of a work plan and/or a particular operation at a particular work site.

#### **[0279] 5. Example Operations and Methods**

**[0280]** In some implementations, the operation of the window cleaning systems 100b-100h disclosed in Section 2 may be preceded by one or more processes to facilitate generation of a work plan by the central control system to clean a set of windows on a structure.

**[0281]** For example, a sales agent may visit a new customer work site to evaluate the work site and schedule a session for cleaning. During the visit, the sales agent may collect data on the work site. For example, the data may include a digital map of the interior and exterior surfaces of the windows. The digital map may include, for example, the coordinate locations of the windows relative to a global ground reference to facilitate navigation to each window, the shape of each window, the dimensions of each window, and the orientation of each window (e.g., vertical, inclined, horizontal). The data on the interior surfaces of the windows may be acquired via a 360-degree camera on a mast. The camera may be carried by the sales agent as they walk around the work site. The data on the exterior surfaces of the windows may be acquired by an aerobot with an imaging system (e.g., a camera, a laser scanner (LiDAR), and/or the like).

**[0282]** During this visit, the customer may select a set of windows for cleaning, which may generally include at least one or, in some instances, all the windows of the structure. The customer may further choose to clean the interior surfaces of the windows, the exterior surfaces of the windows, or both. It should be appreciated that the set of windows selected for interior

cleaning and exterior cleaning may be different. It should also be appreciated that the data collected may be stored and later retrieved, for example, when revisiting the work site for another cleaning service.

[0283] The cleaning of the interior surfaces and exterior surfaces of the set of windows may thereafter be scheduled separately and/or performed separately using different window cleaning systems. In some implementations, the cleaning service may be performed by a single human operator and one or more cleaning systems (each with at least one aerial effector) controlled by a single central control system 108. For example, a human operator may manage five window cleaning systems at a particular work site.

[0284] For an outdoor cleaning service, a work plan may be generated beforehand that specifies different sets of windows to be cleaned by different window cleaning systems according to a planned schedule. The work plan may divide the windows amongst different window cleaning systems based, in part, on the geometry of the building and/or the range of the aerial effectors 102a in each system, which may be limited, in part, by the length of the respective flex arms 150 for the aerial effectors 102a.

[0285] Based on the work plan, the operator may set up the base station 300 for each window cleaning system such that the aerial effectors 102a associated with that particular window cleaning system have access to the assigned set of windows of the structure. If the system includes a separate support system 200, the operator may then connect an umbilical cord 352 at one end to an umbilical port on the base station 300 and the other end of the umbilical cord 352 to the support system 200. Each aerial effector 102a may thereafter be coupled to the support system 200 via a flex arm 150 (e.g., by a connecting a cable to a flex arm port (i.e., the flex arm interface 120b) on the support system 200 and the flex arm interface 120a of the aerial effector 102a). If the base station 300 functions as the support system, each aerial effector 102a may be directly coupled to the base station 300 via a flex arm 150 (e.g., by connecting a cable to a flex arm port (i.e., the flex arm interface 120b) on the base station 300 and the flex arm interface 120a of the aerial effector 102a).

[0286] If the window cleaning system includes a separate support system 200, the base station 300 may begin providing electrical power and cleaning fluid to the support system 200 and/or suction to the support system 200 (for later removal of waste fluid) once connected. The support system 200 may initially close any onboard valves to prevent cleaning fluid from being dispensed to an applicator aerial effector 102b and/or suction being provided to a squeegee

aerial effector 102c. If the base station 300 functions as the support system, the base station 300 may provide electrical power to the aerial effectors 102a. However, the base station 300 may initially close any onboard valves and/or keep any onboard pumps for the cleaning fluid and/or waste fluid off to prevent cleaning fluid from being dispensed to an applicator aerial effector 102b and/or suction being provided to a squeegee aerial effector 102c.

[0287] The window cleaning system may then be activated and initialized before executing the work plan. For example, if the window cleaning system includes a base station 300 with a boom arm 222 deployed on a roof of a structure and a support system 200 suspended from the boom arm 222 via an end pulley 224 (see FIG. 2), the boom arm 222 may first vertically raise the support system 200 off the roof (e.g., by reducing a length of the cable 226 supporting the support system 200 via a cable winch 228). Then, the boom arm 222 and/or the base station 300 may horizontally move the support system 200 so that it can be lowered vertically along a side of the structure that includes windows assigned to the system for cleaning. Before the support system 200 is moved, the aerial effectors 102a may be activated to fly up and then hover above the support system 200 so that as the support system 200 moves, the aerial effectors 102a clear any obstacles on the roof while maintaining slack in their respective flex arms 150. In another example, if the window cleaning system includes a base station 300 deployed on the ground and a support system 200 with thrusters 212 (see FIG. 5), the support system 200 may be activated to fly up off the ground. In some implementations, the aerial effectors 102a may also be activated to fly with the support system 200 to maintain slack in their respective flex arms 150. However, in some implementations, the aerial effectors 102a may remain inactive as the support system 200 flies. In other words, the support system 200 may carry the inactive aerial effectors 102a in the air until the aerial effectors 102a are activated to execute the work plan. In yet another example, if the window cleaning system includes a base station 300 deployed on the ground and aerial effectors 102a directly coupled to the base station 300 with no support system (see FIG. 7), the aerial effectors 102a may be activated to fly up and hover above the ground.

[0288] The robotic controller 160 onboard the support system 200 and/or the base station controller 360 may then receive instructions from the central control system 108 corresponding to the work plan to be executed by the window cleaning system. The window cleaning system may thereafter begin executing the work plan. For example, if the window cleaning system includes a support system 200, the support system 200 may be positioned near the first window in the assigned set of windows and the aerial effectors 102a may then perform their respective

operations on the first window. In another example, if the window cleaning system does not include a support system 200, the base station 300 may move near the first window in the assigned set of windows and the aerial effectors 102a may then perform their respective operations on the first window. In some implementations, the window cleaning system may operate autonomously thereafter with the base station 300, the support system 200 (if present), and the aerial effectors 102a moving to different windows in the assigned set of windows until the work plan is complete. The operator may not be required to interact with the window cleaning system during this period unless an error, interruption, or exception occurs.

**[0289]** In some implementations, the work plan may be designed to reduce the distance traveled by the support system 200 and/or the aerial effectors 102a. For high-rise buildings with roof-mounted base stations 300, the work plan may specify the support system 200 and/or the aerial effectors 102a to clean windows in one vertical column beginning at the top first and progressively work vertically downwards before moving laterally and moving back upwards to clean another adjacent column of windows. For ground-based base stations 300, the support system 200 and/or the aerial effectors 102a may clean windows in one vertical column beginning at the bottom first and progressively work upwards before moving laterally and moving back downwards to clean another adjacent column of windows.

**[0290]** For an indoor cleaning service, the operator may deploy one window cleaning system per room to clean the assigned set of windows in each room. In some implementations, the number of window cleaning systems deployed by an operator may depend, in part, on the time spent by the operator to move and redeploy window cleaning systems to different rooms. For example, if the amount of time typically required to launch a support system 200 (if present) and/or aerial effectors 102a in a room is equal to one-third of the time for the window cleaning system to clean the room, then an operator may keep at most four window cleaning systems busy at all times. Thus, an indoor cleaning service may only include 3-4 window cleaning systems per operator.

**[0291]** For both outdoor and indoor cleaning, the window cleaning system, when cleaning a window, may use one or more onboard sensors (e.g., an imaging system onboard the support system 200 or the base station 300, the location tracking system 170) to identify individual glass panes and/or surrounding frame structures. Each glass pane may then be cleaned. For example, an applicator aerial effector 102b may start at one corner of the pane and thereafter move across the entire pane to apply cleaning fluid and scrub the surface of the window to agitate and release detritus on the surface of the window for suspension in the cleaning fluid.

Once the pane is covered with cleaning fluid, a squeegee aerial effector 102c may remove the resulting waste fluid from the pane. Specifically, the squeegee aerial effector 102c may move along the surface of the window with a squeegee blade to collect the waste fluid, which may be suctioned into the squeegee aerial effector 102c (and transferred to the support system 200 or the base station 300). Once the panes of a window have been cleaned, the window cleaning system may proceed to the next window in the set of windows and repeat the above process.

**[0292]** In some implementations, the full length of the squeegee blade may be kept in continuous contact with the flat glass and the squeegee blade may further be moved with overlapping sweeping motions. In this manner, waste fluid may be removed from the glass with little or, in some instances, no streaks. It should be appreciated, however, this approach is one non-limiting example. In some implementations, the squeegee blade may be intermittently removed from the glass so that the squeegee blade can be repositioned without being constrained, for example, by the frame of the window. The glass of the window may still be cleaned with little to no streaks if the squeegee blade is thereafter placed onto a portion of the window with cleaning fluid and thereafter moved in a sweeping motion to overlap with a previous sweeping motion.

### **[0293] 5.1 Example Trajectories**

**[0294]** The translational and rotational motion of the aerial effectors 102a disclosed herein may generally be controlled over multiple degrees of freedom, which allows for greater maneuverability of the aerial effector 102a to perform various operations (e.g., contact treatment of elevated vertical or inclined surfaces) with sufficient precision. When performing an operation, the translational and rotational motion of the aerial effector 102a may be controlled (e.g., by the robotic controller 160 of the support system 200, the base station controller 360 of the base station 300) so that one or more effectors 106 in the aerial effector 102a follow a particular treatment trajectory across/along a surface. For example, the treatment trajectory may be defined so that an applicator aerial effector 102b applies a cleaning fluid onto at least a portion of a window or a squeegee aerial effector 102c removes waste fluid from at least a portion of the window. It should be appreciated that, for a given surface and type of contact treatment of the surface, different trajectories may be defined for an aerial effector's motion depending on the effector 106 used and the operation being performed.

[0295] Multiple non-limiting examples of treatment trajectories that may be formulated and then executed by the aerial effectors 102a based on control signals received from the support system 200 and/or the base station 300 may be found in the '198 application.

### [0296] 5.2 Example Control Loop Systems

[0297] The operation of the window cleaning system may be facilitated, in part, by use of a closed loop feedback control system. For example, the base station 300, the support system 200 (if present), and the aerial effectors 102a may each move during operation to access and/or clean multiple windows. Accordingly, the motion of each of the base station 300, the support system 200, and the aerial effectors 102a may be controlled using a corresponding control loop. In some implementations, the aerial effector 102a may not include any onboard flight control system, thus the support system 200 or the base station 300 may execute the control loop for the aerial effector 102a and transmit control signals to the thrusters 130 of the aerial effector 102a to adjust the trajectory of the aerial effector 102a. Further details of a control loop that may be implemented to control movement of the aerial effector 102a may be found in the '198 application.

### [0298] 5.3 Example Methods

[0299] Example methods for generating a set of operations for a window cleaning system to perform on a particular window may be found in the '198 application. The methods may be implemented by the window cleaning systems disclosed herein, for example, using the support system 200 and/or the base station 300 to facilitate execution of the operations (e.g., by sending control signals to the aerial effectors 102a to perform an operation).

### [0300] 6. Conclusion

[0301] All parameters, dimensions, materials, and configurations described herein are meant to be example and the actual parameters, dimensions, materials, and/or configurations will depend upon the specific application or applications for which the inventive teachings is/are used. It is to be understood that the foregoing embodiments are presented primarily by way of example and that, within the scope of the appended claims and equivalents thereto, inventive embodiments may be practiced otherwise than as specifically described and claimed. Inventive embodiments of the present disclosure are directed to each individual feature, system, article, material, kit, and/or method described herein.

[0302] In addition, any combination of two or more such features, systems, articles, materials, kits, and/or methods, if such features, systems, articles, materials, kits, and/or methods are not

mutually inconsistent, is included within the inventive scope of the present disclosure. Other substitutions, modifications, changes, and omissions may be made in the design, operating conditions and arrangement of respective elements of the example implementations without departing from the scope of the present disclosure. The use of a numerical range does not preclude equivalents that fall outside the range that fulfill the same function, in the same way, to produce the same result.

**[0303]** Also, various inventive concepts may be embodied as one or more methods, of which an example has been provided. The acts performed as part of the method may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments.

**[0304]** All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety.

**[0305]** All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

**[0306]** The indefinite articles “a” and “an,” as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean “at least one.”

**[0307]** The phrase “and/or,” as used herein in the specification and in the claims, should be understood to mean “either or both” of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with “and/or” should be construed in the same fashion, i.e., “one or more” of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the “and/or” clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to “A and/or B”, when used in conjunction with open-ended language such as “comprising” can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

**[0308]** As used herein in the specification and in the claims, “or” should be understood to have the same meaning as “and/or” as defined above. For example, when separating items in a list, “or” or “and/or” shall be interpreted as being inclusive, i.e., the inclusion of at least one, but

also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as “only one of” or “exactly one of,” or, when used in the claims, “consisting of,” will refer to the inclusion of exactly one element of a number or list of elements. In general, the term “or” as used herein shall only be interpreted as indicating exclusive alternatives (i.e., “one or the other but not both”) when preceded by terms of exclusivity, such as “either,” “one of,” “only one of,” or “exactly one of.” “Consisting essentially of,” when used in the claims, shall have its ordinary meaning as used in the field of patent law.

**[0309]** As used herein in the specification and in the claims, the phrase “at least one,” in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase “at least one” refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, “at least one of A and B” (or, equivalently, “at least one of A or B,” or, equivalently “at least one of A and/or B”) can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

**[0310]** In the claims, as well as in the specification above, all transitional phrases such as “comprising,” “including,” “carrying,” “having,” “containing,” “involving,” “holding,” “composed of,” and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases “consisting of” and “consisting essentially of” shall be closed or semi-closed transitional phrases, respectively, as set forth in the United States Patent Office Manual of Patent Examining Procedures, Section 2111.03.

## CLAIMS

1. A robotic system, comprising:
  - a first robotic limb comprising:
    - a first non-articulated passive flexible arm that does not have powered movement; and
    - a first actuated mobile hand, coupled to the first non-articulated passive flexible arm, to carry a first tool, the first actuated mobile hand configured for at least one of translational or rotational motion with multiple degrees of freedom, wherein:
      - the first actuated mobile hand comprises a first propulsion system to facilitate first mobility of the first actuated mobile hand; and
      - the first non-articulated passive flexible arm carries at least one first control signal to the first propulsion system to control the first mobility of the first actuated mobile hand;
  - a second robotic limb comprising:
    - a second non-articulated passive flexible arm that does not have powered movement; and
    - a second actuated mobile hand, coupled to the second non-articulated passive flexible arm, to carry a second tool, the second actuated mobile hand configured for at least one of translational or rotational motion with multiple degrees of freedom, wherein:
      - the second actuated mobile hand comprises a second propulsion system to facilitate second mobility of the second actuated mobile hand; and
      - the second non-articulated passive flexible arm carries at least one second control signal to the second propulsion system to control the second mobility of the second actuated mobile hand;
  - a perception and localization system to provide at least first location information for the first actuated mobile hand and second location information for the second actuated mobile hand; and
  - a robotic controller, communicatively coupled to the first actuated mobile hand at least in part via the first non-articulated passive flexible arm, communicatively coupled to the

second actuated mobile hand at least in part via the second non-articulated passive flexible arm, and communicatively coupled to the perception and localization system, to:

receive, from the perception and localization system, the first location information for the first actuated mobile hand and the second location information for the second actuated mobile hand;

generate the at least one first control signal based on the received first location information to control the first mobility of the first actuated mobile hand; and

generate the at least one second control signal based on the received second location information to control the second mobility of the second actuated mobile hand.

2. The robotic system of claim 1, wherein:

the first actuated mobile hand is a first flying hand configured for translational and rotational motion through air with multiple degrees of freedom; and

the first propulsion system comprises a first plurality of thrusters.

3. The robotic system of claim 1, wherein:

the first actuated mobile hand is a first swimming hand configured for translational and rotational motion through water with multiple degrees of freedom; and

the first propulsion system comprises a first plurality of thrusters that displace the water.

4. The robotic system of claim 1, wherein:

the first actuated mobile hand is a first rolling hand configured for the at least one of translational and rotational motion on a surface with multiple degrees of freedom; and

the first propulsion system includes a first plurality of motorized wheels or tracks to facilitate the mobility of the first rolling hand on the surface.

5. The robotic system of claim 1, wherein:

the first actuated mobile hand is a first walking hand configured for the at least one of translational and rotational motion on a surface with multiple degrees of freedom; and

the first propulsion system includes a first plurality of motorized articulated legs to facilitate the mobility of the first walking hand on the surface.

6. The robotic system of claim 1, wherein:
  - the first non-articulated passive flexible arm is a first tether cable communicatively coupled to the first actuated mobile hand and at least one of the perception and localization system and the robotic controller to carry the at least one first control signal; and
  - the second non-articulated passive flexible arm is a second tether cable communicatively coupled to the second actuated mobile hand and at least one of the perception and localization system and the robotic controller to carry the at least one second control signal.
  
7. The robotic system of claim 6, wherein:
  - the first tether cable provides the at least one first control signal and first power to the first actuated mobile hand; and
  - the second tether cable provides the at least one second control signal and second power to the second actuated mobile hand.
  
8. The robotic system of claim 6, wherein:
  - the first tether cable carries at least one first fluid to or from the first actuated mobile hand; and
  - the second tether cable carries at least one second fluid to or from the second actuated mobile hand.
  
9. The robotic system of claim 6, wherein:
  - the first tether cable has a first variable length to accommodate the first mobility of the first actuated mobile hand; and
  - the second tether cable has a second variable length to accommodate the second mobility of the second actuated mobile hand.
  
10. The robotic system of claim 1, wherein:
  - the first non-articulated passive flexible arm is at least one first wireless communication link to carry the at least one first control signal to the first actuated mobile hand; and

the second non-articulated passive flexible arm is at least one second wireless communication link to carry the at least one second control signal to the second actuated mobile hand.

11. The robotic system of claim 10, wherein:
  - the first actuated mobile hand includes at least one first battery to provide first power for the first propulsion system; and
  - the second actuated mobile hand includes at least one second battery to provide second power for the second propulsion system.
  
12. The robotic system of claim 1, further comprising the first tool and the second tool, wherein:
  - the first tool facilitates first contact with a first object; and
  - the second tool facilitates second contact with at least one of the first object or a second object.
  
13. The robotic system of claim 12, wherein:
  - each of the first tool and the second tool includes a reflector.
  
14. The robotic system of claim 12, wherein:
  - the first actuated mobile hand consists of:
    - a first frame;
    - a first interface to couple to the first non-articulated passive flexible arm;
    - the first propulsion system; and
    - the first tool; and
  - the second actuated mobile hand consists of:
    - a second frame;
    - a second interface to couple to the second non-articulated passive flexible arm;
    - the second propulsion system; and
    - the second tool.
  
15. The robotic system of claim 12, wherein:
  - the first actuated mobile hand consists of:

- a first frame;
  - a first interface to couple to the first non-articulated passive flexible arm;
  - the first propulsion system;
  - the first tool; and
  - at least one first sensor; and
- the second actuated mobile hand consists of:
- a second frame;
  - a second interface to couple to the second non-articulated passive flexible arm;
  - the second propulsion system; and
  - the second tool; and
  - at least one second sensor.
16. The robotic system of claim 1, wherein:
- the first actuated mobile hand includes at least one first sensor; and
  - the second actuated mobile hand includes at least one second sensor.
17. The robotic system of claim 16, wherein at least one of the at least one first sensor or the at least one second sensor includes at least one pressure sensor.
18. The robotic system of claim 16, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one environmental sensor.
19. The robotic system of claim 16, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one imaging sensor.
20. The robotic system of claim 16, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one inertial measurement unit (IMU).
21. The robotic system of claim 16, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one satellite navigation device.

22. The robotic system of claim 1, wherein at least one of the first actuated mobile hand or the second actuated mobile hand is configured for translational and rotational motion with six degrees of freedom.
23. The robotic system of claim 1, wherein the perception and localization system is arranged in the robotic system within a line-of-sight of the first actuated mobile hand and the second actuated mobile hand.
24. The robotic system of claim 1, wherein the perception and localization system is co-located with the robotic controller.
25. The robotic system of claim 1, wherein the perception and localization system comprises at least one of:  
at least one imaging sensor;  
at least one sound navigation and ranging (SONAR) device;  
at least one satellite navigation device; or  
at least one light detection and ranging (LIDAR) device.
26. The robotic system of claim 1, wherein:  
the perception and localization system is positioned in the robotic system with respect to the first actuated mobile hand and the second actuated mobile hand so as to have a field of view that includes the first mobility of the first actuated mobile hand and the second mobility of the second actuated mobile hand.
27. The robotic system of claim 26, wherein the perception and localization system is configured to be mobile so as to maintain the field of view that includes the first mobility of the first actuated mobile hand and the second mobility of the second actuated mobile hand.
28. The robotic system of claim 27, further comprising:  
a mobile base station; and  
a mounting arm to couple the perception and localization system to the mobile base station.

29. The robotic system of claim 28, wherein:  
the mounting arm is a telescoping mounting arm to facilitate positioning and/or alignment of the perception and localization system relative to the mobile base station.
30. The robotic system of claim 28, wherein:  
the mobile base station comprises a base station controller, separate from the robotic controller, to control at least one function of the mobile base station.
31. The robotic system of claim 1, wherein the robotic controller is configured to:  
autonomously determine, based at least in part on the received first location information, a first trajectory of the first mobility of the first actuated mobile hand;  
generate the at least one first control signal for the first propulsion system of the first actuated mobile hand based at least in part on the determined first trajectory of the first mobility of the first actuated mobile hand;  
autonomously determine, based at least in part on the received second location information, a second trajectory of the second mobility of the second actuated mobile hand;  
and  
generate the at least one second control signal for the second propulsion system of the second actuated mobile hand based at least in part on the determined second trajectory of the second mobility of the second actuated mobile hand.

32. A robotic system, comprising:  
a robotic limb, comprising:  
a non-articulated passive flexible arm that does not have powered movement;  
and  
an actuated mobile hand, coupled to the non-articulated passive flexible arm, to hold a tool, the actuated mobile hand configured for at least one of translational or rotational motion with multiple degrees of freedom,  
wherein:  
the actuated mobile hand comprises a propulsion system to facilitate mobility of the actuated mobile hand; and  
the non-articulated passive flexible arm carries at least one control signal to the propulsion system to control the mobility of the actuated mobile hand; and  
a robotic limb controller, coupled to the robotic limb, to:  
autonomously determine a location of the actuated mobile hand;  
autonomously determine a trajectory of the mobility of the actuated mobile hand based at least in part on the location of the actuated mobile hand; and  
generate the at least one control signal for the propulsion system of the actuated mobile hand based at least in part on the determined trajectory of the mobility of the actuated mobile hand.
33. The robotic system of claim 32, wherein:  
the actuated mobile hand is a flying hand configured for translational and rotational motion through air with multiple degrees of freedom; and  
the propulsion system comprises a plurality of thrusters.
34. The robotic system of claim 32, wherein:  
the actuated mobile hand is a swimming hand configured for translational and rotational motion through water with multiple degrees of freedom; and  
the propulsion system comprises a plurality of thrusters that displace the water.
35. The robotic system of claim 32, wherein:  
the actuated mobile hand is a rolling hand configured for the at least one of translational and rotational motion on a surface with multiple degrees of freedom; and

the propulsion system includes a plurality of motorized wheels or tracks to facilitate the mobility of the rolling hand on the surface.

36. The robotic system of claim 32, wherein:

the actuated mobile hand is a walking hand configured for the at least one of translational and rotational motion on a surface with multiple degrees of freedom; and

the propulsion system includes a plurality of motorized articulated legs to facilitate the mobility of the walking hand on the surface.

37. The robotic system of claim 32, wherein the non-articulated passive flexible arm is a tether cable communicatively coupled to the actuated mobile hand and the robotic limb controller to carry the at least one control signal.

38. The robotic system of claim 37, wherein the tether cable provides the at least one control signal and power to the actuated mobile hand.

39. The robotic system of claim 38, wherein:

the tether cable carries at least one fluid to or from the actuated mobile hand.

40. The robotic system of claim 32, wherein the tether cable has a variable length to accommodate the mobility of the actuated mobile hand.

41. The robotic system of claim 32, wherein the non-articulated passive flexible arm is at least one wireless communication link to carry the at least one first control signal to the actuated mobile hand.

42. The robotic system of claim 41, wherein the actuated mobile hand includes at least one battery to provide power for the propulsion system.

43. The robotic system of claim 32, further comprising the tool, wherein the tool facilitates contact with an object.

44. The robotic system of claim 43, wherein the tool includes a reflector.

45. The robotic system of claim 32, wherein the actuated mobile hand consists of:  
a frame;  
an interface to couple to the non-articulated passive flexible arm;  
the propulsion system; and  
the tool.
46. The robotic system of claim 32, wherein the actuated mobile hand consists of:  
a frame;  
an interface to couple to the non-articulated passive flexible arm;  
the first system;  
the tool; and  
at least one sensor.
47. The robotic system of claim 32, wherein the actuated mobile hand includes at least one sensor.
48. The robotic system of claim 47, wherein the at least one sensor includes at least one pressure sensor.
49. The robotic system of claim 47, wherein the at least one sensor includes at least one environmental sensor.
50. The robotic system of claim 47, wherein the at least one sensor includes at least one imaging sensor.
51. The robotic system of claim 47, wherein the at least one sensor includes at least one inertial measurement unit (IMU).
52. The robotic system of claim 47, wherein the at least one sensor includes at least one satellite navigation device.
53. The robotic system of claim 32, wherein the actuated mobile hand is configured for translational and rotational motion with six degrees of freedom.

54. The robotic system of claim 32, wherein the robotic limb controller is arranged in the robotic system within a line-of-sight of the actuated mobile hand.
55. The robotic system of claim 32, wherein the robotic limb controller comprises at least one of:
- at least one imaging sensor;
  - at least one sound navigation and ranging (SONAR) device;
  - at least one satellite navigation device; or
  - at least one light detection and ranging (LIDAR) device.
56. The robotic system of claim 32, wherein:
- the robotic limb controller is positioned in the robotic system with respect to the actuated mobile hand so as to have a field of view that includes the mobility of the actuated mobile hand.
57. The robotic system of claim 56, wherein the robotic limb controller is configured to be mobile so as to maintain the field of view that includes the mobility of the actuated mobile hand.
58. A robotic system, comprising:
- a robotic limb, comprising:
    - a non-articulated passive flexible arm that does not have powered movement;
  - and
  - an actuated mobile hand coupled to the non-articulated passive flexible arm and configured for at least one of translational or rotational motion with multiple degrees of freedom, wherein the actuated mobile hand is not capable of planning or executing a trajectory of the actuated mobile hand; and
  - a robotic limb controller, coupled to the robotic limb, to:
    - autonomously determine a location of the actuated mobile hand; and
    - autonomously determine the trajectory of the actuated mobile hand based at least in part on the location of the actuated mobile hand.
59. A distributed robotic system, comprising:

an aerial end effector configured for translational and rotational motion in air with multiple degrees of freedom, the aerial end effector including a plurality of thrusters;

a flexible arm coupled to the aerial end effector to provide at least one control signal to at least one thruster of the plurality of thrusters;

a localization system, disposed separately from the aerial end effector, to provide location information for the aerial end effector; and

a controller, disposed separately from the aerial end effector, communicatively coupled to the aerial end effector via the flexible arm, and communicatively coupled to the localization system, to receive the location information for the aerial end effector and generate the at least one control signal based on the received location information to control the plurality of thrusters so as to cause the aerial end effector to move along a predetermined trajectory.

60. The system of claim 59, wherein the flexible arm is a tether cable coupled to the aerial end effector and the controller to carry the at least one control signal.

61. The system of claim 59, wherein the flexible arm provides the at least one control signal and power to the aerial end effector.

62. The system of claim 59, wherein the flexible arm is at least one wireless communication link to carry the at least one control signal from the controller to the aerial end effector.

63. The system of claim 62, wherein the aerial end effector includes at least one battery to provide power for at least the plurality of thrusters.

64. The system of claim 59, wherein the aerial end effector does not include a processor, and all operation of the aerial end effector is controlled by the controller.

65. The system of claim 59, wherein the aerial end effector includes at least one contact tool to facilitate contact with an object.

66. The system of claim 65, wherein the aerial end effector includes at least one reflector.
67. The system of claim 65, wherein the aerial end effector consists of:  
a frame;  
an interface to couple to the flexible arm;  
the plurality of thrusters; and  
the at least one contact tool.
68. The system of claim 65, wherein the at least one contact tool facilitates repair of the object.
69. The system of claim 65, wherein the at least one contact tool facilitates harvesting of a crop.
70. The system of claim 65, wherein the at least one contact tool facilitates contact treatment of a surface.
71. The system of claim 70, wherein the at least one contact tool facilitates cleaning of a surface.
72. The system of claim 71, wherein the at least one contact tool includes a squeegee.
73. The system of claim 71, wherein the at least one contact tool includes a cleaning fluid applicator and/or scrubber.
74. The system of claim 73, wherein the aerial end effector includes a reservoir for the cleaning fluid.

75. The system of claim 71, wherein the at least one contact tool facilitates cleaning of an interior surface of a pipe or a tank.
76. The system of claim 70, wherein the at least one contact tool facilitates painting of a surface.
77. The system of claim 59, wherein the aerial end effector does not include a sensor.
78. The system of claim 59, wherein the aerial end effector includes at least one sensor.
79. The system of claim 78, wherein the at least one sensor includes at least one pressure sensor.
80. The system of claim 78, wherein the at least one sensor includes at least one environmental sensor.
81. The system of claim 78, wherein the at least one sensor includes at least one imaging sensor.
82. The system of claim 78, wherein the at least one sensor includes at least one inertial measurement unit (IMU).
83. The system of claim 78, wherein the at least one sensor includes at least one satellite navigation device.
84. The system of claim 59, wherein the aerial end effector is configured for translational and rotational motion in air with six degrees of freedom.
85. The system of claim 59, wherein the localization system is disposed within a line-of-sight of the aerial end effector.

86. The system of claim 59, wherein:  
the aerial end effector is a first aerial end effector;  
the flexible arm is a first flexible arm; and  
the localization system comprises:  
    a second aerial end effector configured for translational and rotational motion in air with multiple degrees of freedom; and  
    a second flexible arm coupled to the second aerial end effector and the controller.
87. The system of claim 59, wherein the localization system is co-located with the controller.
88. The system of claim 59, wherein the localization system comprises at least one of:  
at least one imaging sensor;  
at least one satellite navigation device;  
at least one SONAR device; or  
at least one light detection and ranging (LIDAR) device.
89. The system of claim 59, wherein the controller is configured as a mobile base station.
90. The system of claim 59, wherein the controller is an aerobot configured for translational and rotational motion in air with multiple degrees of freedom.
91. A robotic system, comprising:  
an end effector system, comprising:  
    an end effector to interact with an environment; and  
    an actuated effector mount, coupled to the end effector, having a propulsion system to facilitate substantially independent movement of the end effector system so as to at least one of position or orient the end effector in the environment;

a flexible arm coupled to the end effector system to provide at least one control signal for the propulsion system;

a perception and localization system, disposed separately from the end effector system, to provide location information on the end effector system; and

a controller, disposed separately from the end effector system, communicatively coupled to the end effector system via the flexible arm, and communicatively coupled to the location tracking system, to receive the location information from the location tracking system and generate the at least one control signal for the propulsion system based at least on the location information so as to cause the end effector system to move along a desired path,

wherein the end effector system is unable to generate any control signal for the propulsion system.

92. The system of claim 91, wherein the propulsion system includes a plurality of thrusters to facilitate movement of the end effector system in air.

93. The system of claim 91, wherein the propulsion system includes a plurality of thrusters to facilitate movement of the end effector system in water.

94. The system of claim 91, wherein the propulsion system includes at least one of a motorized wheel or an articulated leg to facilitate movement of the end effector system on ground.

95. The system of claim 91, wherein the flexible arm is a tether cable coupled to the end effector system and the controller to carry the at least one control signal.

96. The system of claim 91, wherein:

the perception and localization system has a field of view of the environment; and  
the perception and localization system is configured to keep the end effector system within the field of view during operation so as to acquire the location information on the end effector system.

97. The system of claim 96, wherein the perception and localization system is fixed in position in the environment with respect to the end effector system.
98. The system of claim 96, wherein:  
the propulsion system is a first propulsion system; and  
the system further comprises:  
a second propulsion system, coupled to the perception and localization system, to facilitate movement of the location tracking system with respect to the end effector system so as to maintain the end effector system within the field of view of the location tracking system.
99. A distributed robotic system, comprising:  
a plurality of end effector systems, each end effector system of the plurality of end effector systems comprising:  
an end effector to interact with an environment; and  
an actuated effector mount, coupled to the end effector, having a propulsion system to facilitate substantially independent movement of the end effector system so as to at least one of position or orient the end effector in the environment;  
a plurality of flexible arms, each flexible arm of the plurality of flexible arms being coupled to one end effector system of the plurality of end effector systems to provide at least one control signal for the propulsion system of that end effector system;  
a perception and localization system, disposed separately from the end effector system, to provide location information on each end effector system of the plurality of end effector systems; and  
a controller, disposed separately from the plurality of end effector systems, communicatively coupled to each end effector system of the plurality of the end effector systems via one flexible arm of the plurality of flexible arms, and communicatively coupled to the location tracking system, to receive the location information from the location tracking system on each end effector system of the plurality of end effector systems and generate the at least one control signal for respective propulsion systems of the plurality of end effector systems so as to cause each end effector system of the plurality of the end effector systems to move along a desired path,

wherein each end effector system of the plurality of end effector systems is unable to generate any control signal for the propulsion system of that end effector system.

100. A distributed robotic system, comprising:

an aerial end effector configured for translational and rotational motion in air with multiple degrees of freedom to facilitate contact treatment of a surface using a fluid, the aerial end effector including a plurality thrusters;

a tether cable coupled to the aerial end effector to provide at least power, at least one control signal, and the fluid to the aerial end effector;

a cable support system comprising:

a cable coupling assembly to support the tether cable; and

a perception and localization system to provide location information relating to a first location for the aerial end effector and a second location for the cable coupling assembly; and

a support system controller, communicatively coupled to the cable support system, to receive the location information and control the cable support system based on the received location information such that the cable coupling assembly is above the aerial end effector and in substantial vertical alignment with the aerial end effector so as to significantly reduce or substantially offset at least one of a cable payload on the aerial end effector or at least one force acting on the tether cable that is transferred to the aerial end effector during the contact treatment of the surface.

101. A method of controlling translational and rotational motion of an aerial end effector with multiple degrees of freedom to facilitate contract treatment of an elevated vertical or inclined surface, the aerial end effector including a plurality of thrusters, the method comprising:

A) generating location information relating to a first location information for the aerial end effector from a localization system disposed separately from the aerial end effector;

B) controlling at least some of the plurality of thrusters of the aerial end effector, based at least in part on the location information generated in A), so as to direct the aerial end effector along a treatment trajectory comprising:

a plurality of side-to-side phases, each side-to-side phase having a significant horizontal component across a width of the vertical or inclined surface; and

a plurality of reverse-direction phases, each reverse-direction phase including an arcuate or curvilinear path to gradually reverse a direction of the treatment trajectory,

wherein the treatment trajectory generally proceeds from a top portion of the vertical or inclined surface via a series of alternating side-to-side/reverse-direction phases, such that the aerial end effector makes successive overlapping sweeps in opposite directions across the surface while gradually proceeding downward toward a bottom perimeter edge of the surface;

C) controlling the aerial end effector such that, during at least one side-to-side phase of the treatment trajectory, a contact profile of the aerial end effector is oriented with respect to the treatment trajectory at an acute angle such that a top edge of the contact profile leads a bottom edge of the contact profile along a substantial portion of the at least one side-to-side phase; and

D) controlling the aerial end effector such that, during at least one reverse-direction phase, the contact profile of the aerial end-effector is gradually rotated such that the bottom edge of the contact profile during a previous side-to-side phase becomes the top edge of the contact profile during a next side-to-side phase and is positioned such that a next sweep of the aerial end effector during the next side-to-side phase overlaps a previous sweep of the aerial end effector during the previous side-to-side phase.

102. A distributed robotic system, comprising:

flying means for aerial translational and rotational motion with multiple degrees of freedom;

contact means, coupled to the flying means, for contact treatment of a vertical or inclined surface;

sensing means, coupled to the contact means, for measuring at least one contact pressure applied to the surface by the contact means; and

control means, communicatively coupled to the flying means and the sensing means, for controlling the translational and rotational motion of the flying means so as to direct the contact means along a treatment trajectory having a significant horizontal component across the surface and ensure sufficient contact of the contact means with the surface, based at least

in part on the measured at least one contact pressure, to effectively perform the contact treatment of the surface.

103. The distributed robotic system of claim 102, further comprising:

localization means, coupled to the control means, for determining a location of the flying means.

104. A distributed robotic system, comprising:

flying means for aerial translational and rotational motion with multiple degrees of freedom;

contact means, coupled to the flying means, for contact treatment of a surface using a fluid;

cable means for providing at least power to the flying means and the fluid to the contact means;

support means including coupling means to support the cable means; and

control means, communicatively coupled to the flying means and the support means, to monitor a first location information for the flying means and a second location information for the coupling means and control the support means such that the coupling means is above the flying means and in substantial vertical alignment with the flying means so as to significantly reduce or substantially offset at least one of a cable means payload on the flying means or at least one force acting on the cable means that is transferred to the flying means during the contact treatment of the surface.

105. A distributed robotic system, comprising:

a first aerial end effector configured for first translational and rotational motion in air and including a first plurality thrusters;

a second aerial end effector configured for second translational and rotational motion in air and including a second plurality thrusters;

a first flexible arm coupled to the first aerial end effector to provide at least one first control signal to at least one thruster of the first plurality of thrusters;

a second flexible arm coupled to the second aerial end effector to provide at least one second control signal to at least one thruster of the second plurality of thrusters;

a perception and localization system to provide at least first location information for the first aerial end effector and second location information for the second aerial end effector; and

a robotic controller, communicatively coupled to the first aerial end effector at least in part via the first flexible arm, communicatively coupled to the second aerial end effector at least in part via the second flexible arm, and communicatively coupled to the perception and localization system, to:

receive, from the perception and localization system, the first location information for the first aerial end effector and the second location information for the second aerial end effector;

generate the at least one first control signal based on the received first location information to control the first plurality of thrusters so as to cause the first aerial end effector to perform the first translational and rotational motion; and

generate the at least one second control signal based on the received second location information to control the second plurality of thrusters so as to cause the second aerial end effector to perform the second translational and rotational motion.

106. The distributed robotic system of claim 105, further comprising:  
a mobile base station; and  
a mounting arm to couple the perception and localization system to the mobile base station.

107. The distributed robotic system of claim 106, wherein:  
the mounting arm is a telescoping mounting arm to facilitate positioning and/or alignment of the perception and localization system relative to the mobile base station.

108. The distributed robotic system of claim 106, further comprising:  
one or more deployable and retractable legs, coupled to the mobile base station, to provide mechanical stability for the distributed robotic system when the mobile base station is stationary.

109. The distributed robotic system of claim 106, wherein:  
the mobile base station comprises a base station controller, separate from the robotic controller, to control at least one function of the mobile base station.
110. The distributed robotic system of claim 105, further comprising:  
a first landing pad for the first aerial end effector and a second landing pad for the second aerial end effector, each of the first landing pad and the second landing pad being movably coupled to the perception and localization system to be operable between a stowed position and a deployed position.
111. The distributed robotic system of claim 105, wherein:  
the first flexible arm is a first tether cable communicatively coupled to the first aerial end effector and at least one of the perception and localization system and the robotic controller to carry the at least one first control signal; and  
the second flexible arm is a second tether cable communicatively coupled to the second aerial end effector and at least one of the perception and localization system and the robotic controller to carry the at least one second control signal.
112. The distributed robotic system of claim 111, wherein:  
the first flexible arm provides the at least one first control signal and first power to the first aerial end effector; and  
the second flexible arm provides the at least one second control signal and second power to the second aerial end effector.
113. The distributed robotic system of claim 111, wherein:  
the first flexible arm carries at least one first fluid to or from the first aerial end effector; and  
the second flexible arm carries at least one second fluid to or from the second aerial end effector.
114. The distributed robotic system of claim 105, wherein:

the first flexible arm is at least one first wireless communication link to carry the at least one first control signal to the first aerial end effector; and

the second flexible arm is at least one second wireless communication link to carry the at least one second control signal to the second aerial end effector.

115. The distributed robotic system of claim 114, wherein each of the first aerial end effector and the second aerial end effector includes at least one battery to provide power for at least the plurality of thrusters.

116. The distributed robotic system of claim 105, wherein each of the first aerial end effector and the second aerial end effector does not include a processor, and all operation of the first aerial end effector and the second aerial end effector is controlled by the robotic controller.

117. The distributed robotic system of claim 105, wherein:

the first aerial end effector includes at least one first contact tool to facilitate first contact with a first object; and

the second aerial end effector includes at least one second contact tool to facilitate second contact with at least one of the first object or a second object.

118. The system of claim 117, wherein:

the first aerial end effector consists of:

a first frame;

a first interface to couple to the first flexible arm;

the first plurality of thrusters; and

the at least one first contact tool; and

the second aerial end effector consists of:

a second frame;

a second interface to couple to the second flexible arm;

the second plurality of thrusters; and

the at least one second contact tool.

119. The distributed robotic system of claim 117, wherein at least one of the at least one first contact tool or the at least one second contact tool facilitates harvesting of at least one crop.

120. The distributed robotic system of claim 117, wherein at least one of the at least one first contact tool or the at least one second contact tool facilitates contact treatment of at least one surface.

121. The distributed robotic system of claim 120, wherein the at least one of the at least one first contact tool or the at least one second contact tool facilitates cleaning of at least one surface.

122. The distributed robotic system of claim 121, wherein the at least one of the at least one first contact tool or the at least one second contact tool facilitates the cleaning of at least one surface via at least one fluid.

123. The distributed robotic system of claim 123, wherein the at least first one contact tool includes a squeegee.

124. The distributed robotic system of claim 123, wherein the at least one second contact tool includes a cleaning fluid applicator and/or scrubber.

125. The distributed robotic system of claim, wherein:  
the first aerial end effector includes at least one first sensor; and  
the second aerial end effector includes at least one second sensor.

126. The distributed robotic system of claim 125, wherein at least one of the at least one first sensor or the at least one second sensor includes at least one pressure sensor.

127. The distributed robotic system of claim 125, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one environmental sensor.

128. The distributed robotic system of claim 125, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one imaging sensor.

129. The distributed robotic system of claim 125, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one inertial measurement unit (IMU).

130. The distributed robotic system of claim 125, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one satellite navigation device.

131. The distributed robotic system of claim 105, wherein at least one of the first aerial end effector or the second aerial end effector is configured for translational and rotational motion in air with six degrees of freedom.

132. The distributed robotic system of claim 105, wherein the perception and localization system is disposed within a line-of-sight of the first aerial end effector and the second aerial end effector.

133. The distributed robotic system of claim 105, wherein the perception and localization system is co-located with the robotic controller.

134. The distributed robotic system of claim 105, wherein the perception and localization system comprises at least one of:

at least one imaging sensor;

at least one sound navigation and ranging (SONAR) device;

at least one satellite navigation device; or

at least one light detection and ranging (LIDAR) device.

135. The distributed robotic system of claim 106, wherein the distributed robotic system is configured to resemble an animal.

136. The distributed robotic system of claim 135, wherein the animal is a giraffe.
137. The distributed robotic system of claim 136, and depending also from claim 107, further comprising:
- a perception and localization system housing for the perception and localization system, the perception and localization system housing being configured to resemble a head of the giraffe; and
  - a base station housing for the mobile base station, the base station housing being configured to resemble a body of the giraffe,
- wherein the telescoping mounting arm is configured to resemble a neck of the giraffe.
138. The distributed robotic system of claim 137, wherein:
- the one or more deployable and retractable legs are configured to resemble respective legs of the giraffe.
139. The distributed robotic system of claim 137 or claim 138, and depending also from claim 110, wherein the first landing pad for the first aerial end effector and the second landing pad for the second aerial end effector are configured to resemble respective ears of the giraffe.
140. A distributed robotic window-washing system, comprising:
- a first aerial end effector configured for first translational and rotational motion in air and including a first plurality thrusters, the first aerial end effector including at least one first contact tool to facilitate contact cleaning of a first surface via a first fluid;
  - a second aerial end effector configured for second translational and rotational motion in air and including a second plurality thrusters, the second aerial end effector including at least one second contact tool to facilitate contact cleaning of the first surface or a second surface;
  - a first flexible arm coupled to the first aerial end effector to provide at least one first control signal and first power to at least one thruster of the first plurality of thrusters, the first

flexible arm further configured to carry at least the first fluid to or from the first aerial end effector;

a second flexible arm coupled to the second aerial end effector to provide at least one second control signal and second power to at least one thruster of the second plurality of thrusters, the second flexible arm further configured to carry at least the first fluid or a second fluid to or from the second aerial end effector;

a perception and localization system to provide at least first location information for the first aerial end effector and second location information for the second aerial end effector, the perception and localization system including a perception and localization system housing;

a first landing pad for the first aerial end effector and a second landing pad for the second aerial end effector, each of the first landing pad and the second landing pad being movably coupled to the perception and localization system to be operable between a stowed position and a deployed position;

a robotic controller, communicatively coupled to the first aerial end effector at least in part via the first flexible arm, communicatively coupled to the second aerial end effector at least in part via the second flexible arm, and communicatively coupled to the perception and localization system, to:

receive, from the perception and localization system, the first location information for the first aerial end effector and the second location information for the second aerial end effector;

generate the at least one first control signal based on the received first location information to control the first plurality of thrusters so as to cause the first aerial end effector to perform the first translational and rotational motion; and

generate the at least one second control signal based on the received second location information to control the second plurality of thrusters so as to cause the second aerial end effector to perform the second translational and rotational motion;

a mobile base station comprising a base station controller, separate from the robotic controller, to control at least one function of the mobile base station, the mobile base station including a base station housing;

a telescoping mounting arm to couple the perception and localization system to the mobile base station and to facilitate positioning and/or alignment of the perception and localization system relative to the mobile base station; and

one or more deployable and retractable legs, coupled to the mobile base station, to provide mechanical stability for the distributed robotic window-washing system when the mobile base station is stationary,

wherein:

the perception and localization system housing is configured to resemble a head of a giraffe;

the base station housing is configured to resemble a body of the giraffe;

the telescoping mounting arm is configured to resemble a neck of the giraffe;

the one or more deployable and retractable legs are configured to resemble respective legs of the giraffe; and

the first landing pad for the first aerial end effector and the second landing pad for the second aerial end effector are configured to resemble respective ears of the giraffe.

141. The system of claim 140, wherein the at least first one contact tool includes a squeegee.

142. The system of claim 141, wherein the at least one second contact tool includes a cleaning fluid applicator and/or scrubber.

143. The system of claim 140, wherein:

the first aerial end effector includes at least one first sensor; and

the second aerial end effector includes at least one second sensor.

144. The system of claim 143, wherein at least one of the at least one first sensor or the at least one second sensor includes at least one pressure sensor.

145. The system of claim 143, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one environmental sensor.

146. The system of claim 143, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one imaging sensor.

147. The system of claim 143, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one inertial measurement unit (IMU).

148. The system of claim 143, wherein the at least one of the at least one first sensor or the at least one second sensor includes at least one satellite navigation device.

149. The system of claim 140, wherein at least one of the first aerial end effector or the second aerial end effector is configured for translational and rotational motion in air with six degrees of freedom.

150. The system of claim 140, wherein the perception and localization system is disposed within a line-of-sight of the first aerial end effector and the second aerial end effector.

151. The system of claim 140, wherein the perception and localization system is co-located with the robotic controller in the head of the giraffe.

152. The system of claim 140, wherein the perception and localization system comprises at least one of:

at least one imaging sensor;

at least one sound navigation and ranging (SONAR) device;

at least one satellite navigation device; or

at least one light detection and ranging (LIDAR) device.

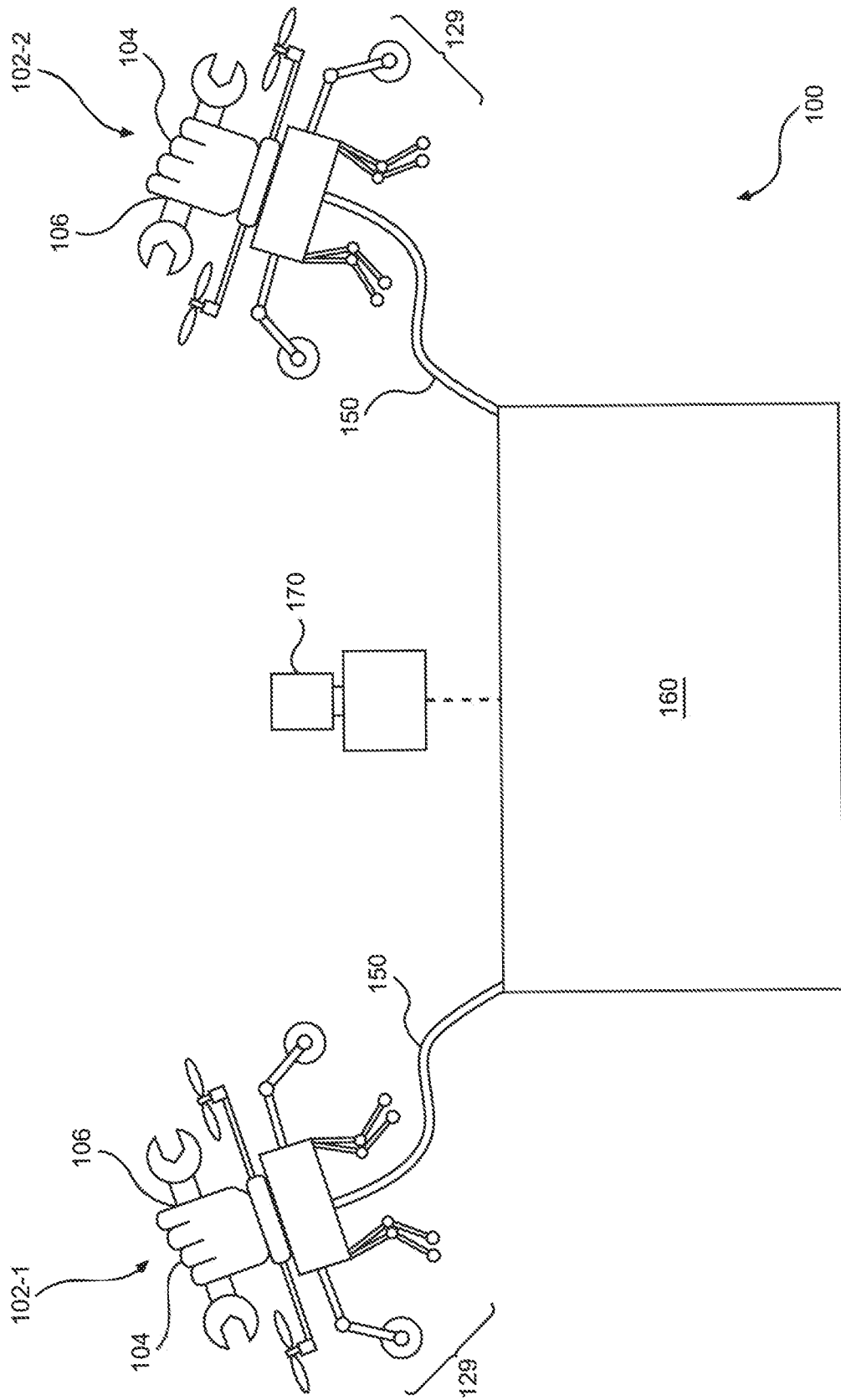


FIG. 1A

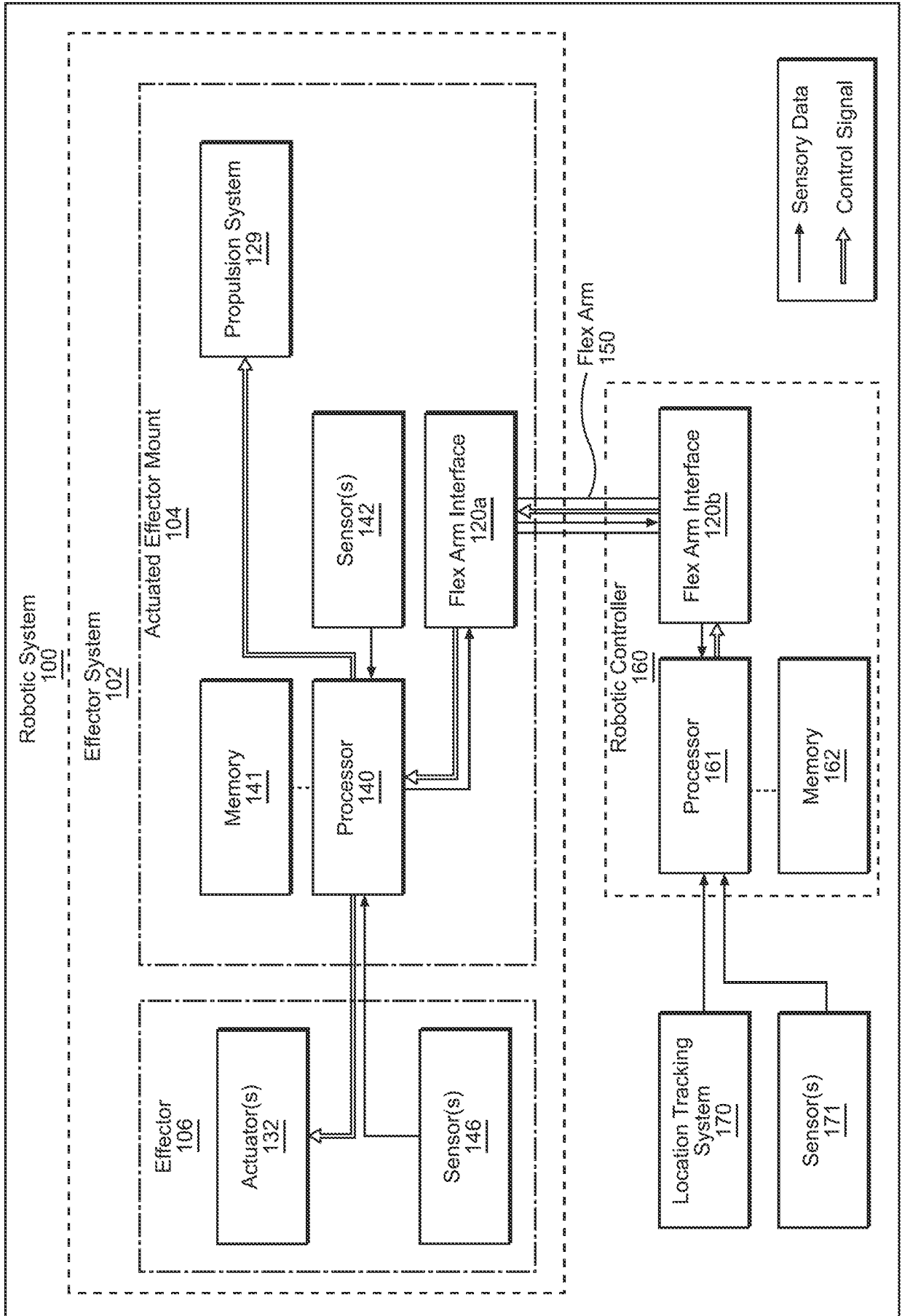


FIG. 1B

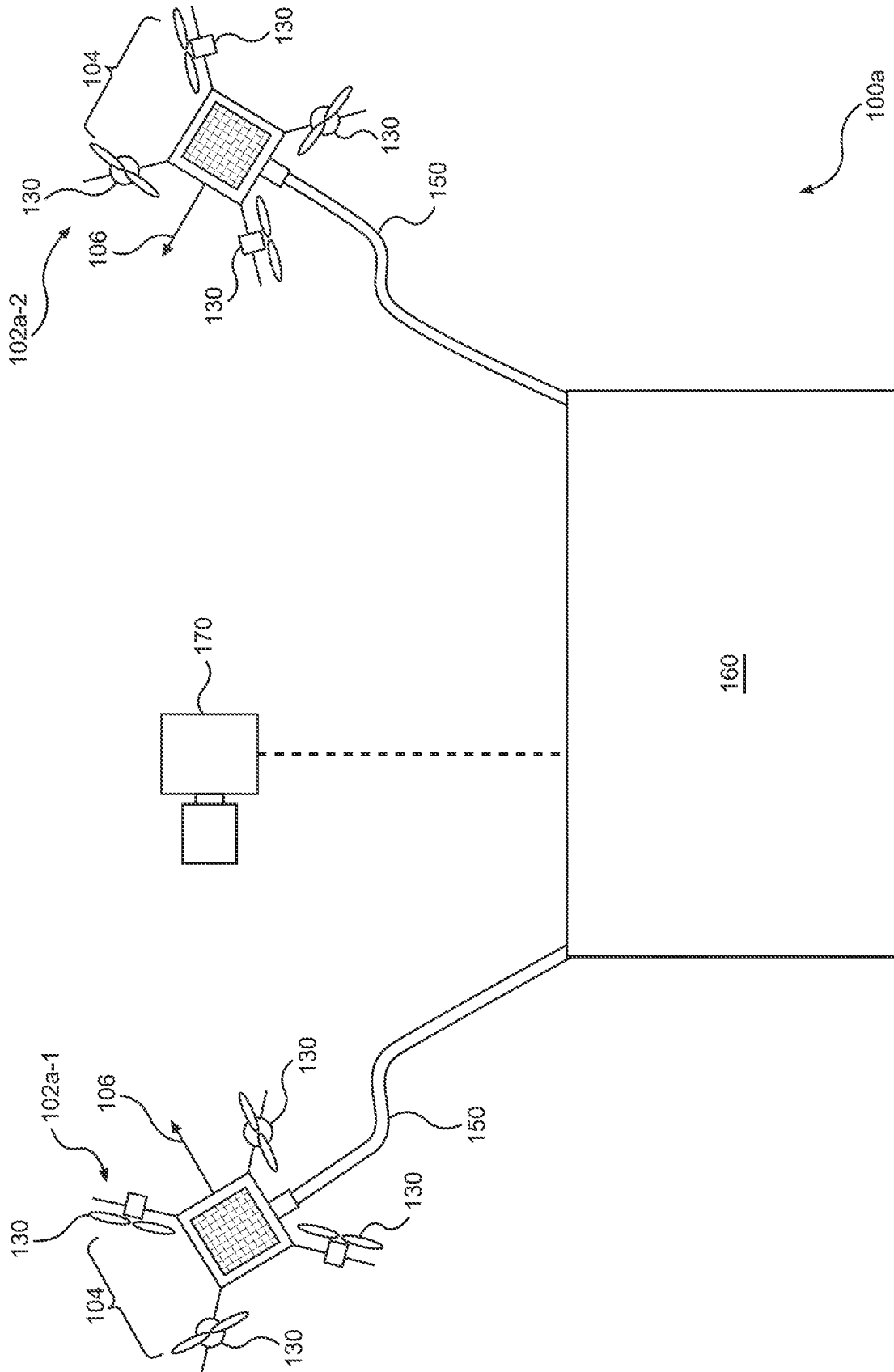
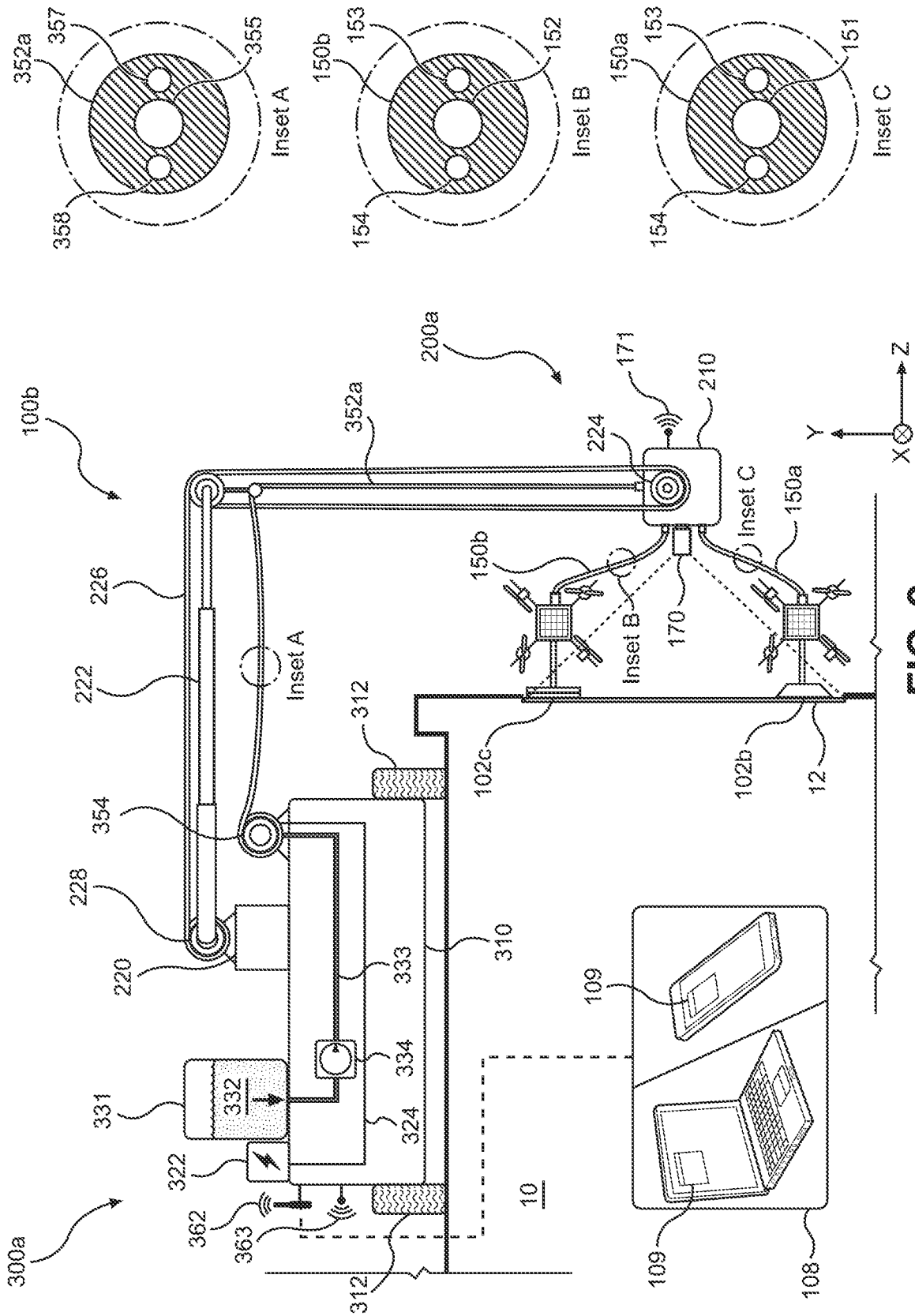


FIG. 1C



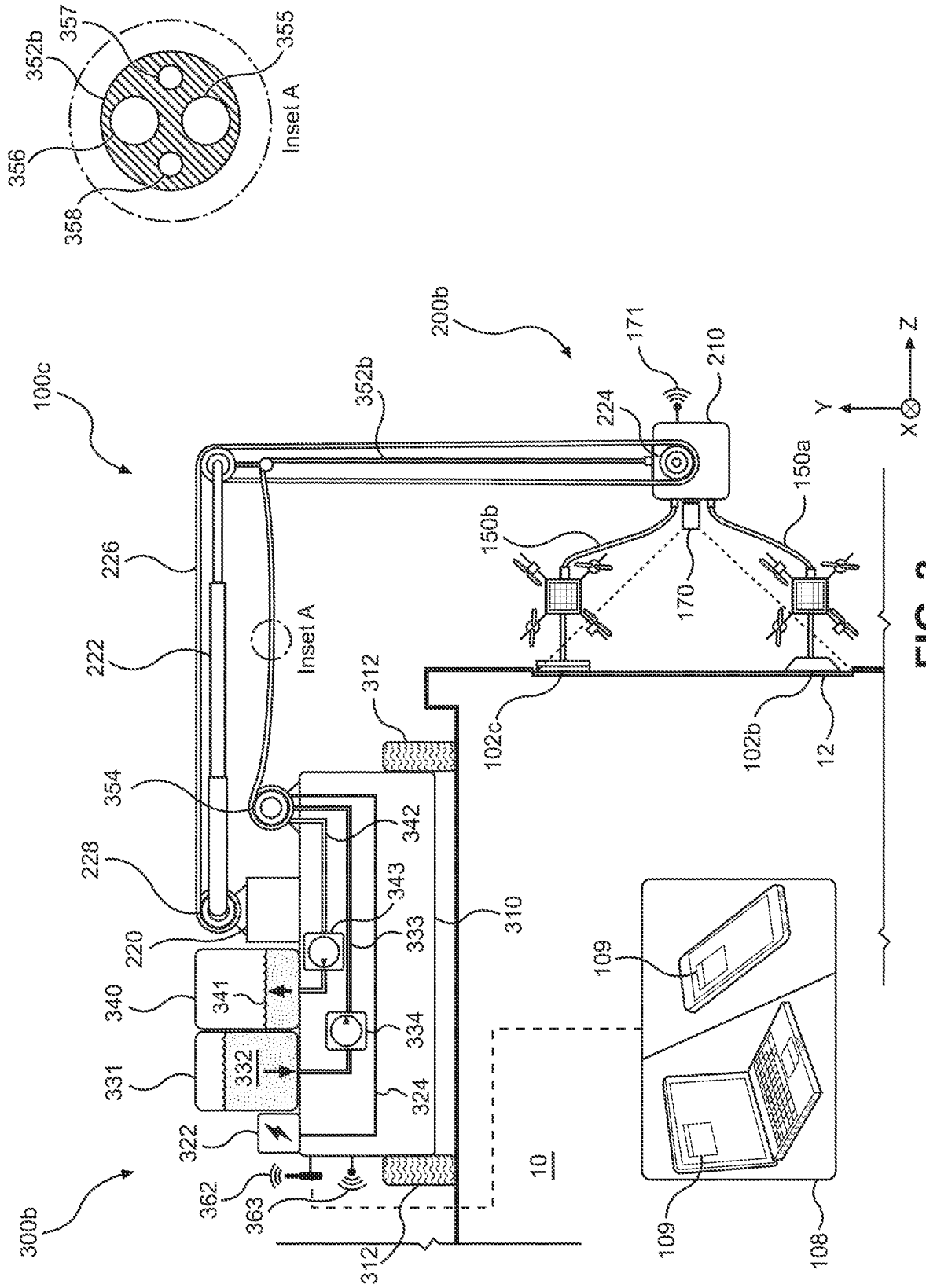


FIG. 3

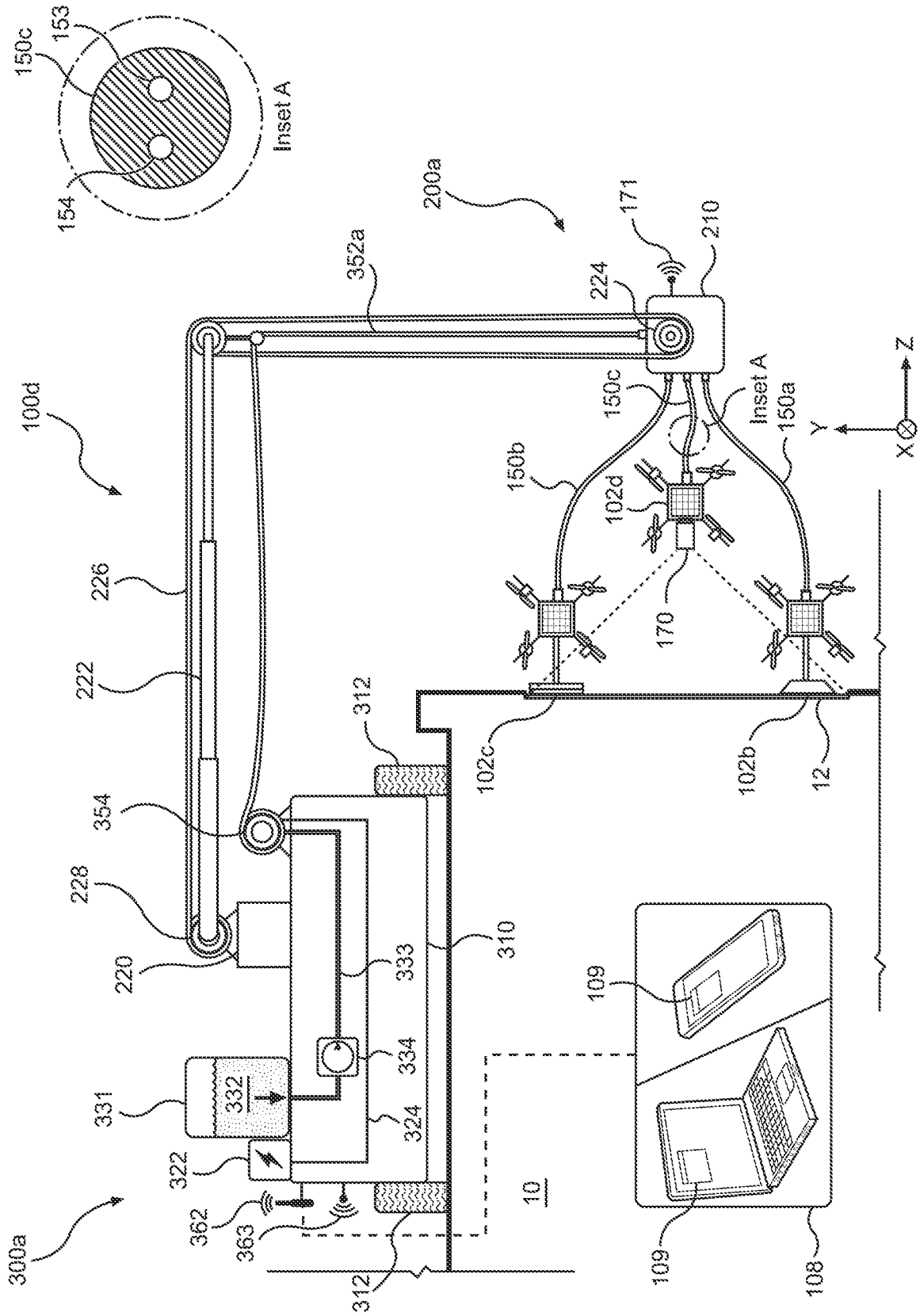


FIG. 4

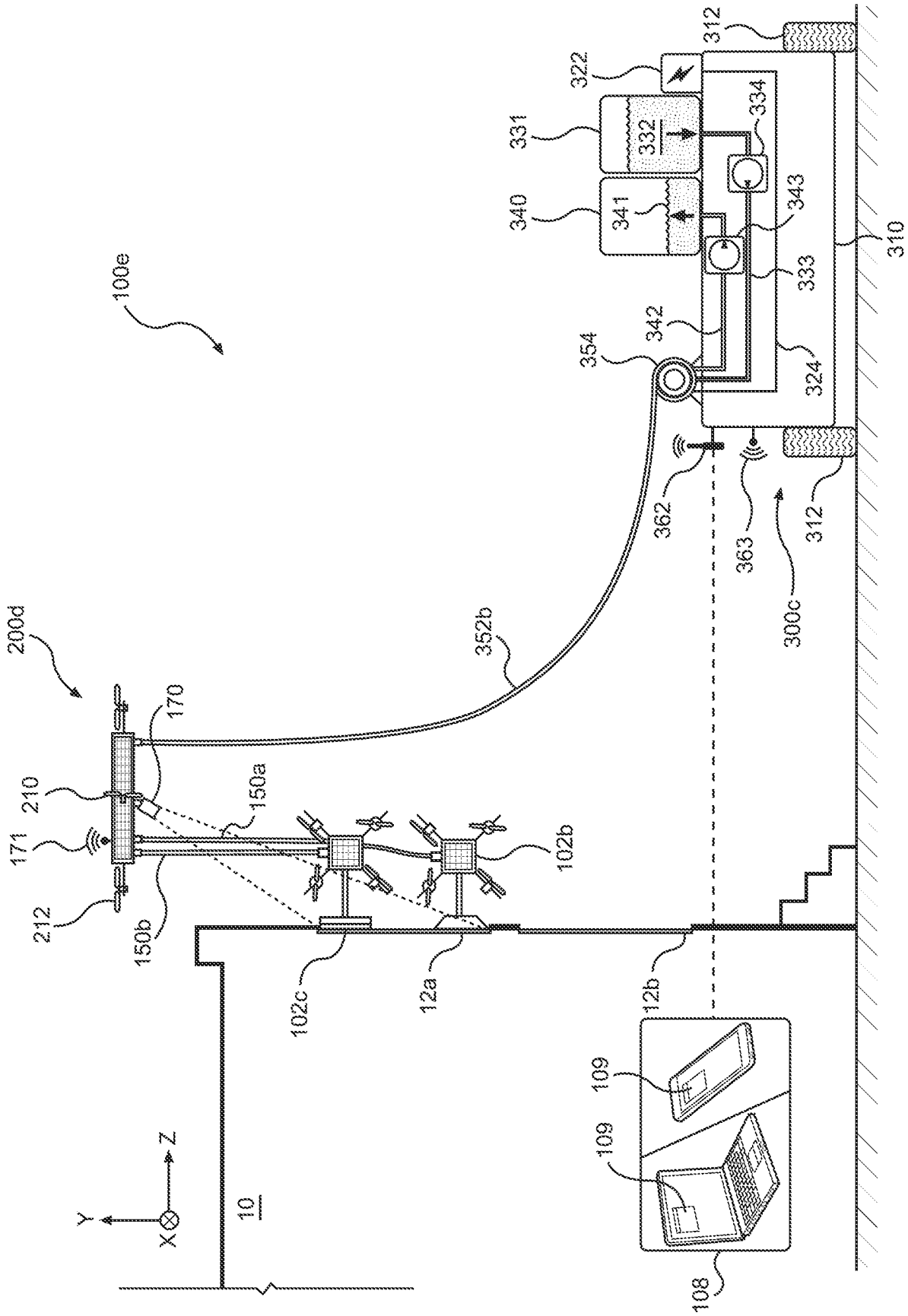


FIG. 5

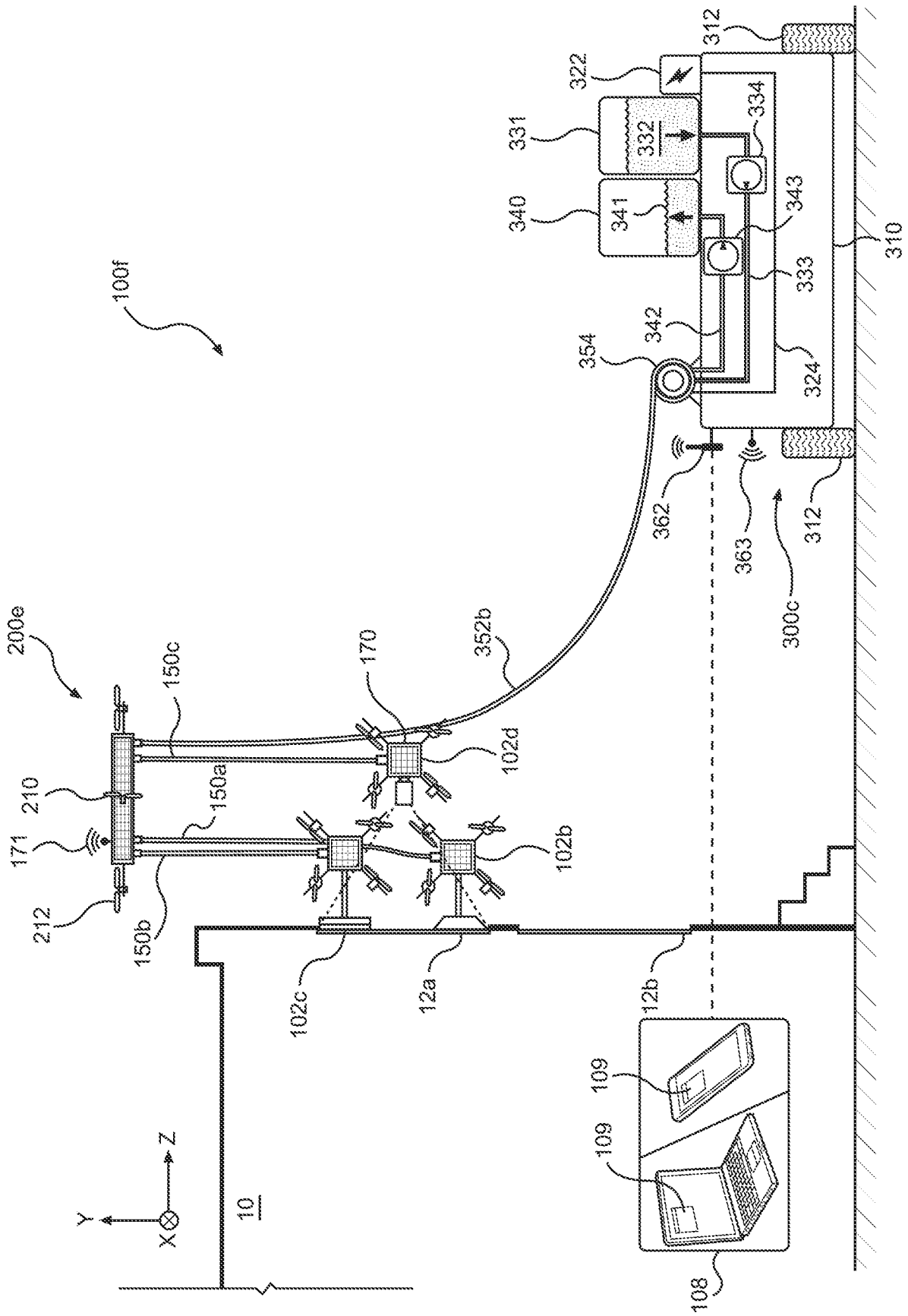


FIG. 6

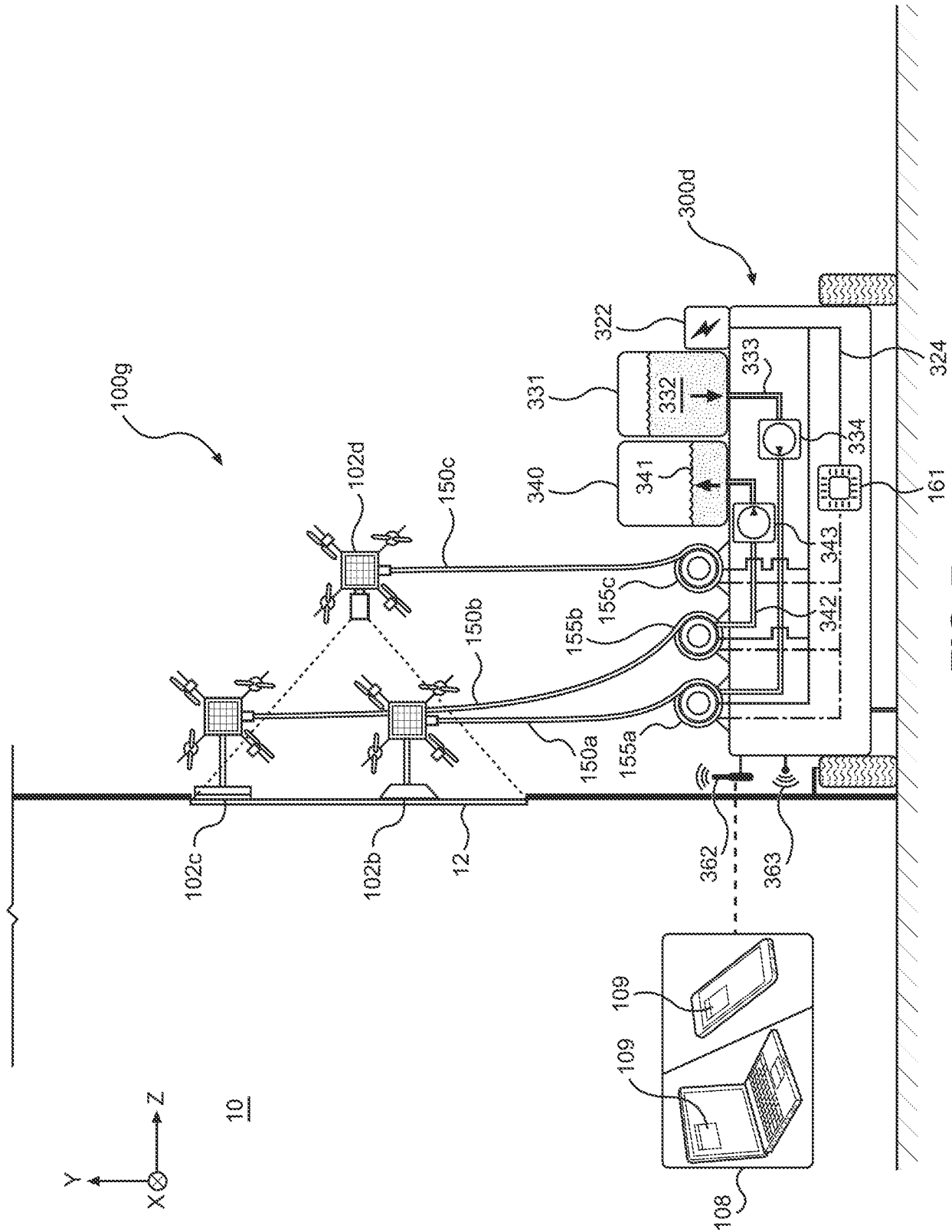


FIG. 7

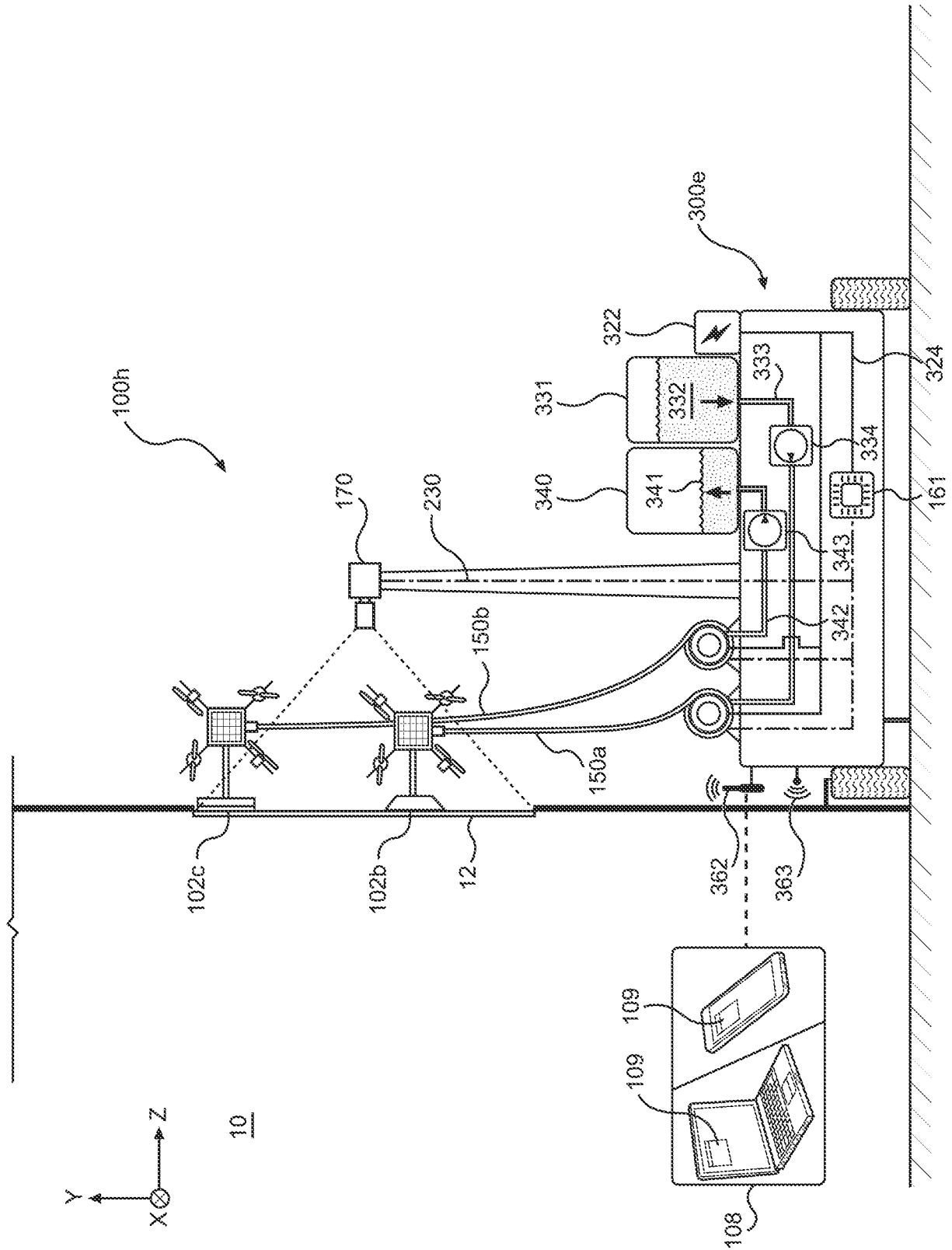


FIG. 8

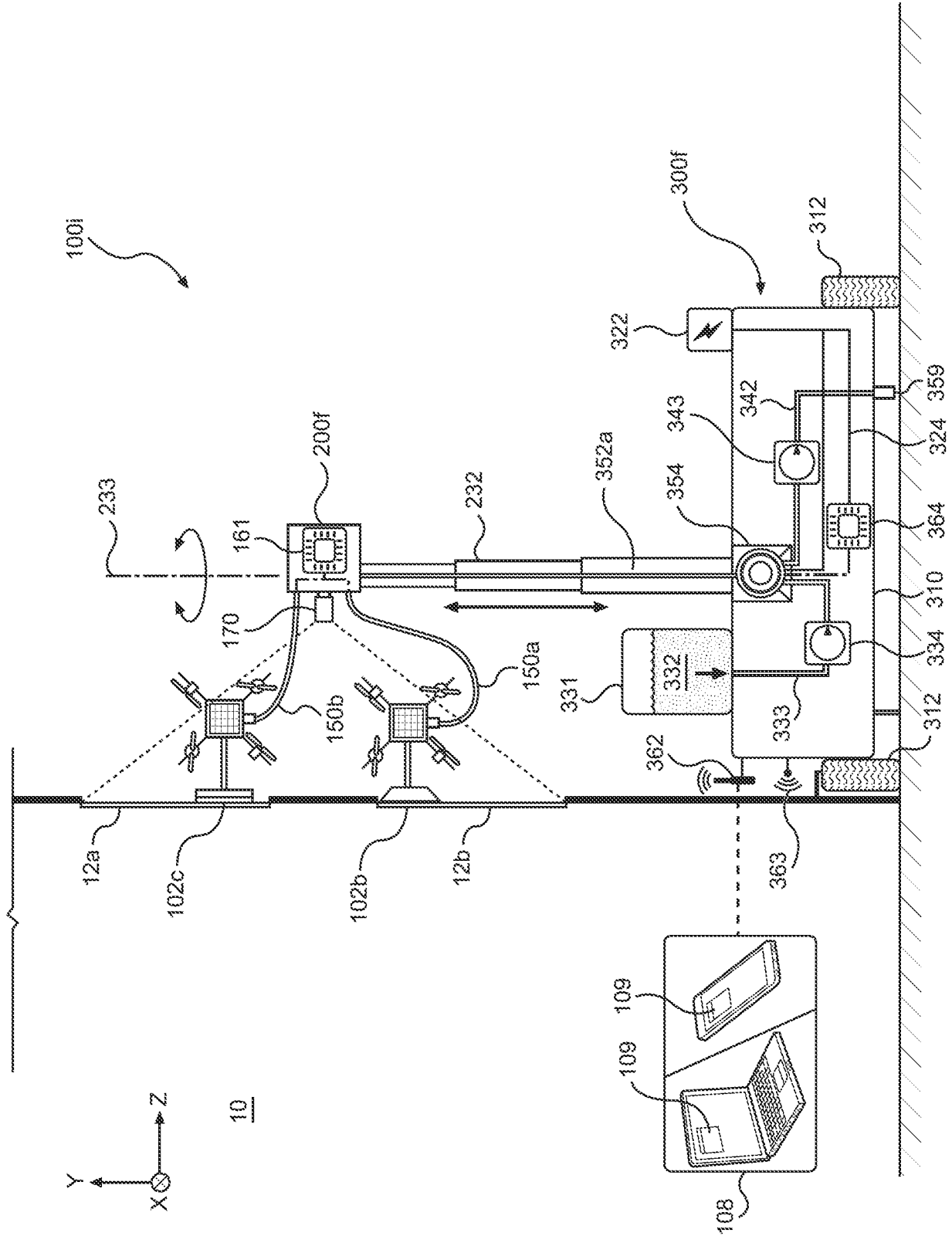


FIG. 9

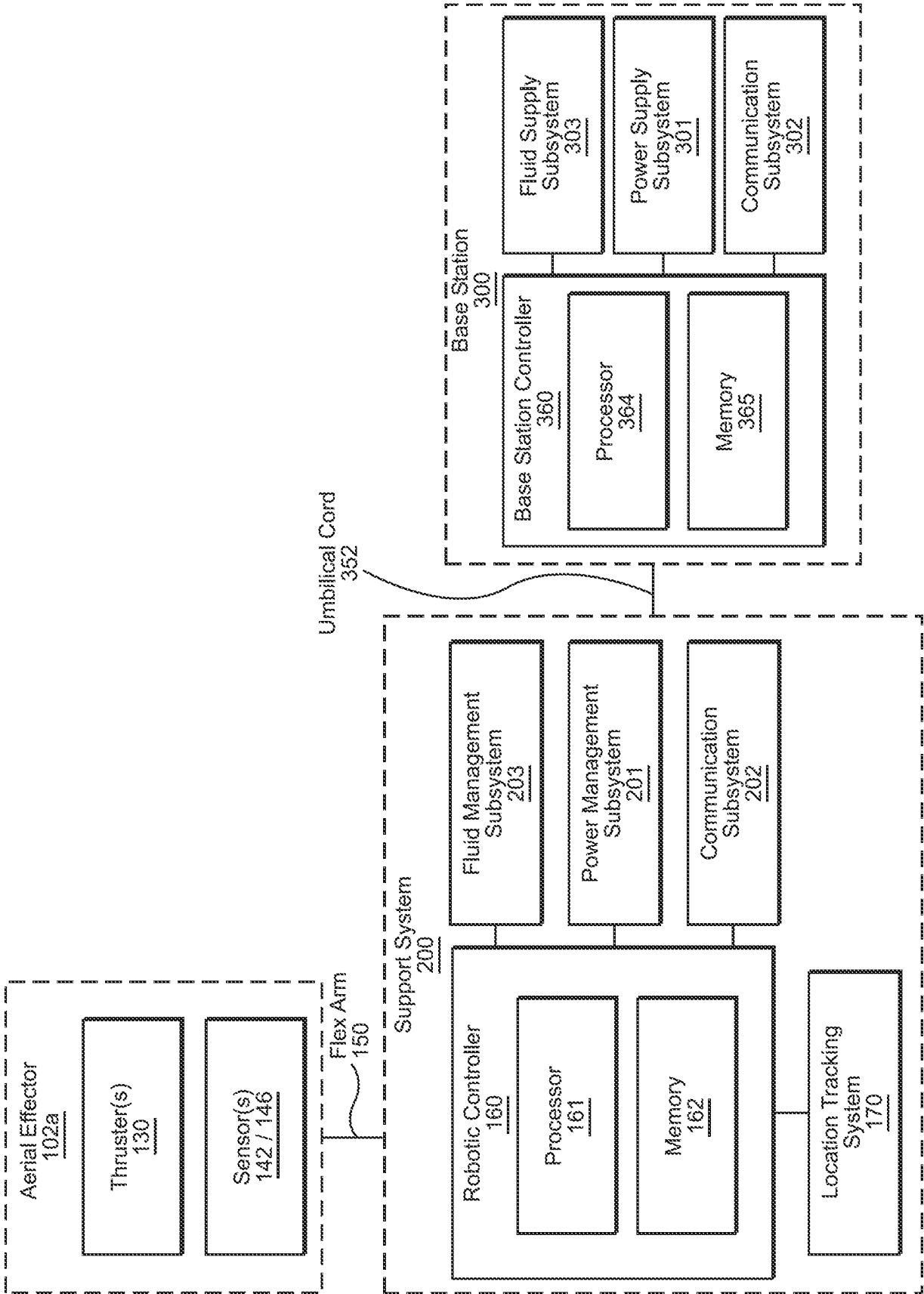


FIG. 10

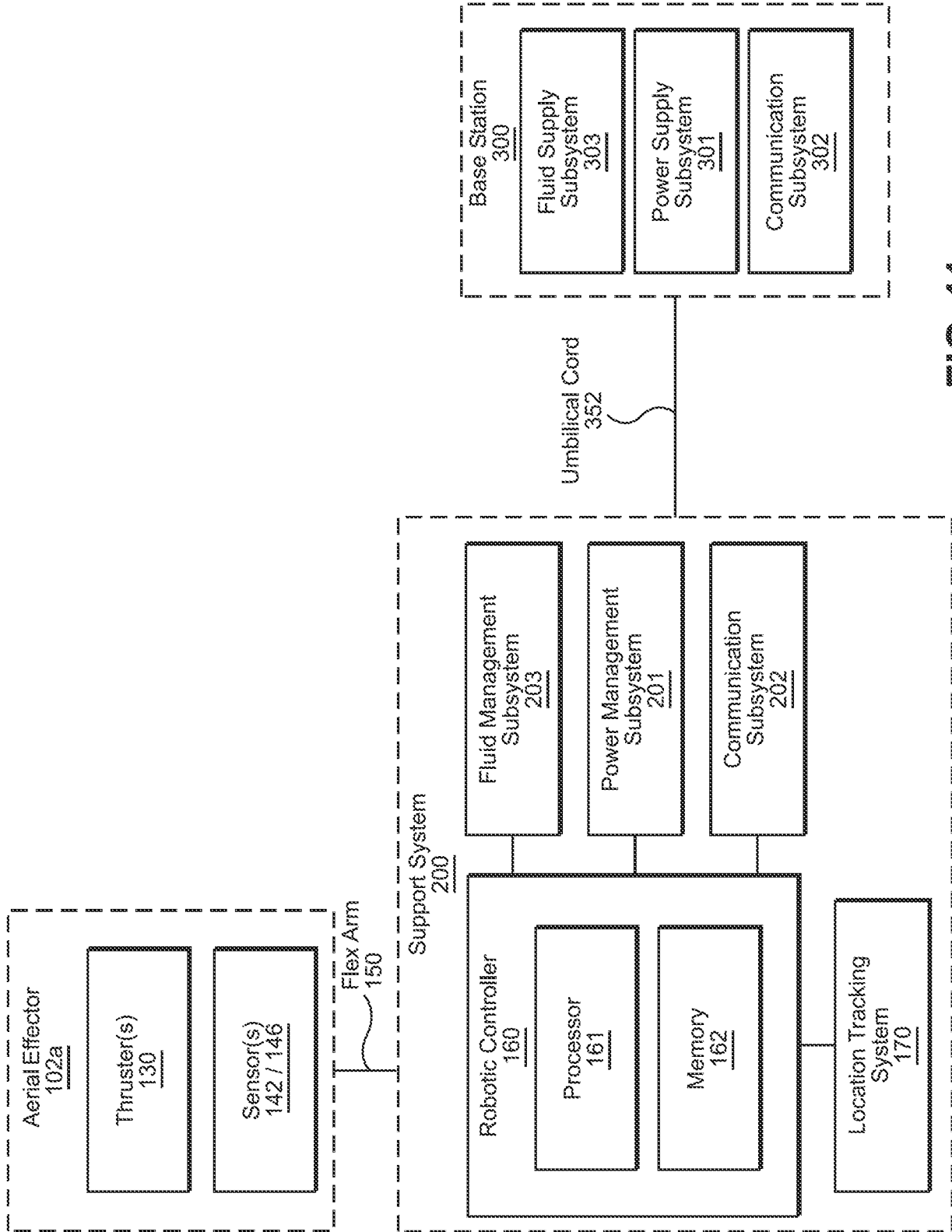


FIG. 11

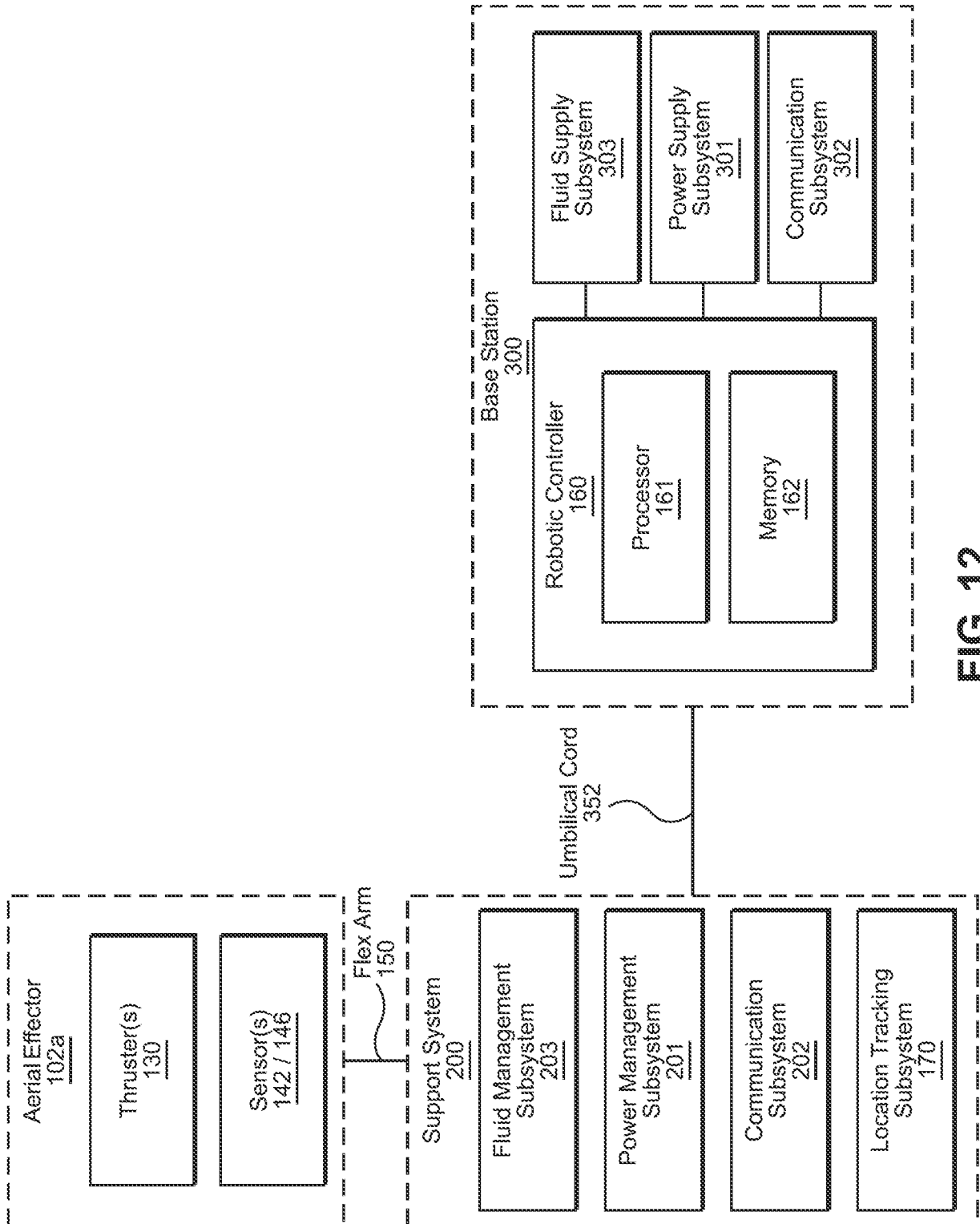


FIG. 12

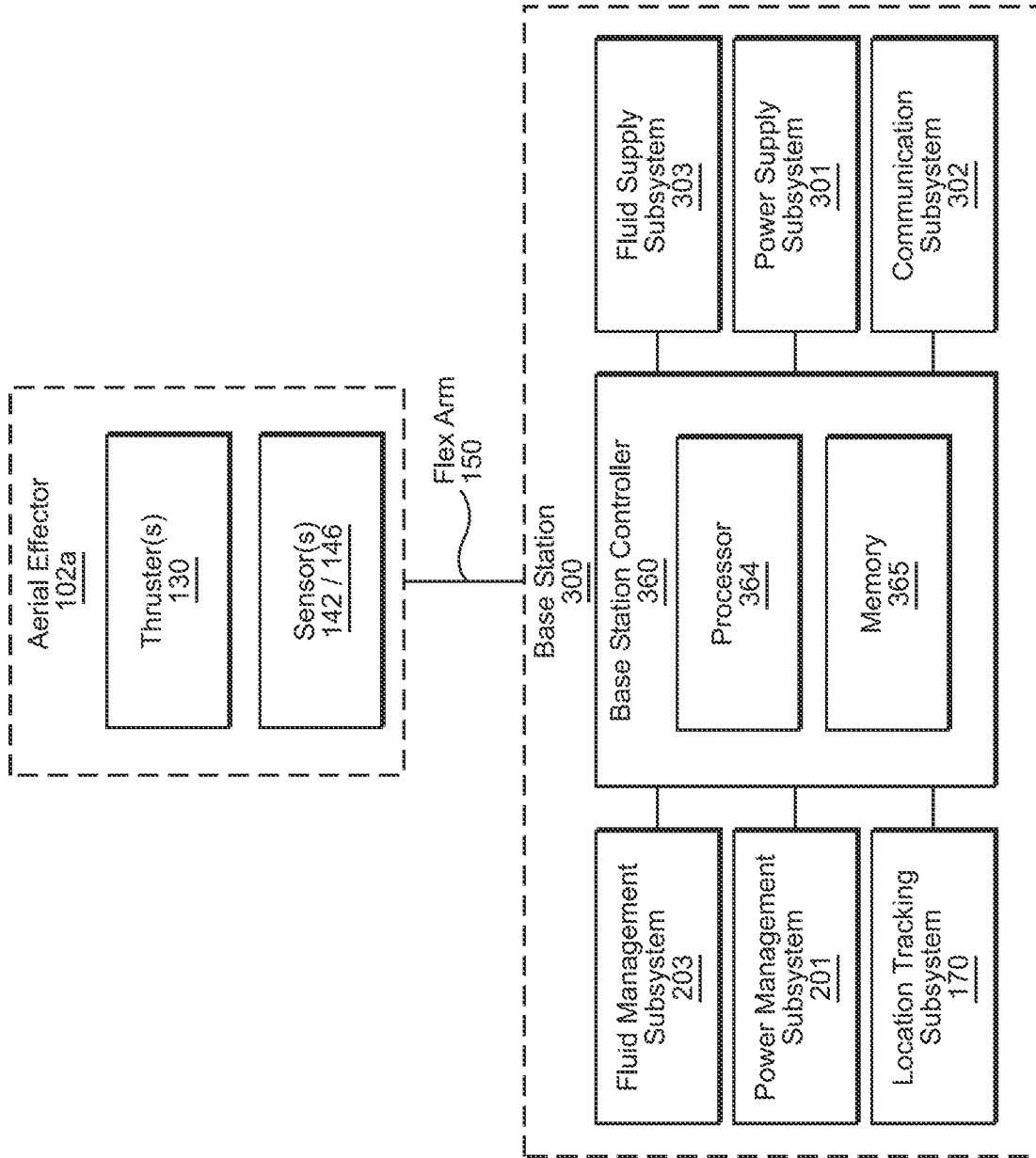


FIG. 13

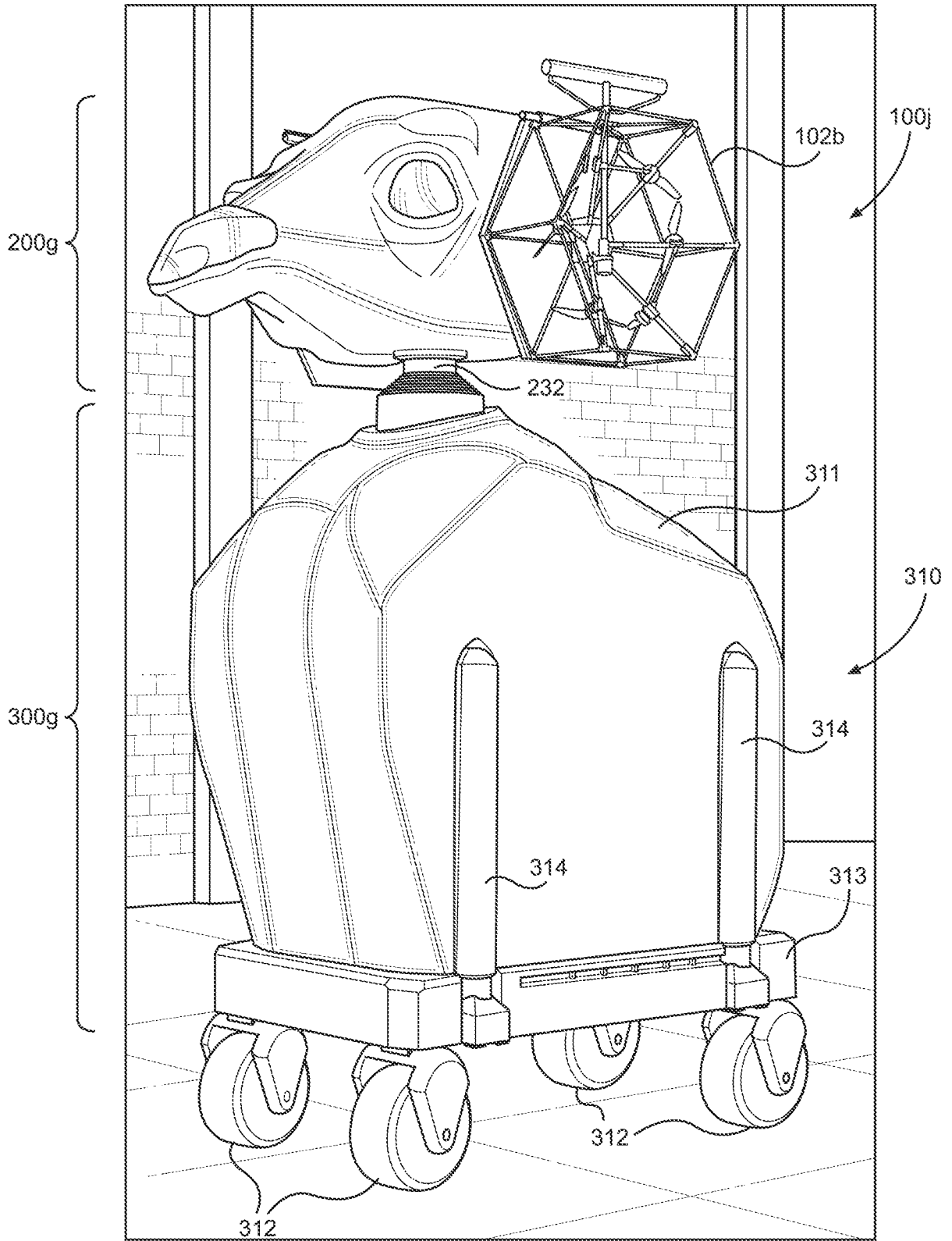


FIG. 14A

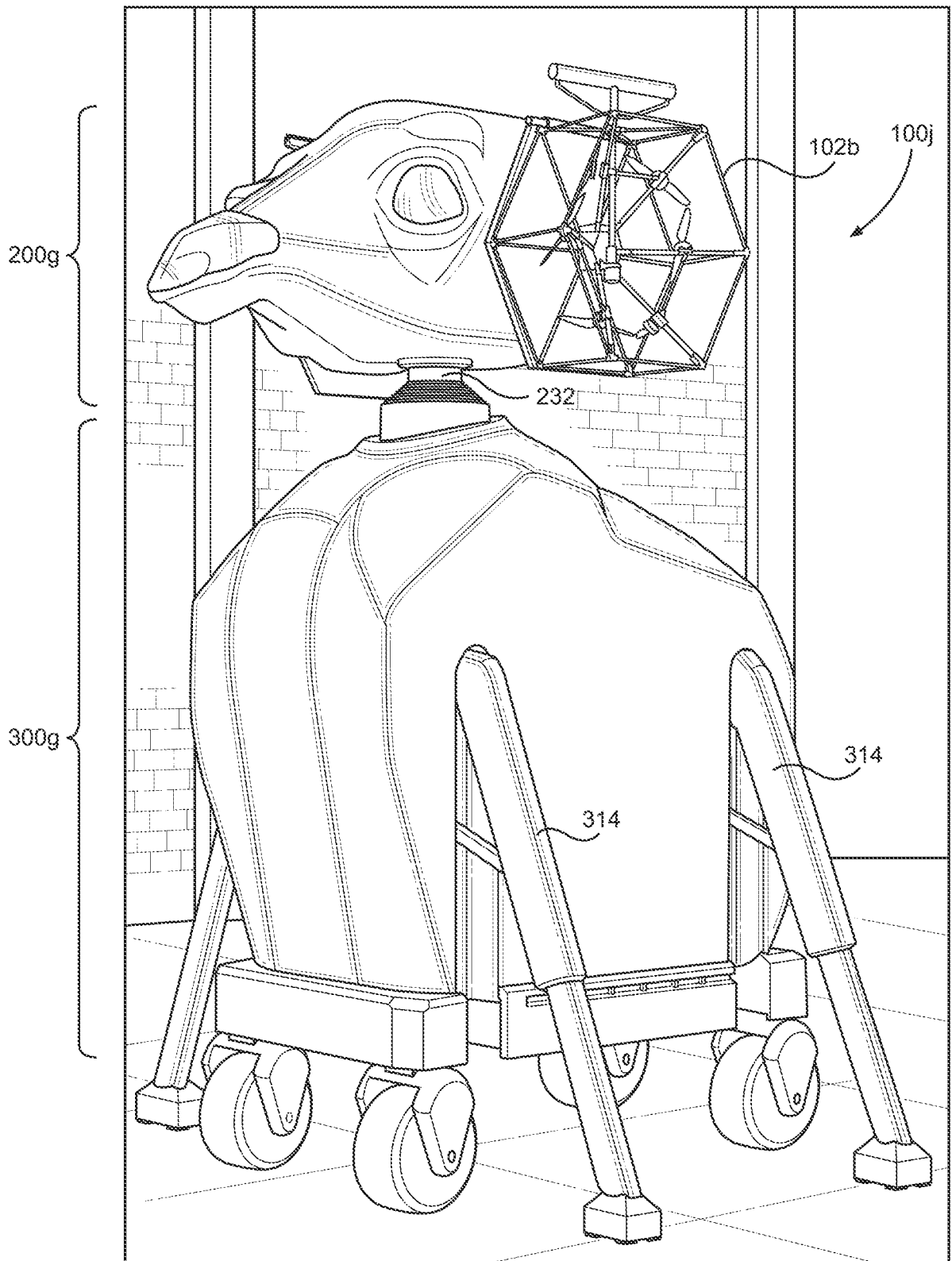


FIG. 14B

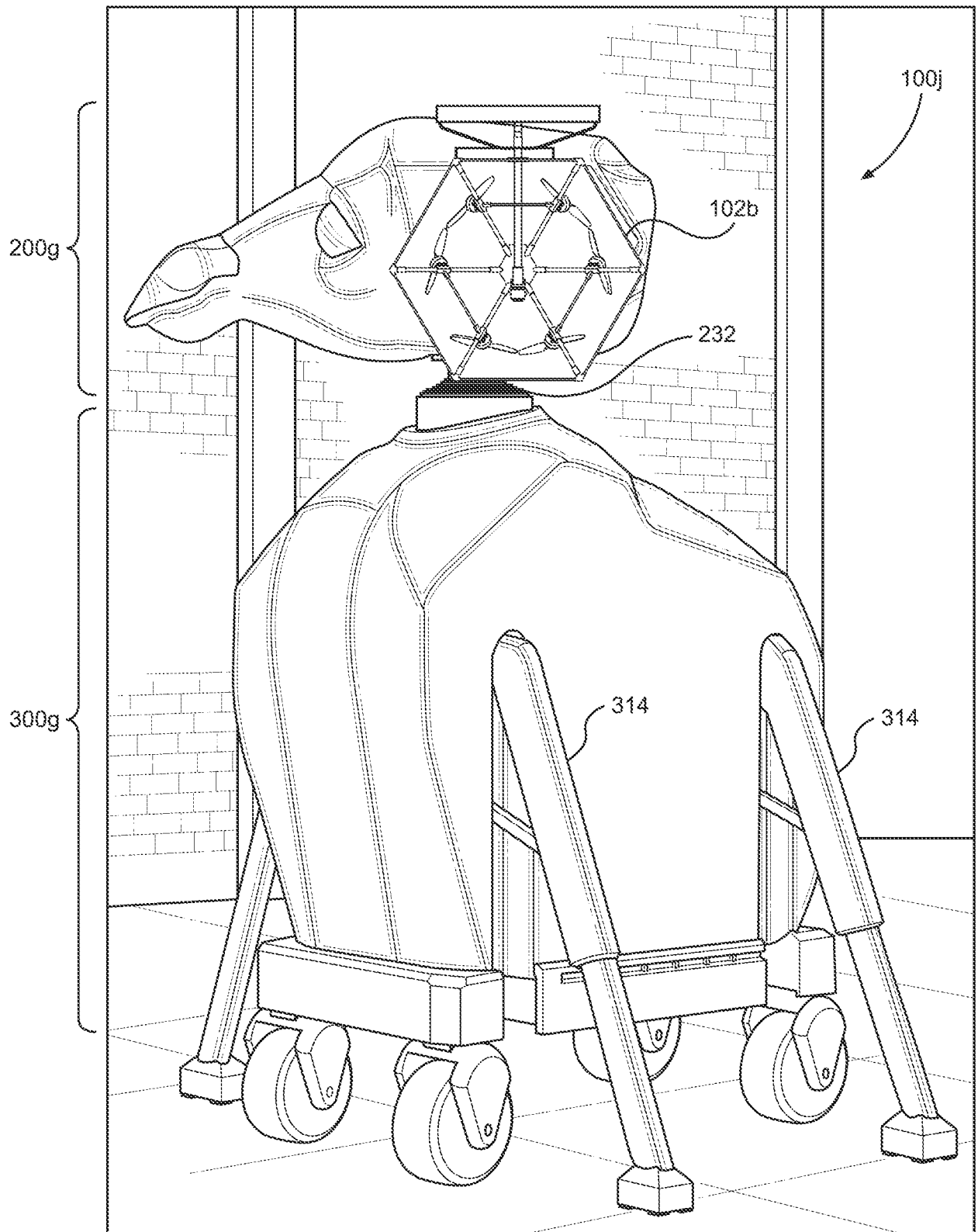


FIG. 14C

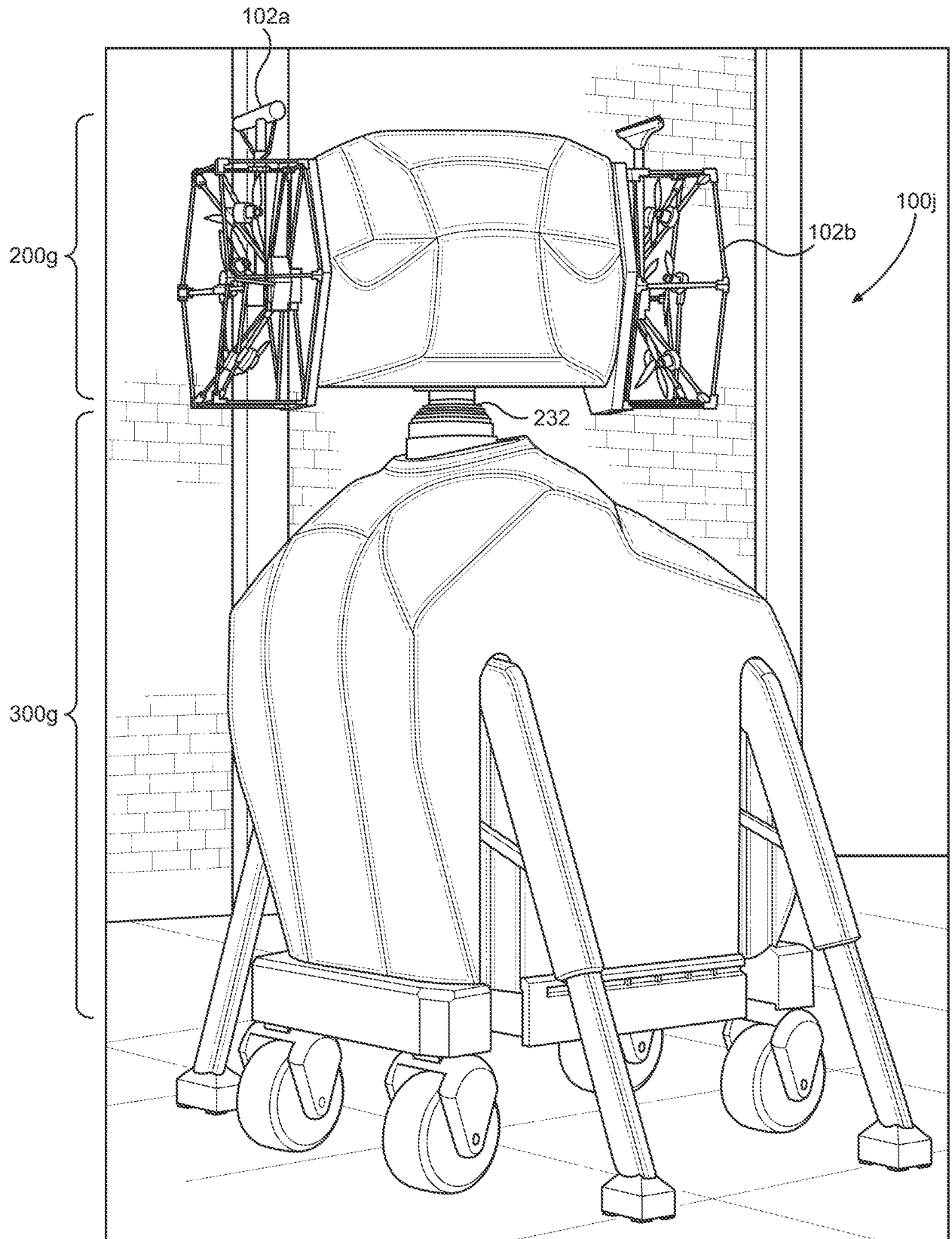


FIG. 14D

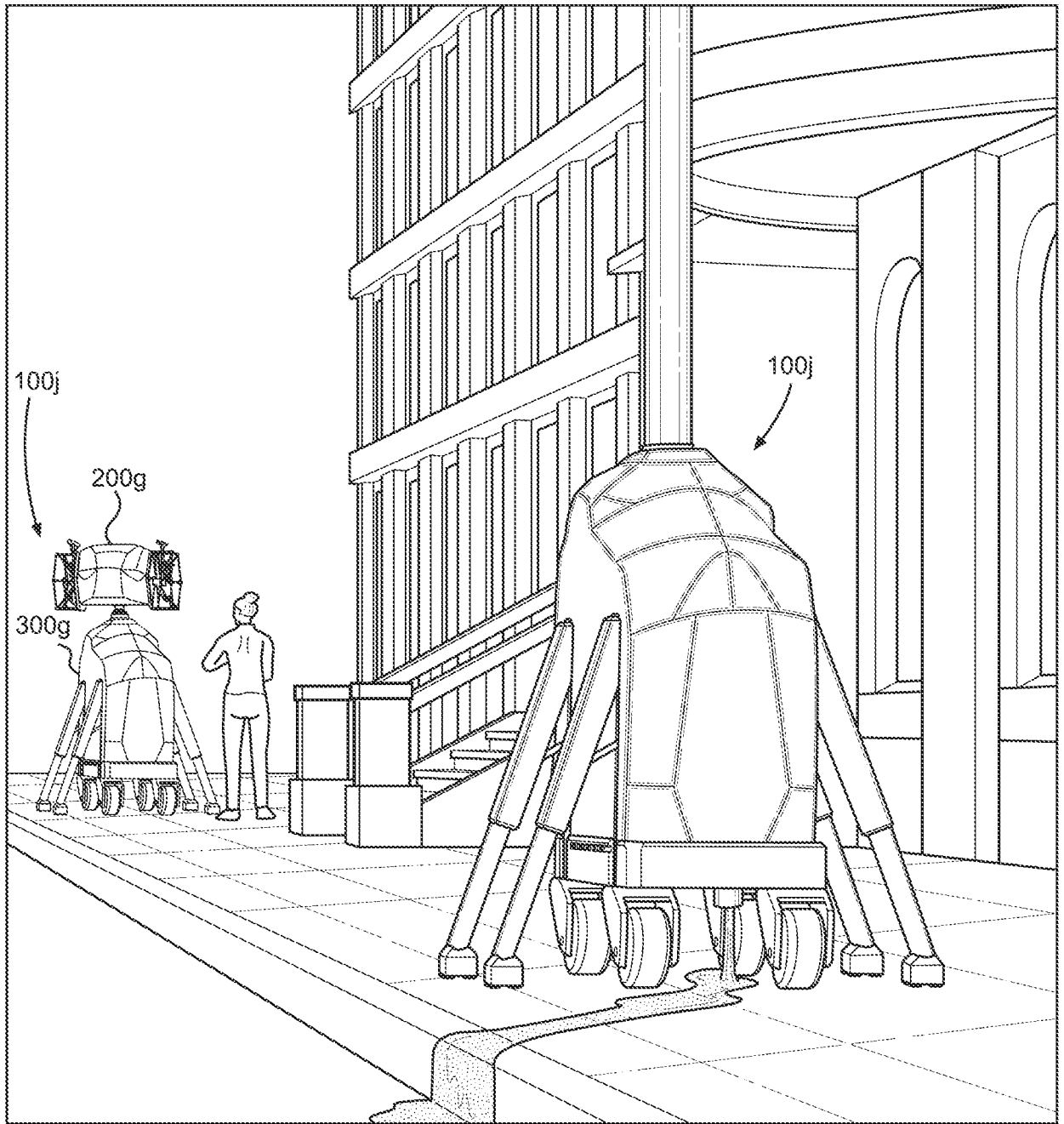


FIG. 14E

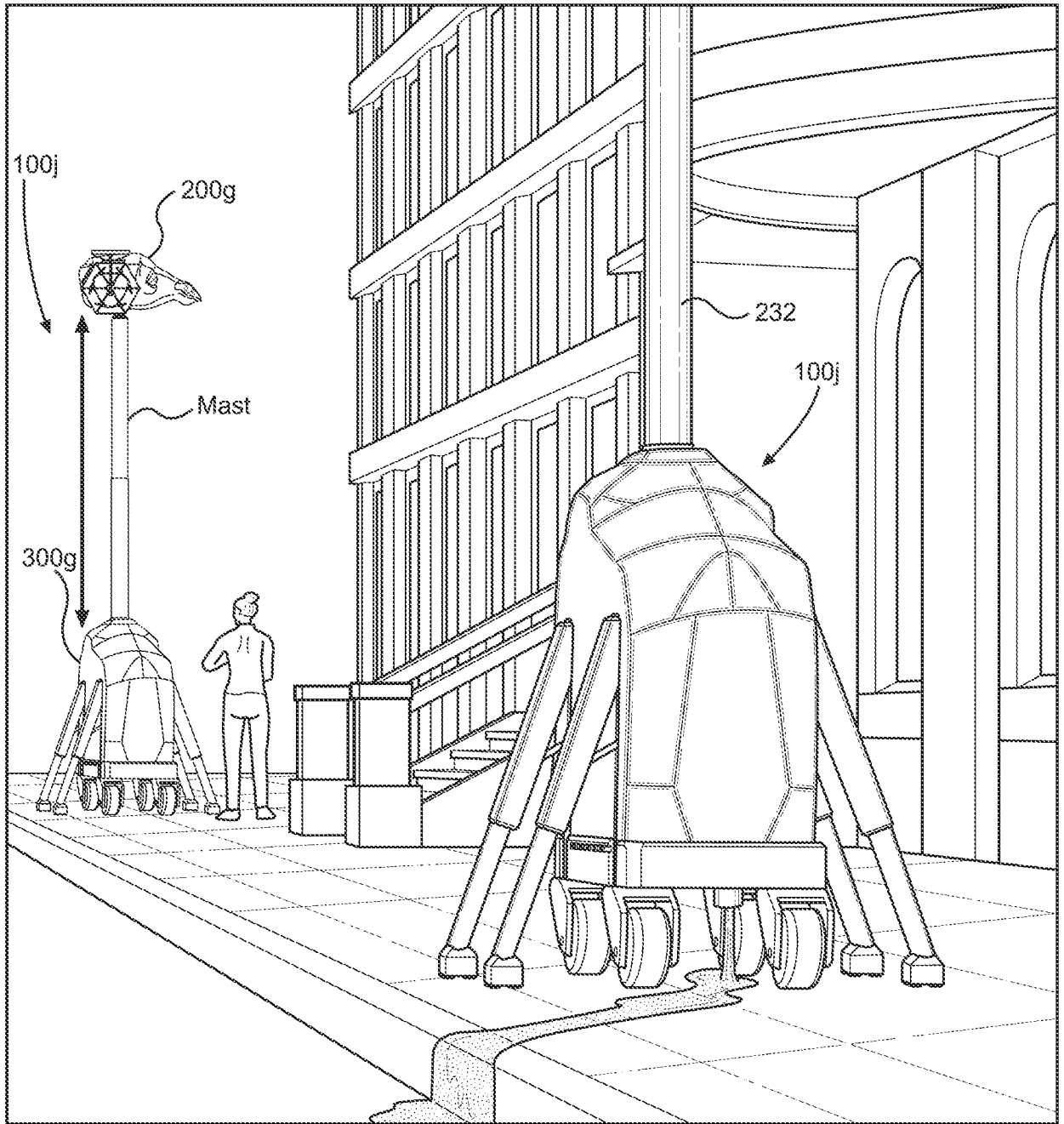


FIG. 14F

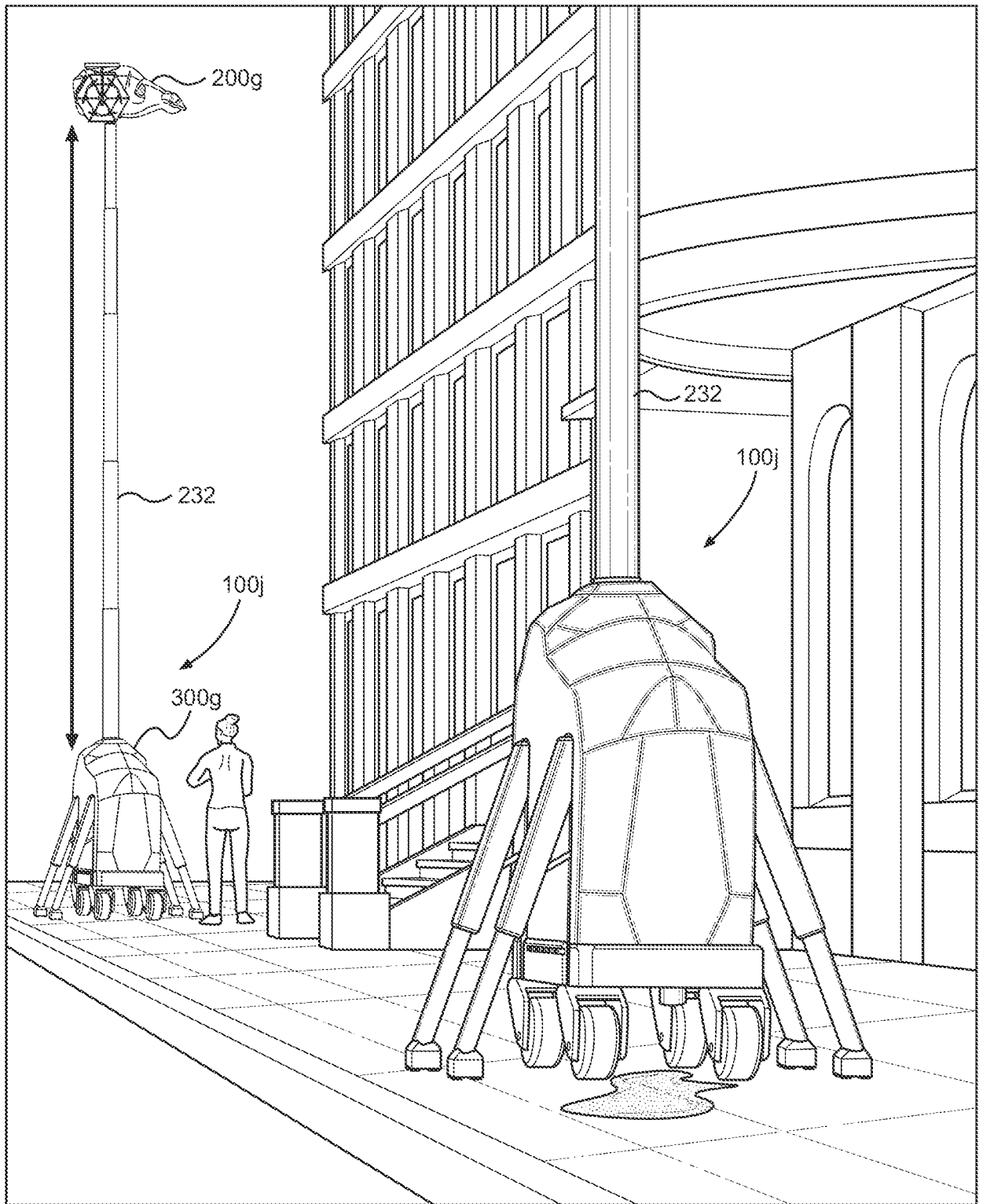


FIG. 14G

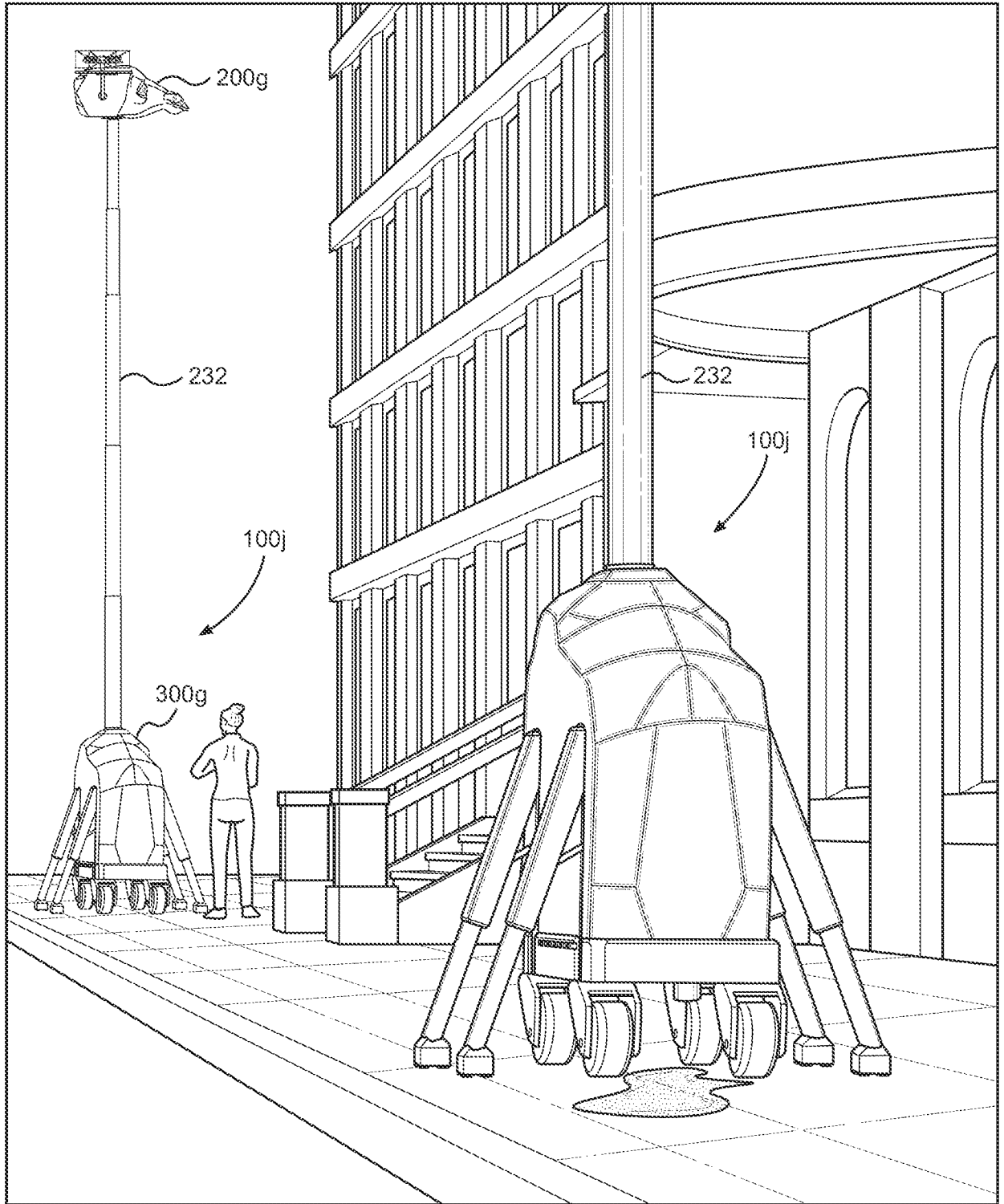


FIG. 14H

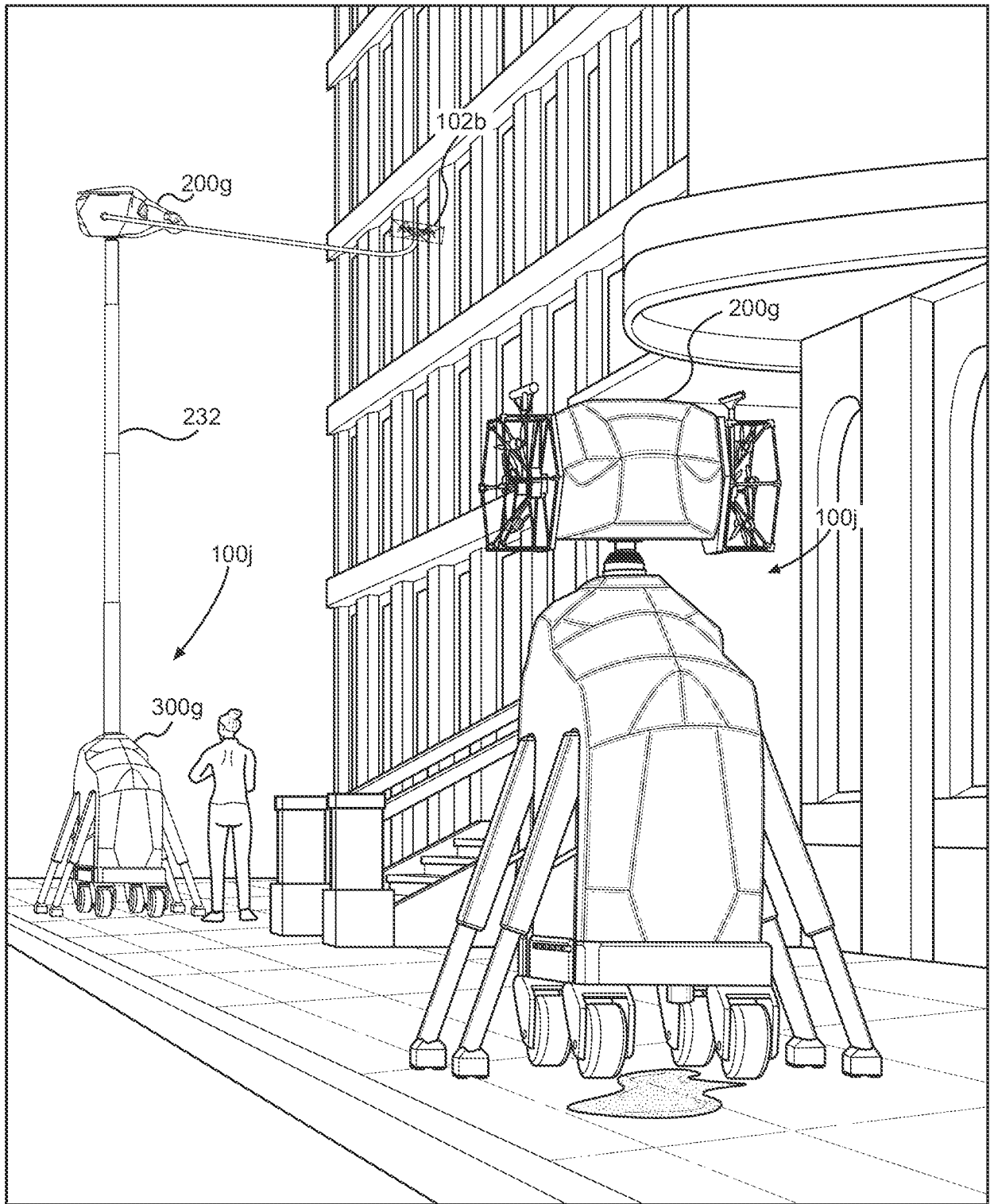


FIG. 14I

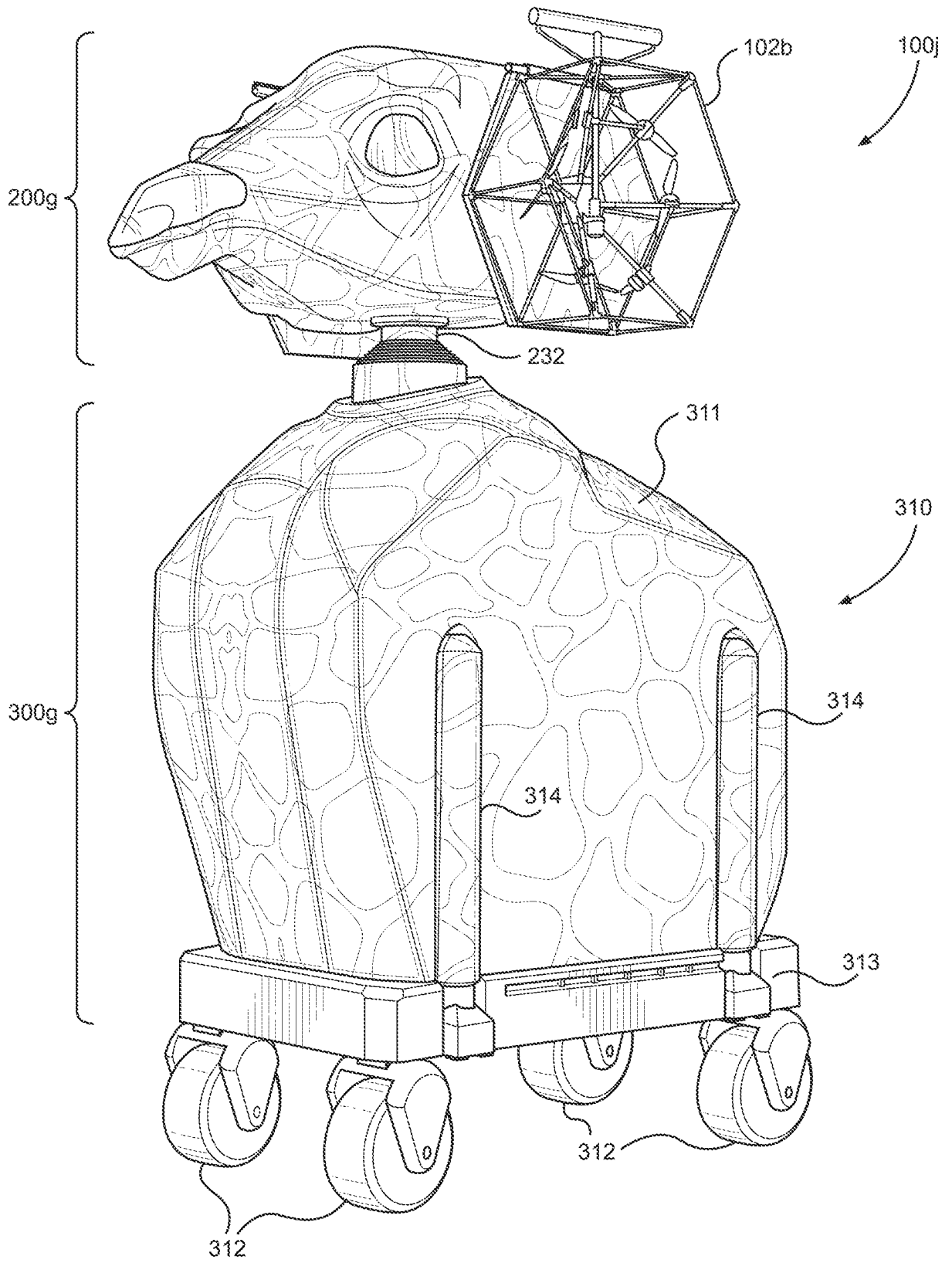


FIG. 14J

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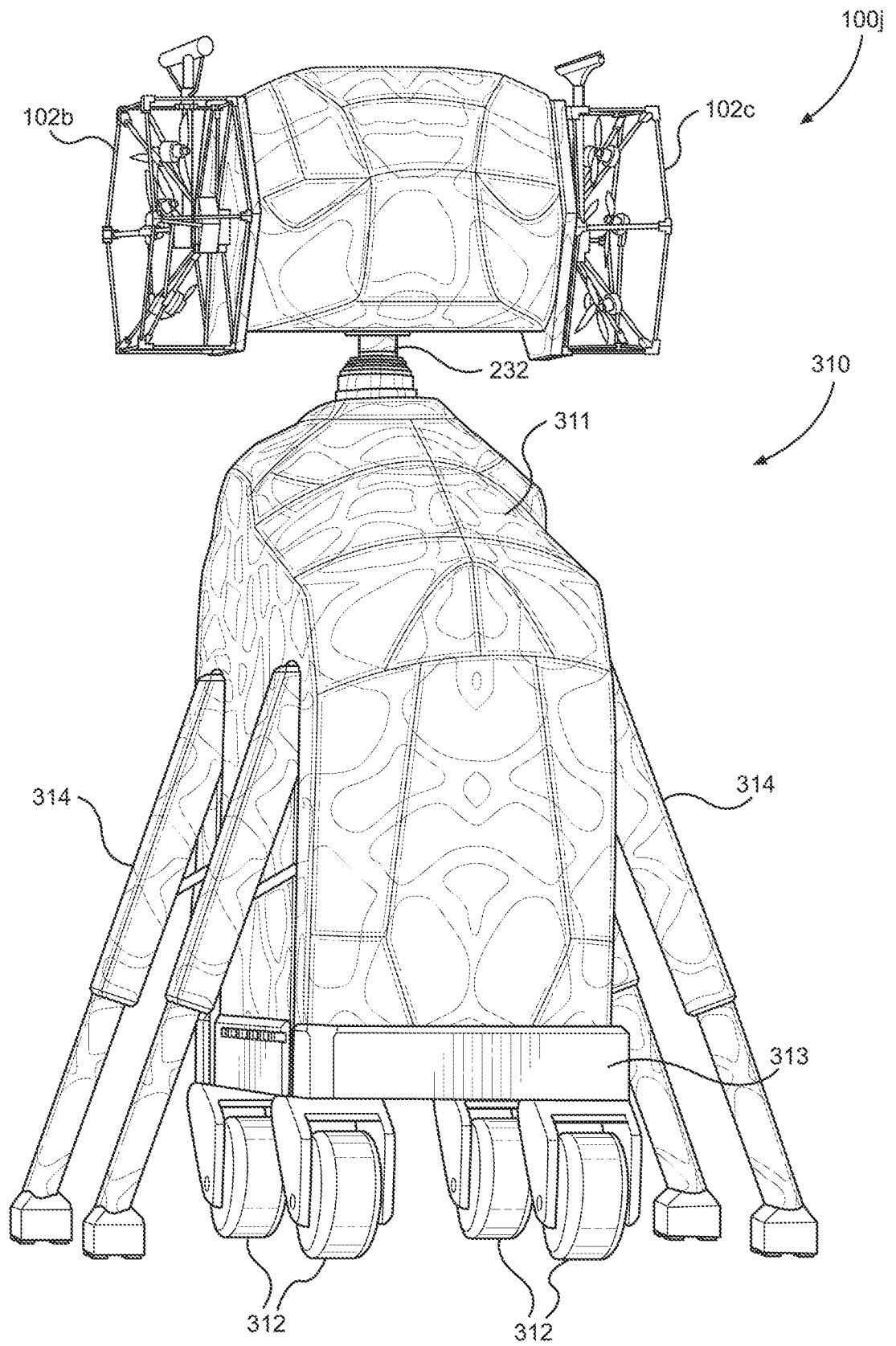


FIG. 14K

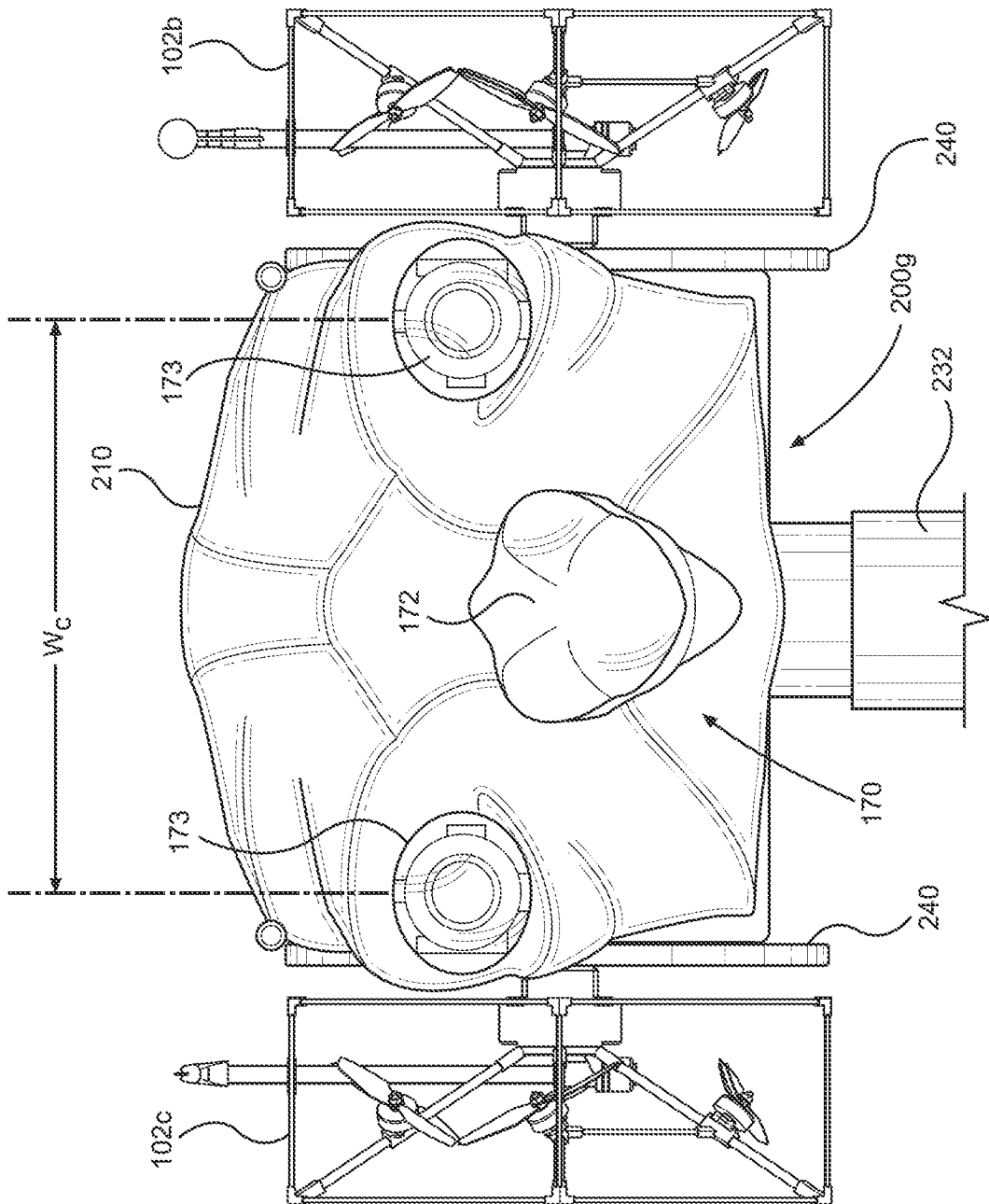


FIG. 15A

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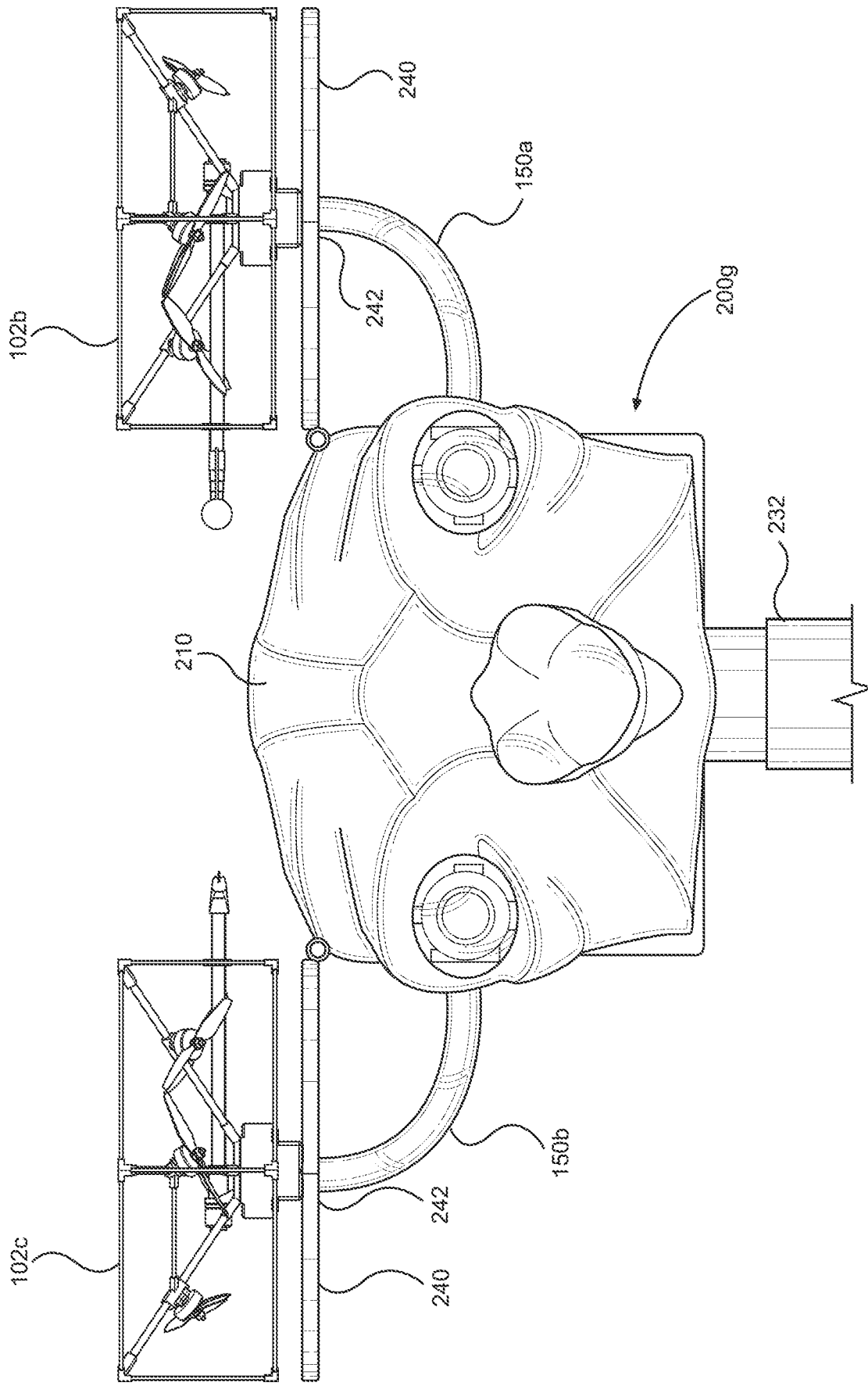


FIG. 15B

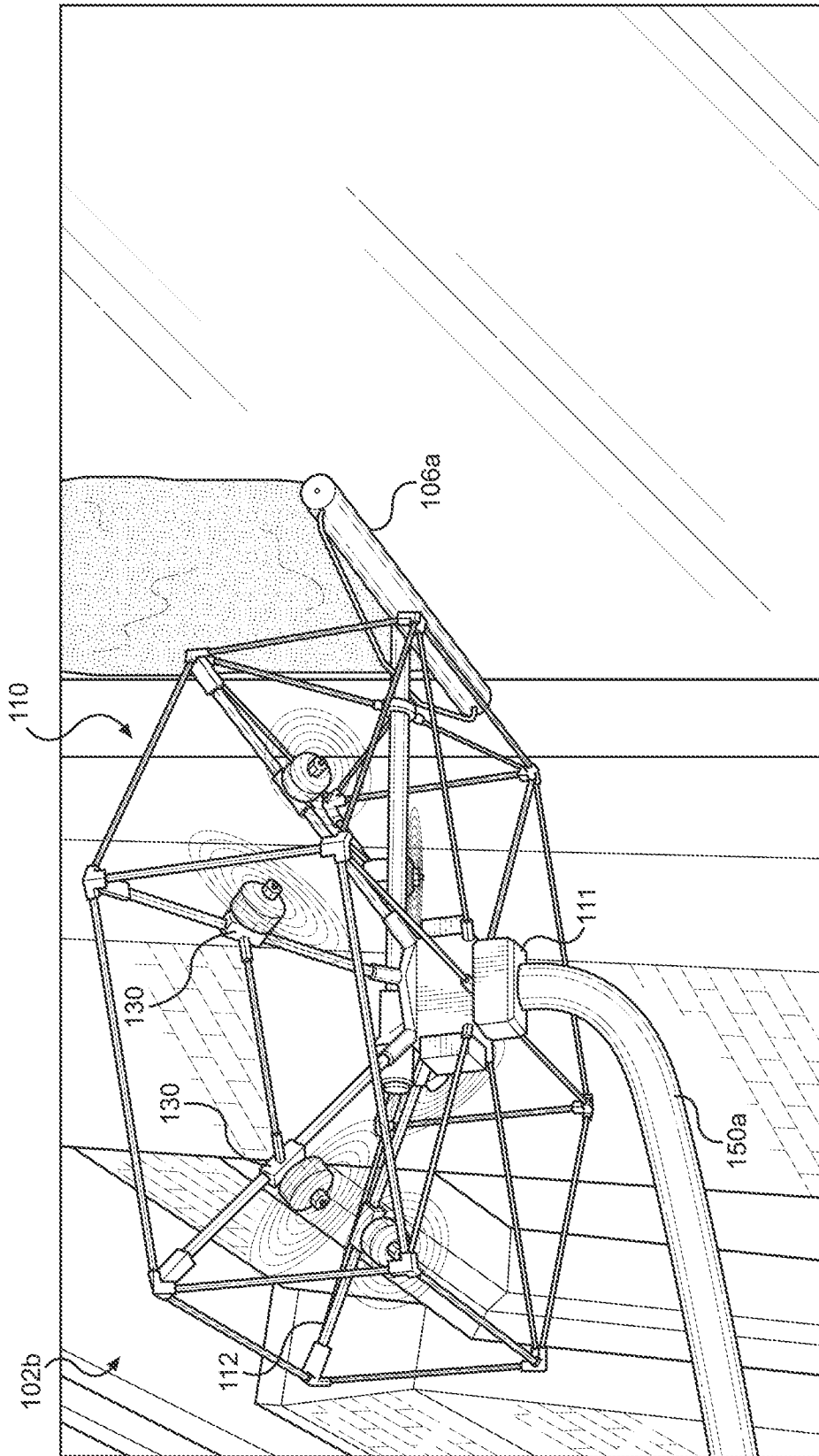


FIG. 16A

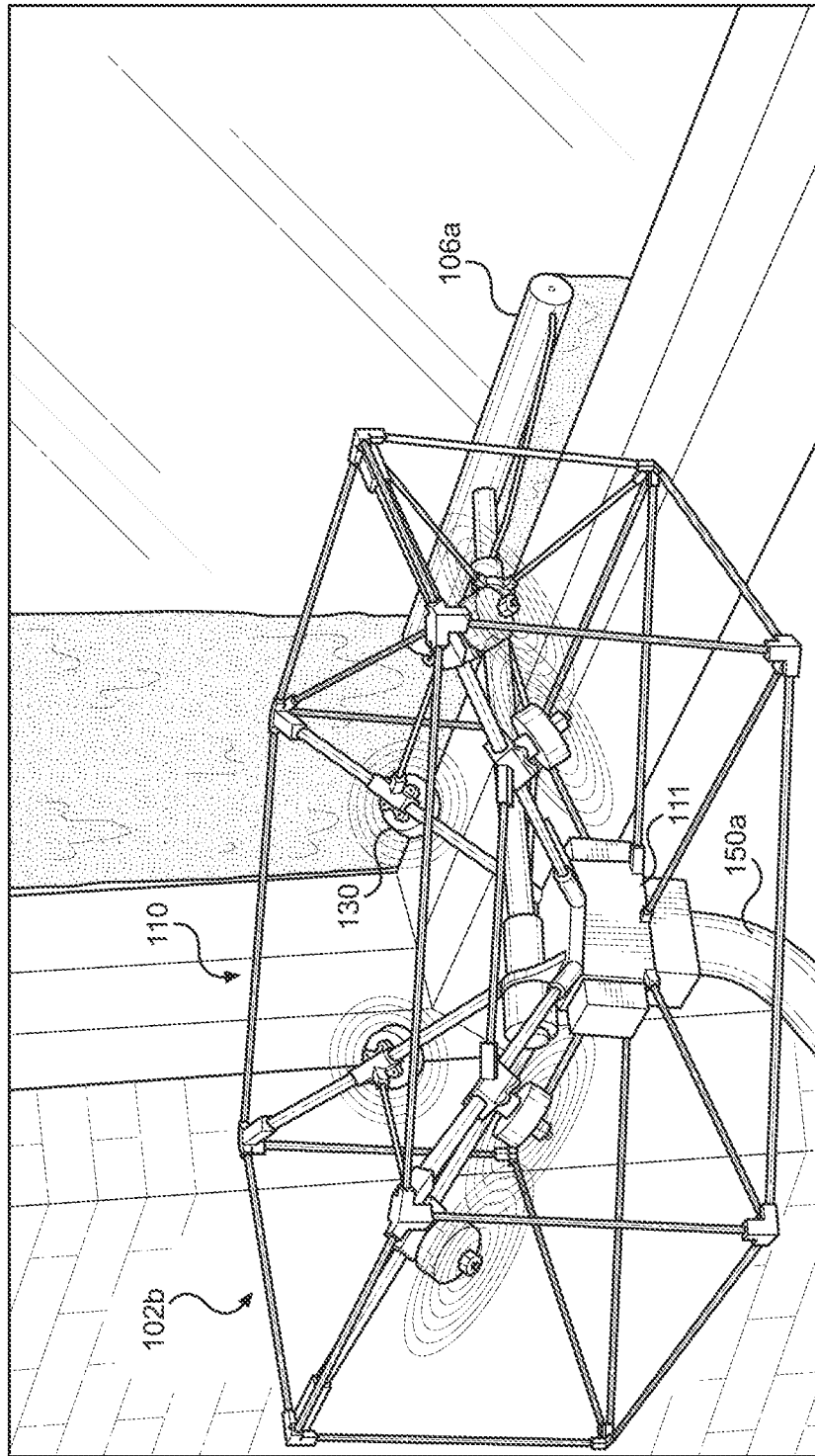


FIG. 16B

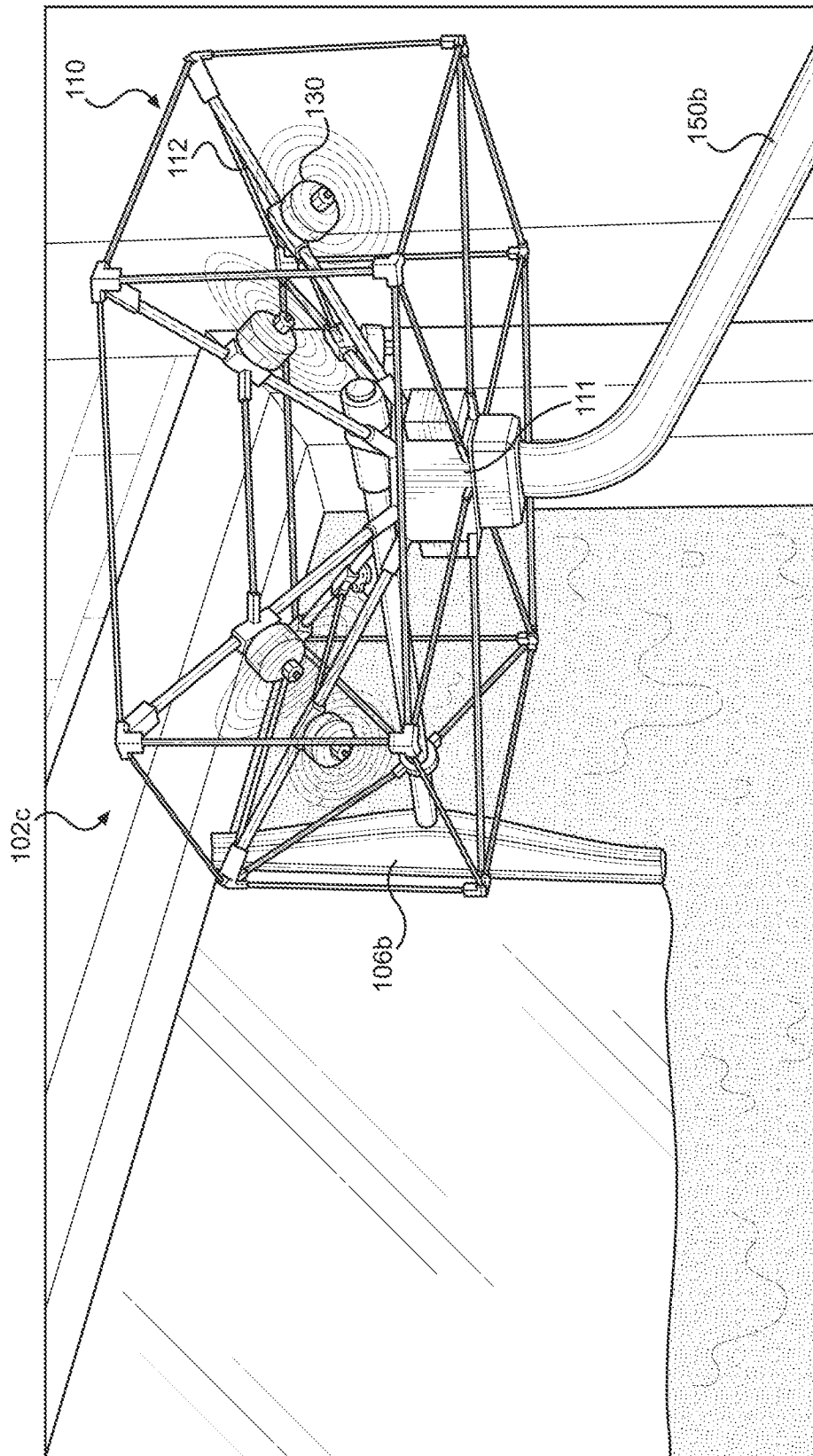


FIG. 17A

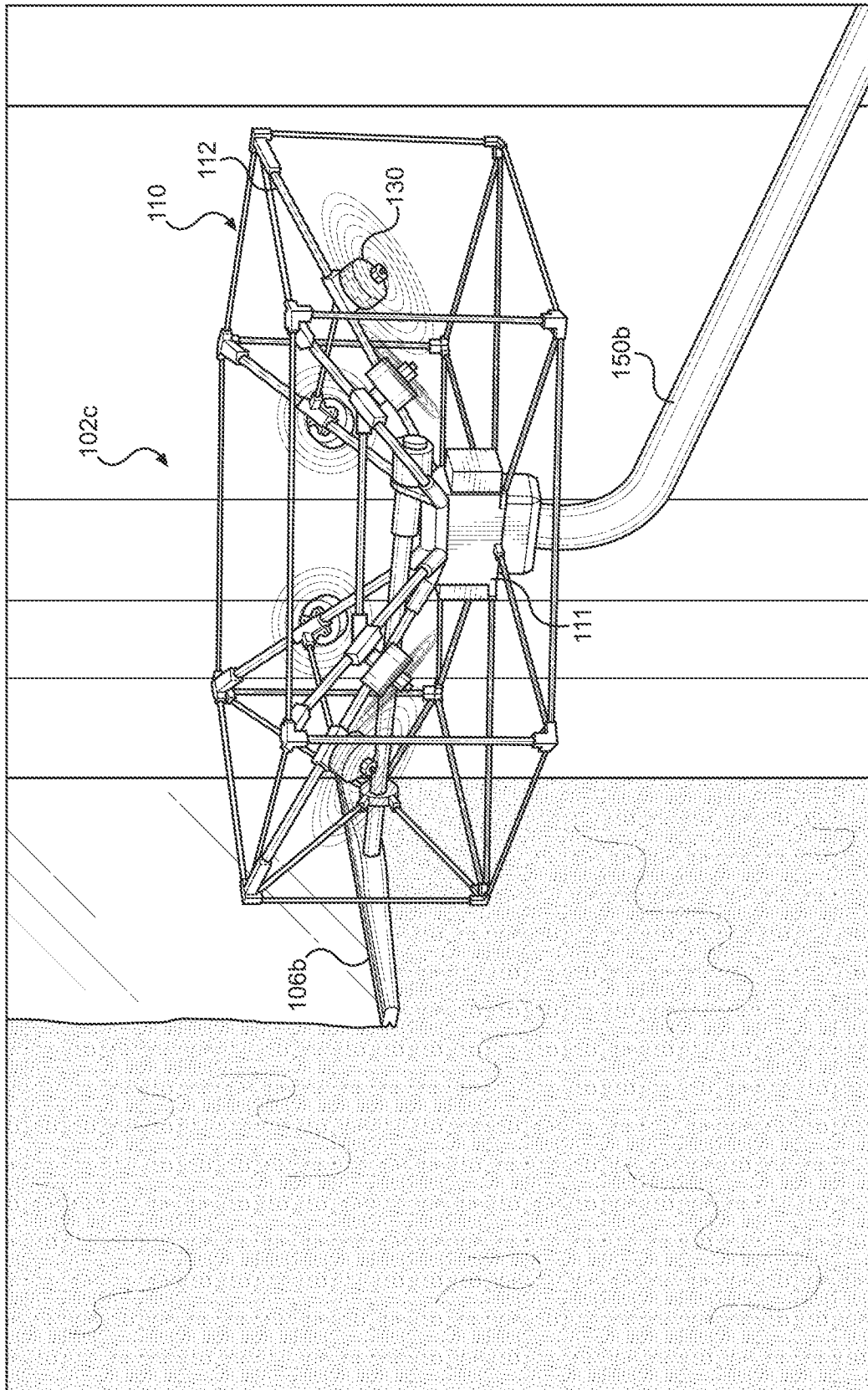


FIG. 17B

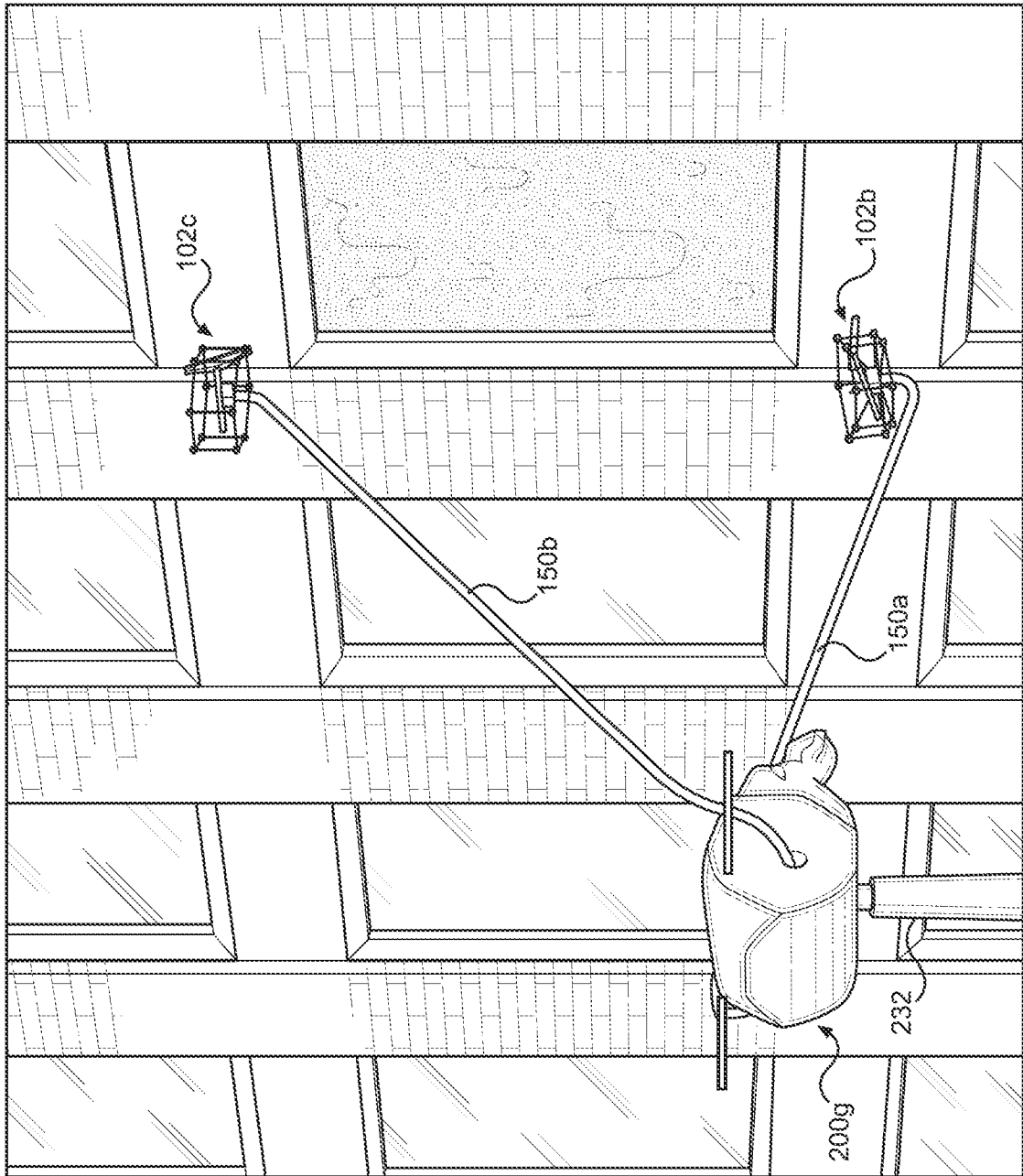


FIG. 18A

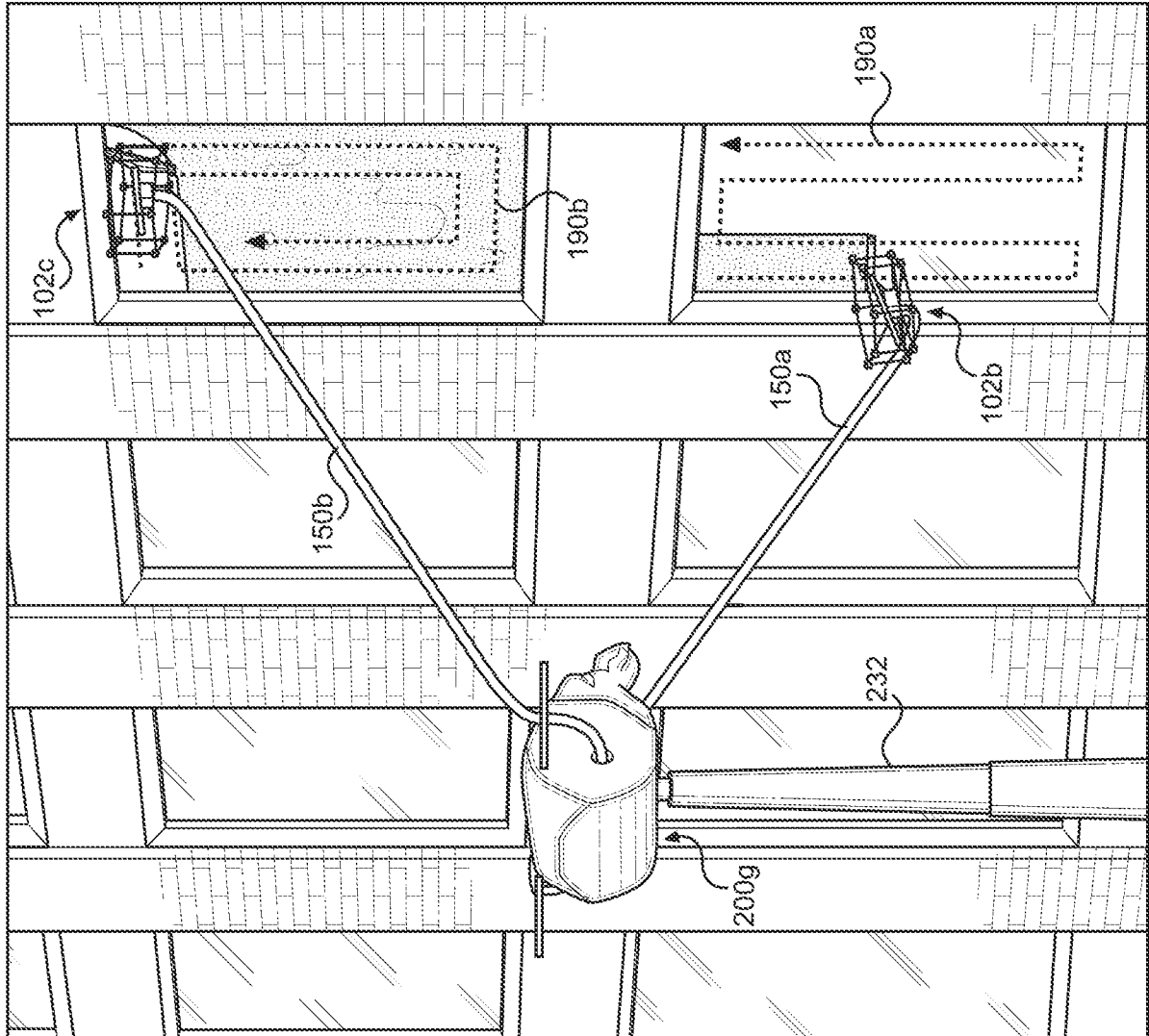


FIG. 18B

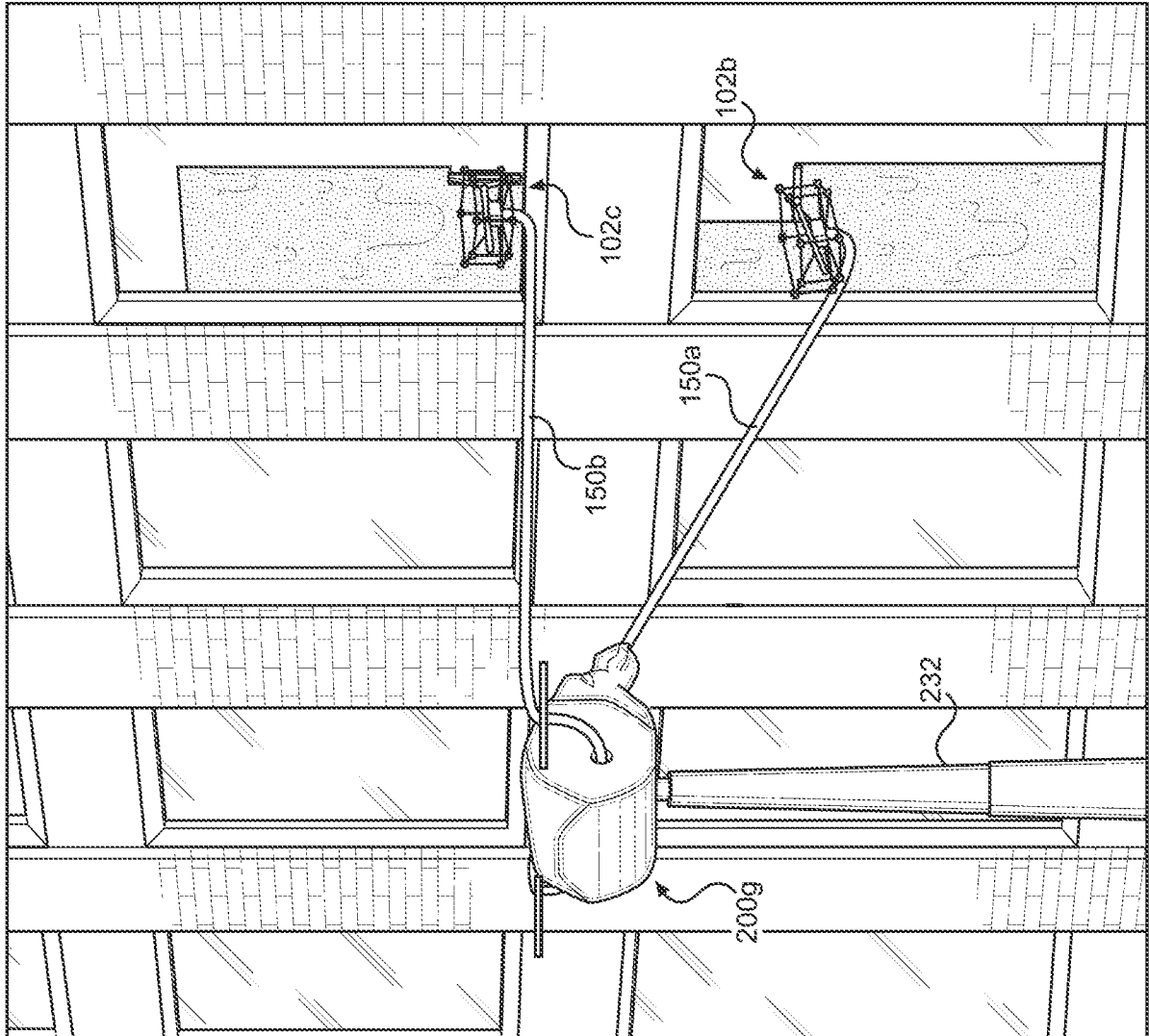


FIG. 18C

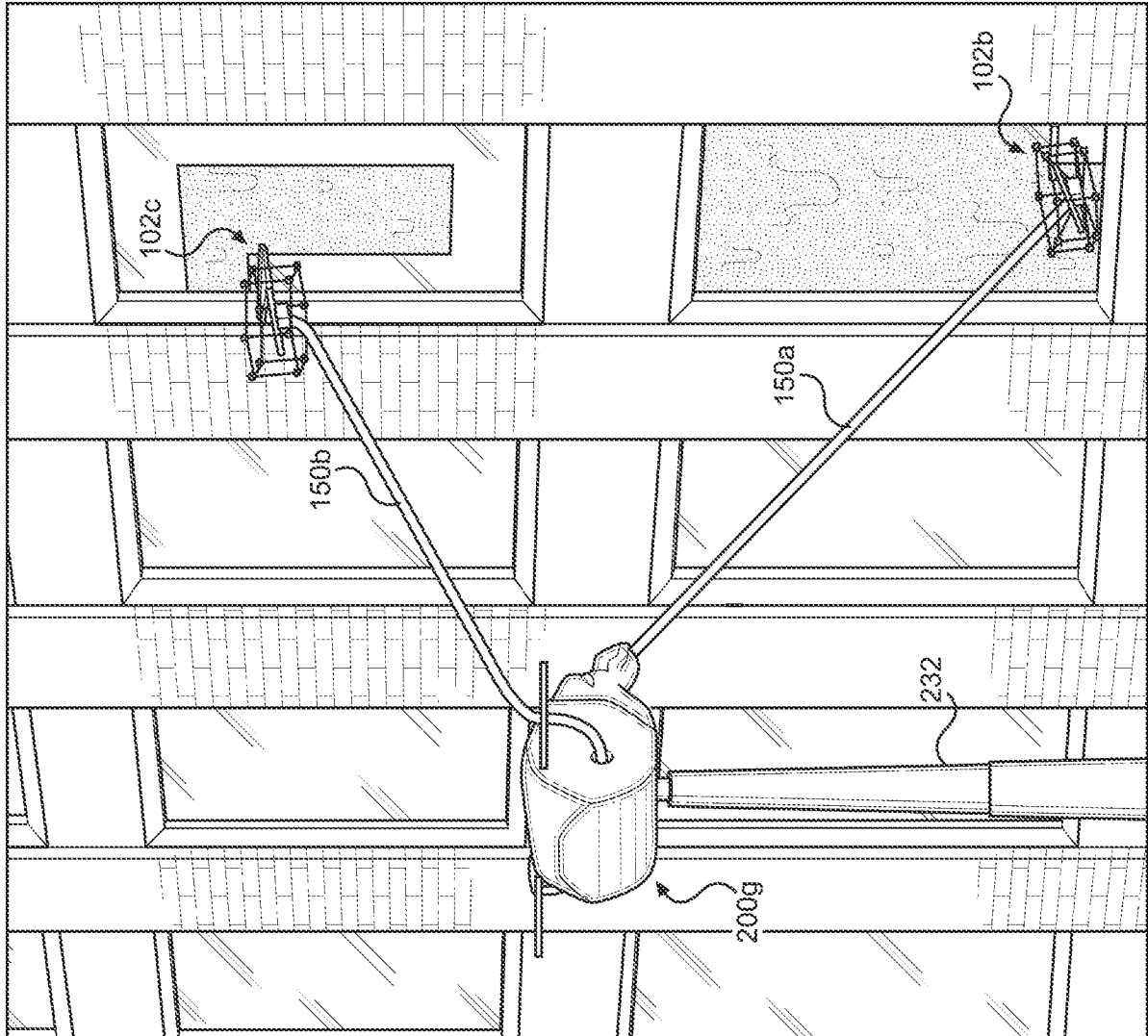
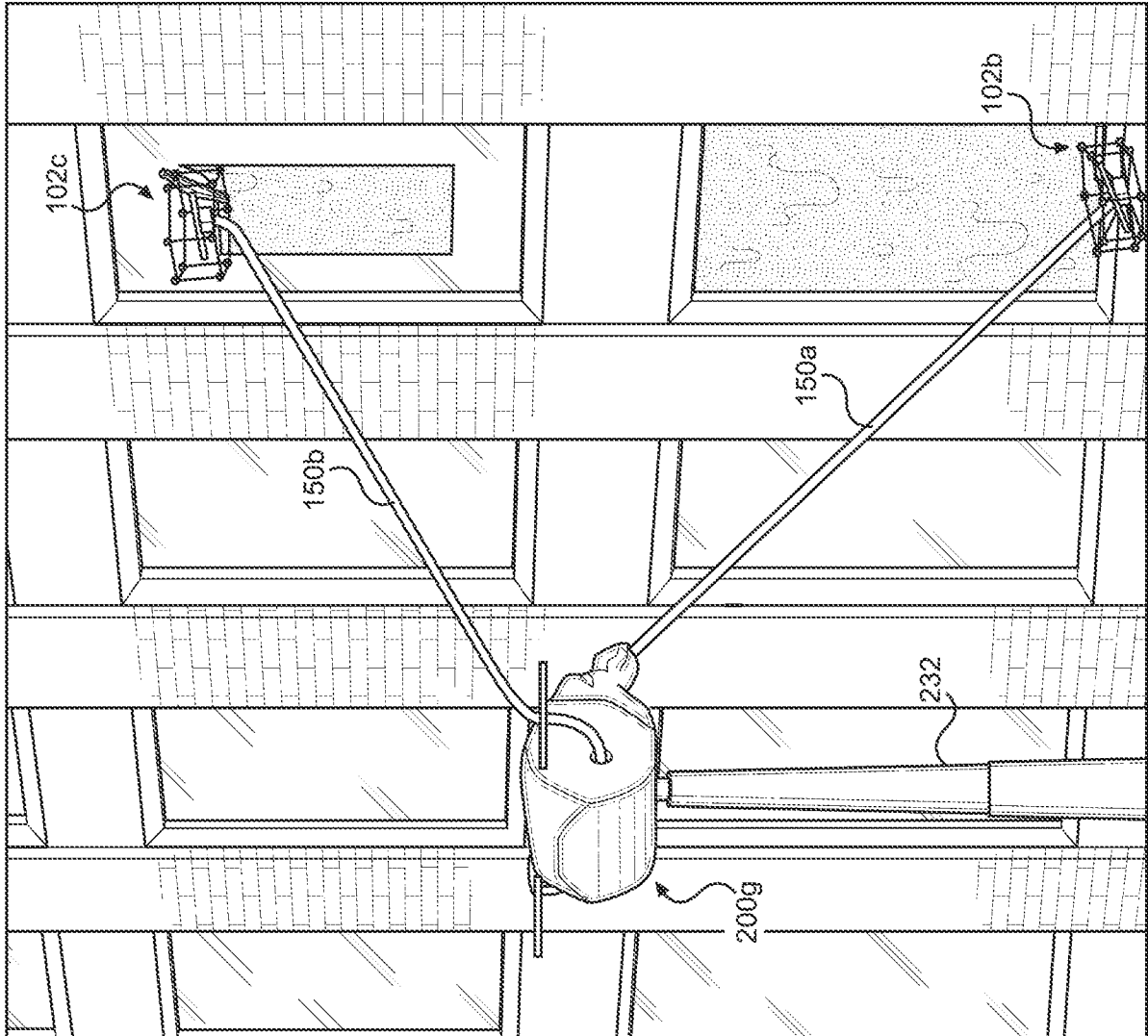


FIG. 18D



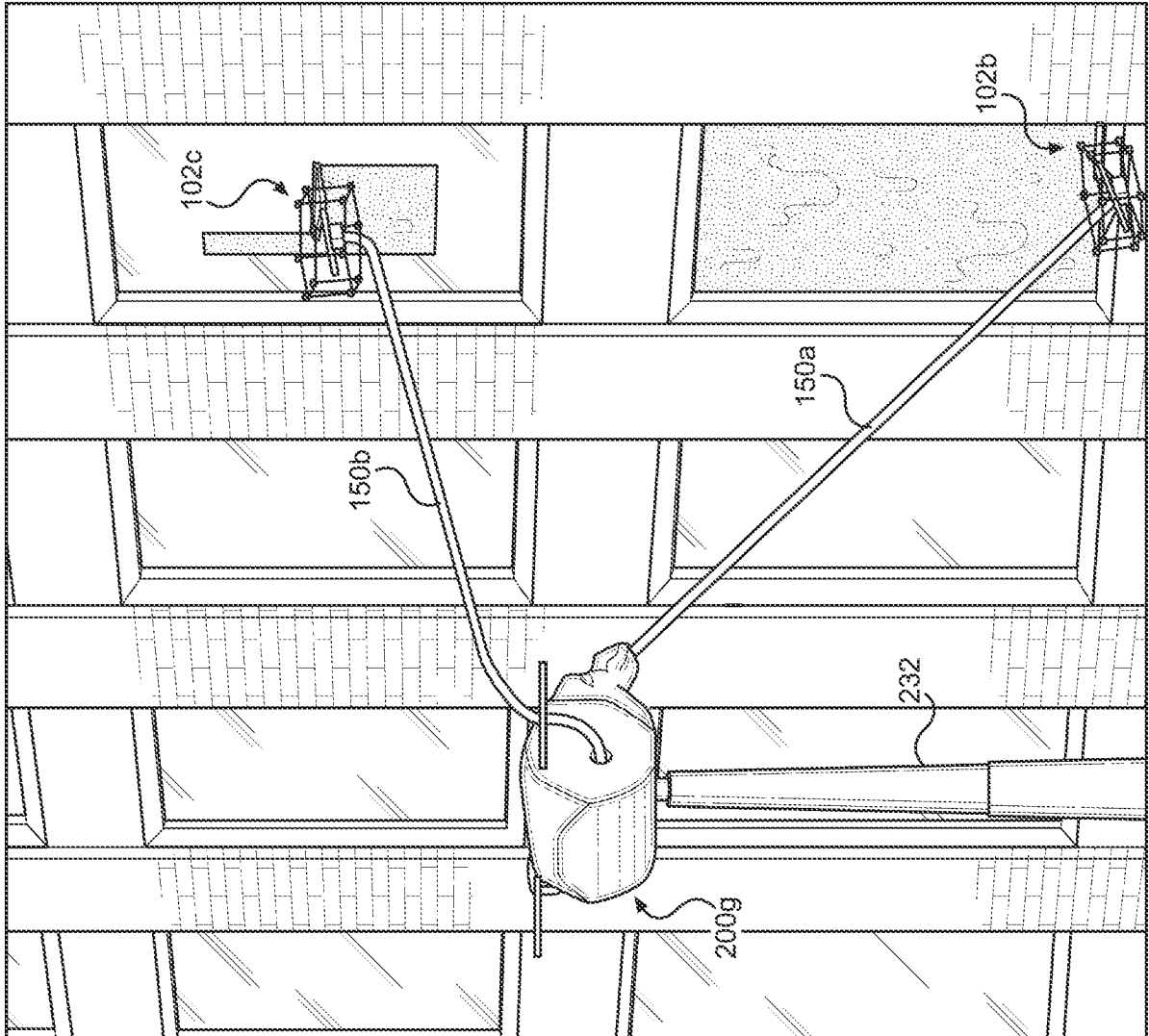


FIG. 18F

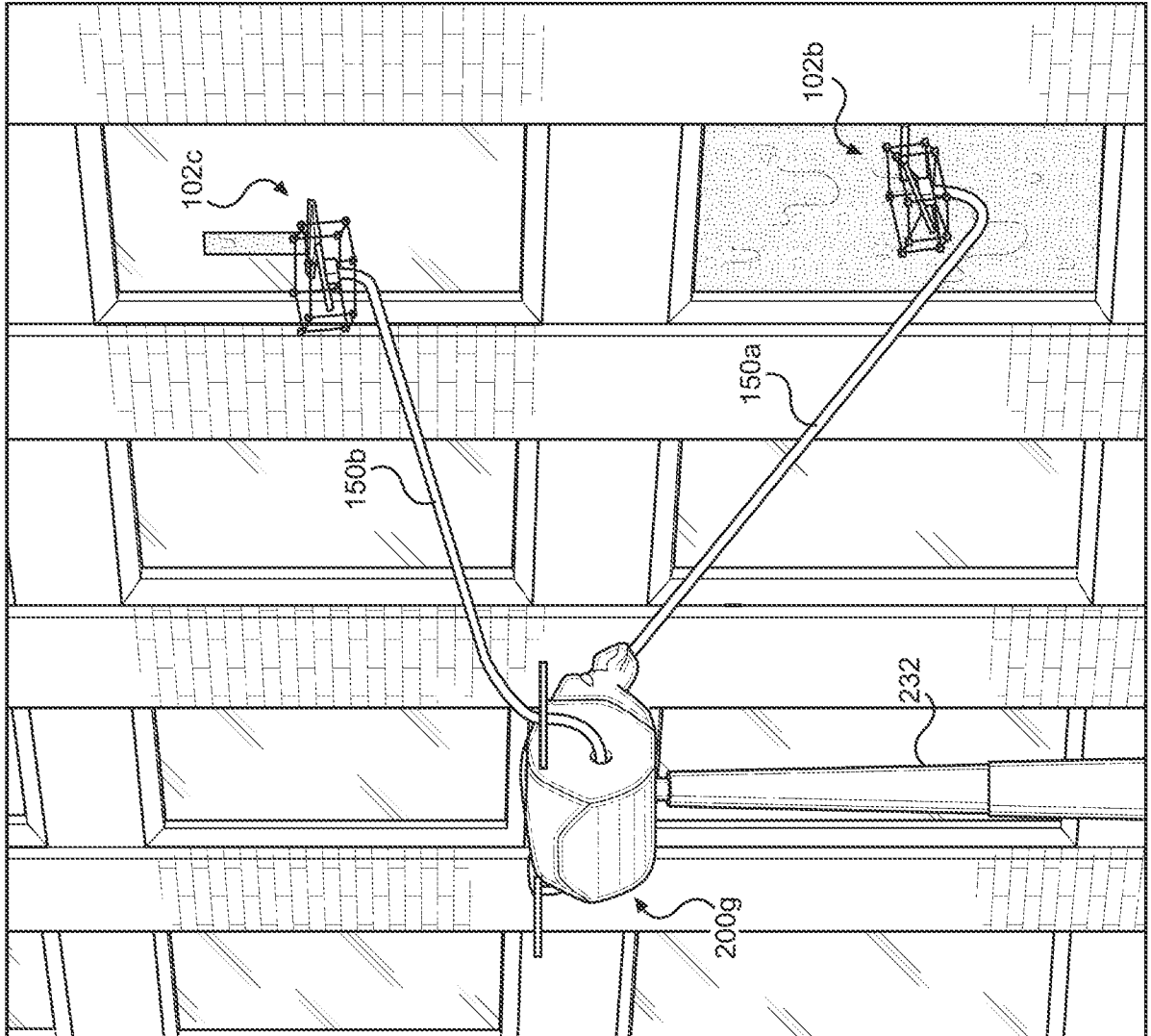


FIG. 18G

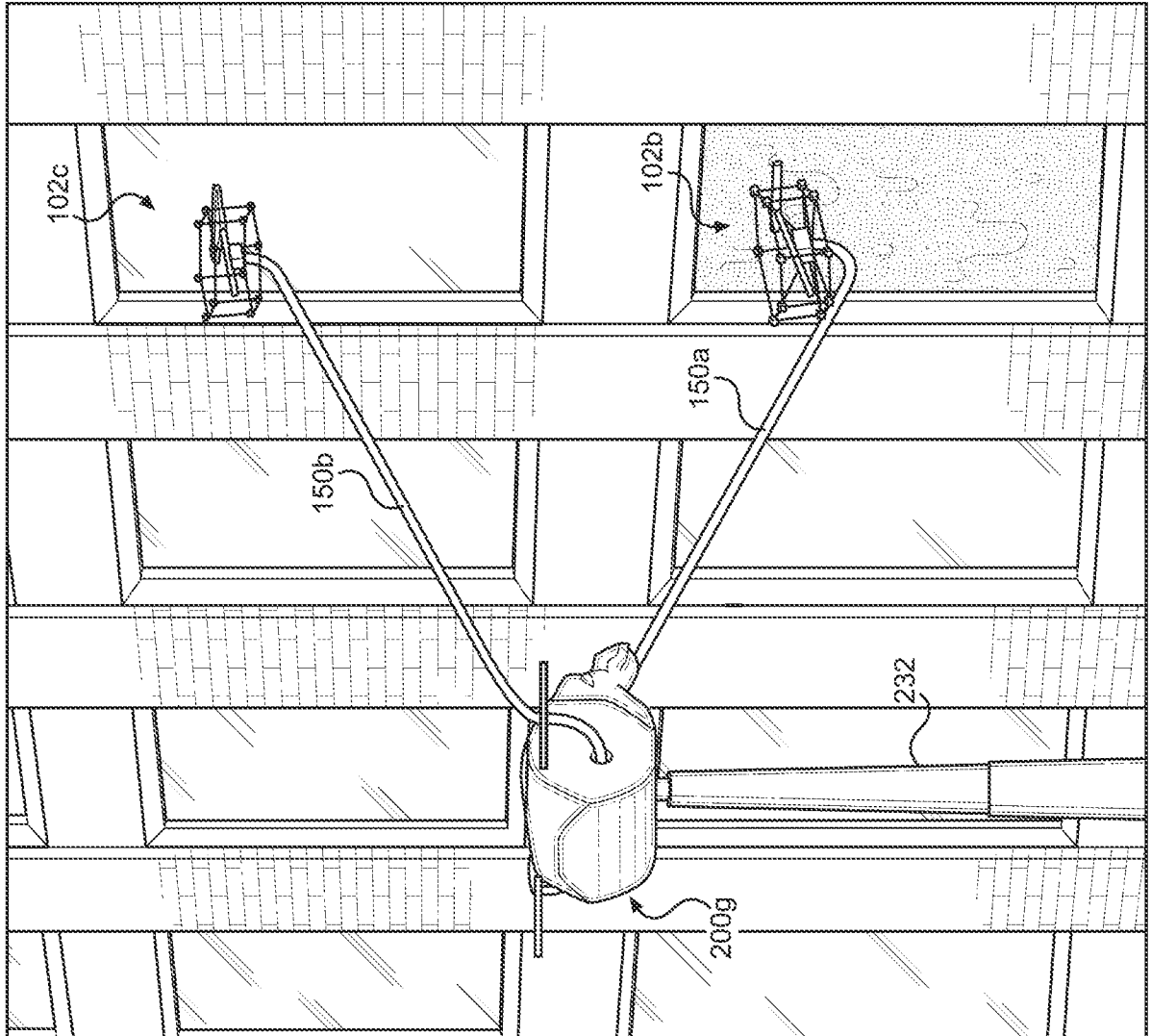


FIG. 18H

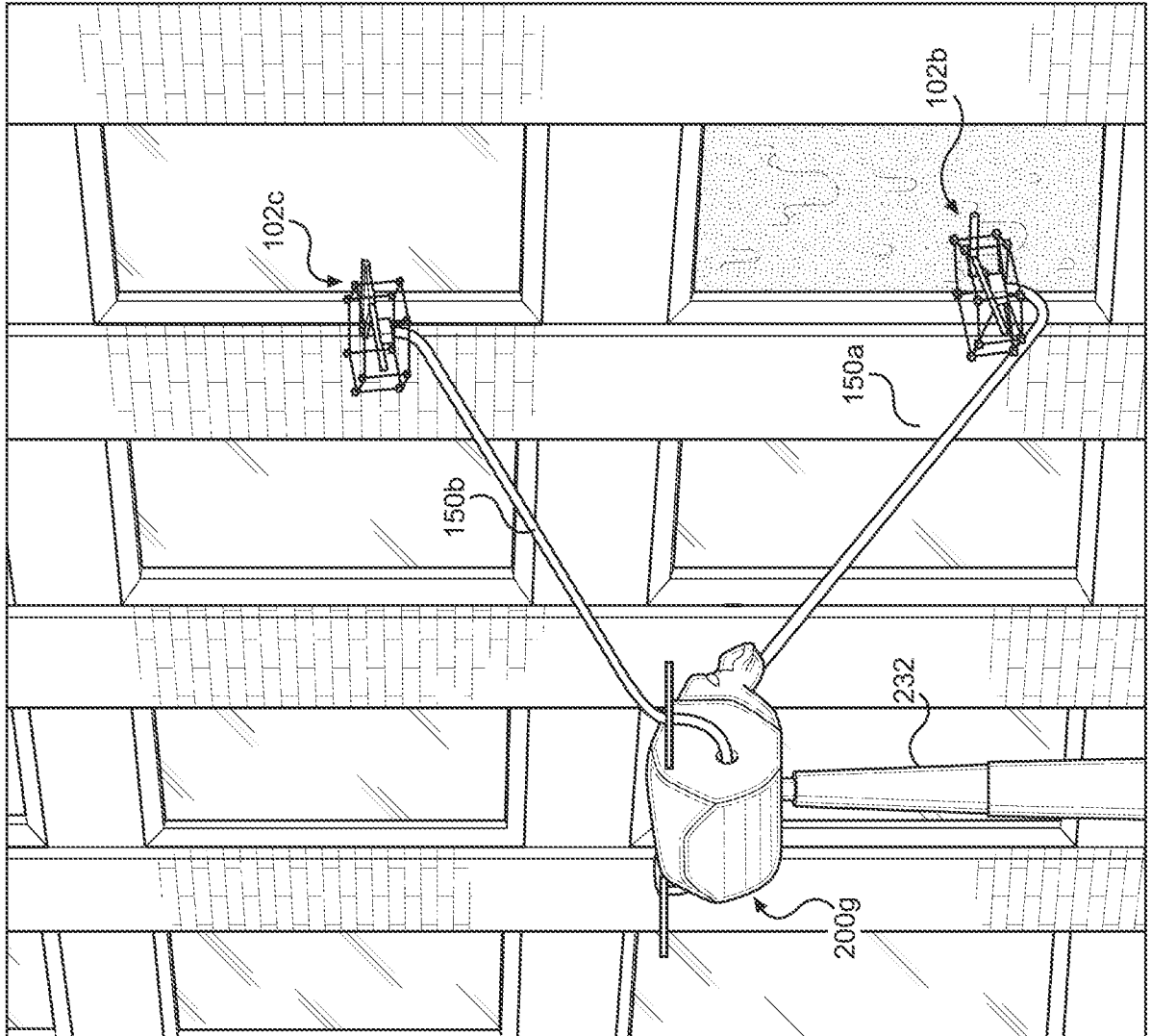


FIG. 18I

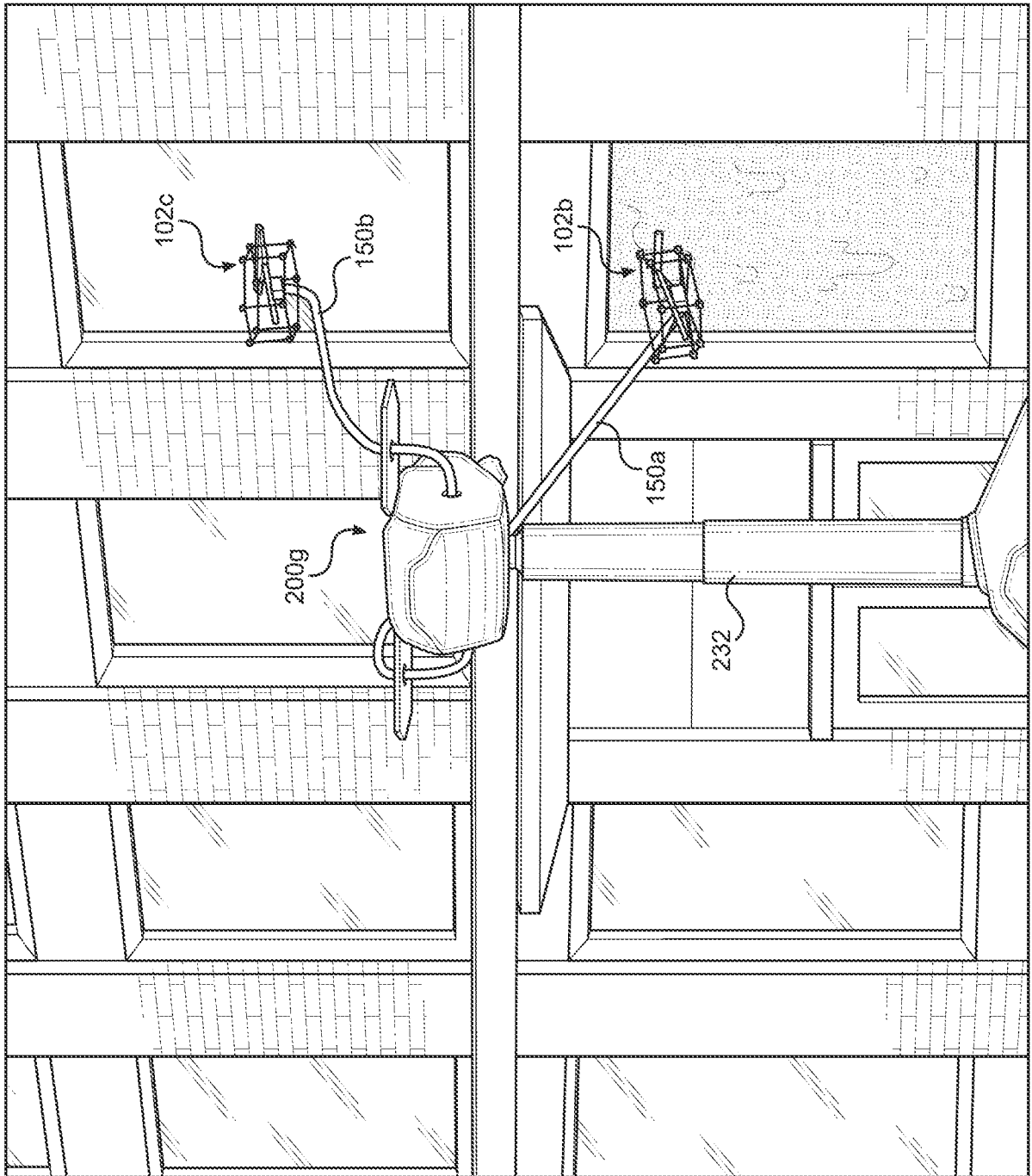


FIG. 19A

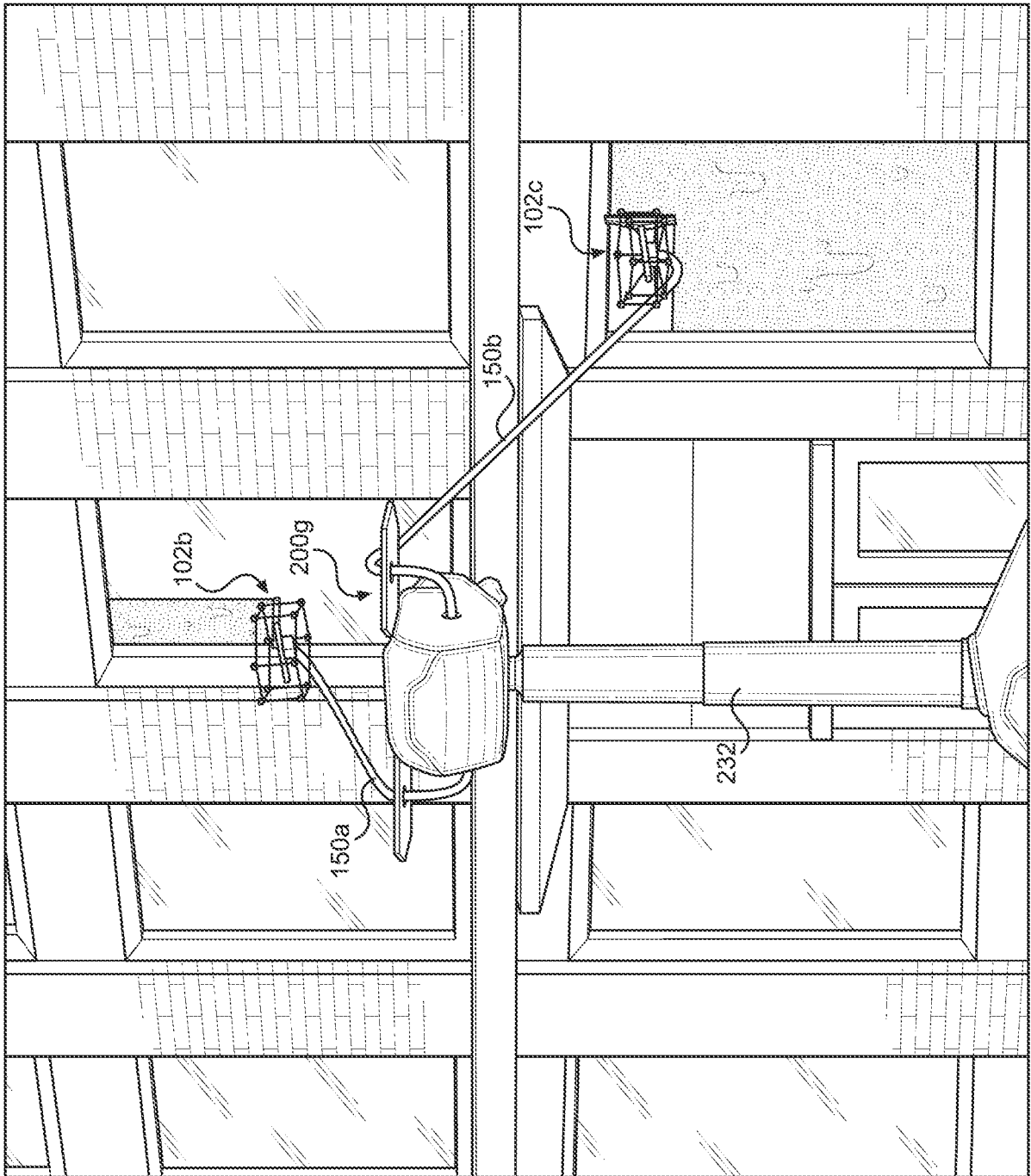


FIG. 19B

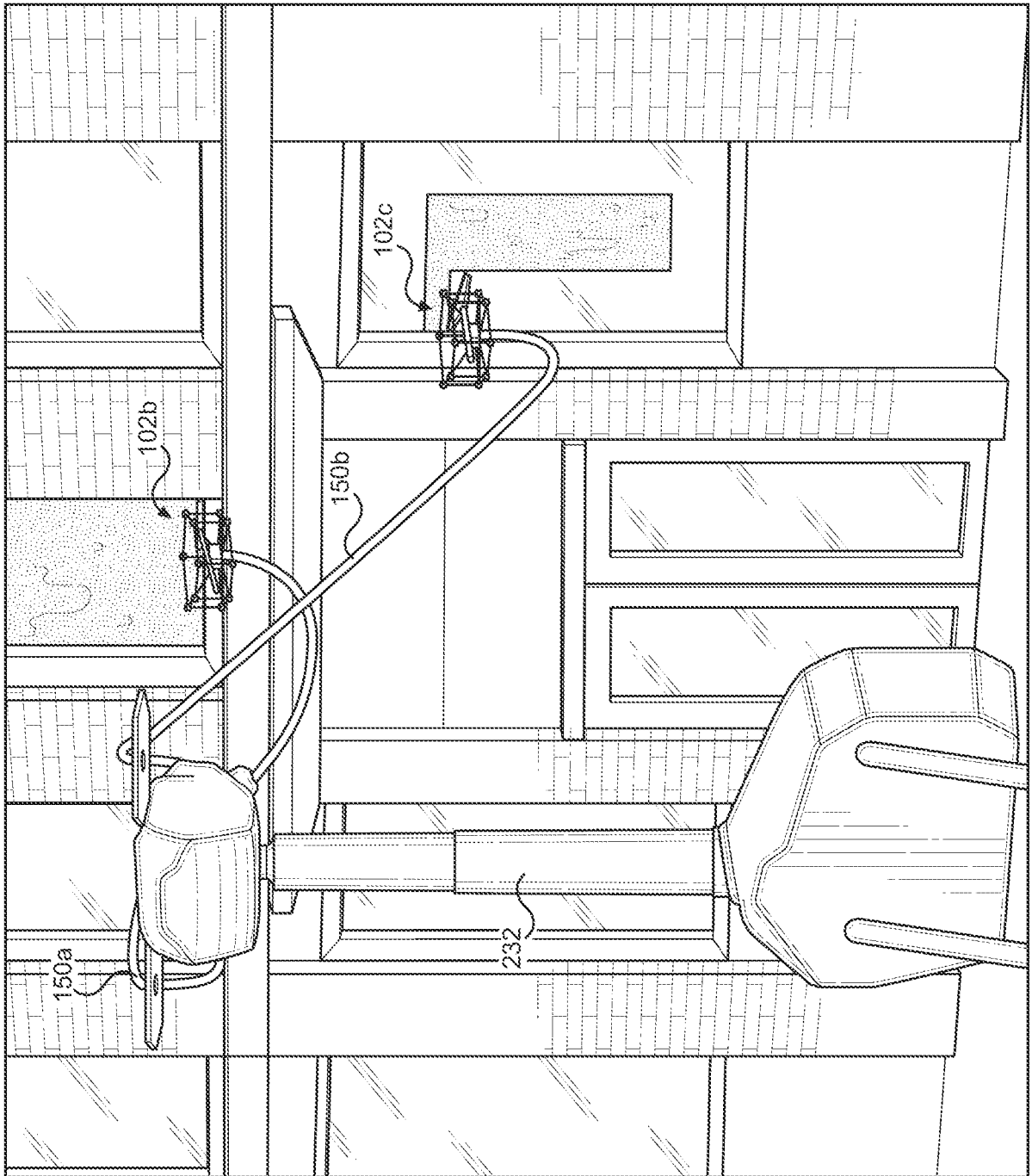


FIG. 19C

45/84

100j

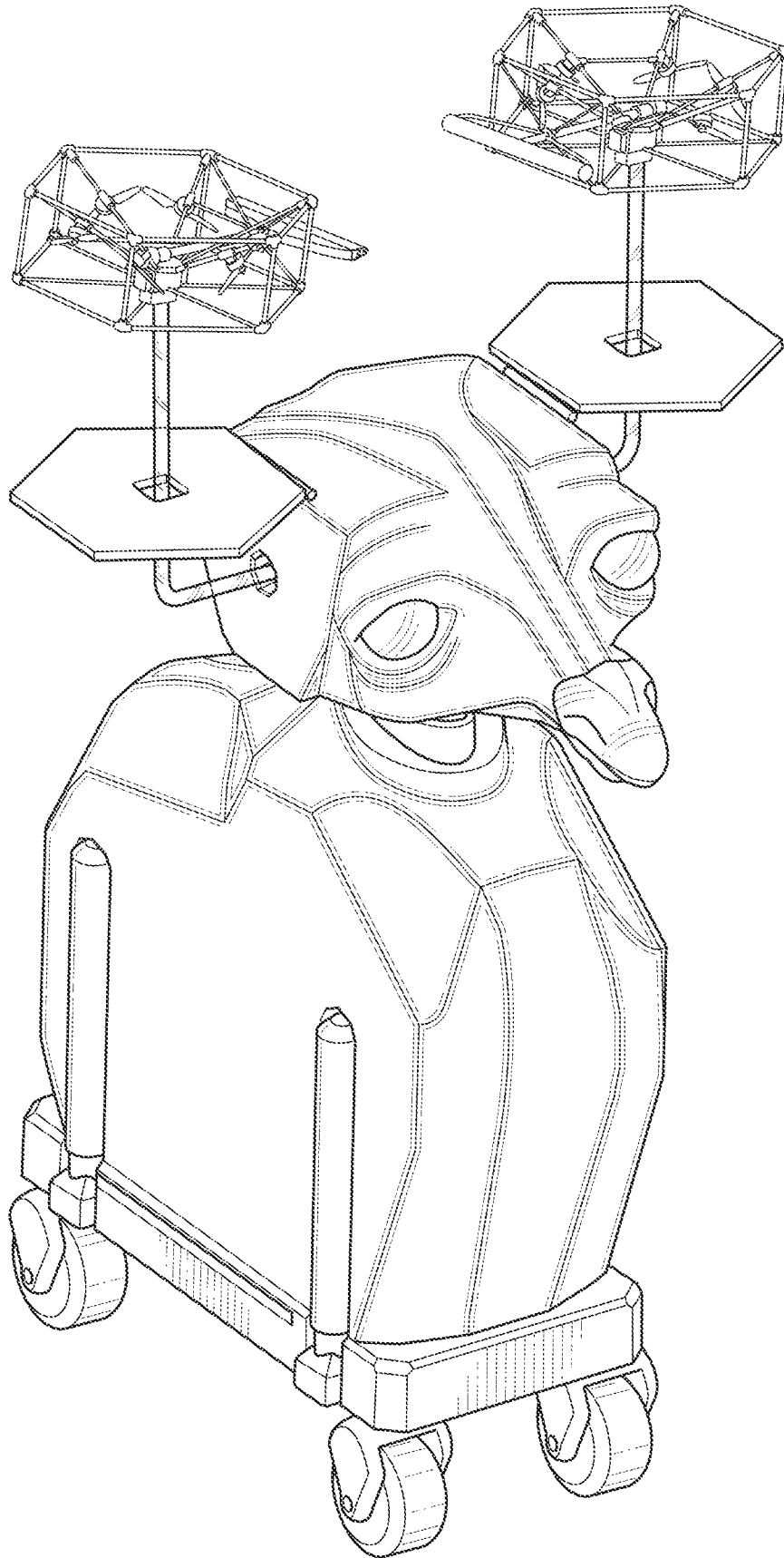


FIG. 20A

46/84

100j

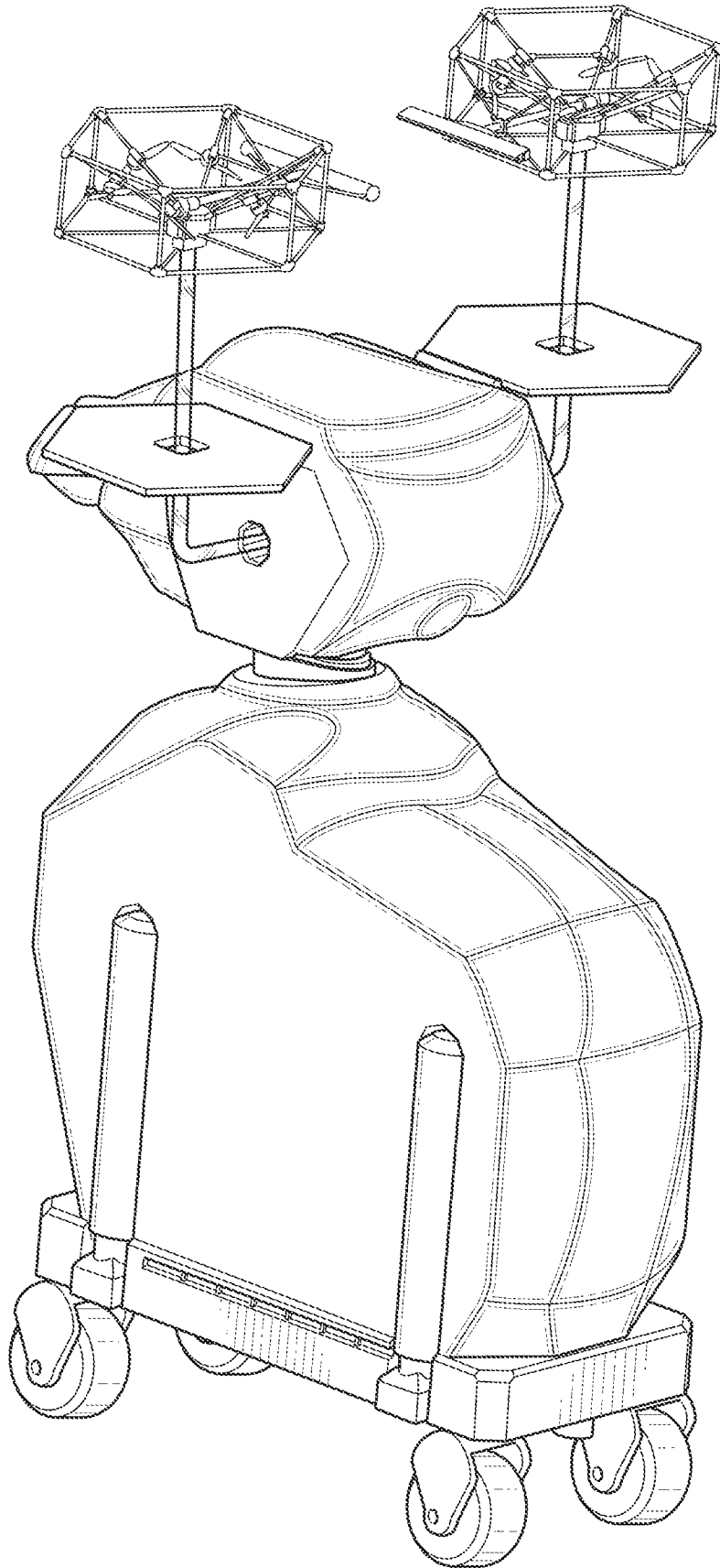


FIG. 20B

47/84

100j

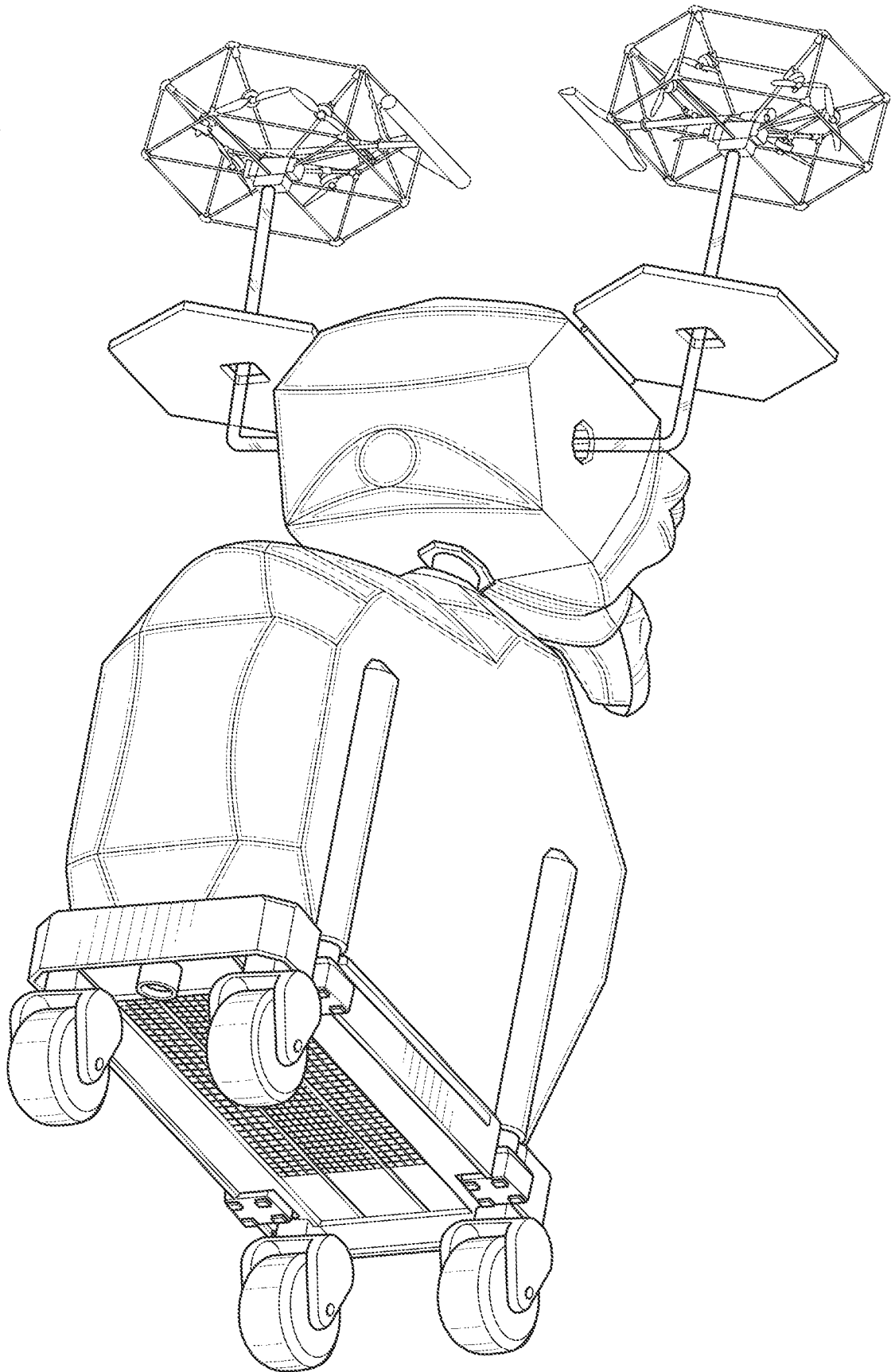


FIG. 20C

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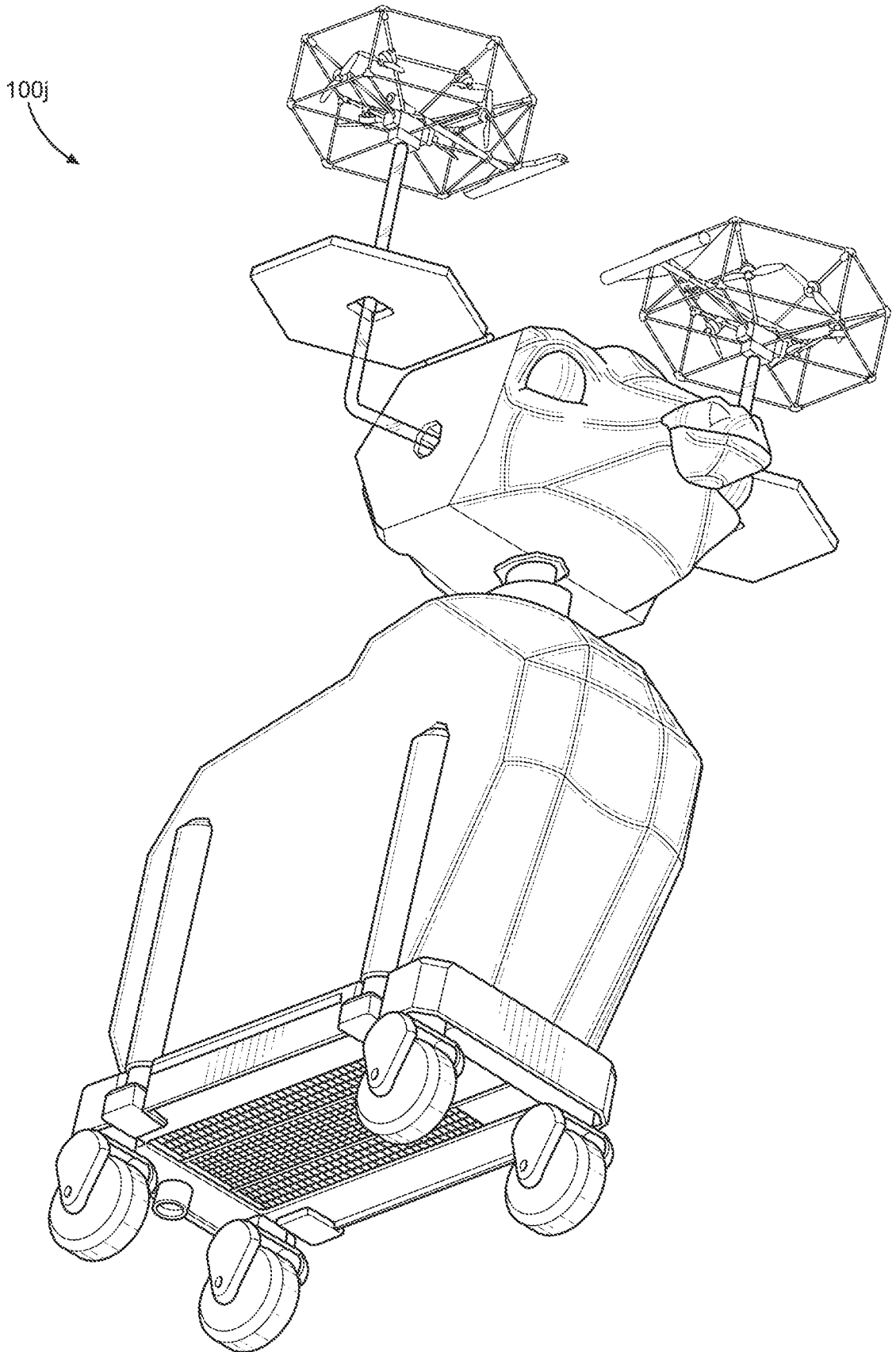


FIG. 20D

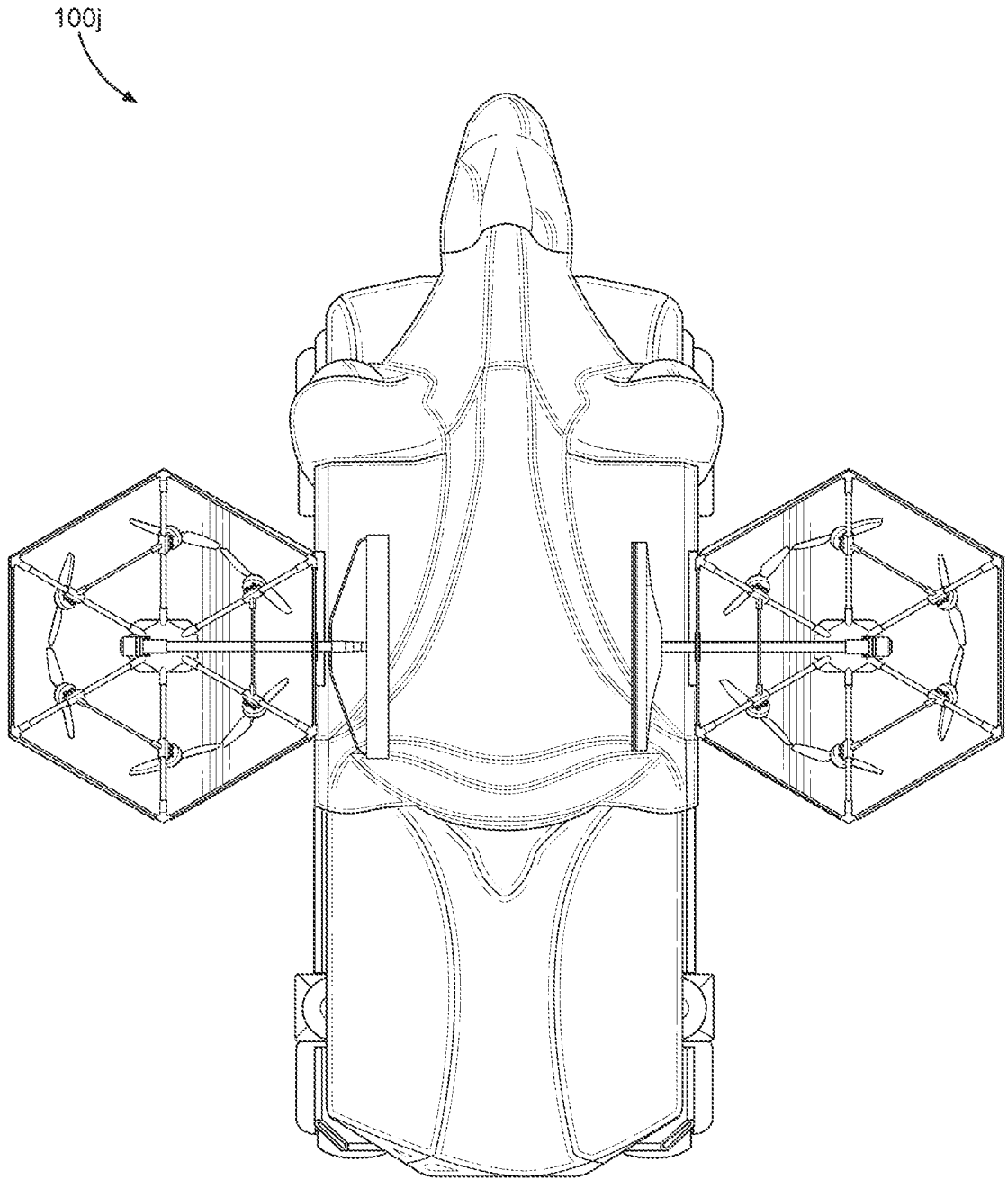


FIG. 20E

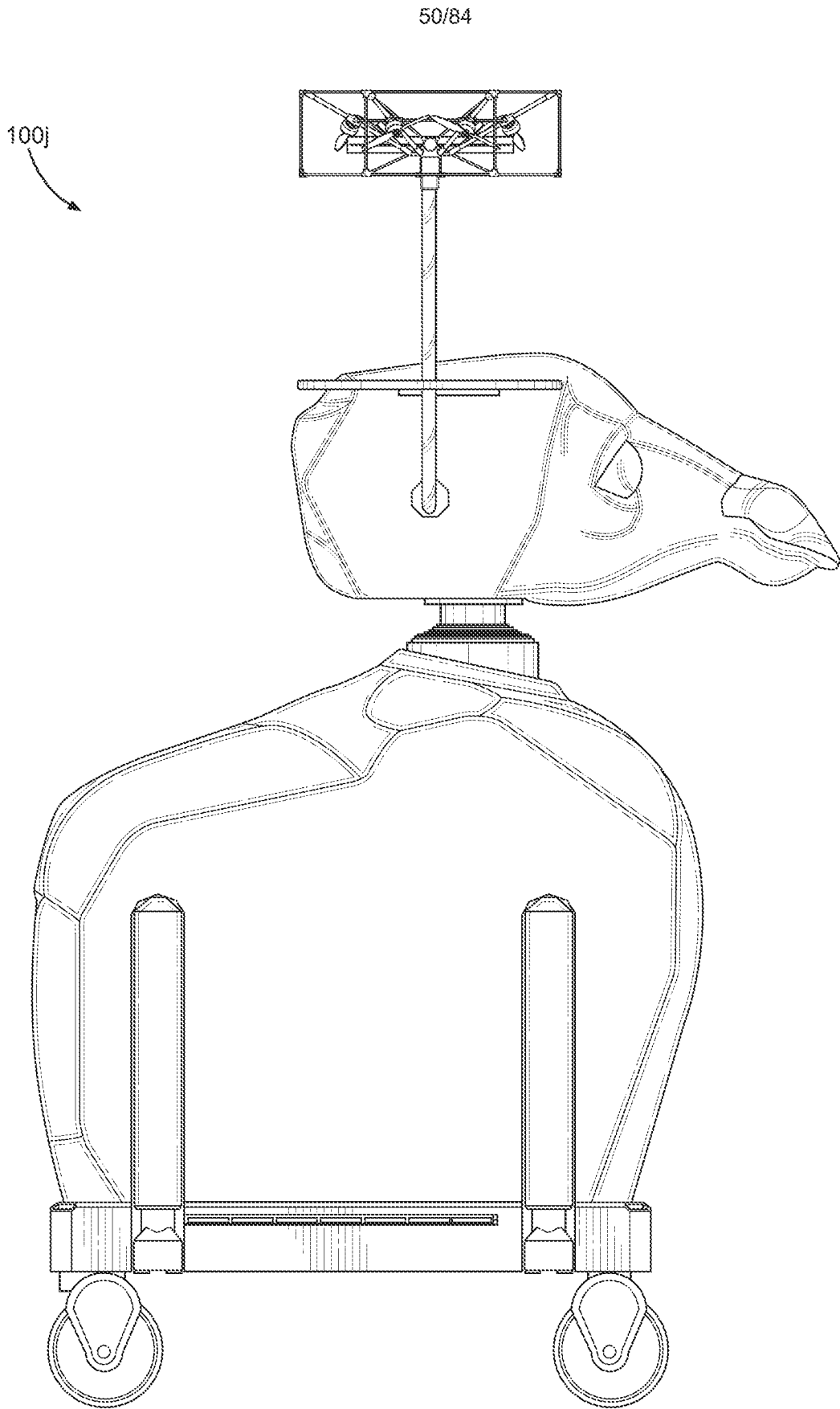


FIG. 20F

51/84

100j

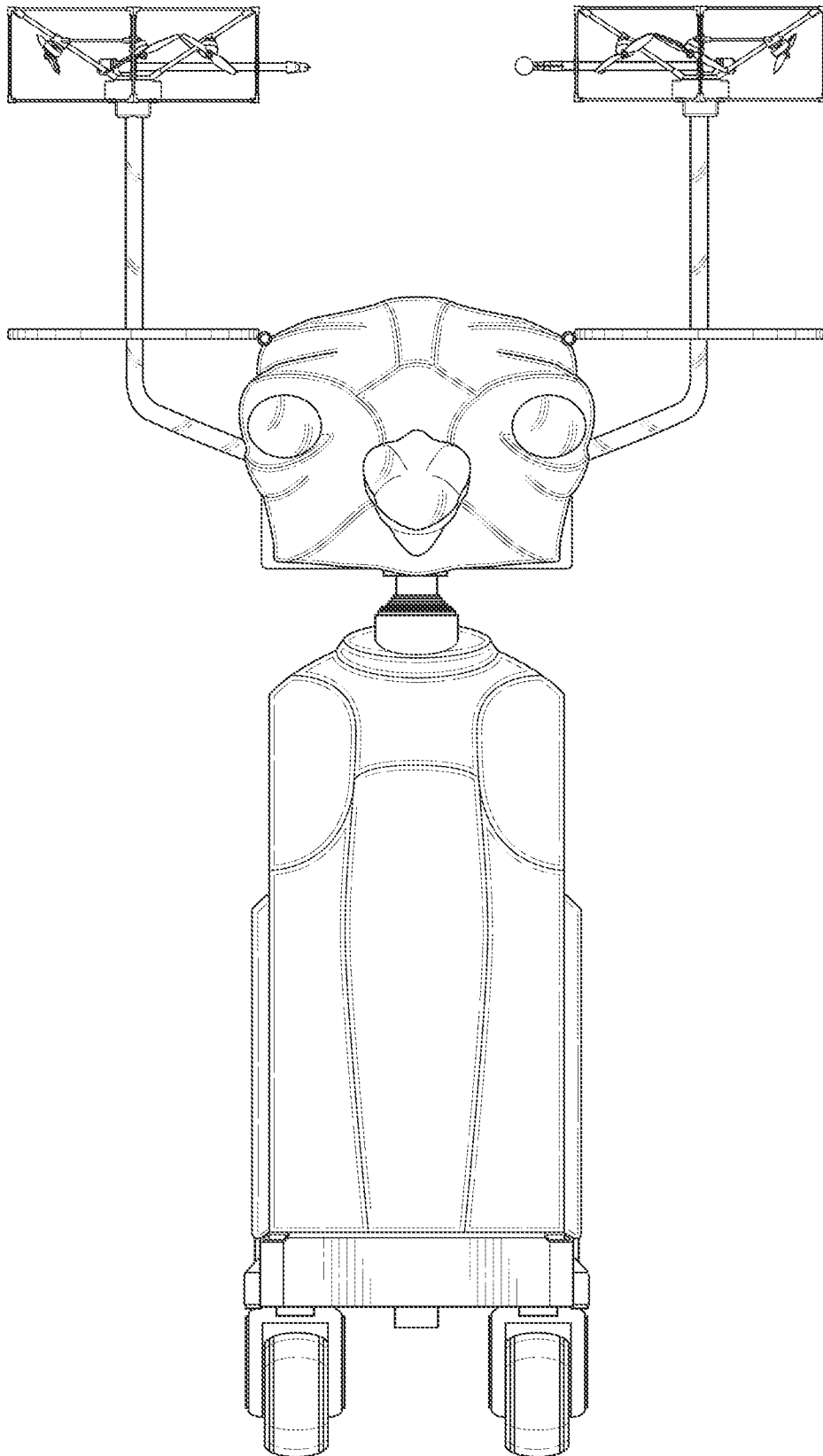


FIG. 20G

52/84

100j

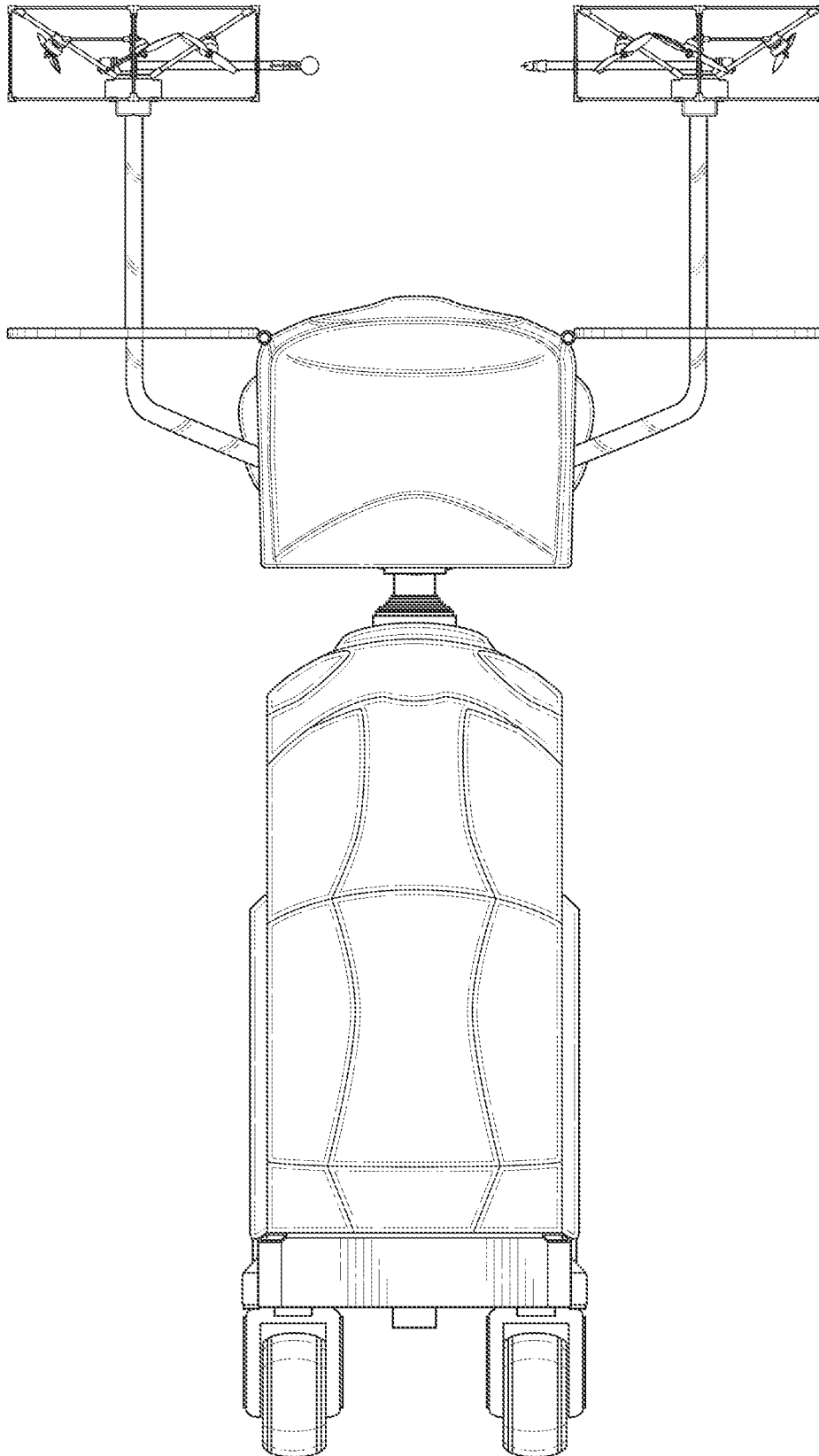


FIG. 20H

53/84

100j

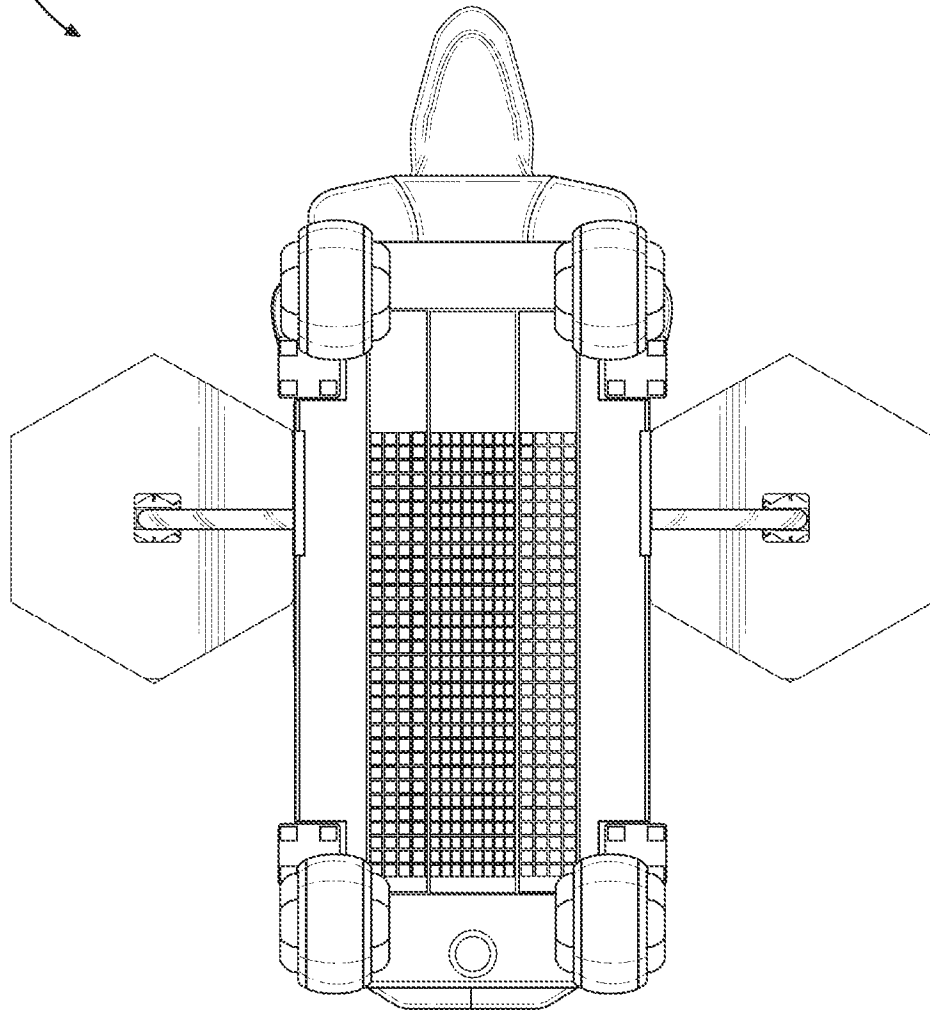


FIG. 20I

54/84

100j

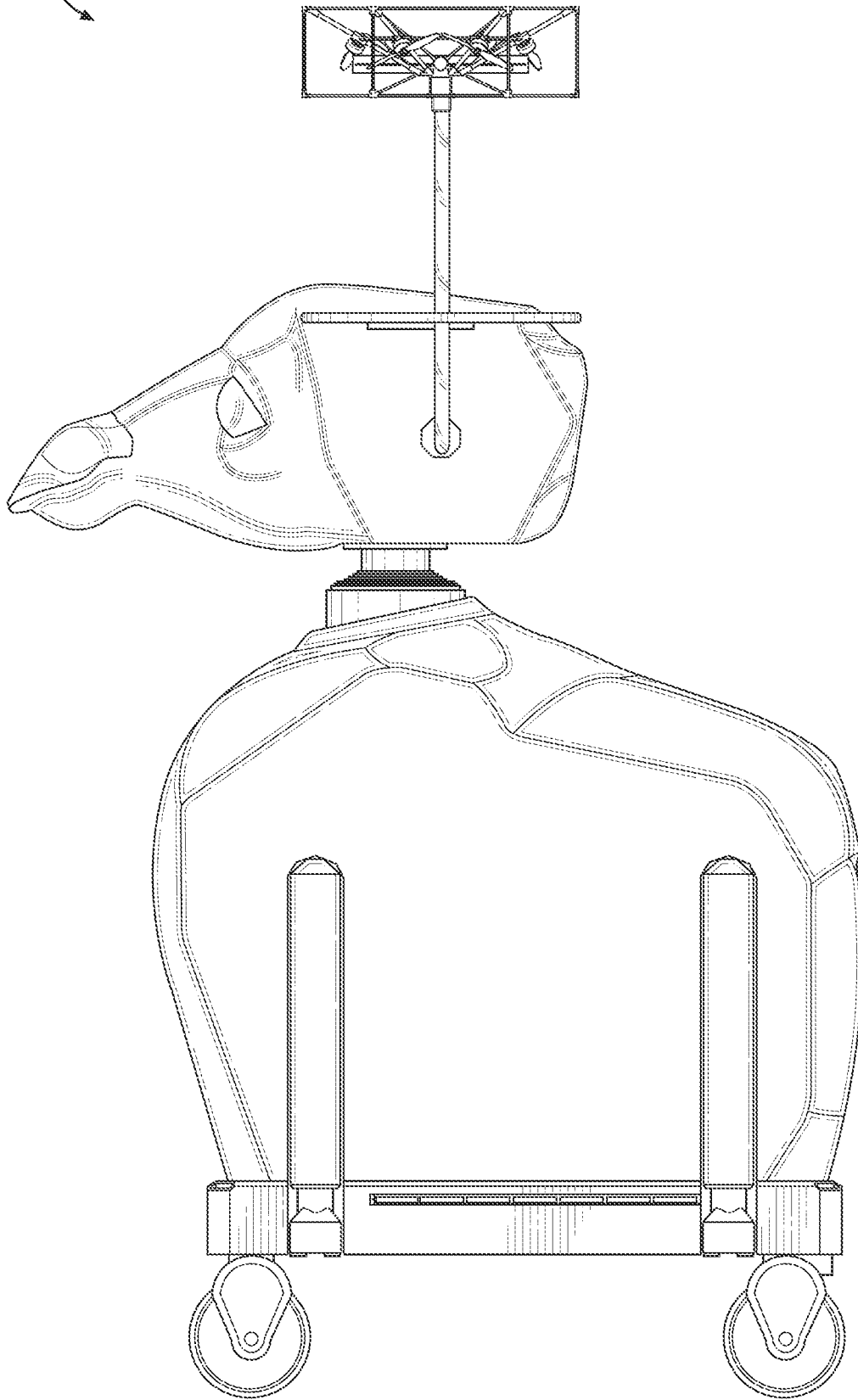


FIG. 20J

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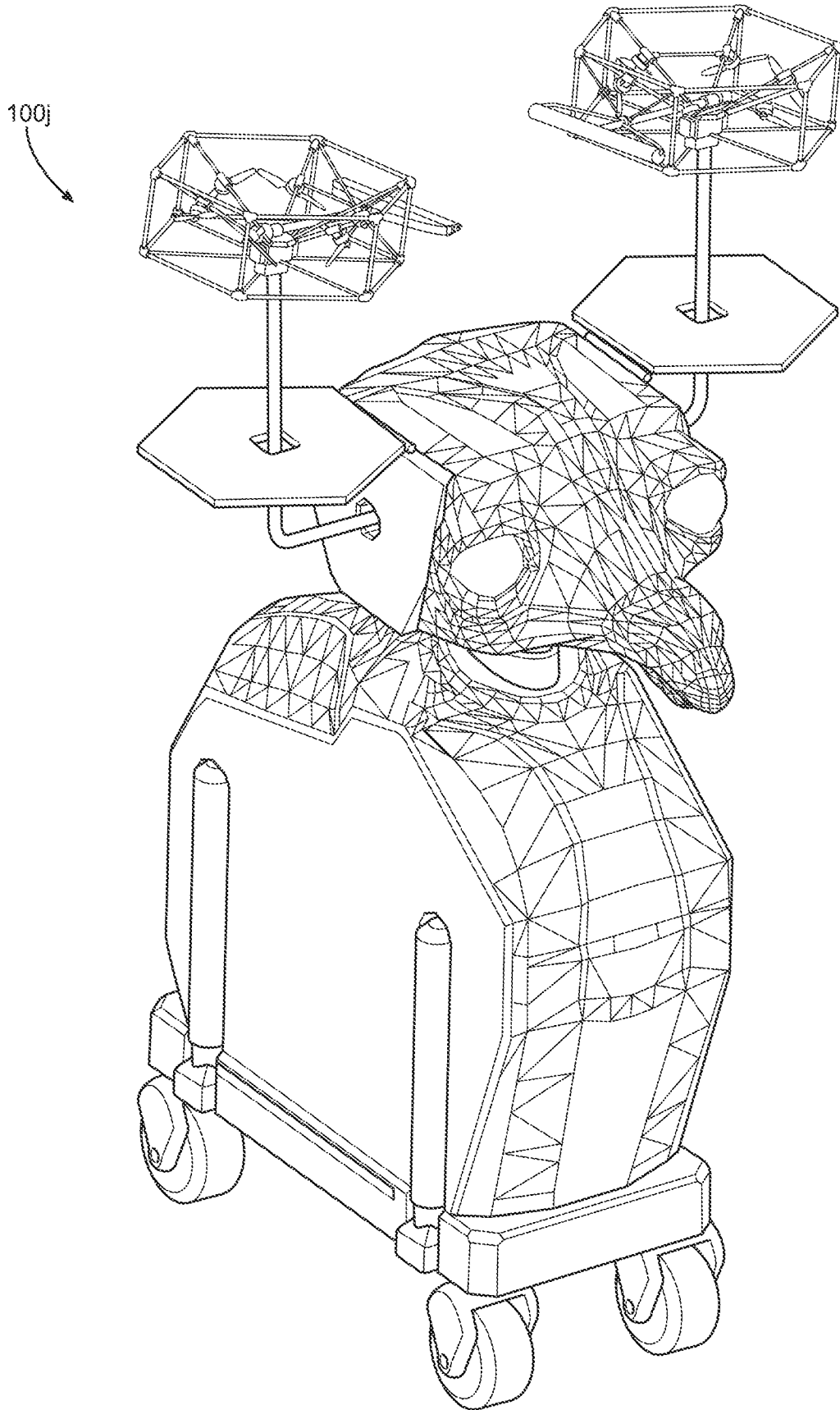
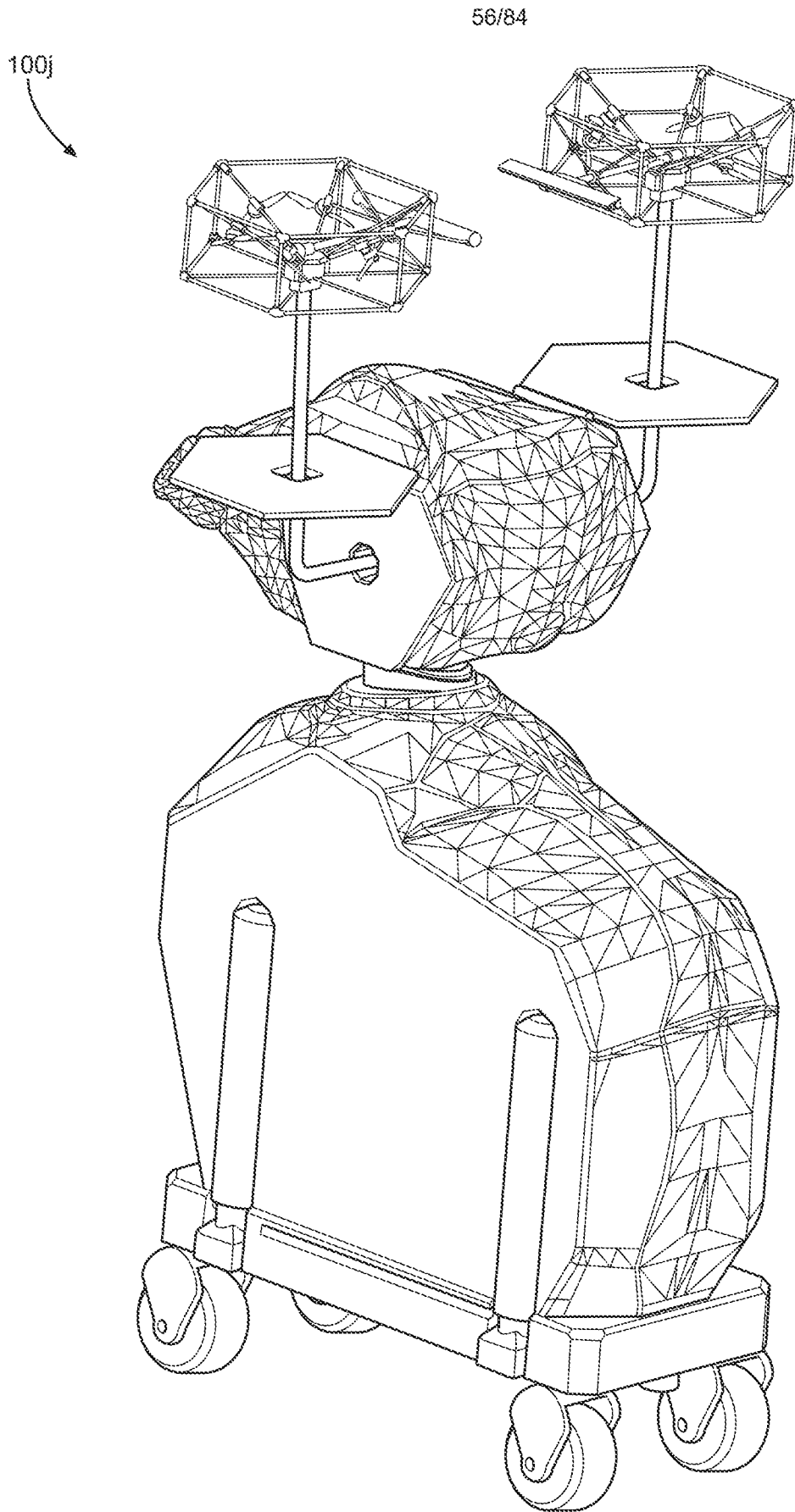


FIG. 21A



**FIG. 21B**

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100j

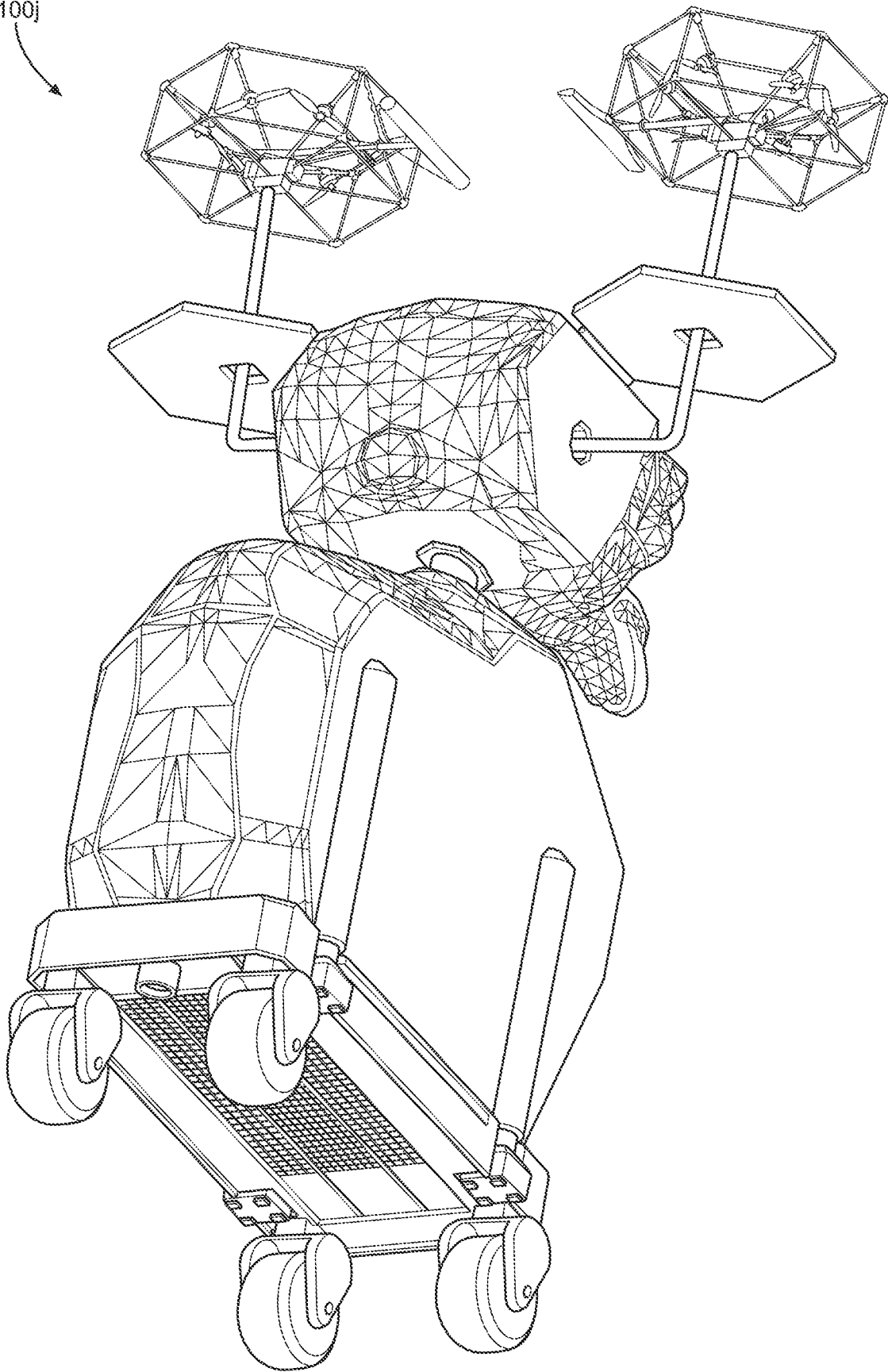


FIG. 21C

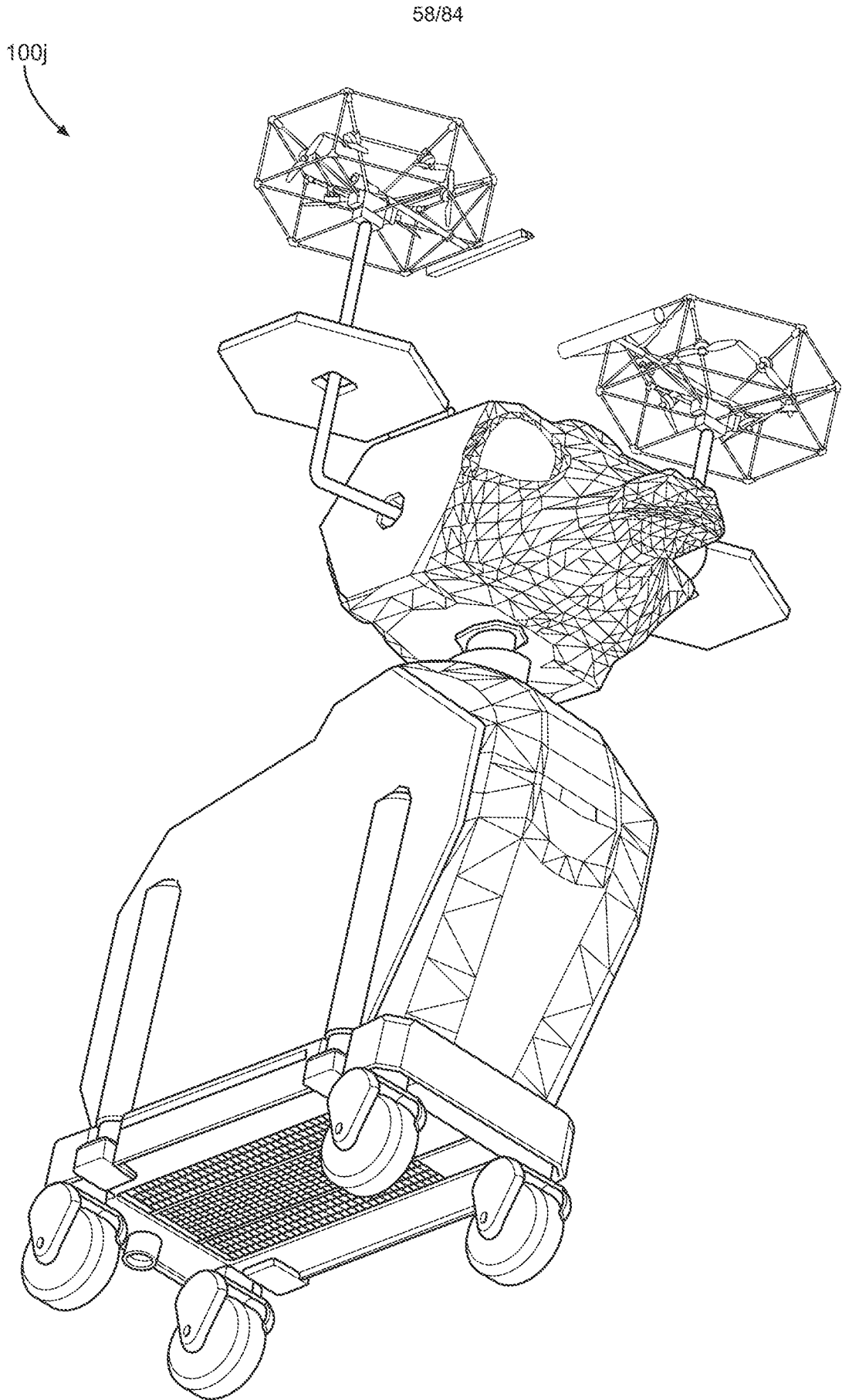


FIG. 21D

100j

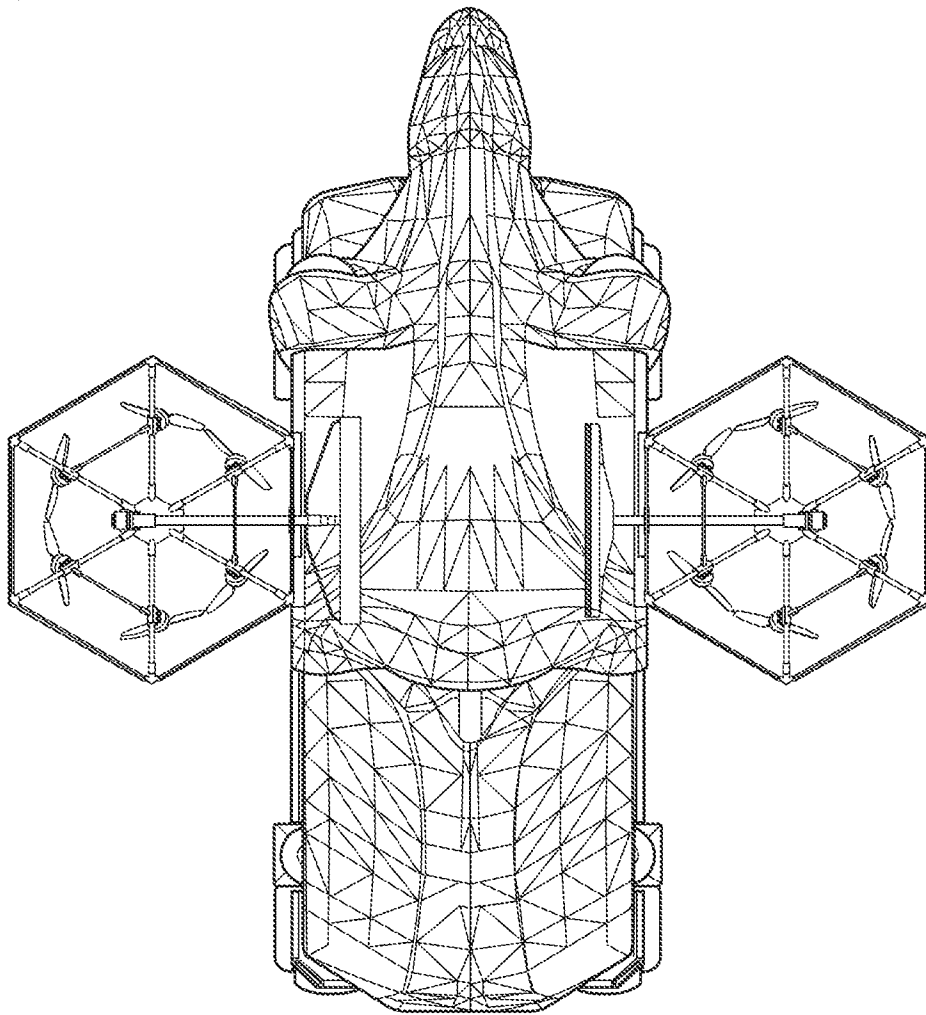


FIG. 21E

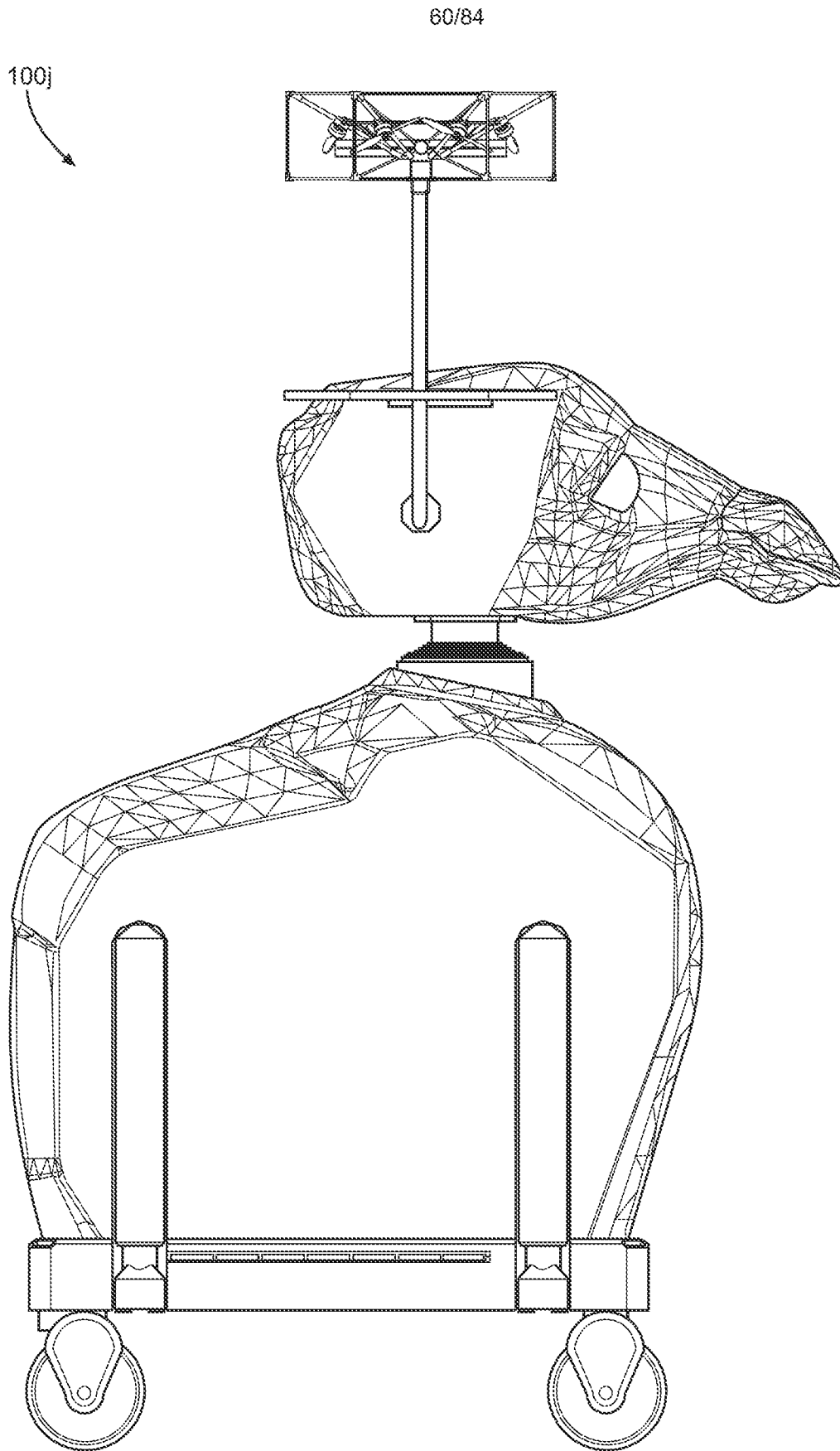


FIG. 21F

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100j

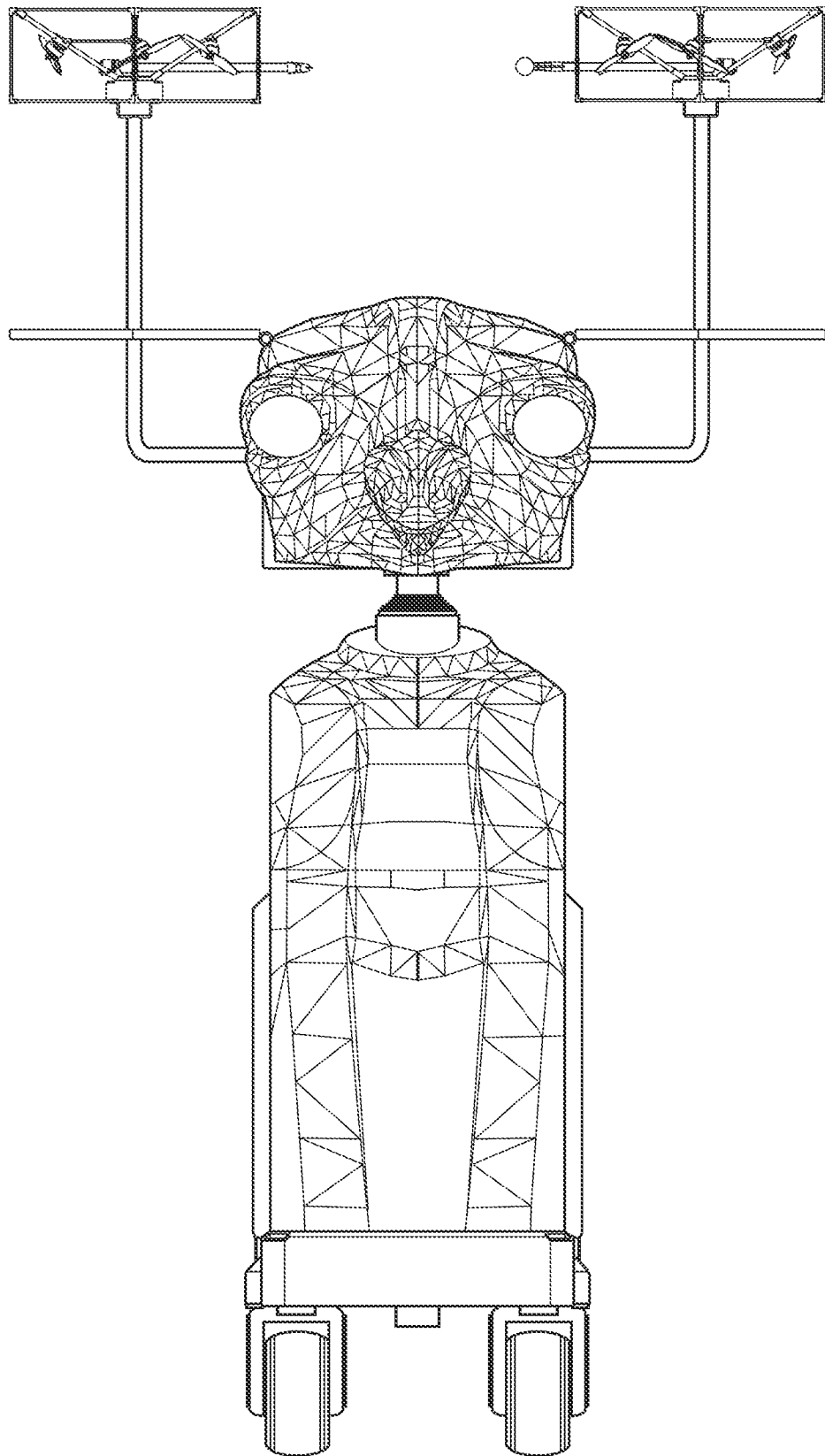


FIG. 21G

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100j

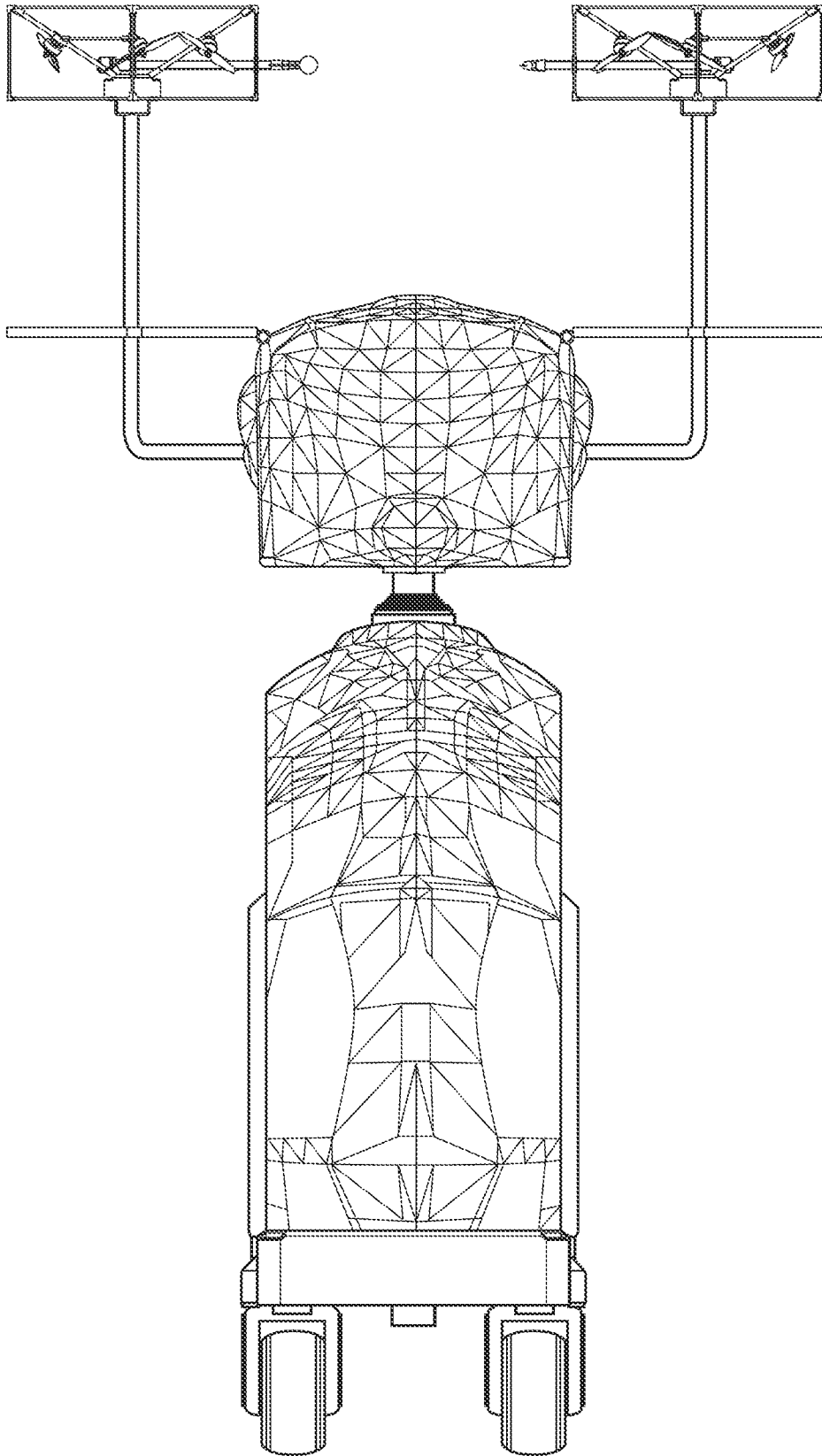
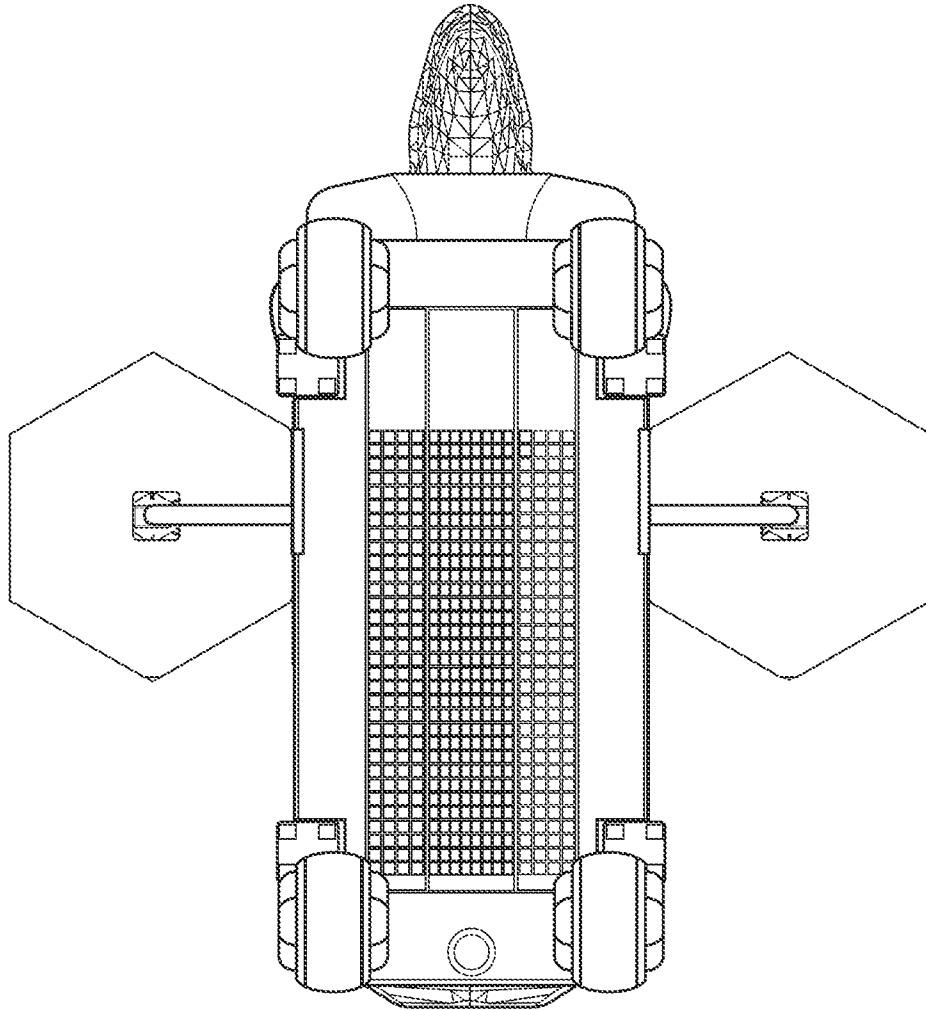


FIG. 21H

100j



**FIG. 21I**

100j

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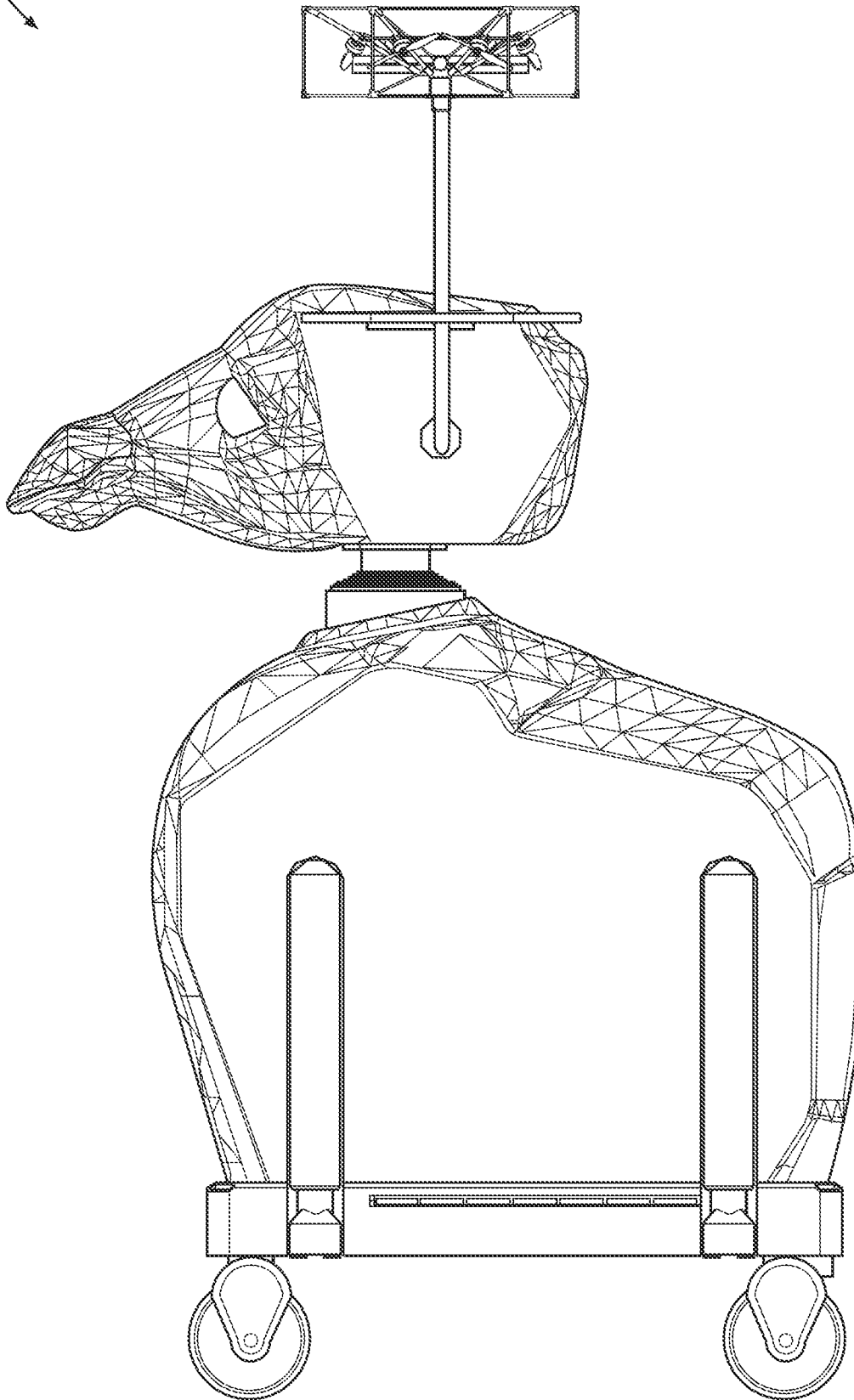


FIG. 21J

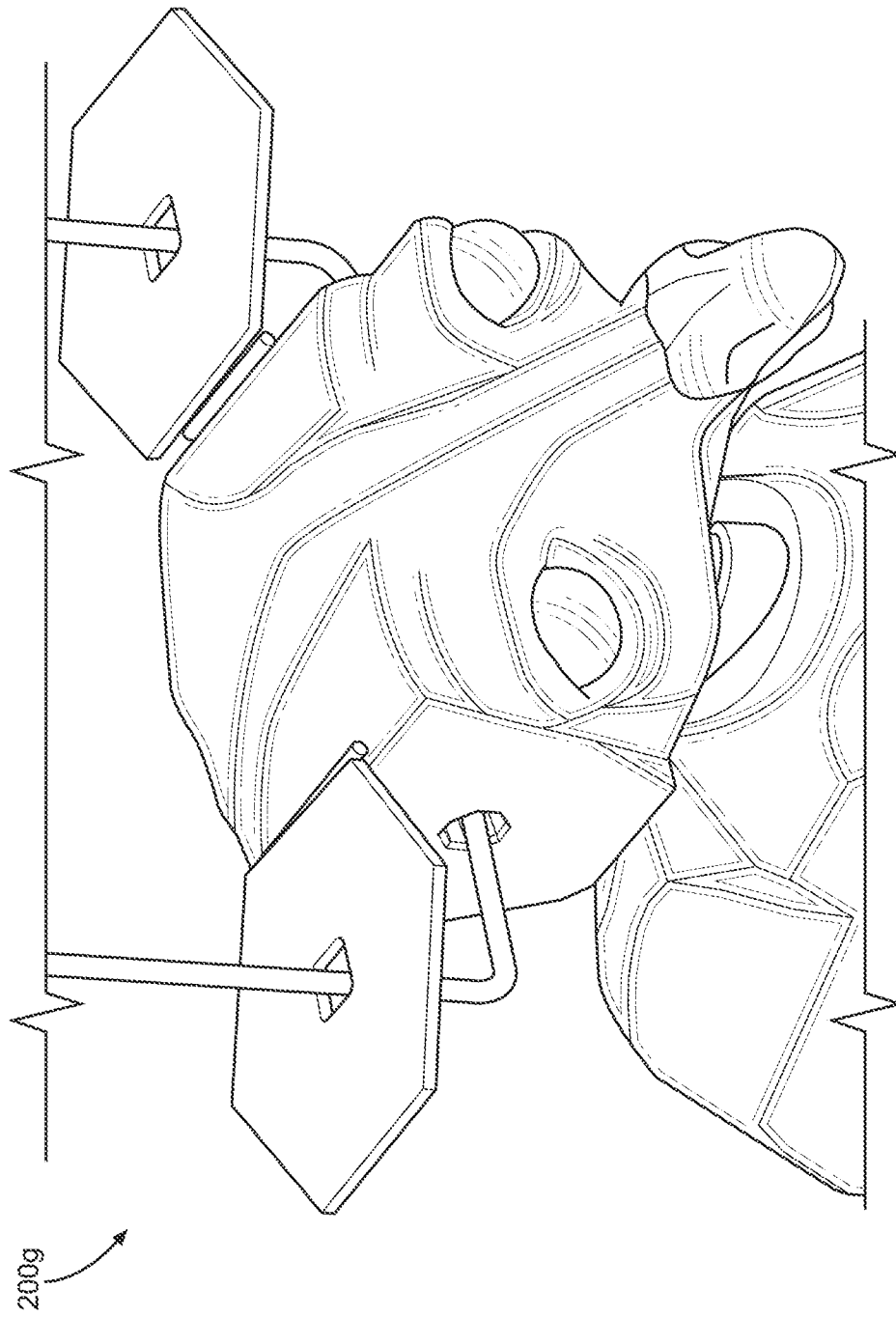


FIG. 22A

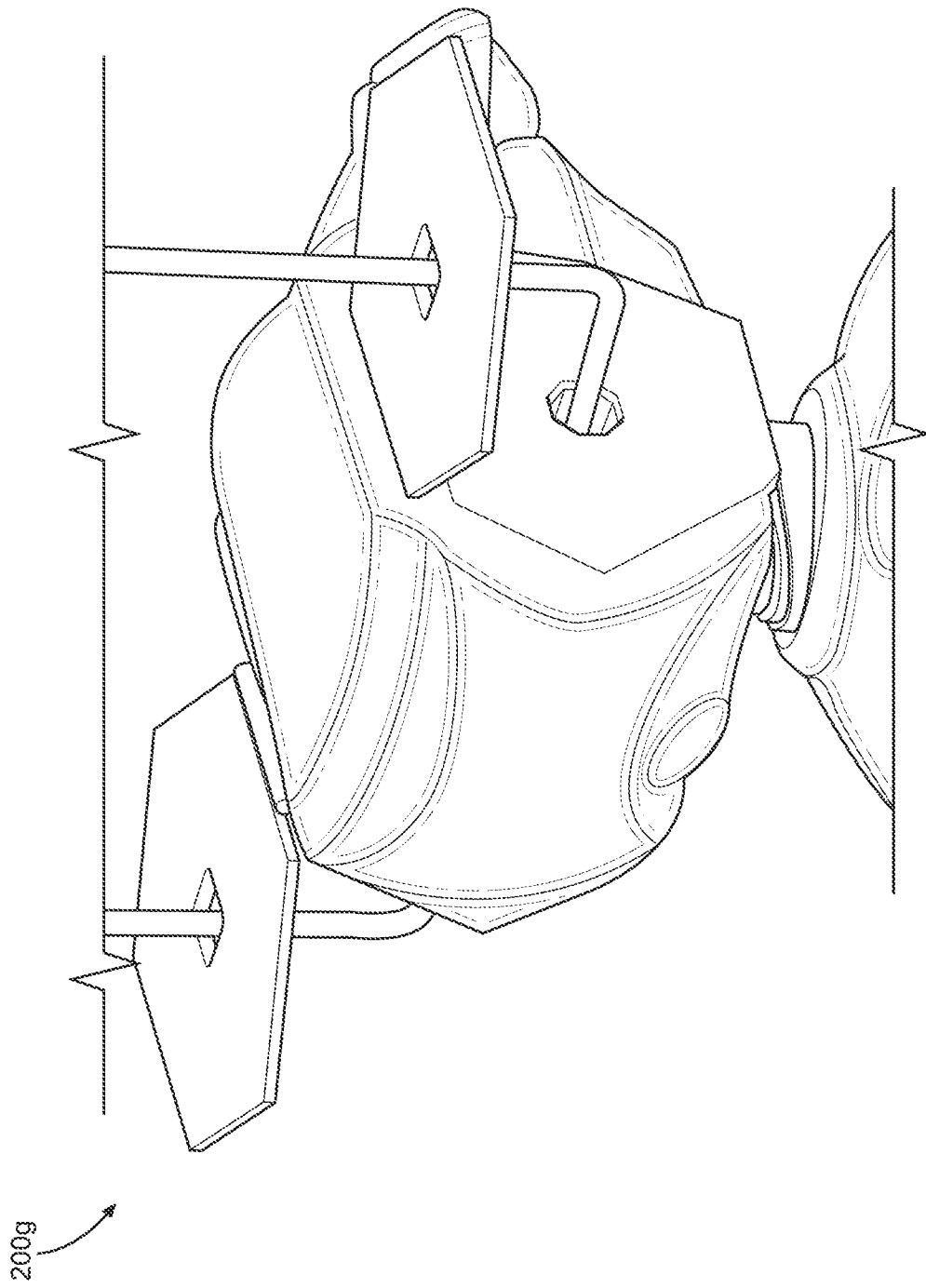


FIG. 22B

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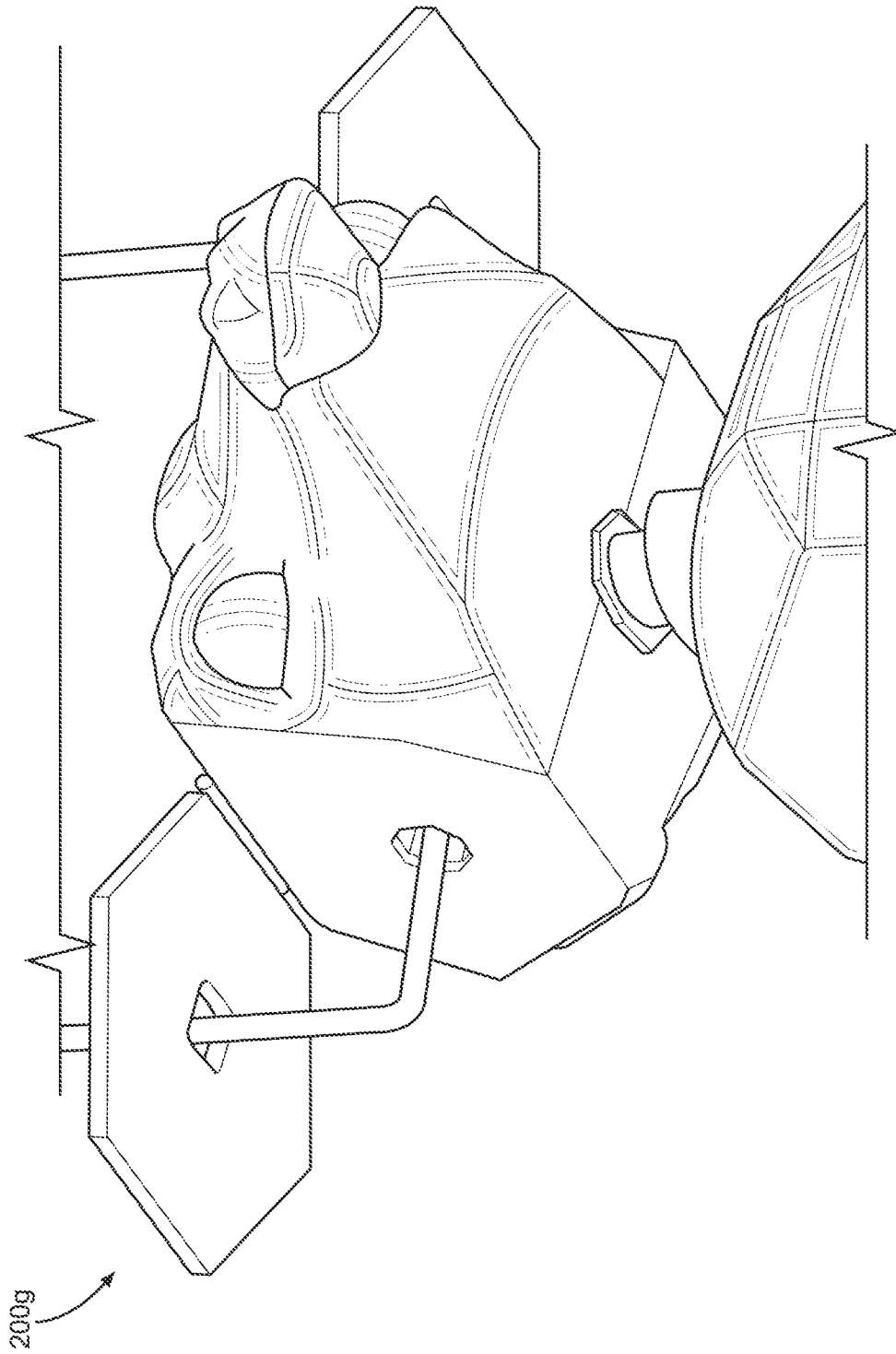


FIG. 22C

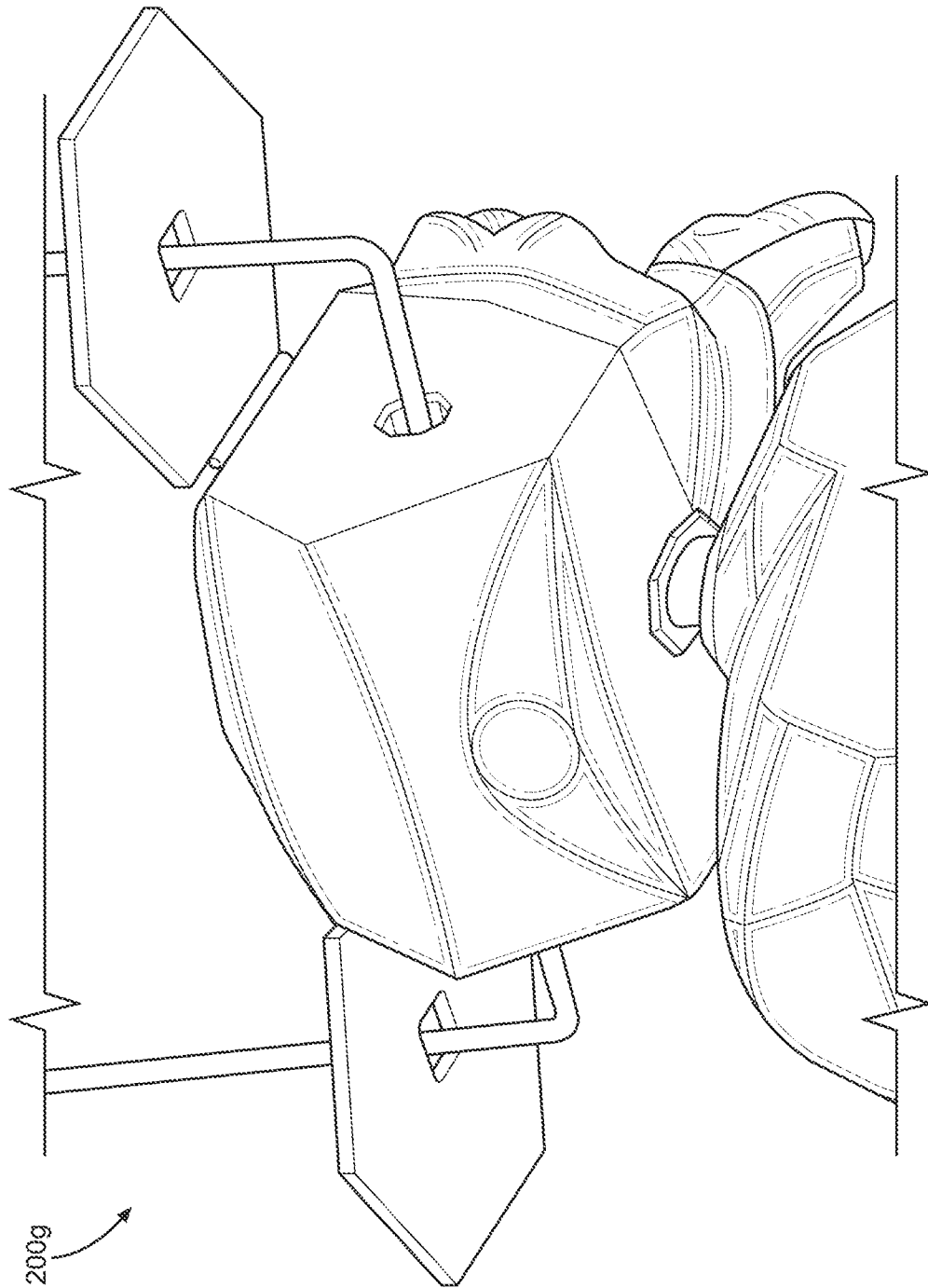


FIG. 22D

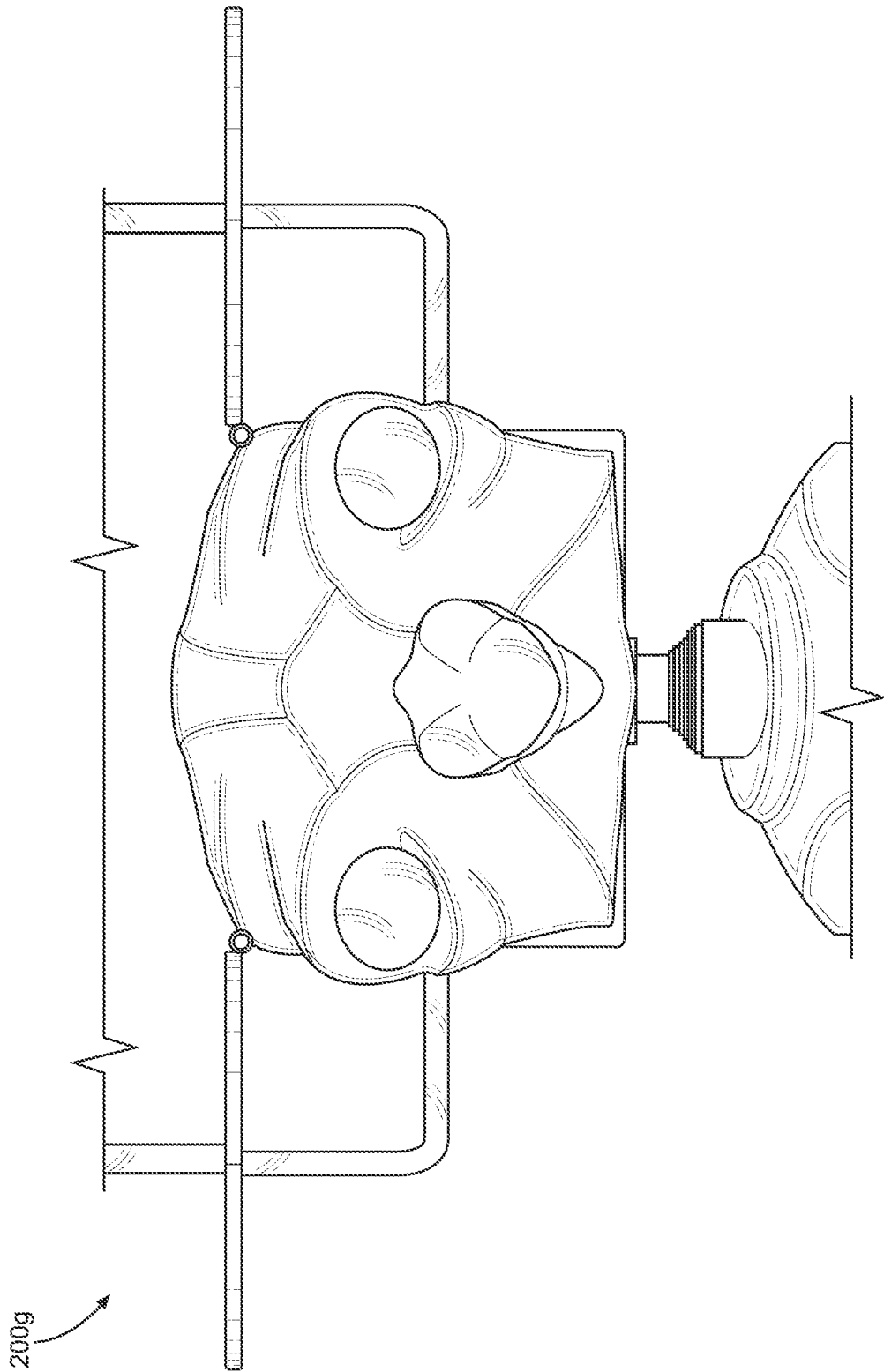


FIG. 22E

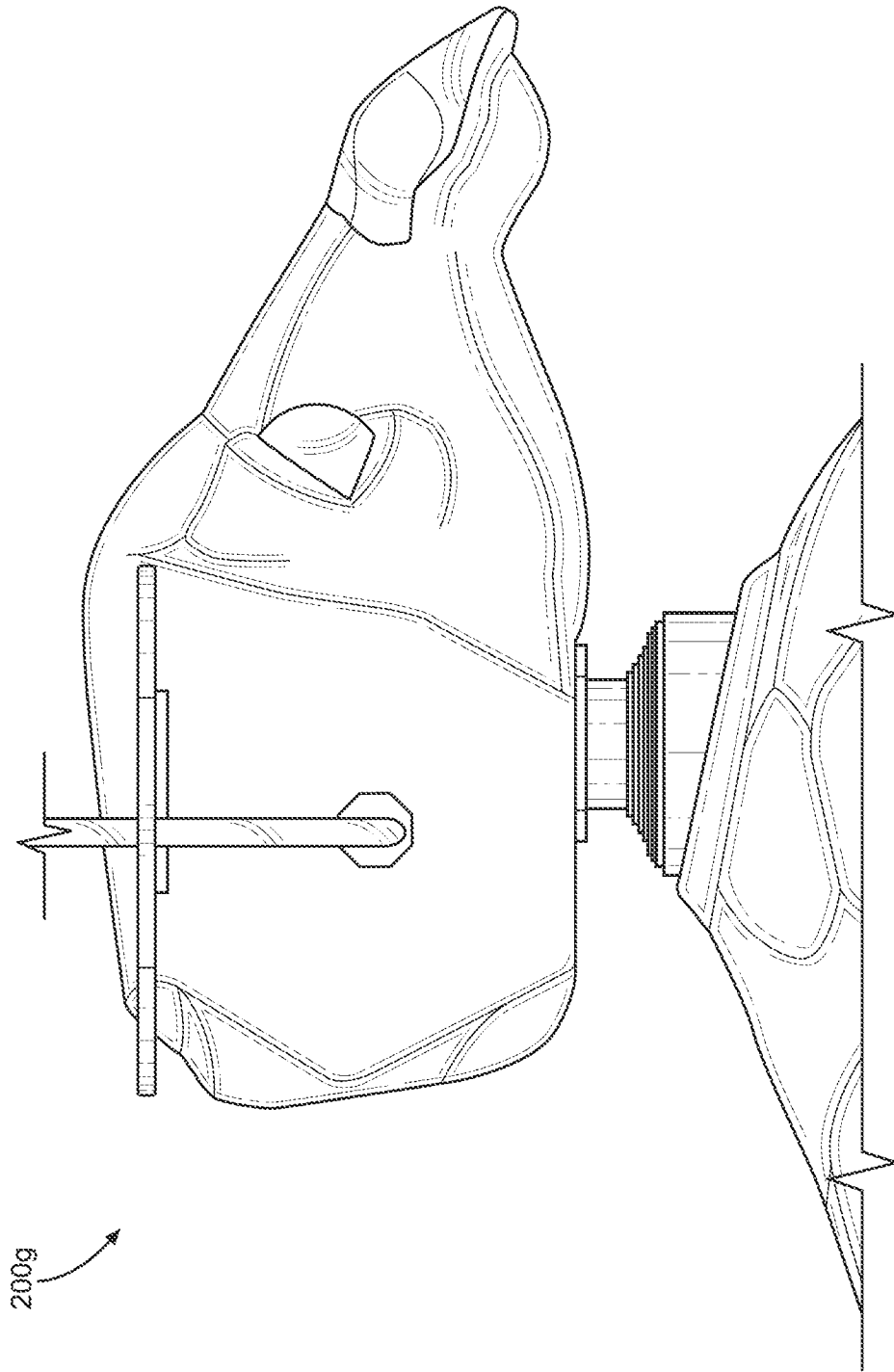


FIG. 22F

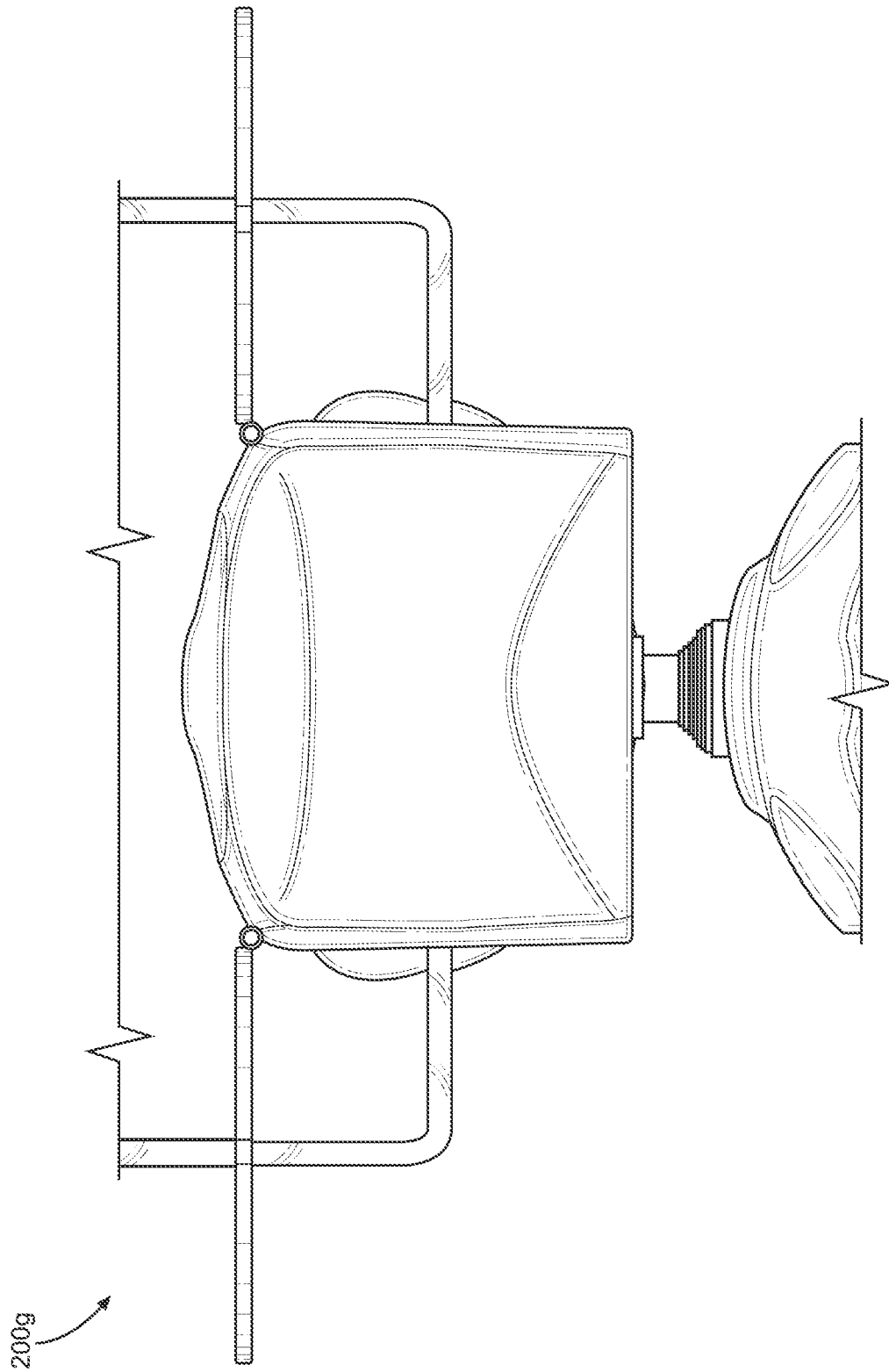


FIG. 22G

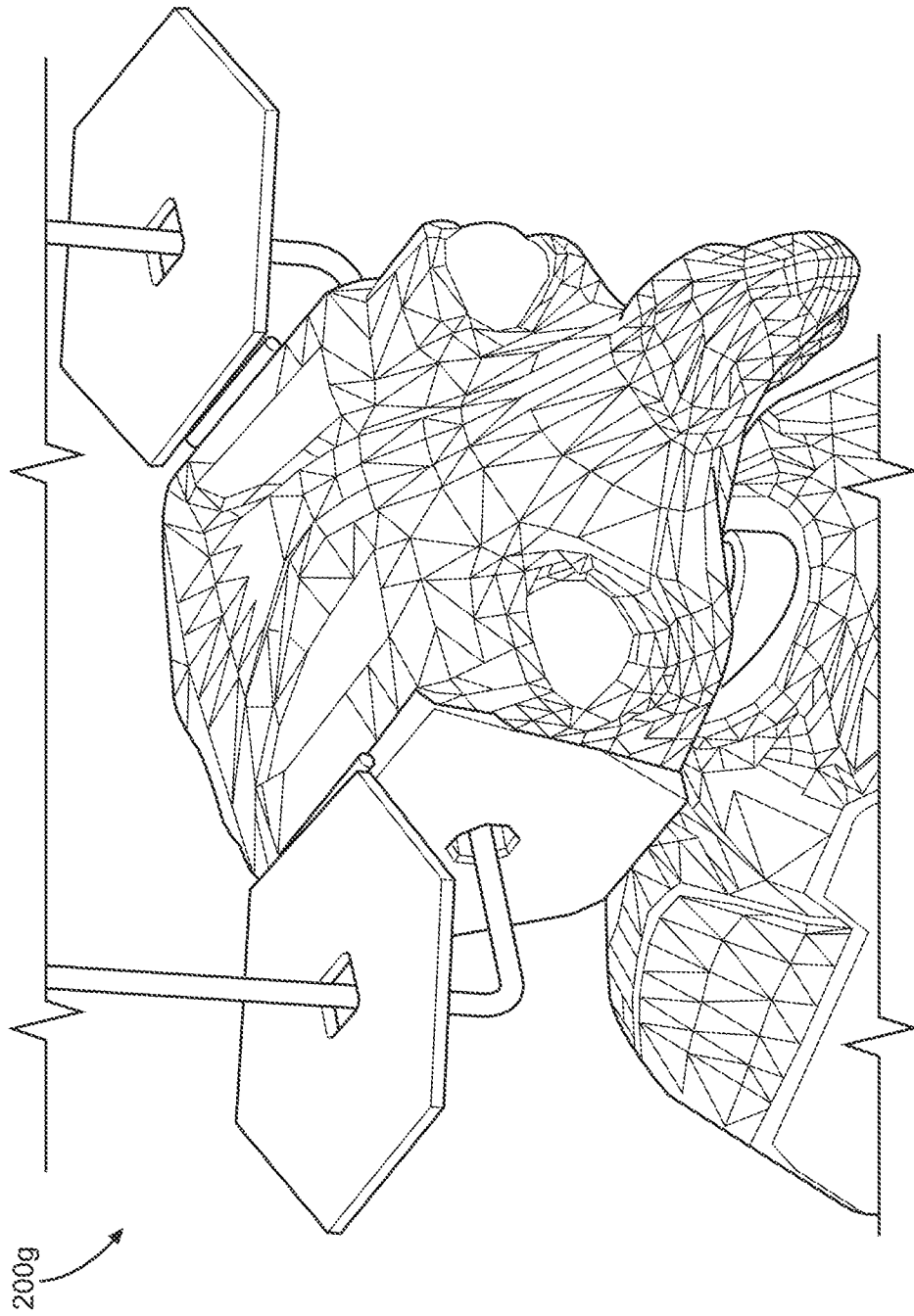


FIG. 23A

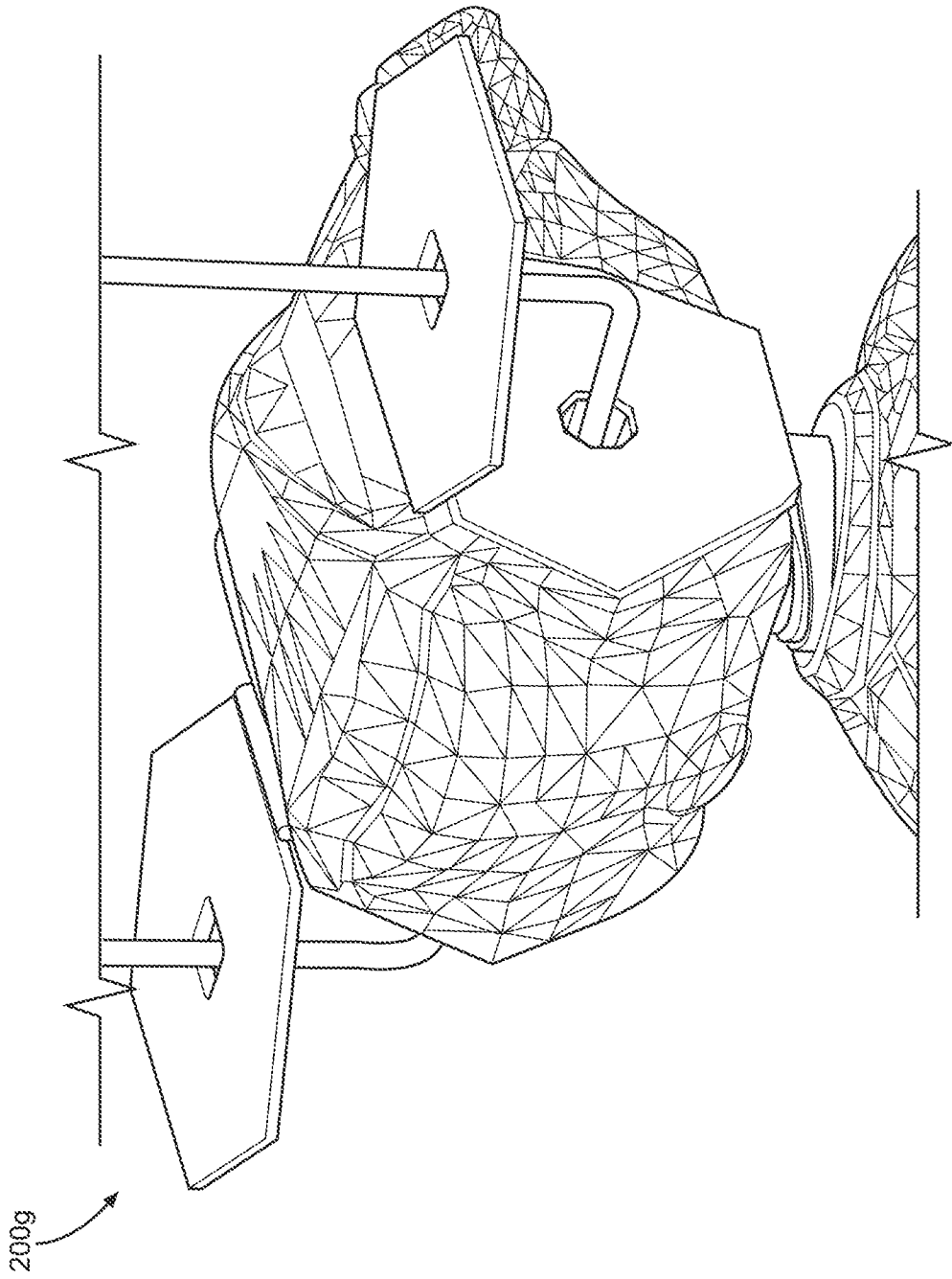


FIG. 23B

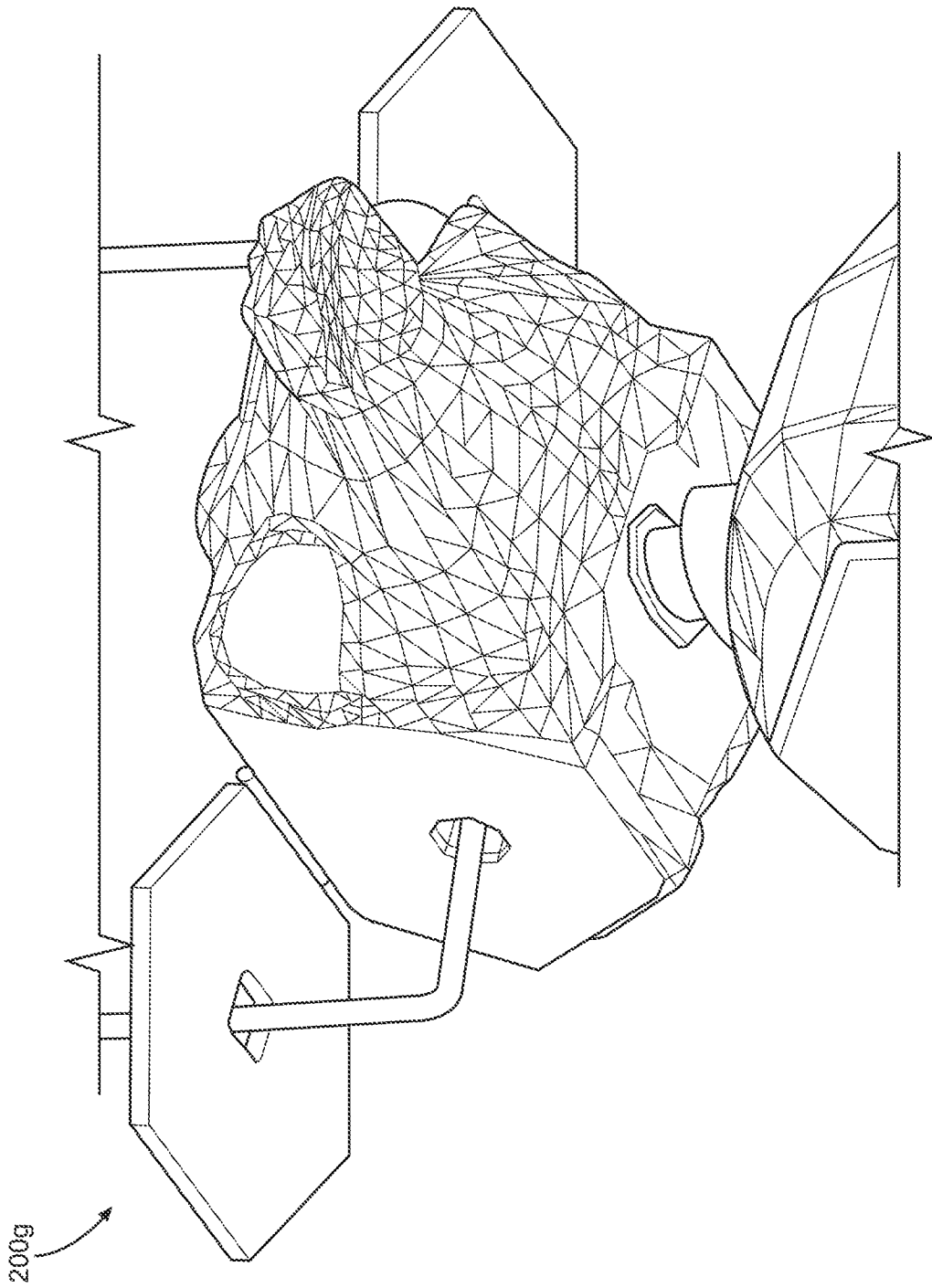


FIG. 23C

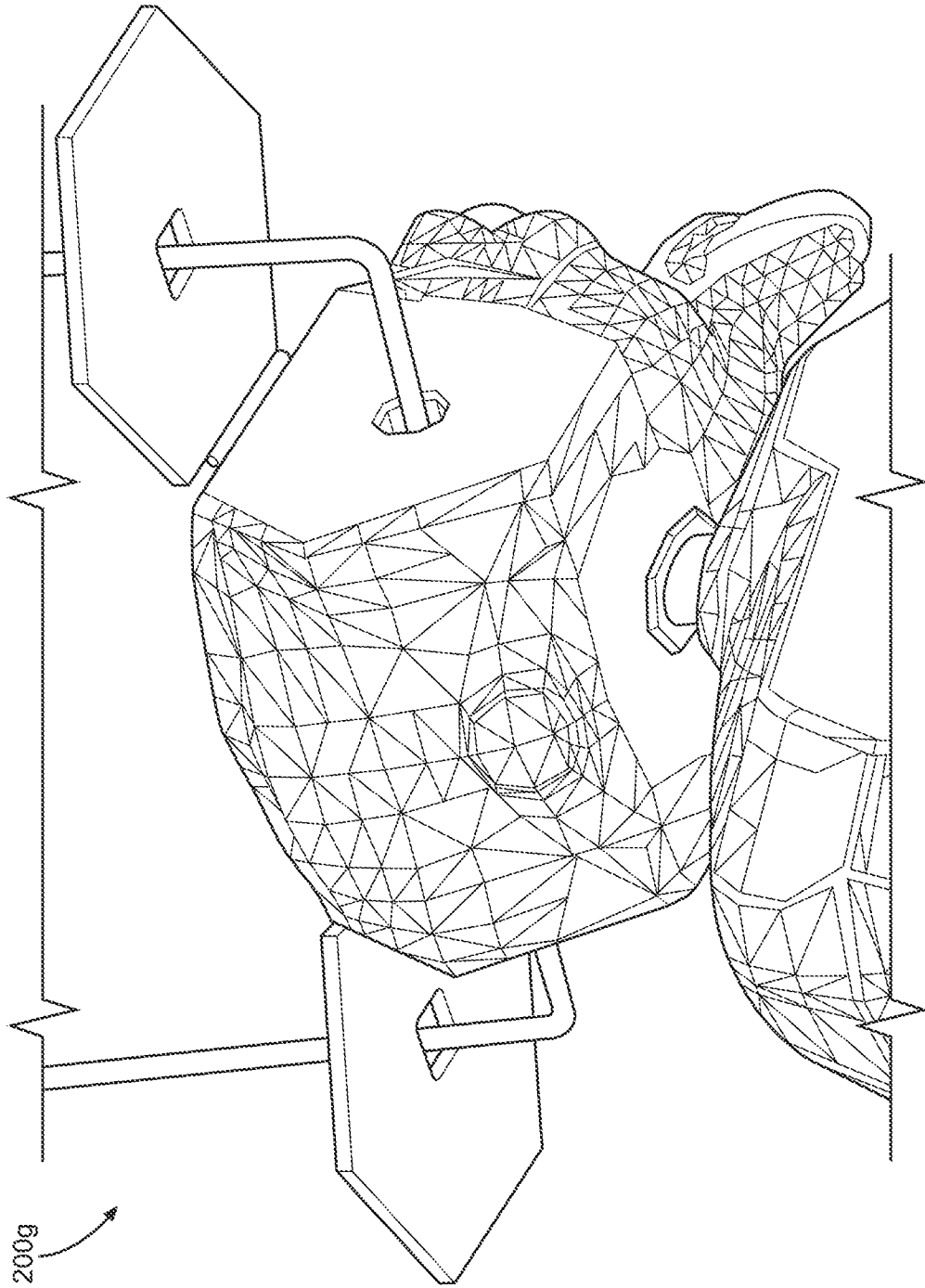


FIG. 23D

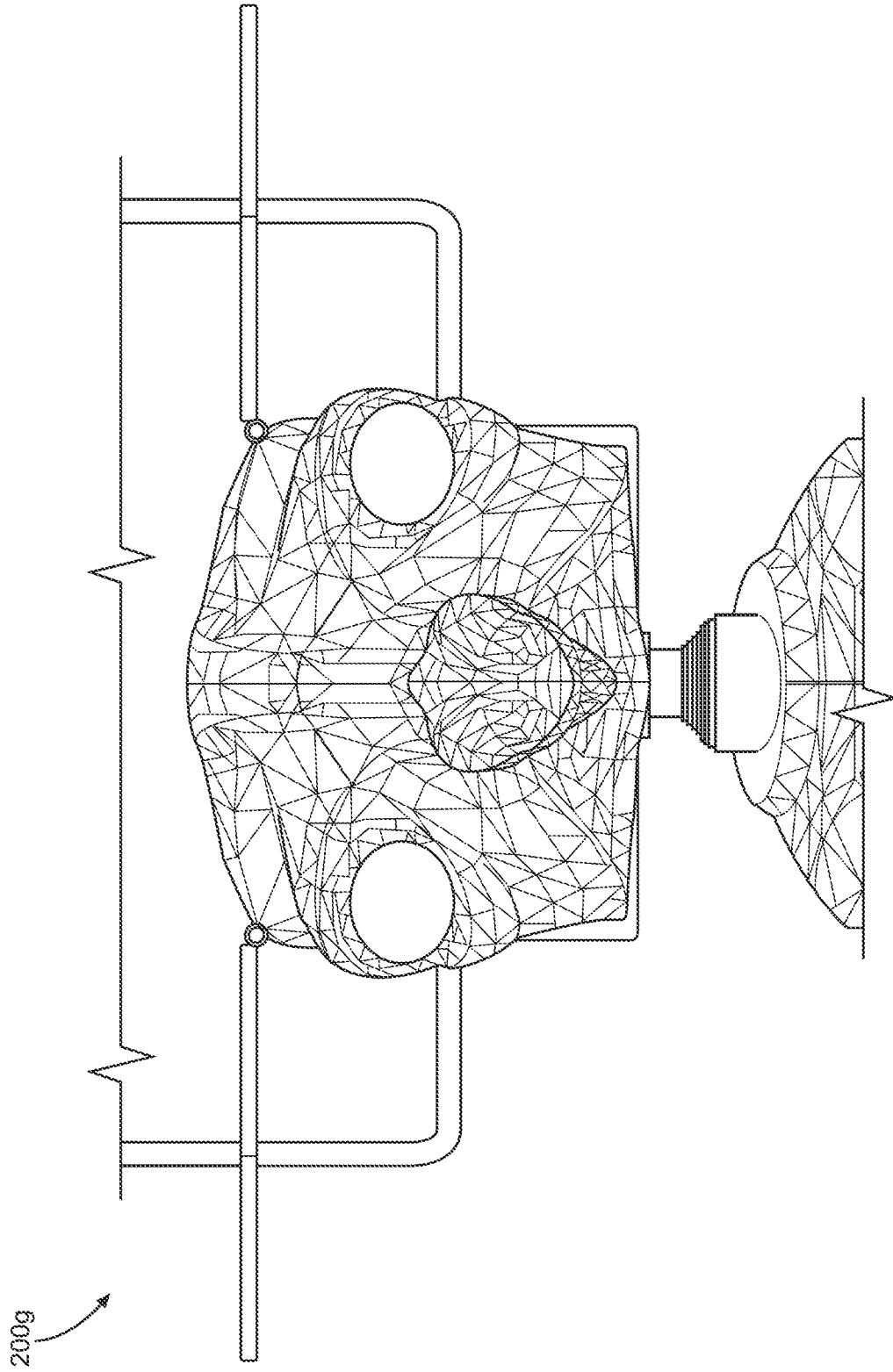


FIG. 23E

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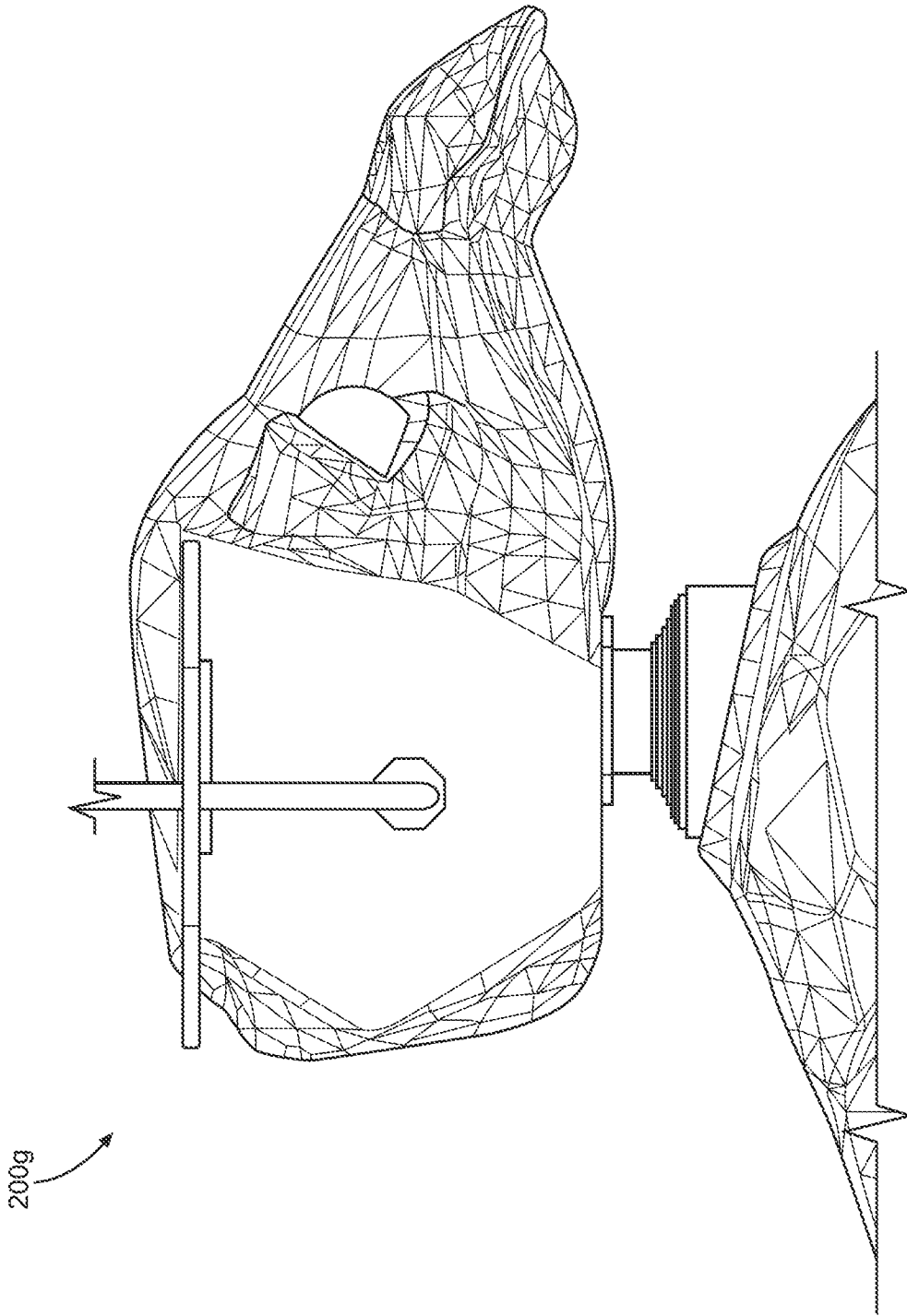


FIG. 23F

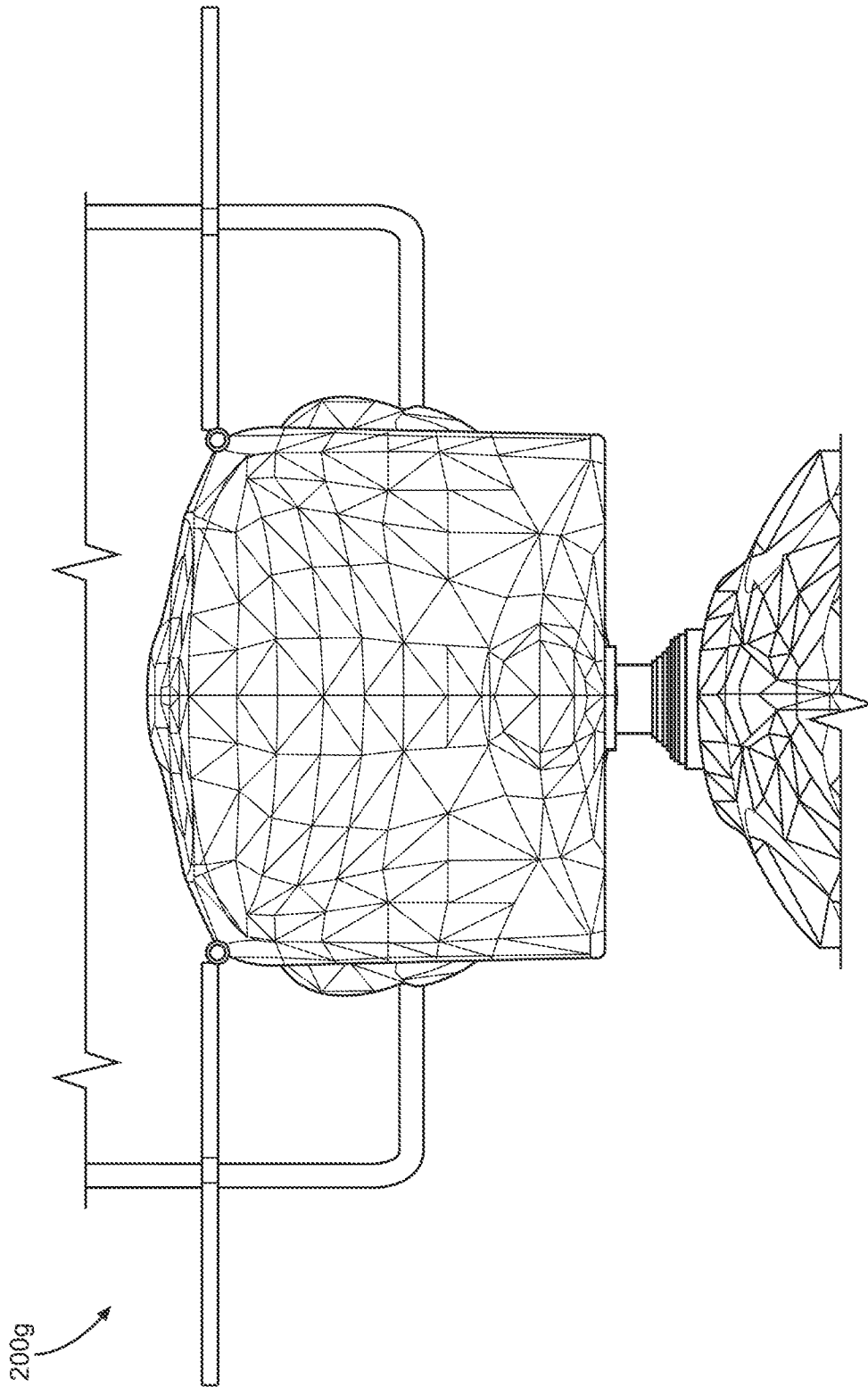


FIG. 23G



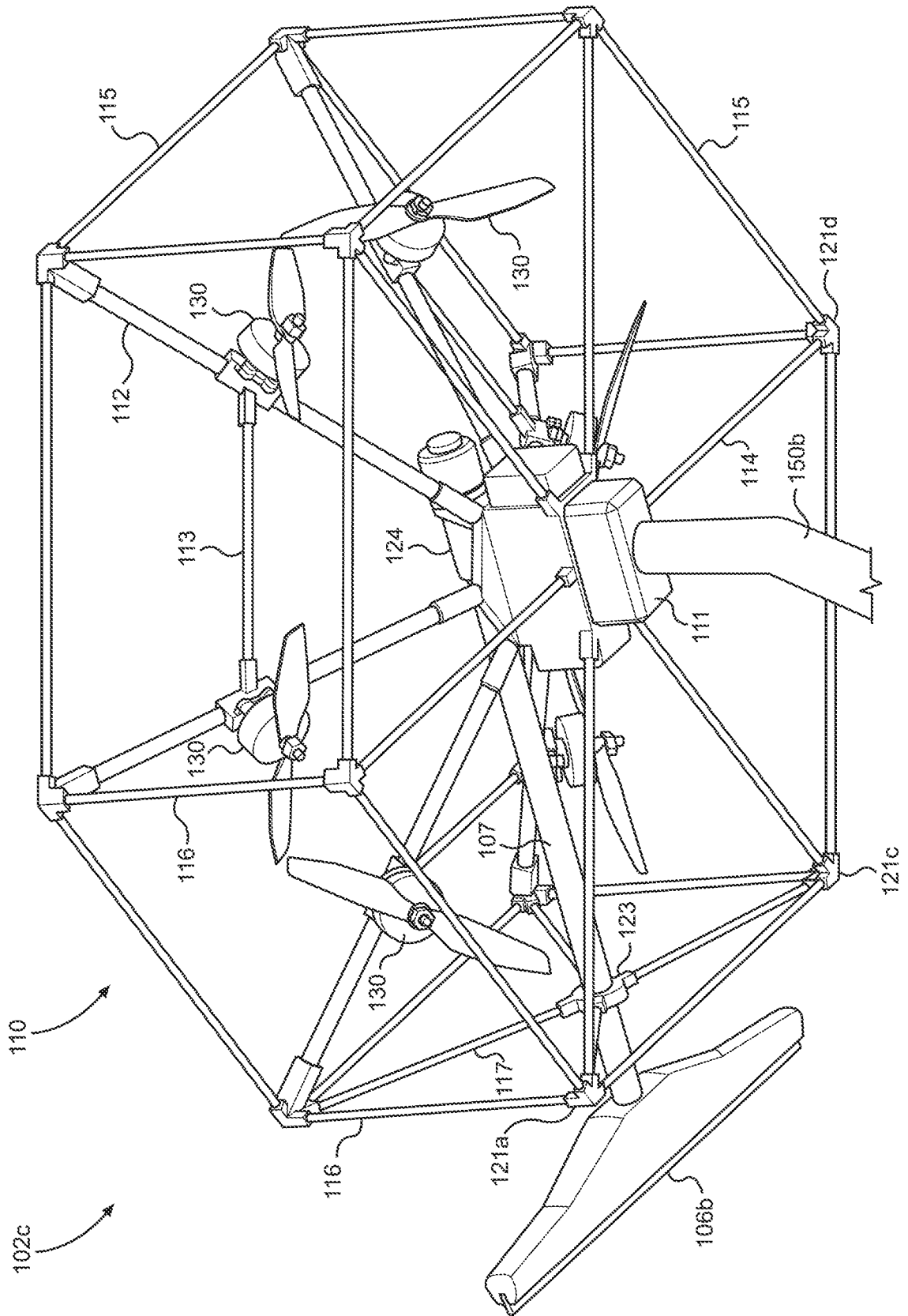


FIG. 24B

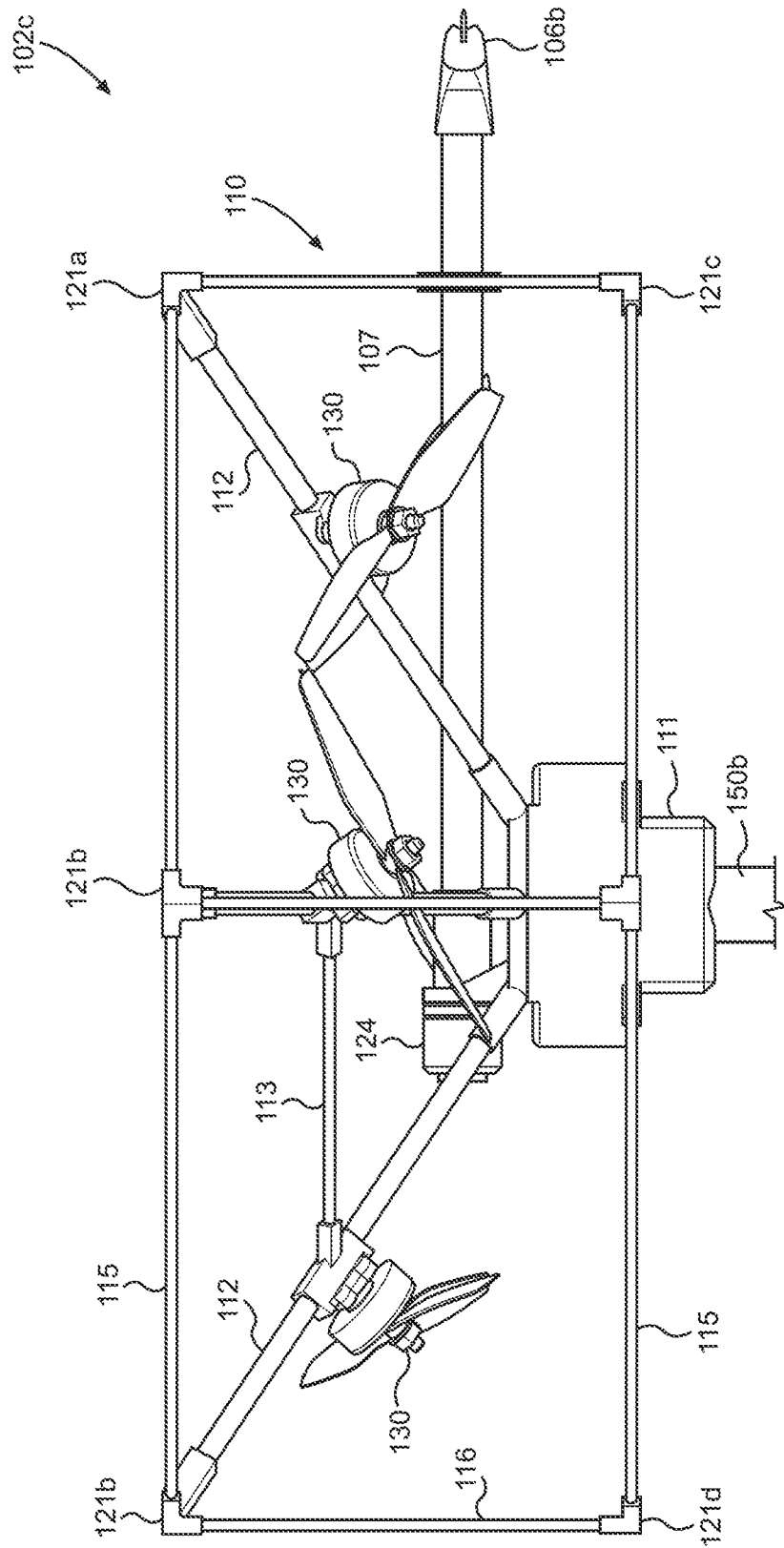


FIG. 24C



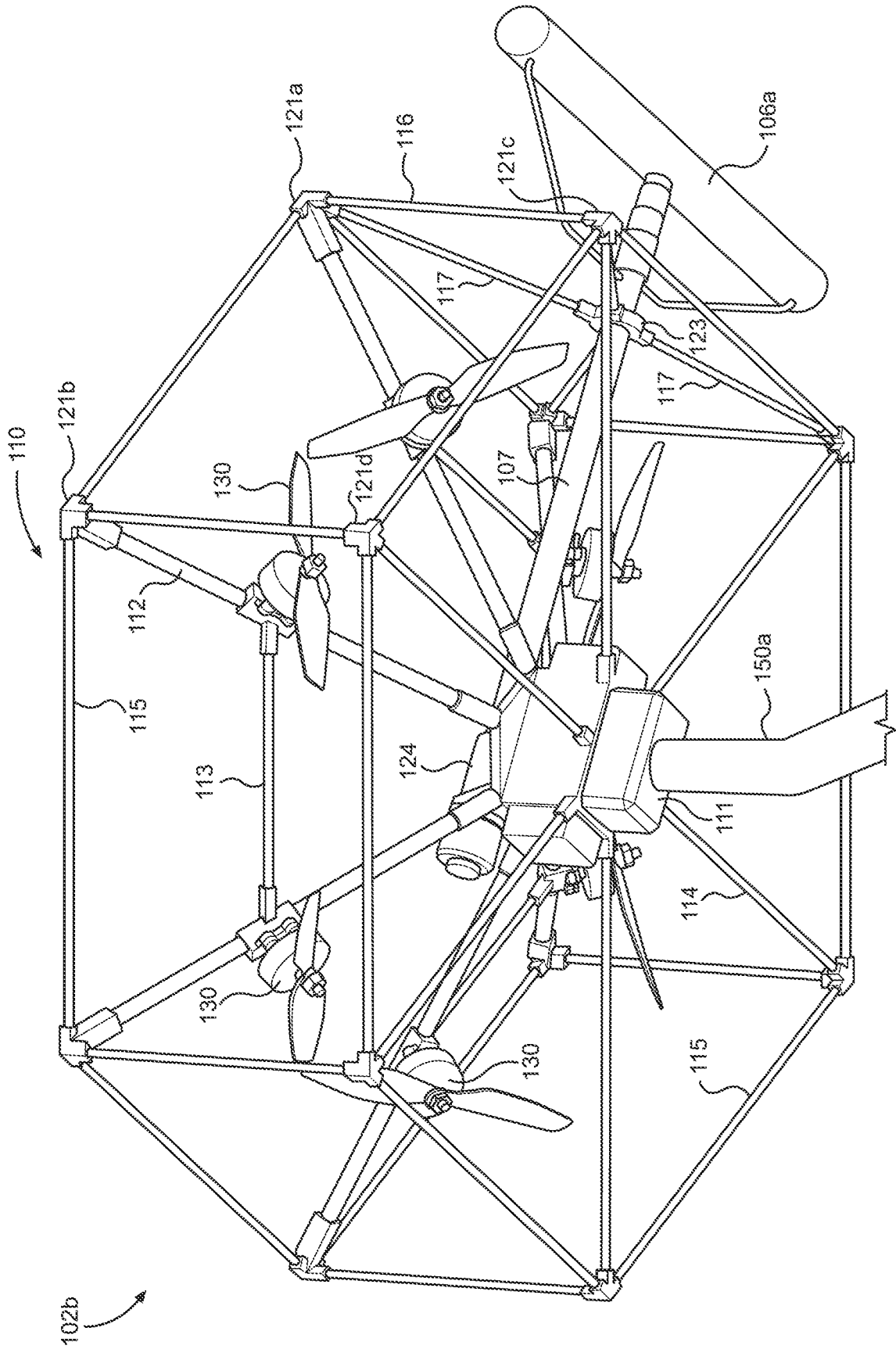


FIG. 25B

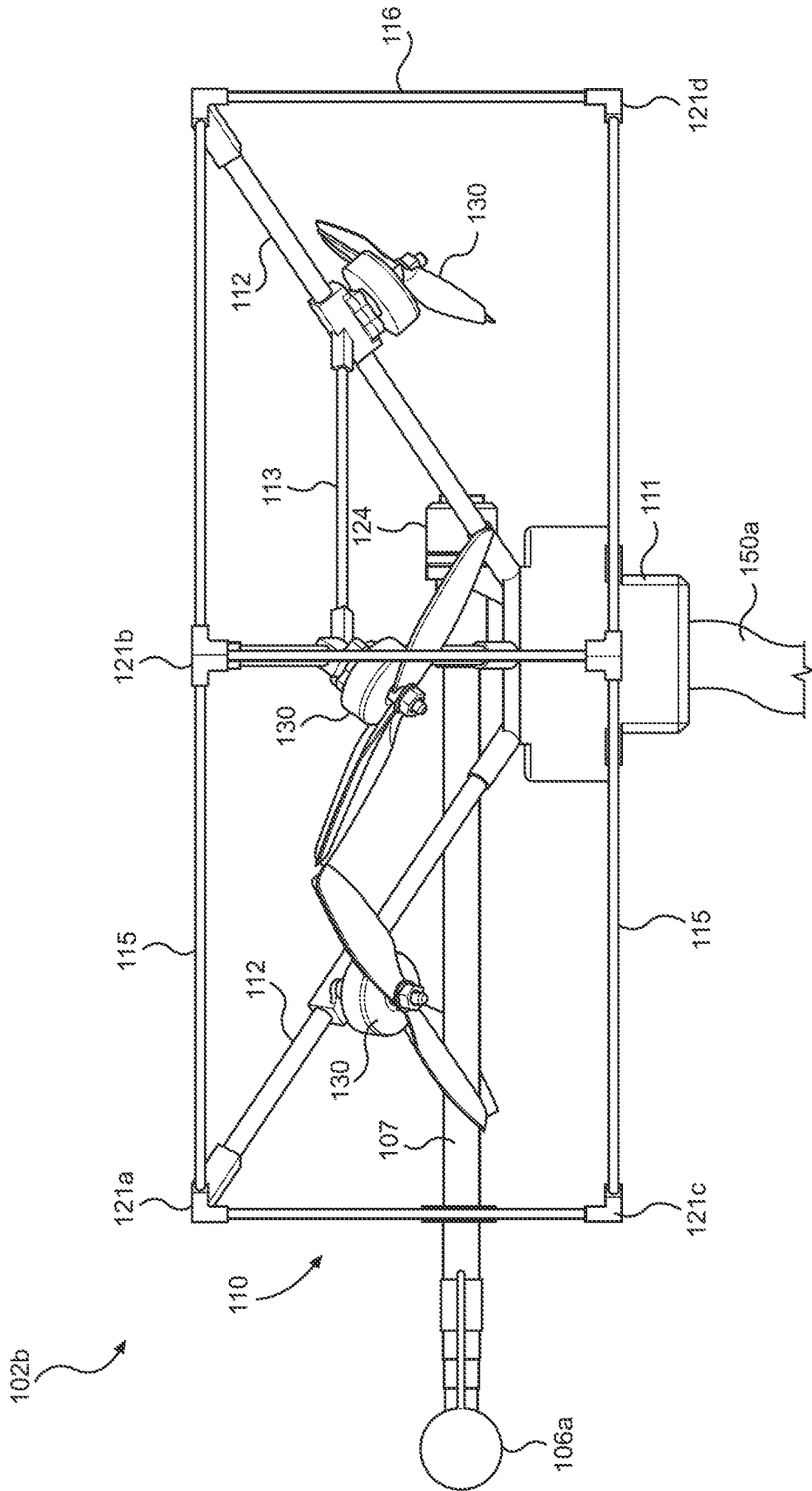


FIG. 25C