US 20260249644A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2026/0249644 A1**

Degele et al. (43) **Pub. Date: Aug. 27, 2026**

(54) **SINGLE POD DIFFERENTIAL SWERVE DRIVE SYSTEM**

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(21) Appl. No.: **19/432,399**

(22) Filed: **Dec. 24, 2025**

Publication Classification

(51) **Int. Cl.**

B60B 19/00	(2006.01)
B25J 5/00	(2006.01)
B60K 1/02	(2006.01)
B62D 9/00	(2006.01)
B62D 61/06	(2006.01)
G05D 1/245	(2024.01)
G05D 109/18	(2024.01)

(52) **U.S. Cl.**

CPC ***B60B 19/003*** (2013.01); ***B25J 5/007*** (2013.01); ***B60K 1/02*** (2013.01); ***B62D 9/00*** (2013.01); ***B62D 61/06*** (2013.01); ***G05D 1/245*** (2024.01); *G05D 2109/18* (2024.01)

(57) **ABSTRACT**

A robotic vehicle includes an omni-directional drive system having a single centrally mounted differential swerve pod with a traction wheel steerable to substantially any azimuth. First and second electric motors drive cooperative gear trains that, through differential operation, selectively rotate the pod housing for steering and rotate the traction wheel for propulsion, including coordinating their actions to provide simultaneous steering and propulsion. Chassis stability is provided by support elements spaced from the traction wheel, including laterally positioned omni-wheels and additional chassis support points, enabling constrained pitch and roll while permitting unrestricted yaw. In some embodiments, the omni-wheels are driven by continuous-rotation servos through a clutch to provide controllable chassis yaw. A controller uses encoder feedback to coordinate wheel steering, propulsion, and field-oriented motion.

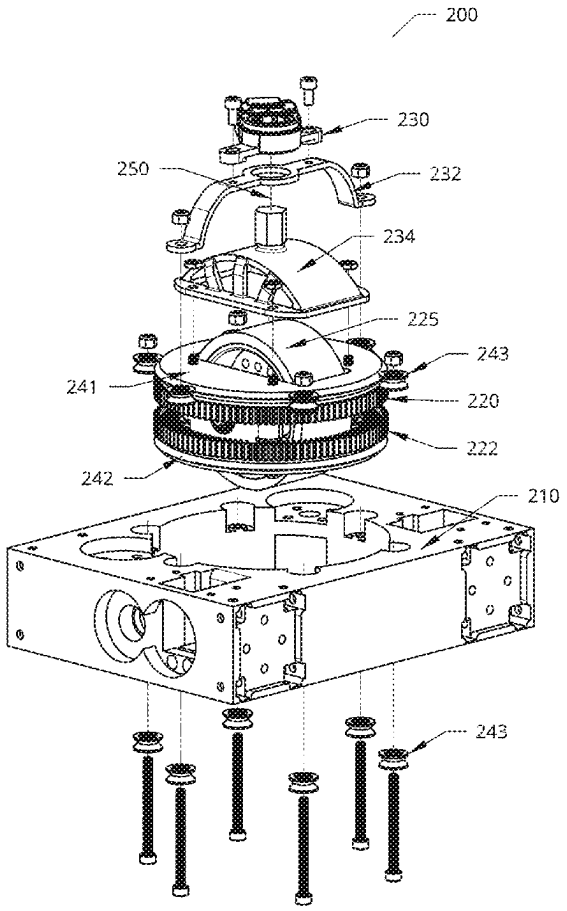


Figure 1a

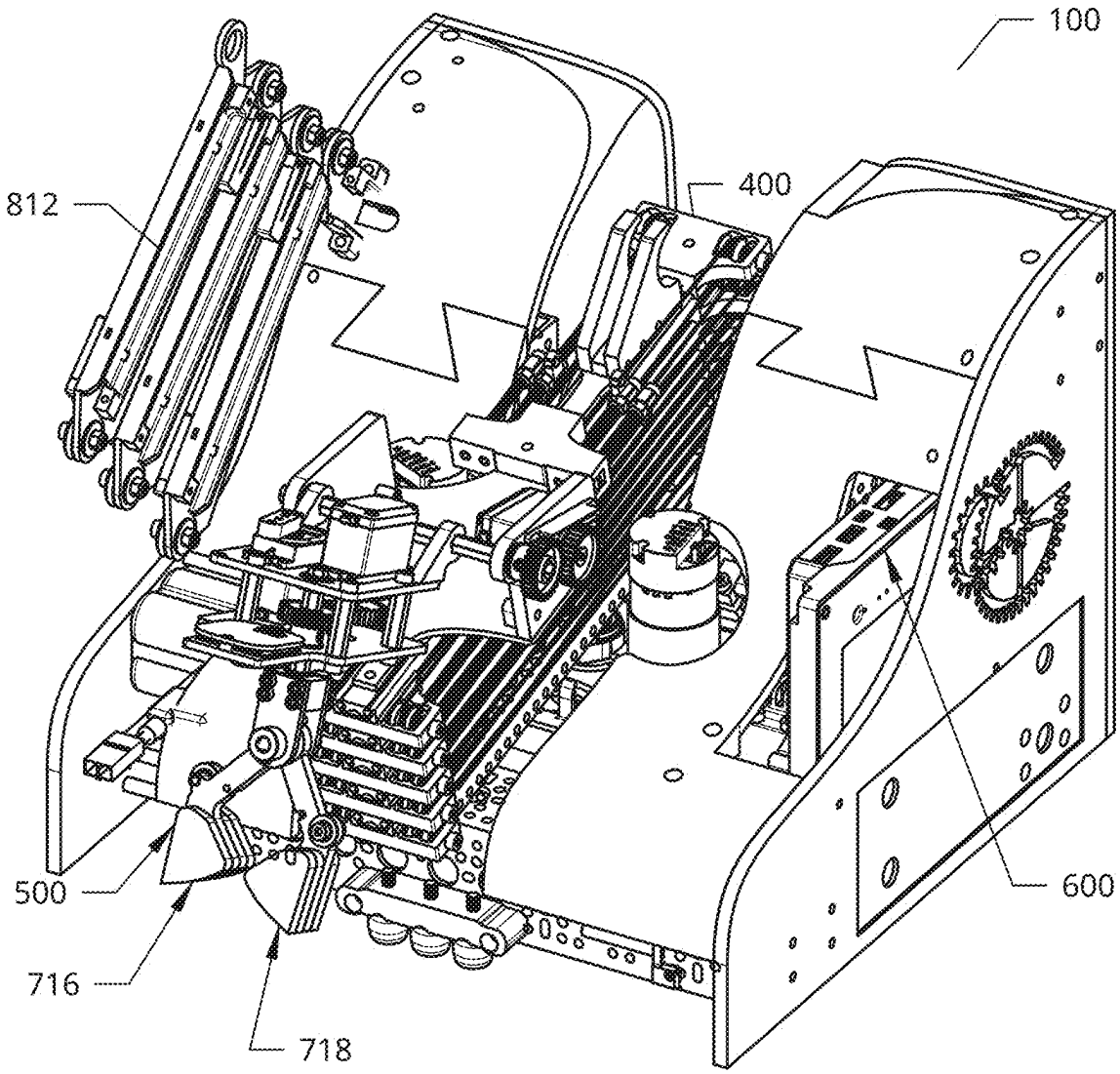


Figure 1b

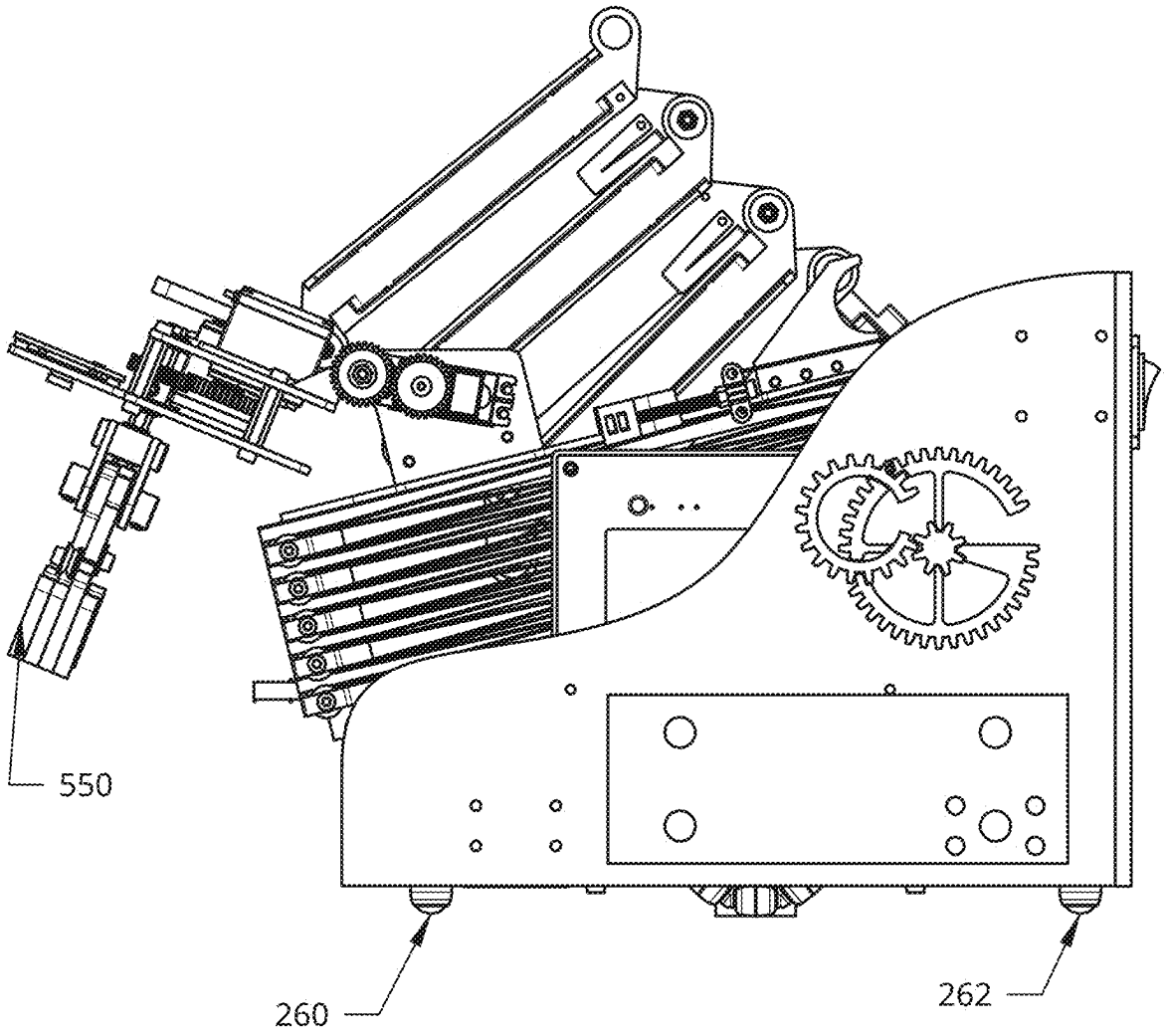


Figure 1c

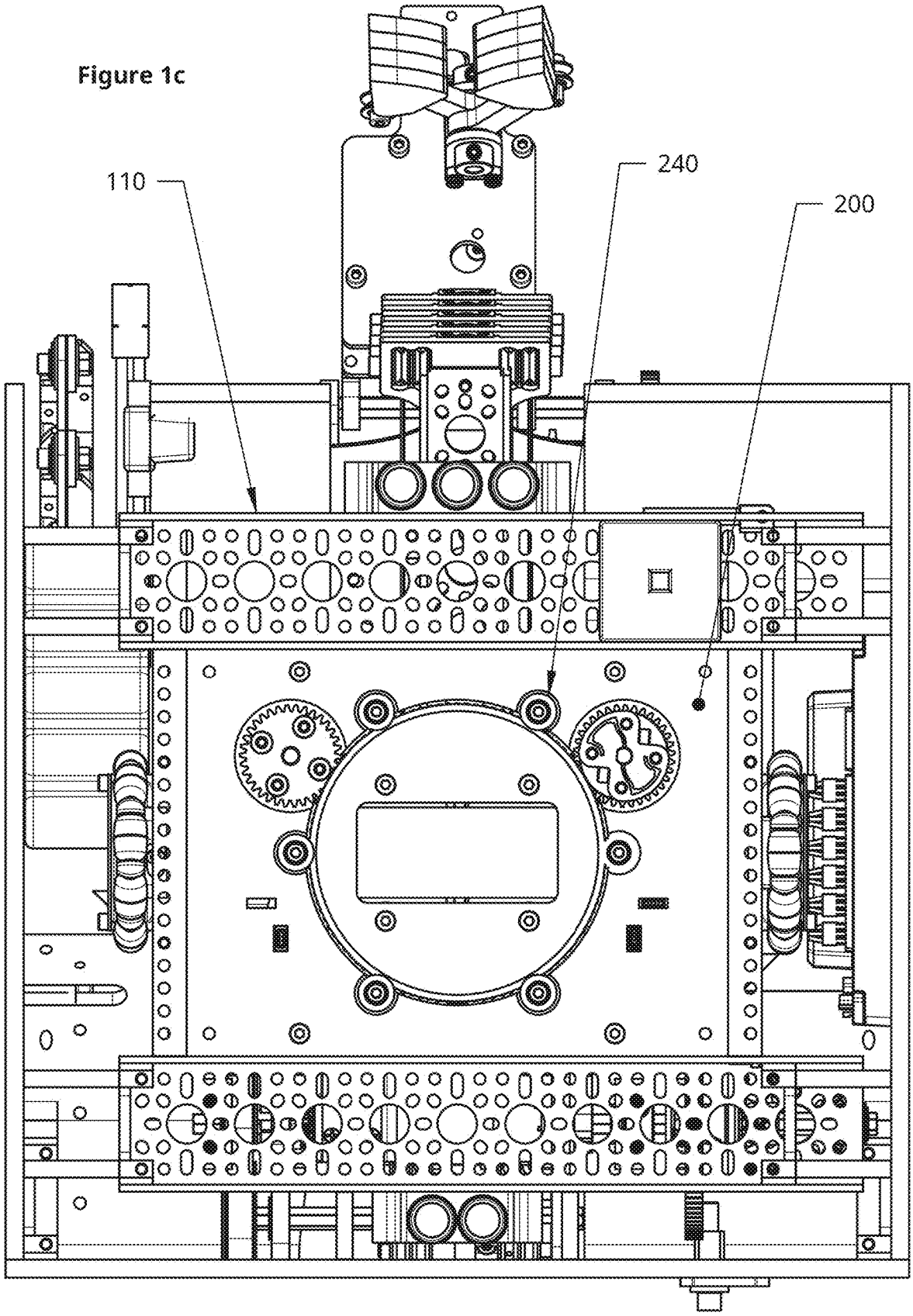


Figure 1d

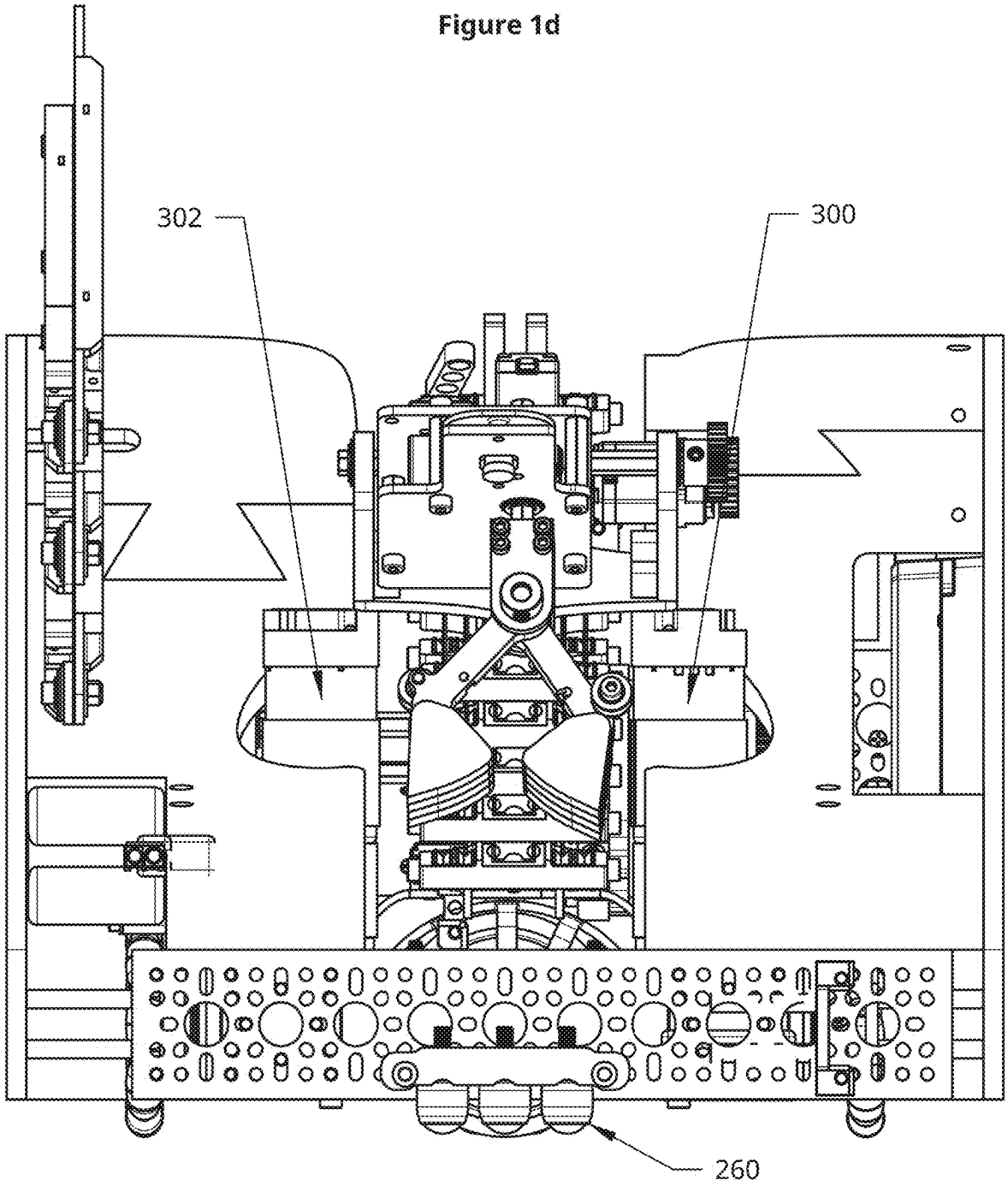


Figure 2a

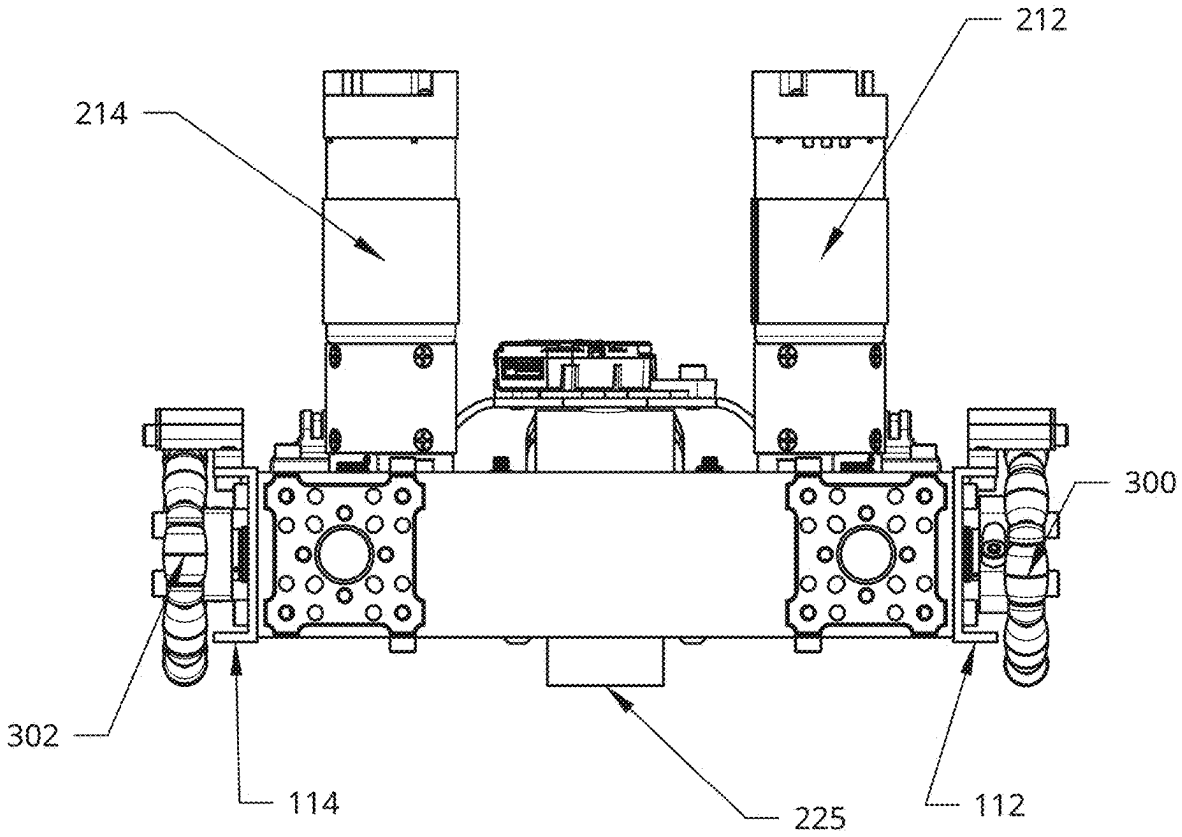


Figure 2b

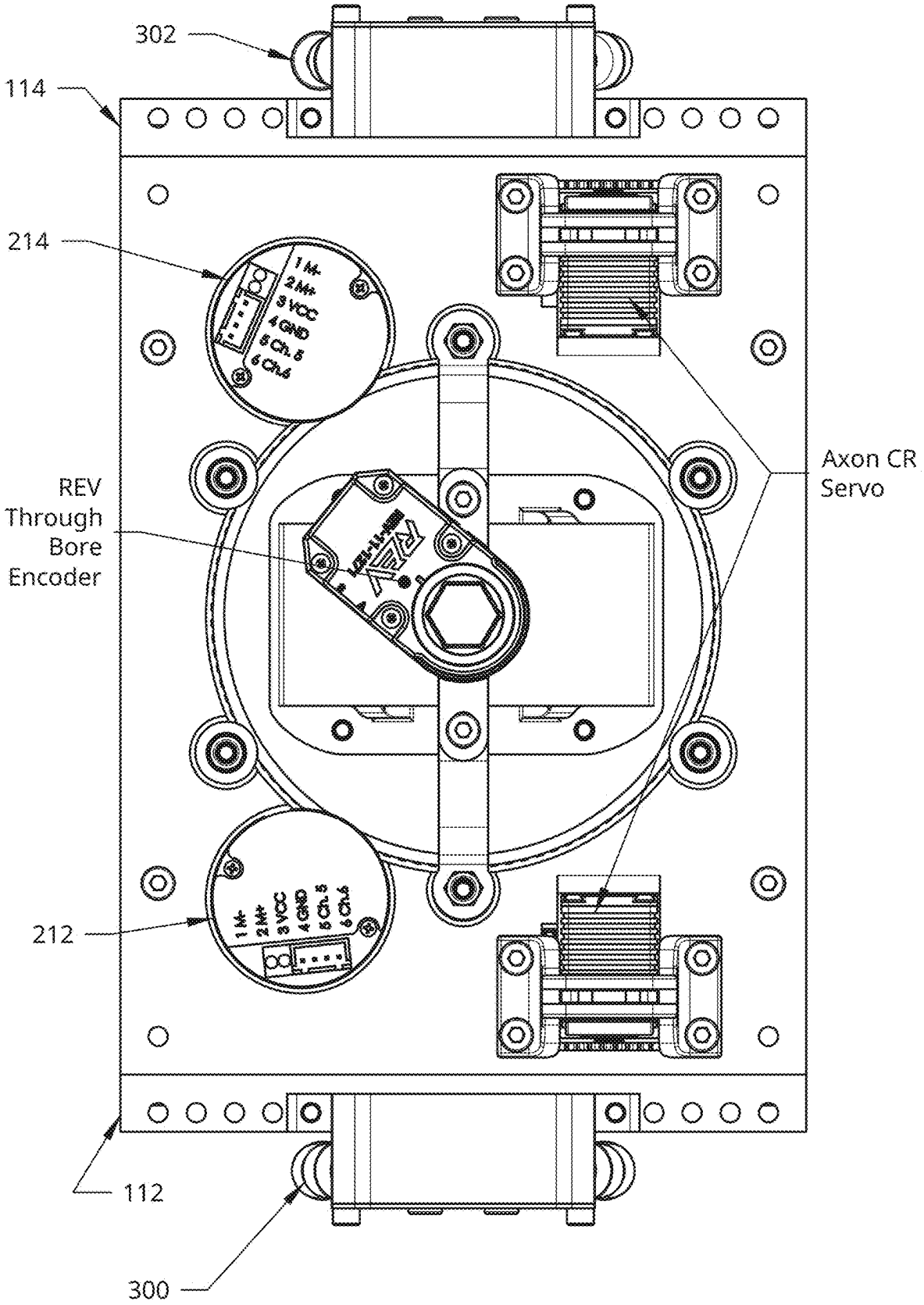

302
114
214
REV
Through
Bore
Encoder
Axon CR
Servo
212
112
300

Figure 2c

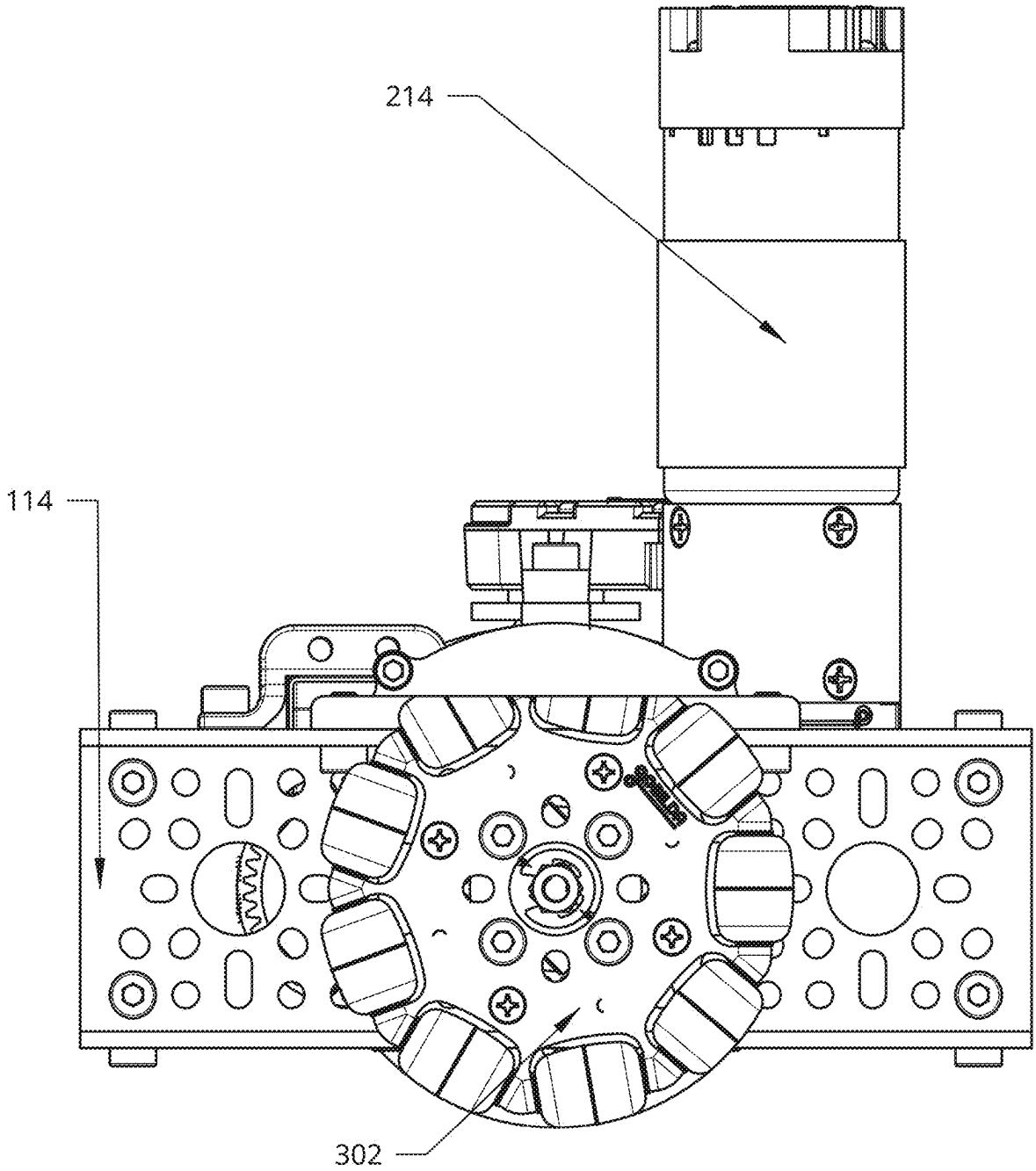


Figure 3

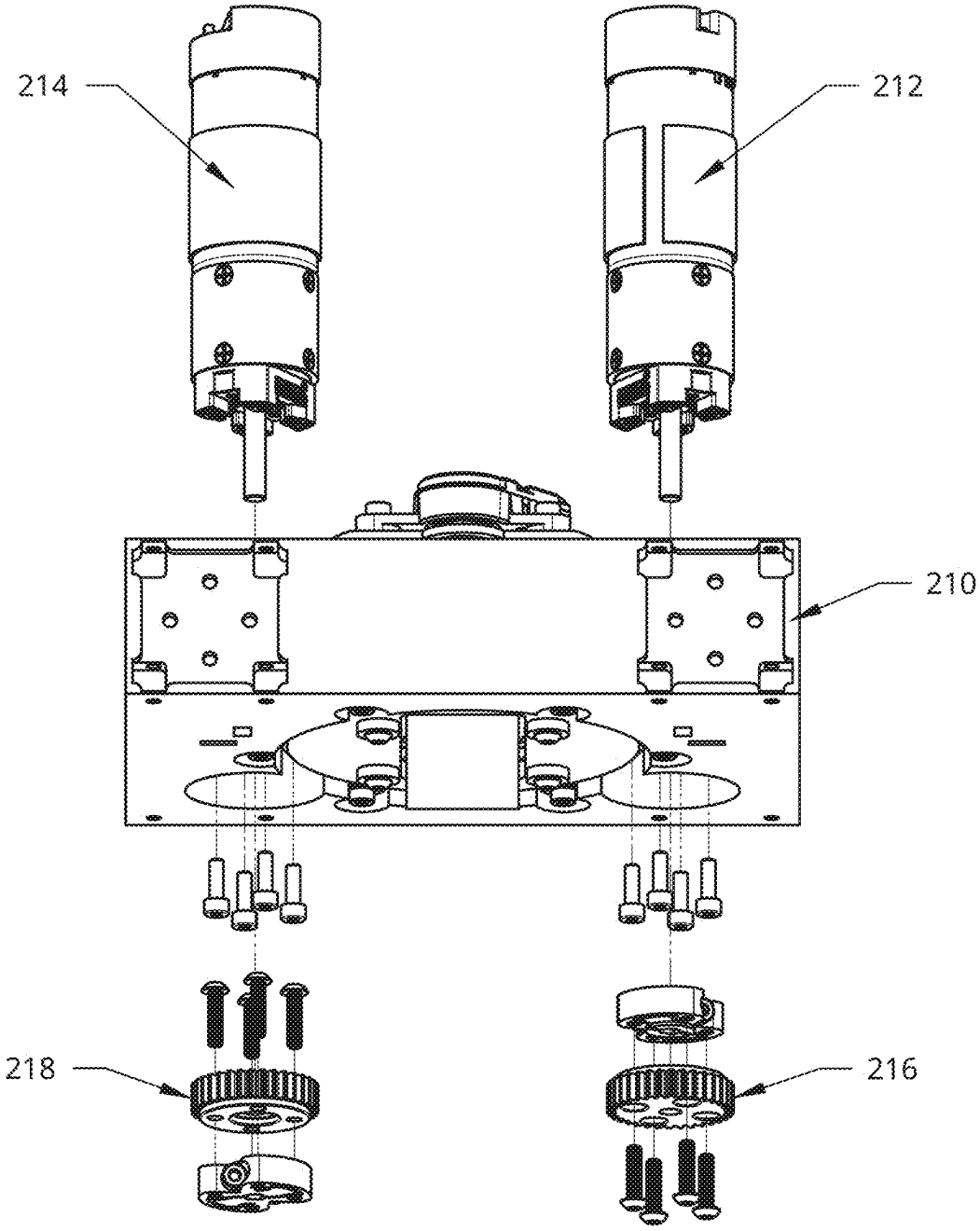


Figure 4

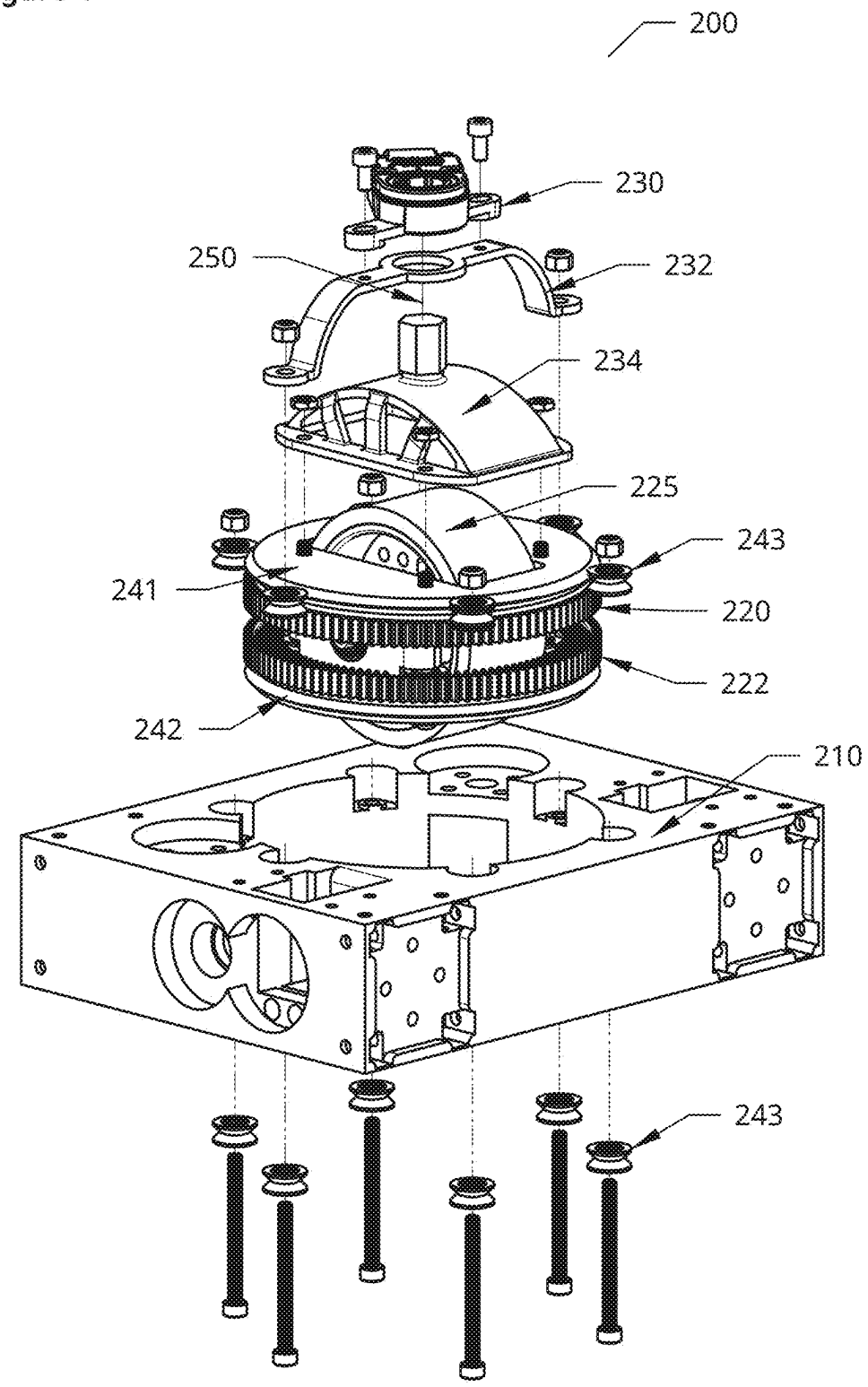


Figure 5

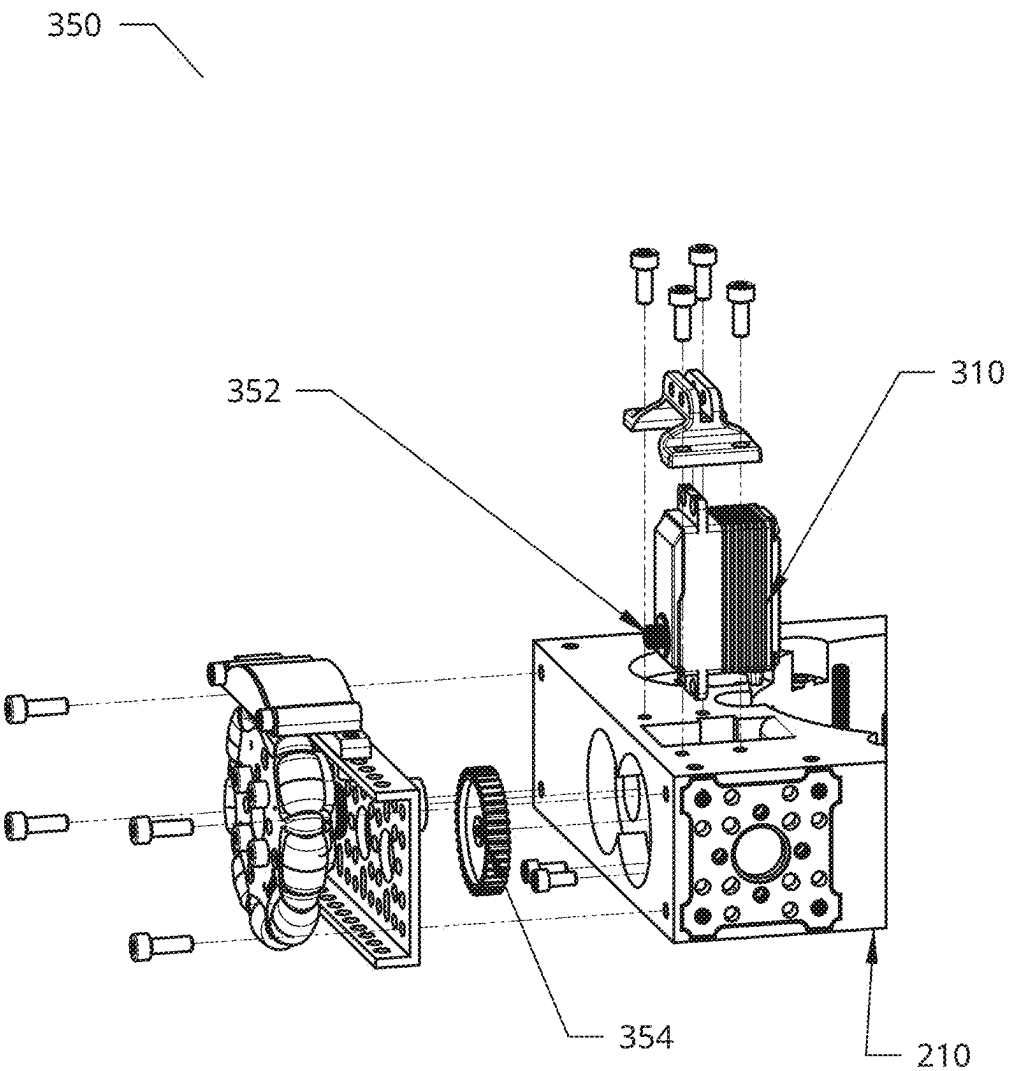


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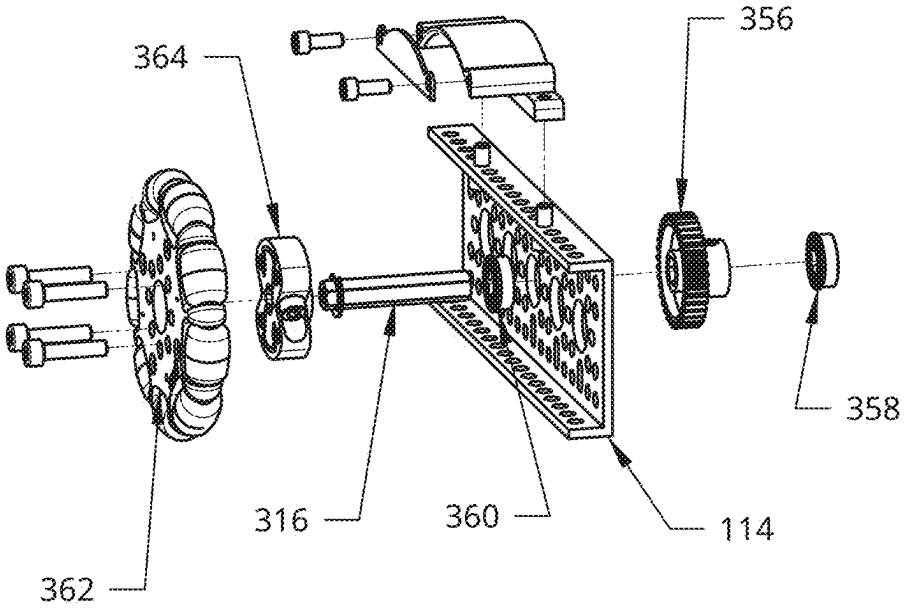


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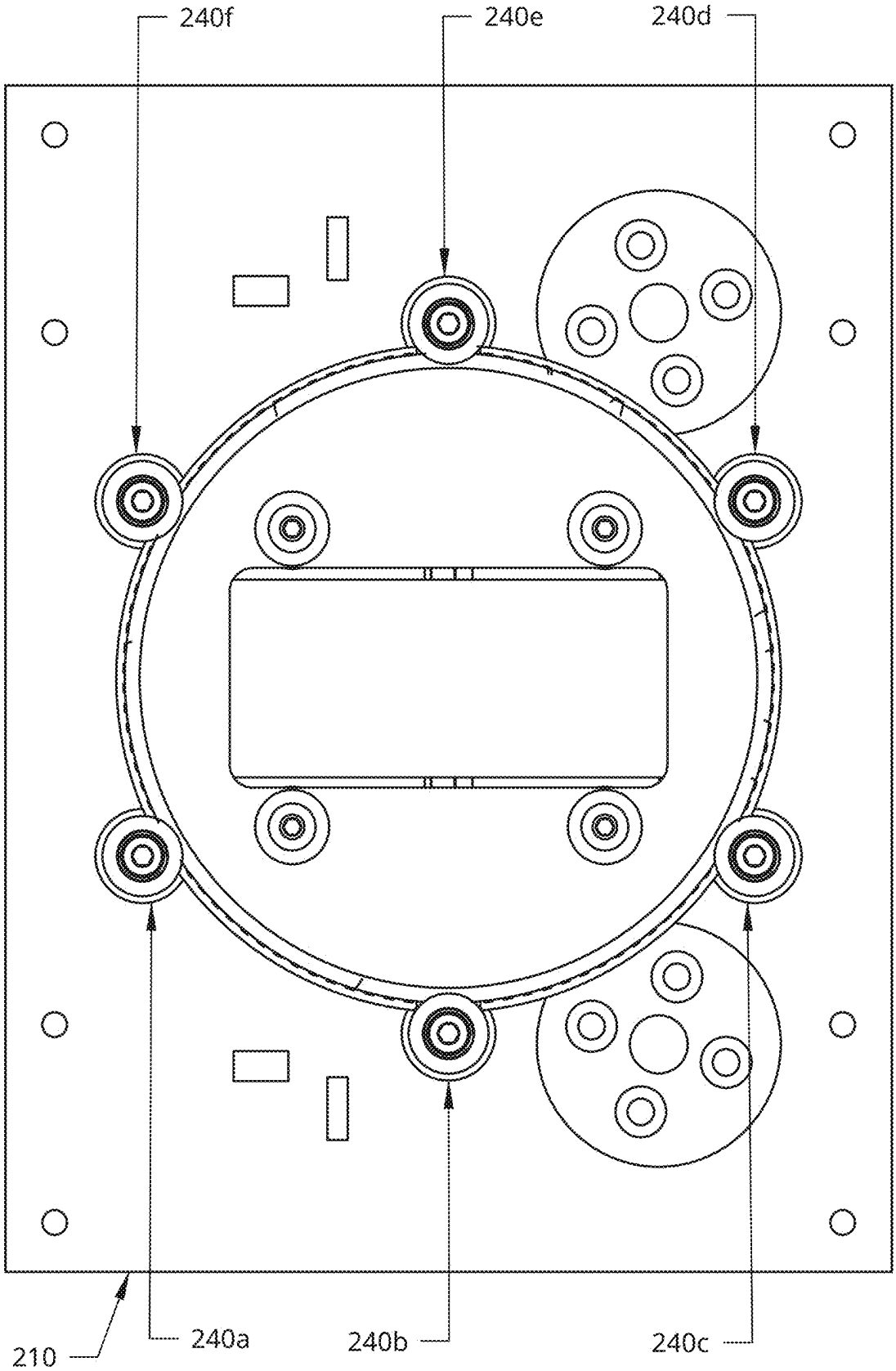


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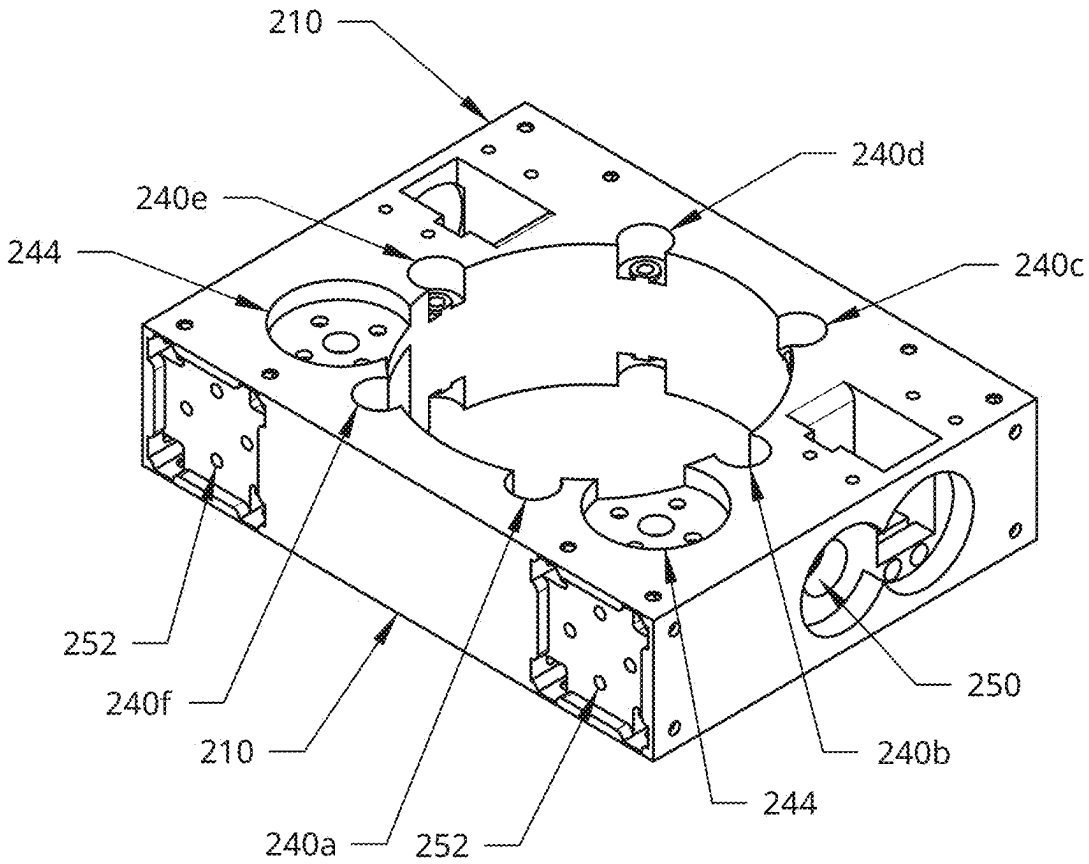


Figure 9a

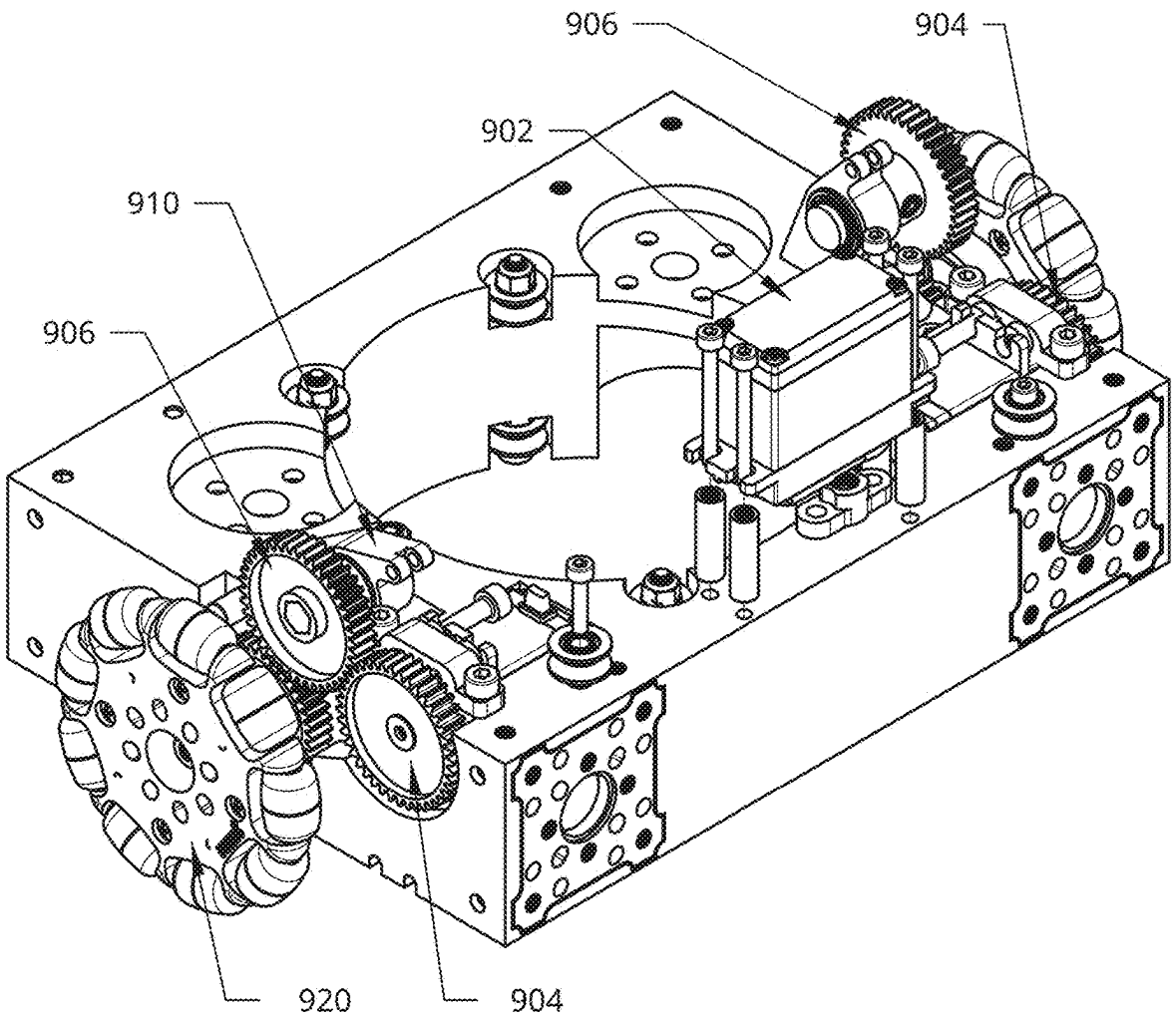


Figure 9b

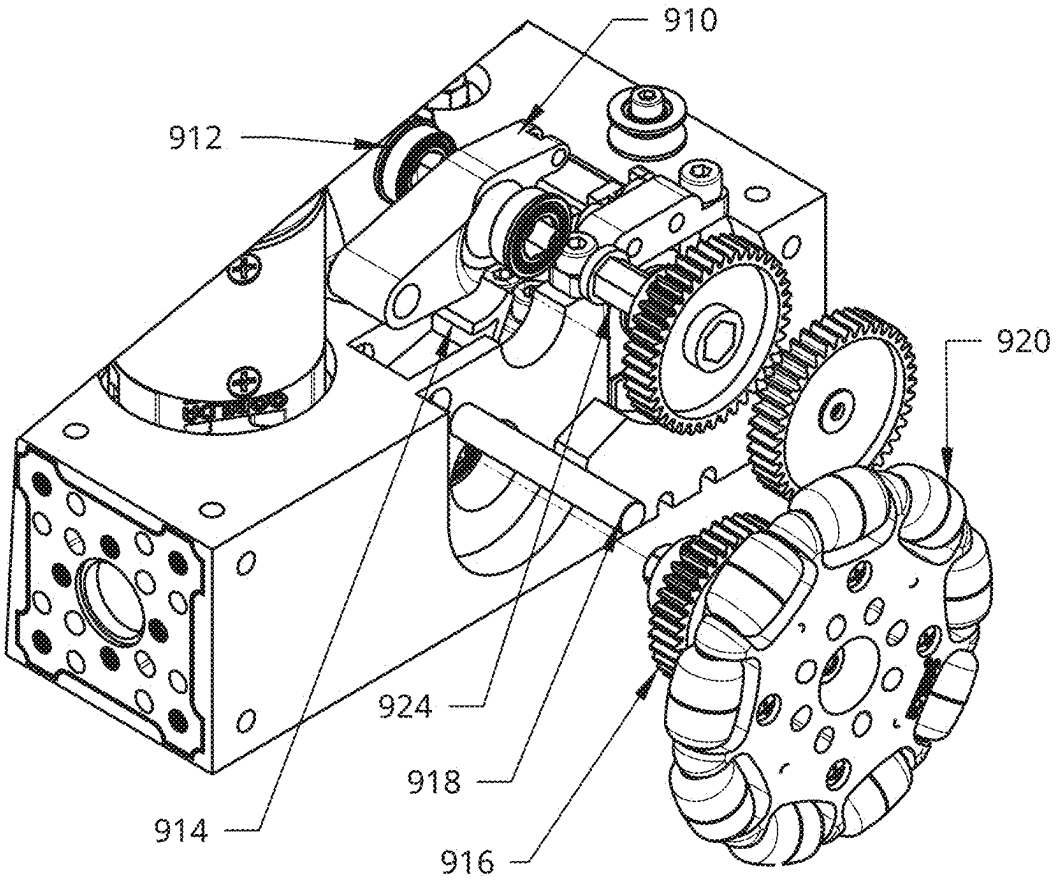


Figure 10a

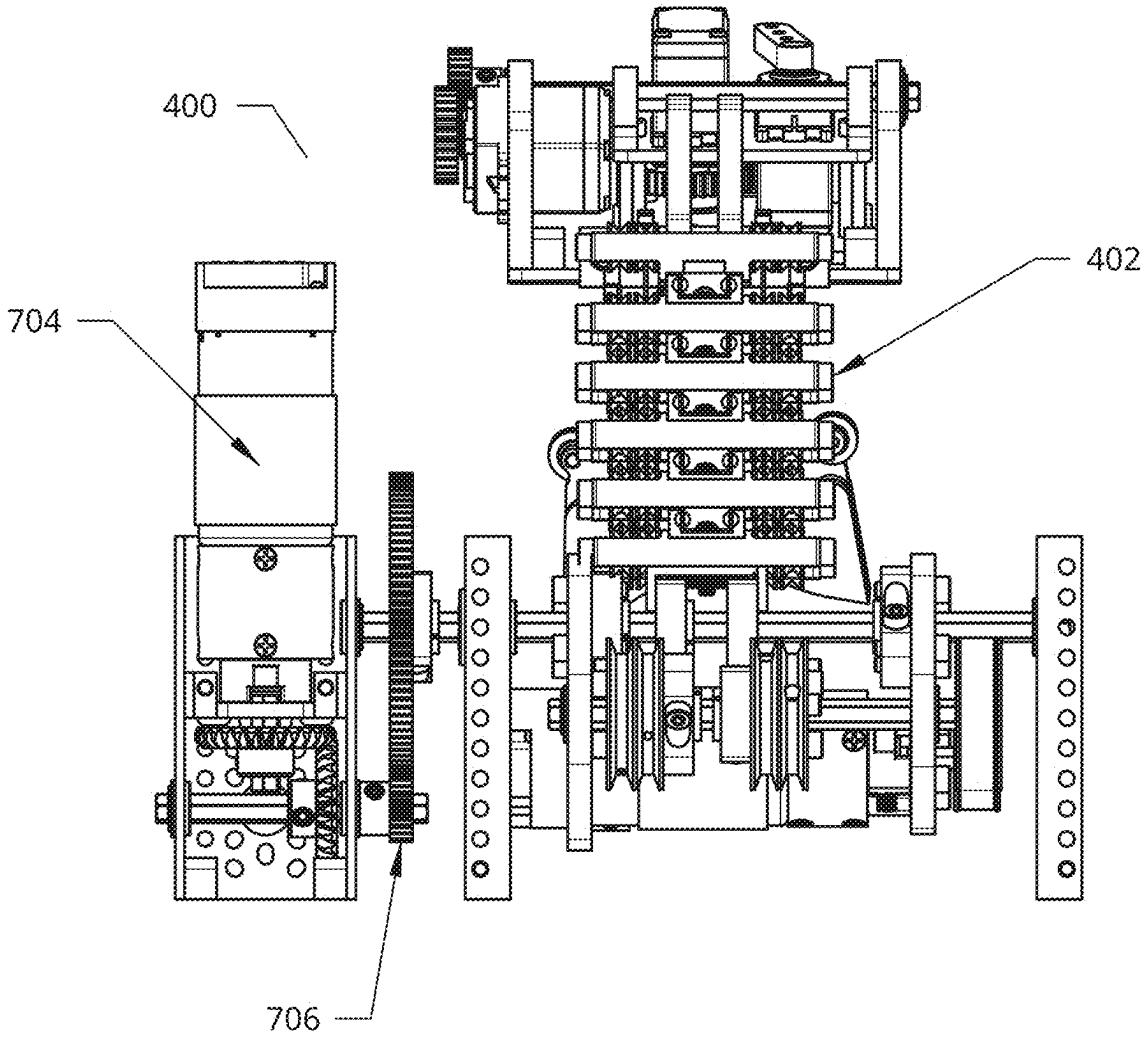


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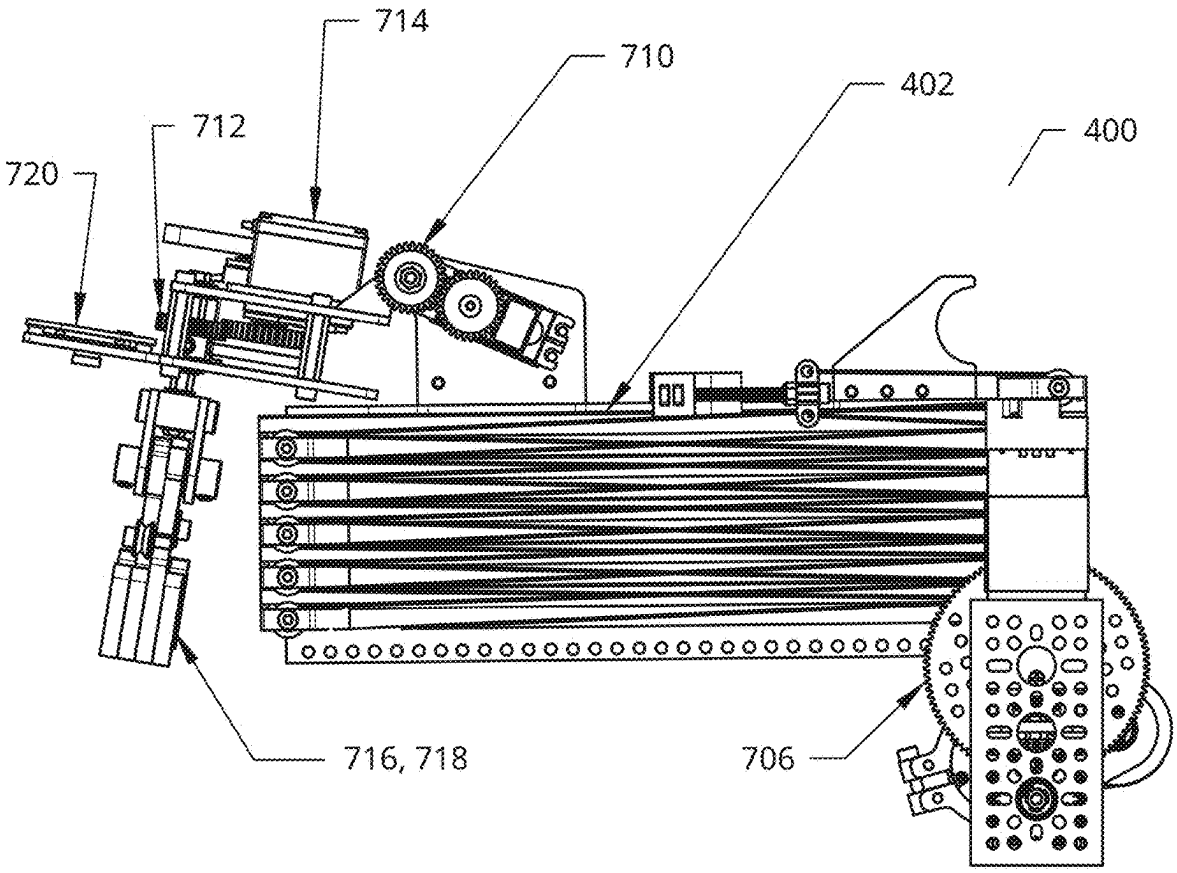


Figure 11a

Figure 11b

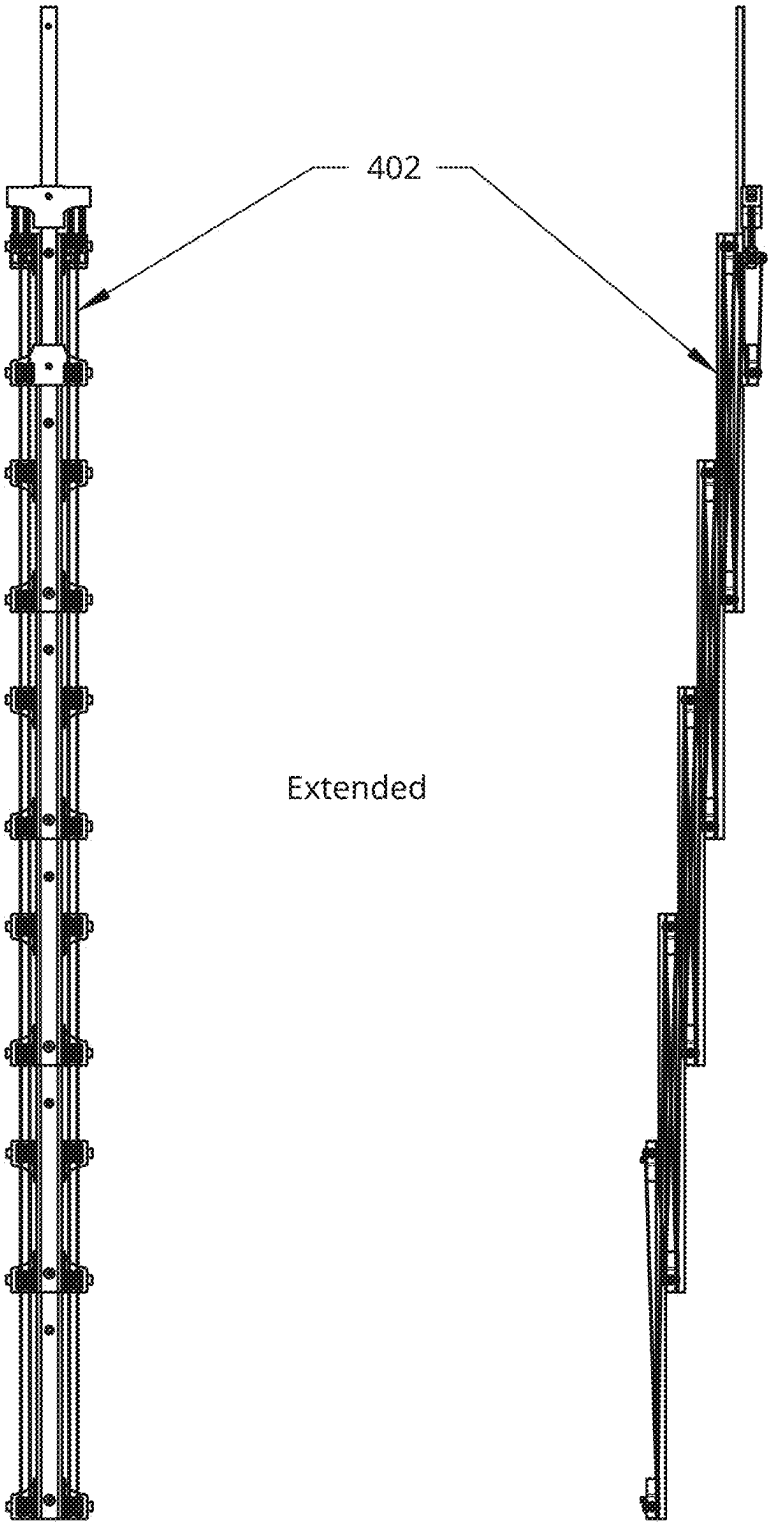


Figure 12

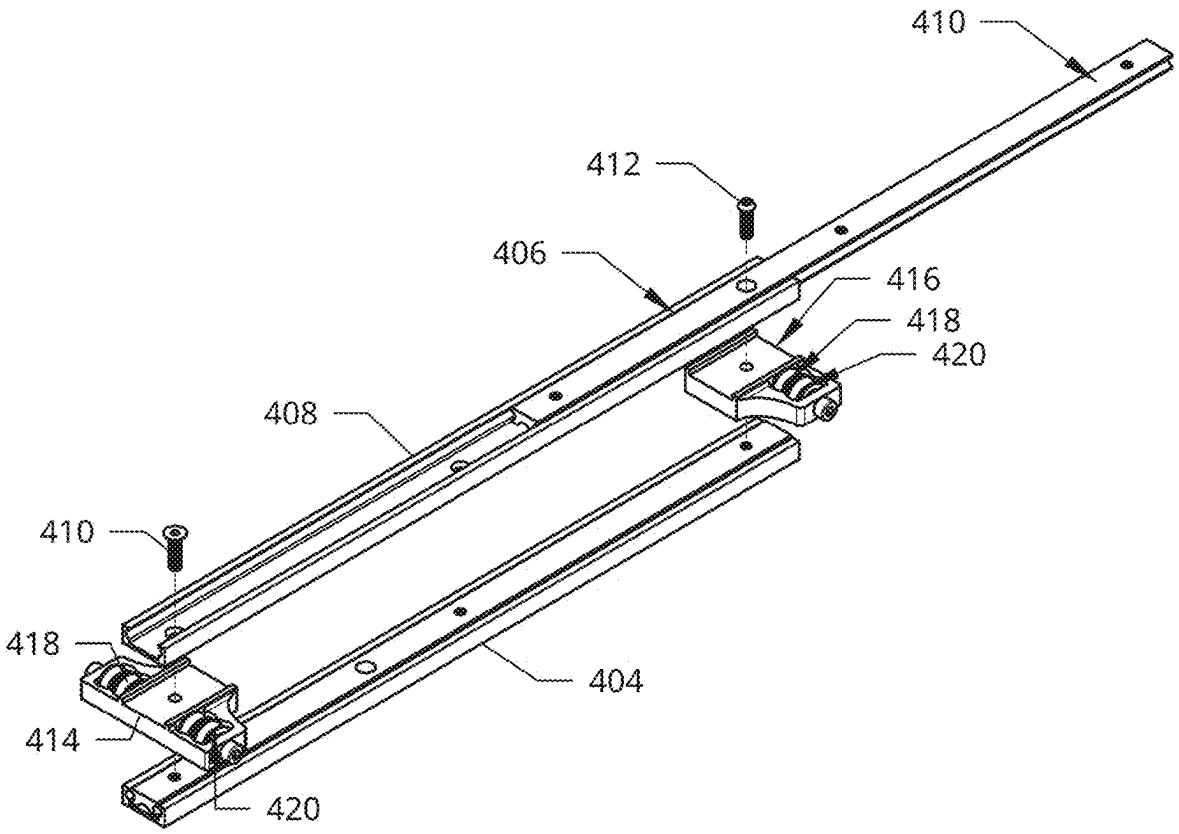


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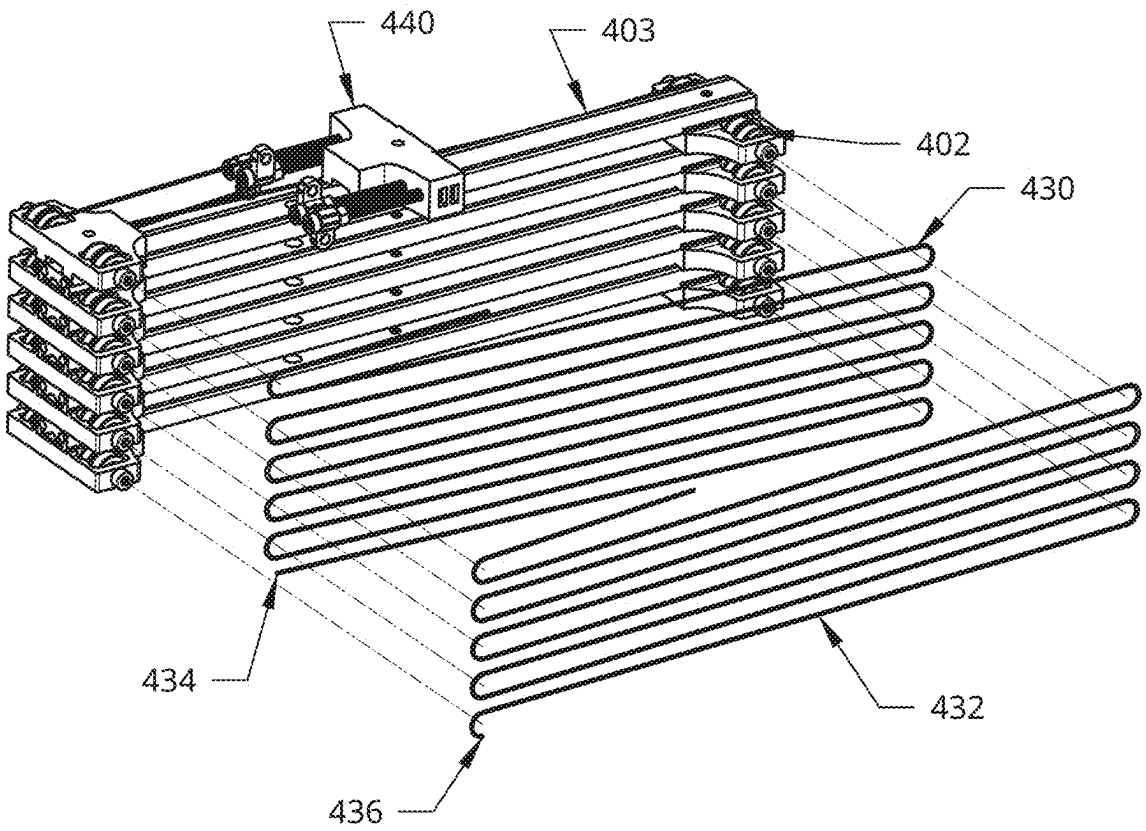


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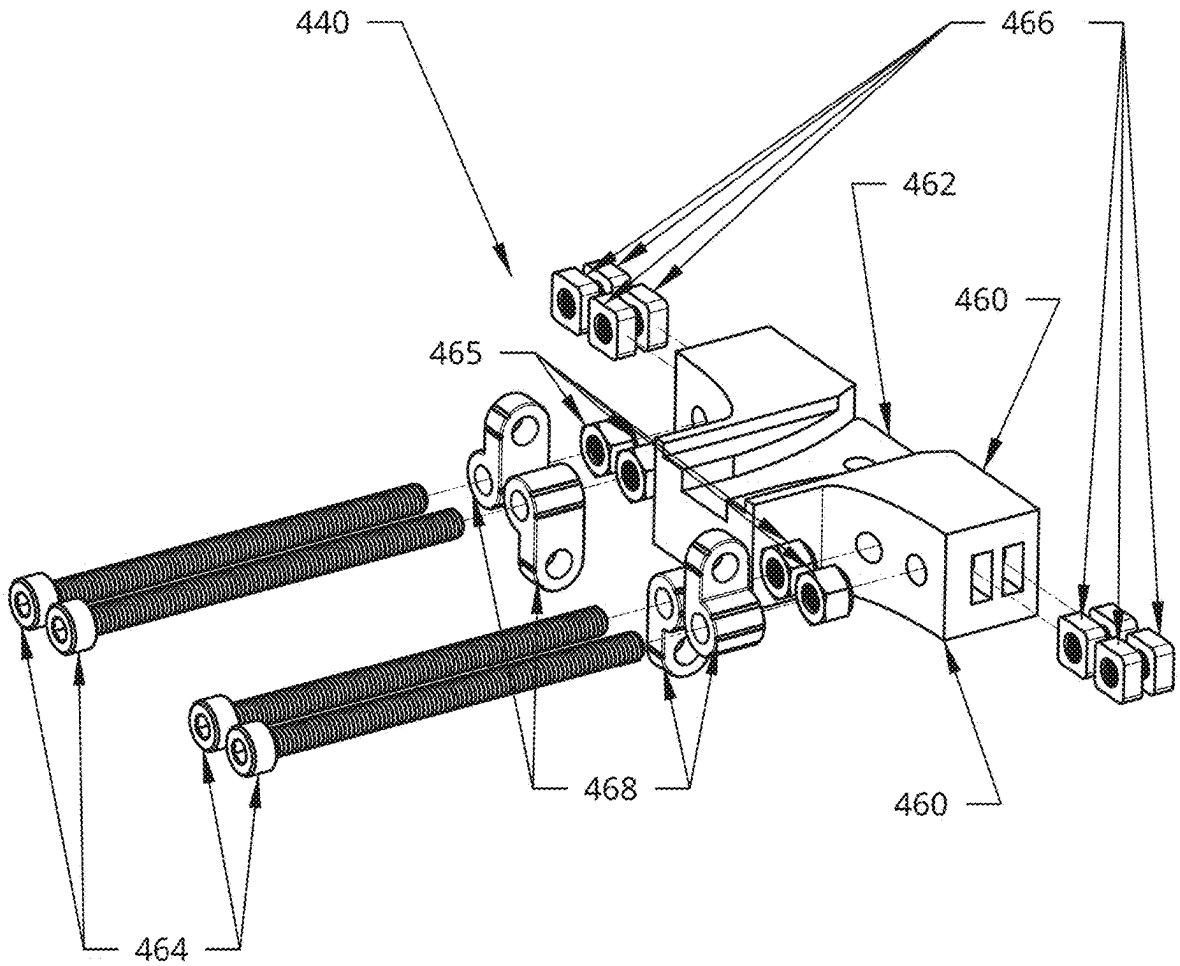


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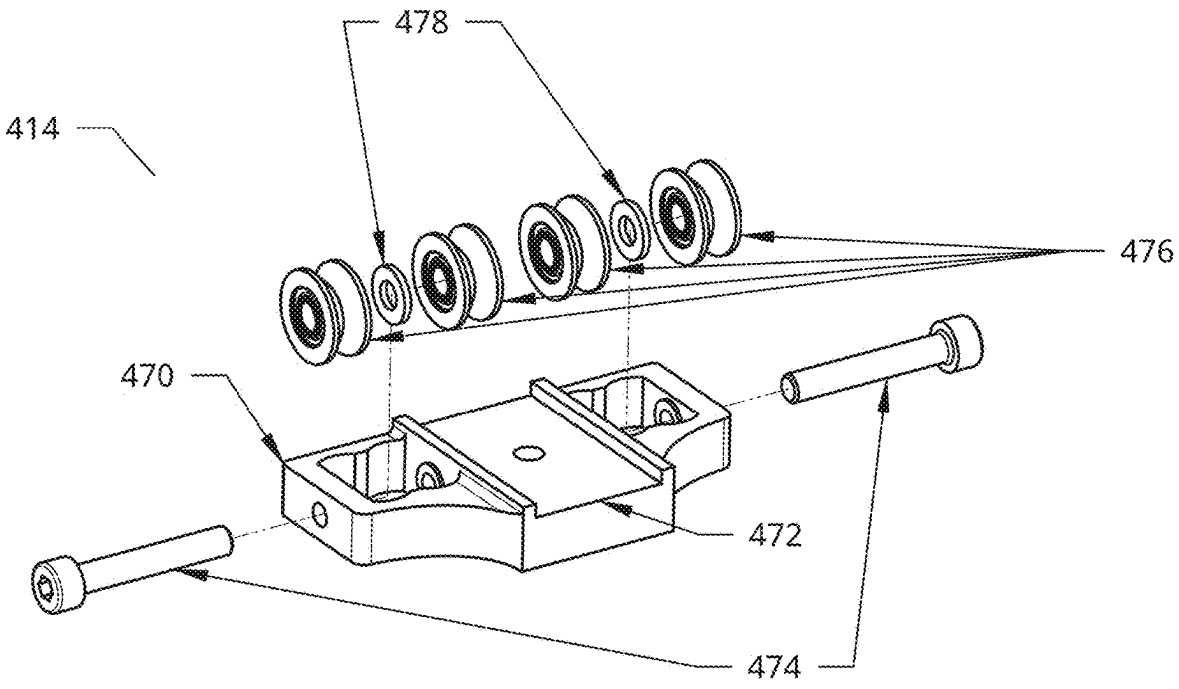


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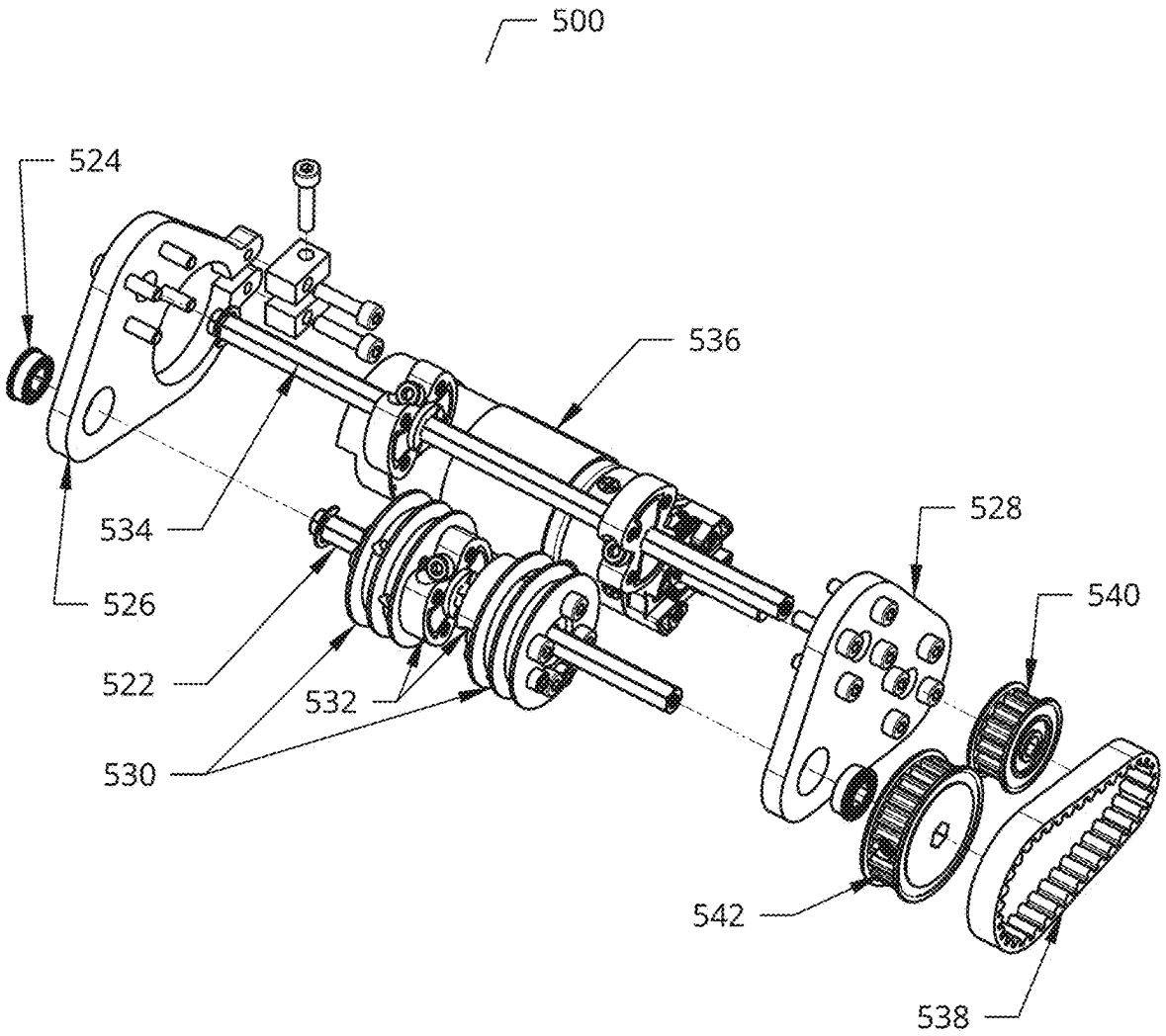


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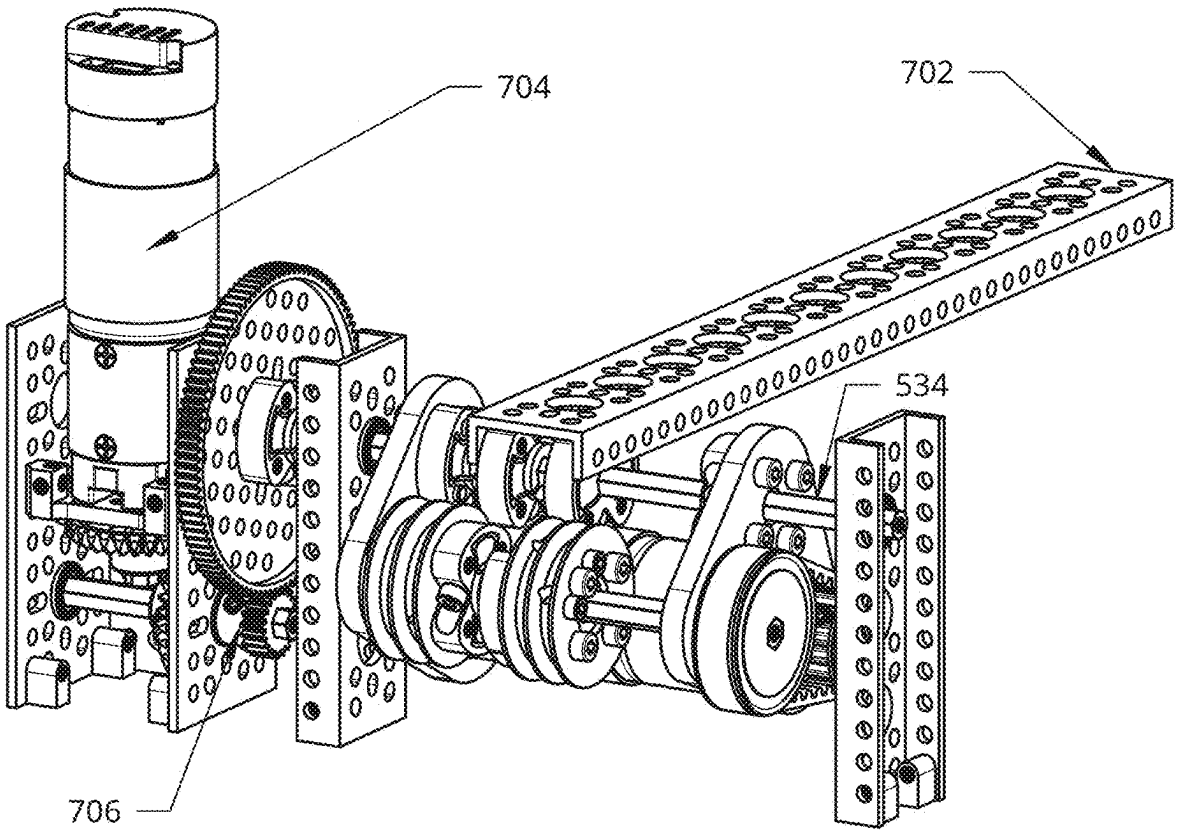


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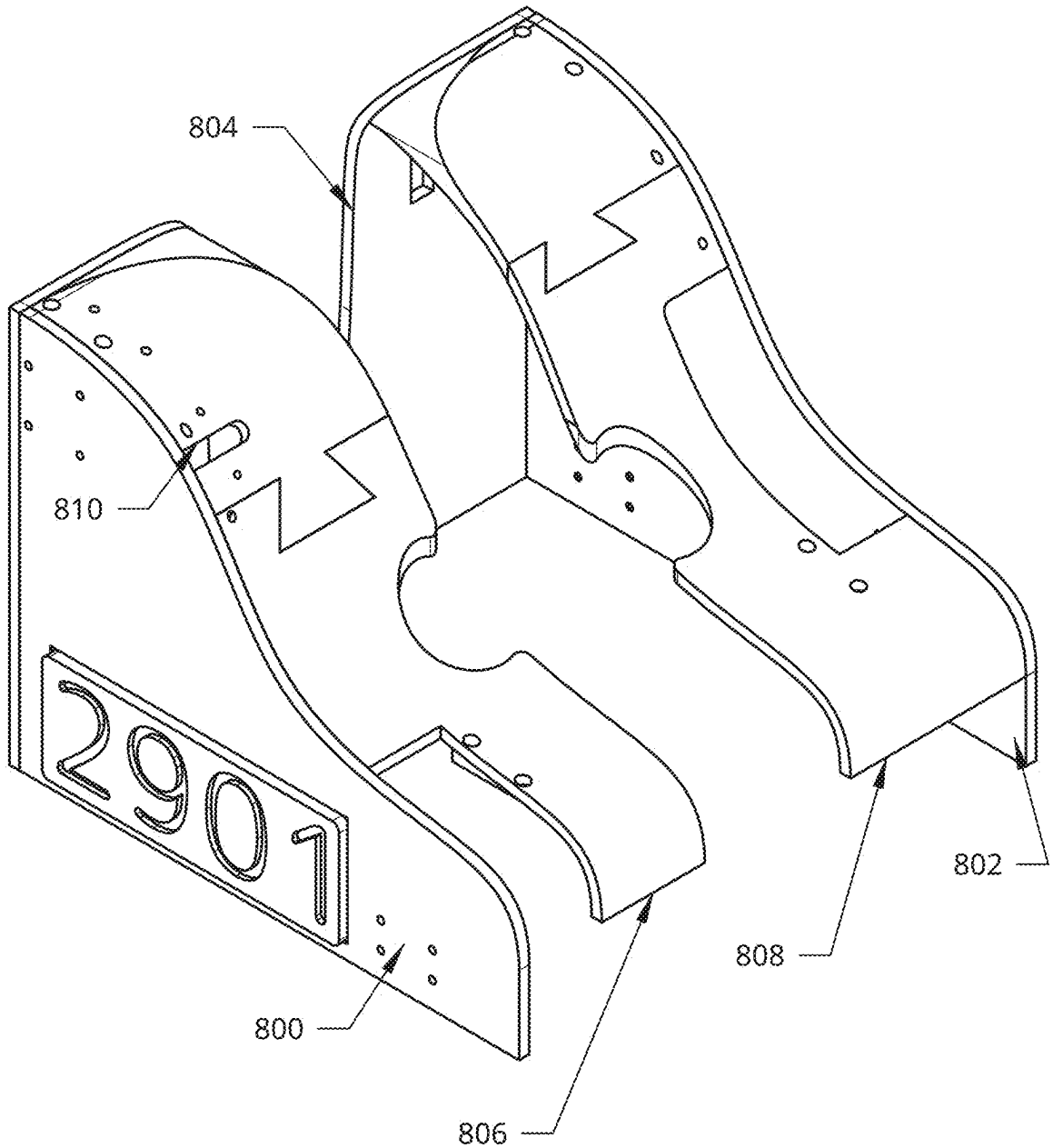


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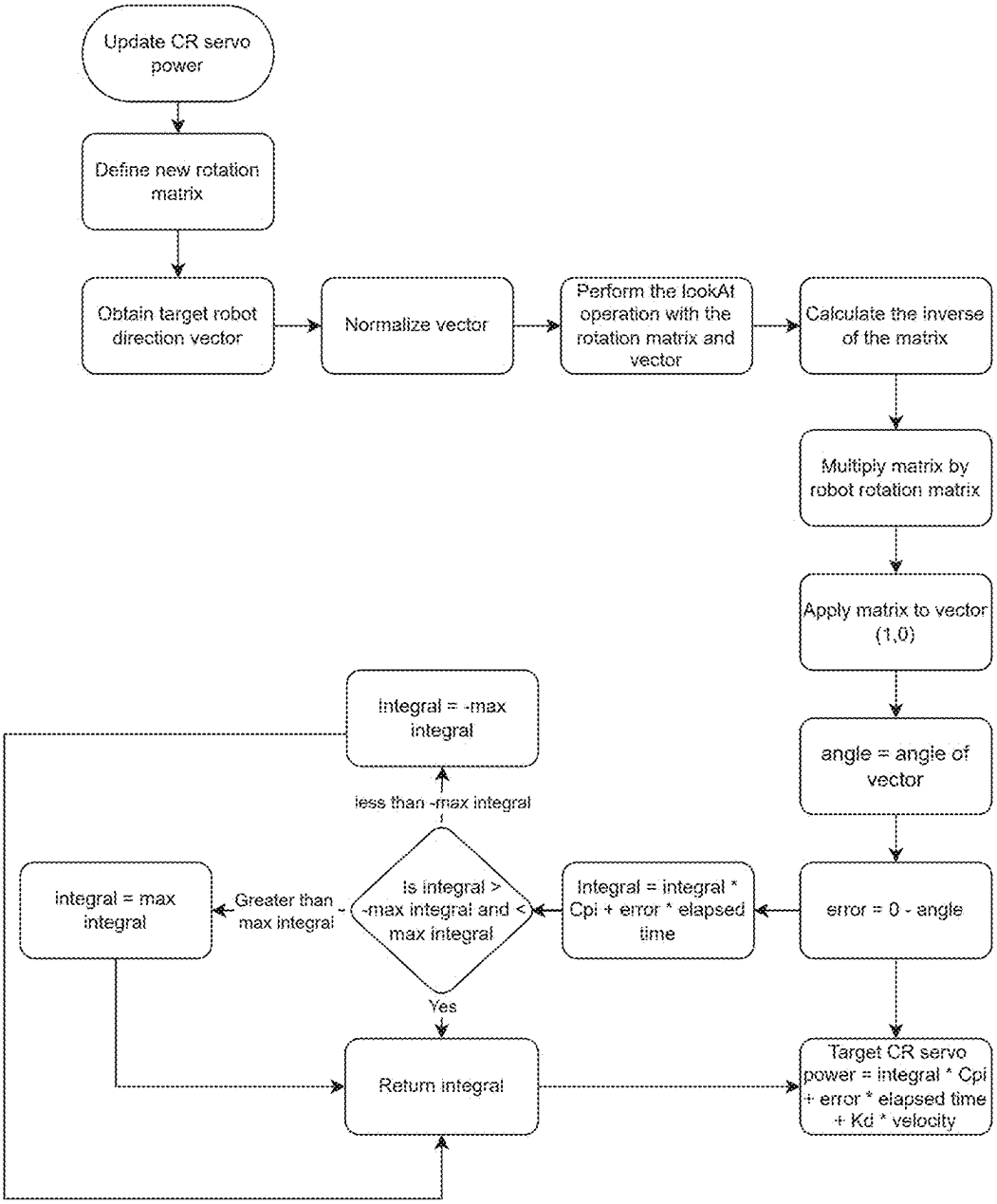

Update CR servo power
Define new rotation matrix
Obtain target robot direction vector
Normalize vector
Perform the lookAt operation with the rotation matrix and vector
Calculate the inverse of the matrix
Multiply matrix by robot rotation matrix
Apply matrix to vector (1,0)
angle = angle of vector
error = 0 - angle
Integral = integral * Cpi + error * elapsed time
Is integral > -max integral and < max integral
Greater than max integral
integral = max integral
less than -max integral
Integral = -max integral
Yes
Return integral
Target CR servo power = integral * Cpi + error * elapsed time + Kd * velocity

Figure 20

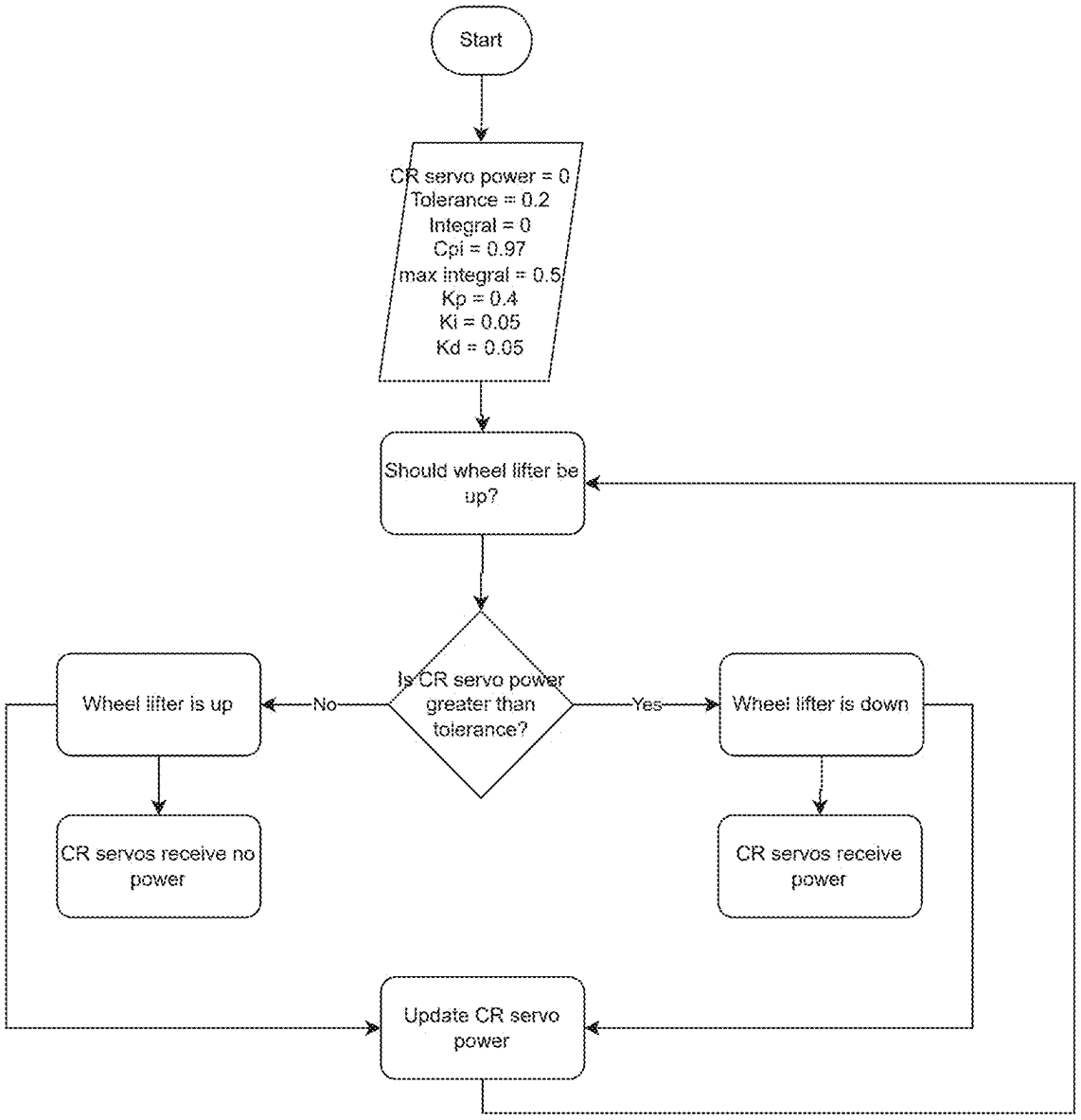

Start
CR servo power = 0
Tolerance = 0.2
Integral = 0
Cpi = 0.97
max integral = 0.5
Kp = 0.4
Ki = 0.05
Kd = 0.05
Should wheel lifter be up?
Is CR servo power greater than tolerance?
No
Yes
Wheel lifter is up
Wheel lifter is down
CR servos receive no power
CR servos receive power
Update CR servo power

Figure 21

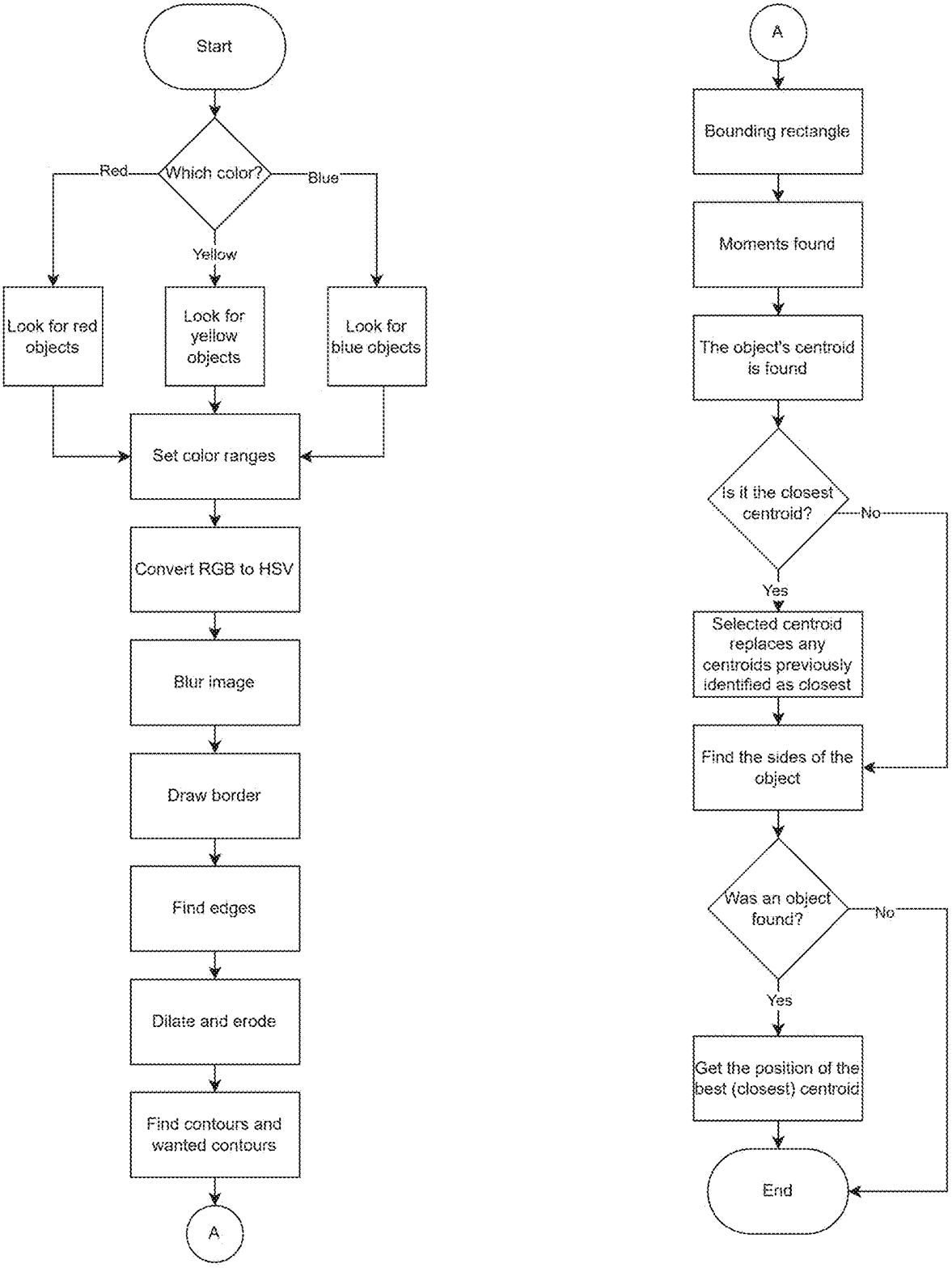

Start
Which color?
Red
Blue
Yellow
Look for red objects
Look for yellow objects
Look for blue objects
Set color ranges
Convert RGB to HSV
Blur image
Draw border
Find edges
Dilate and erode
Find contours and wanted contours
A
A
Bounding rectangle
Moments found
The object's centroid is found
Is it the closest centroid?
No
Yes
Selected centroid replaces any centroids previously identified as closest
Find the sides of the object
Was an object found?
No
Yes
Get the position of the best (closest) centroid
End

Figure 22

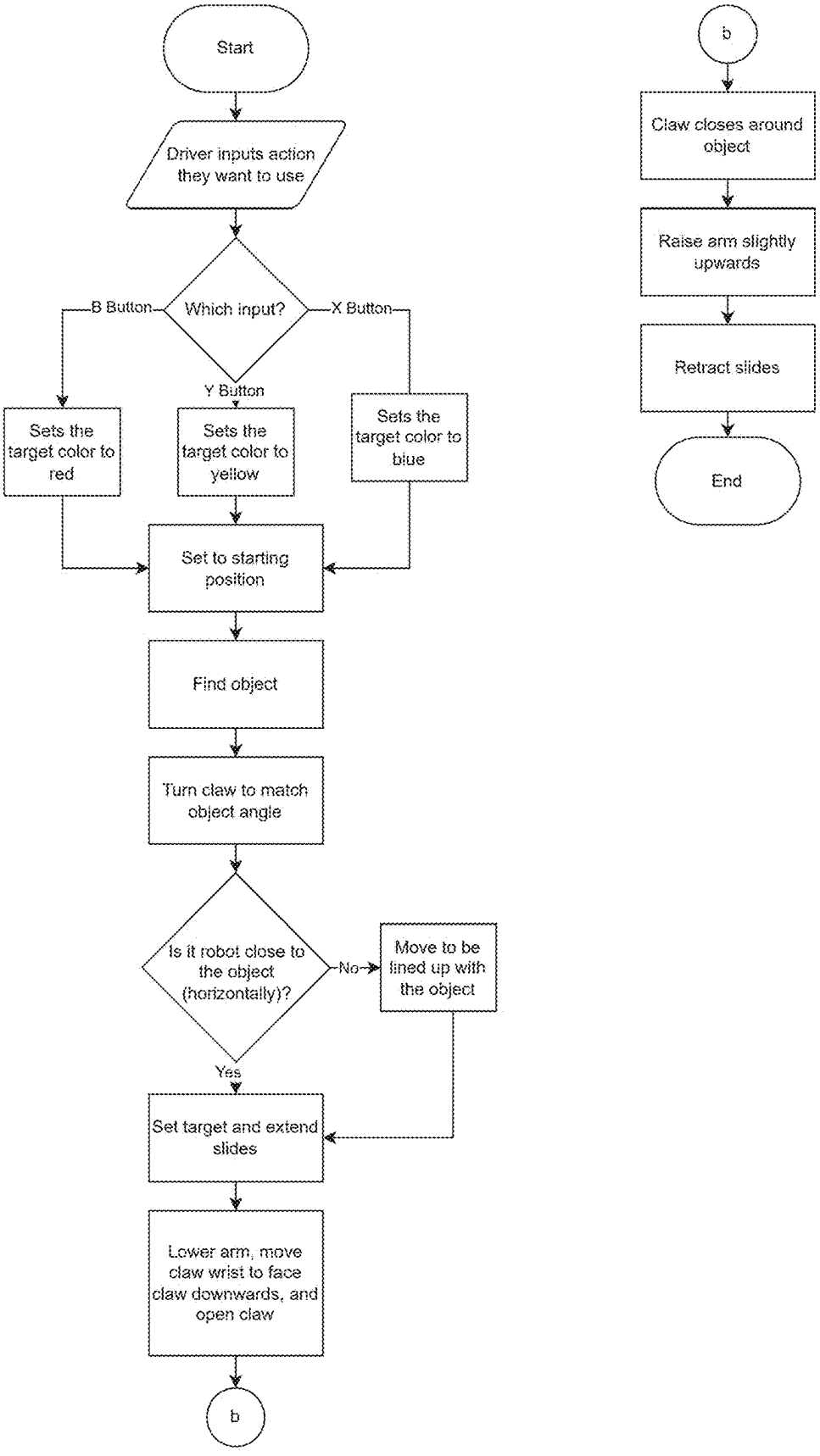

Start
Driver inputs action they want to use
Which input?
B Button
Y Button
X Button
Sets the target color to red
Sets the target color to yellow
Sets the target color to blue
Set to starting position
Find object
Turn claw to match object angle
Is it robot close to the object (horizontally)?
No
Move to be lined up with the object
Yes
Set target and extend slides
Lower arm, move claw wrist to face claw downwards, and open claw
b
b
Claw closes around object
Raise arm slightly upwards
Retract slides
End

Figure 23

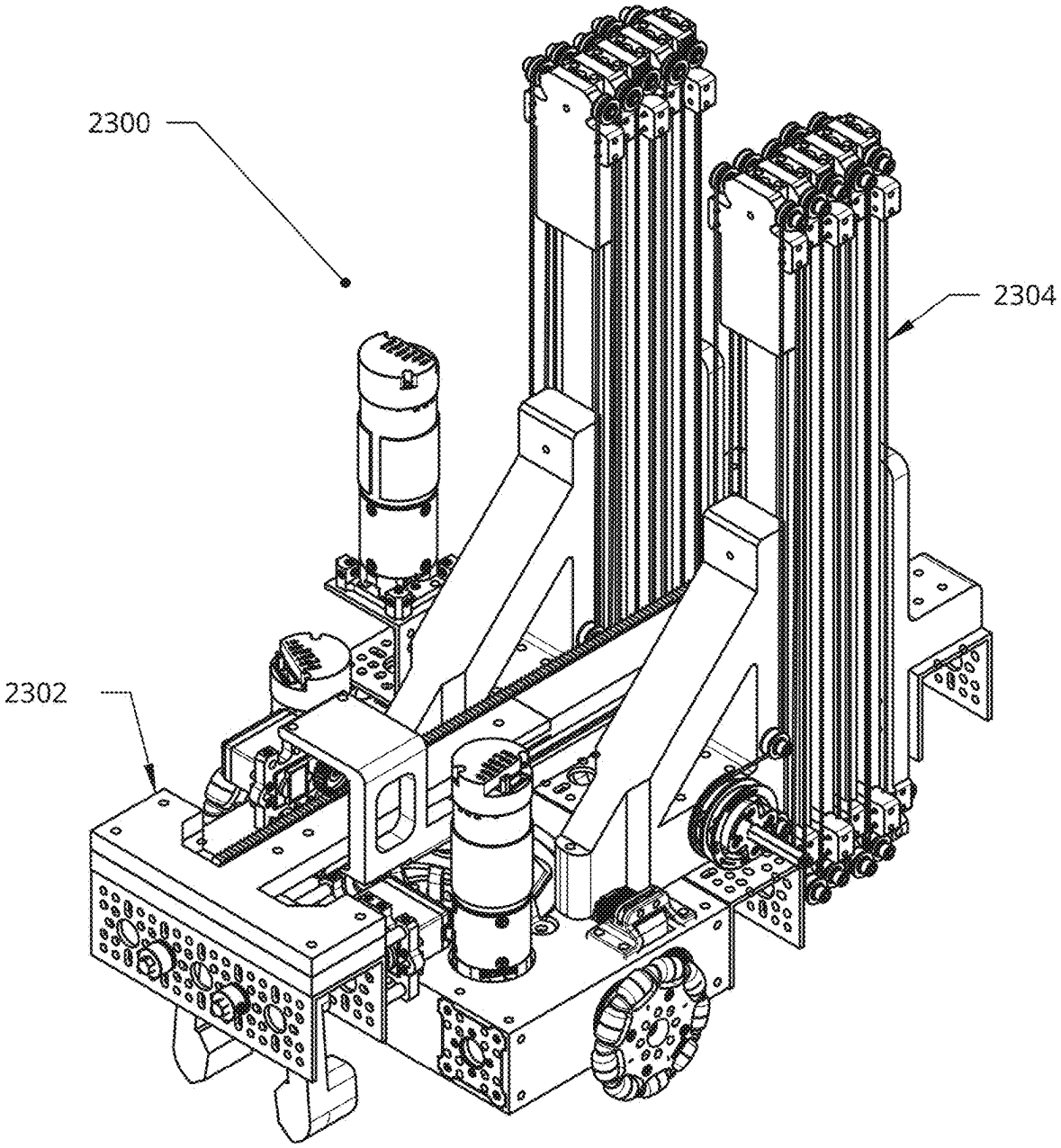


Figure 24

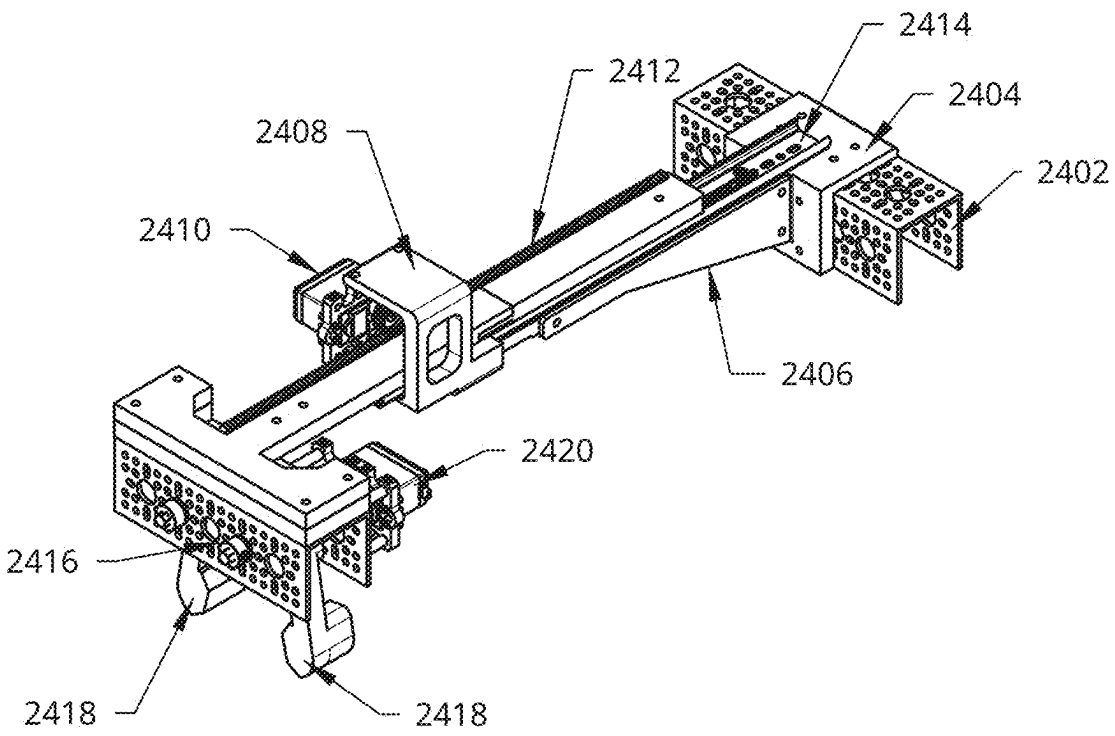


Figure 25

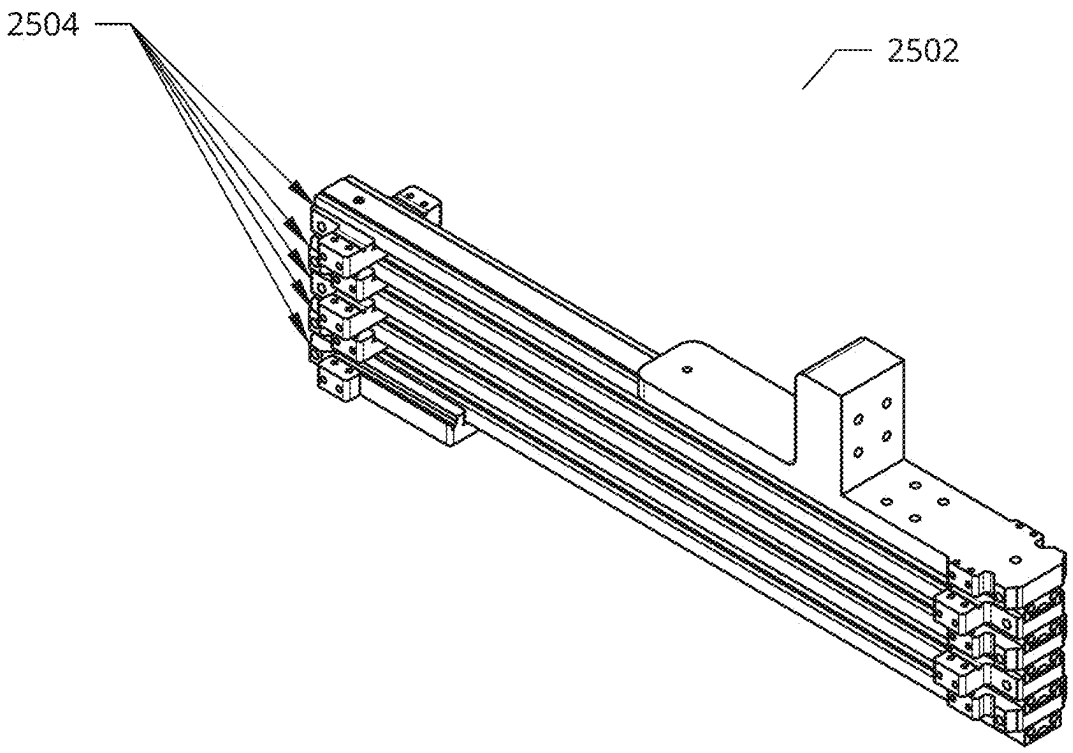


Figure 26

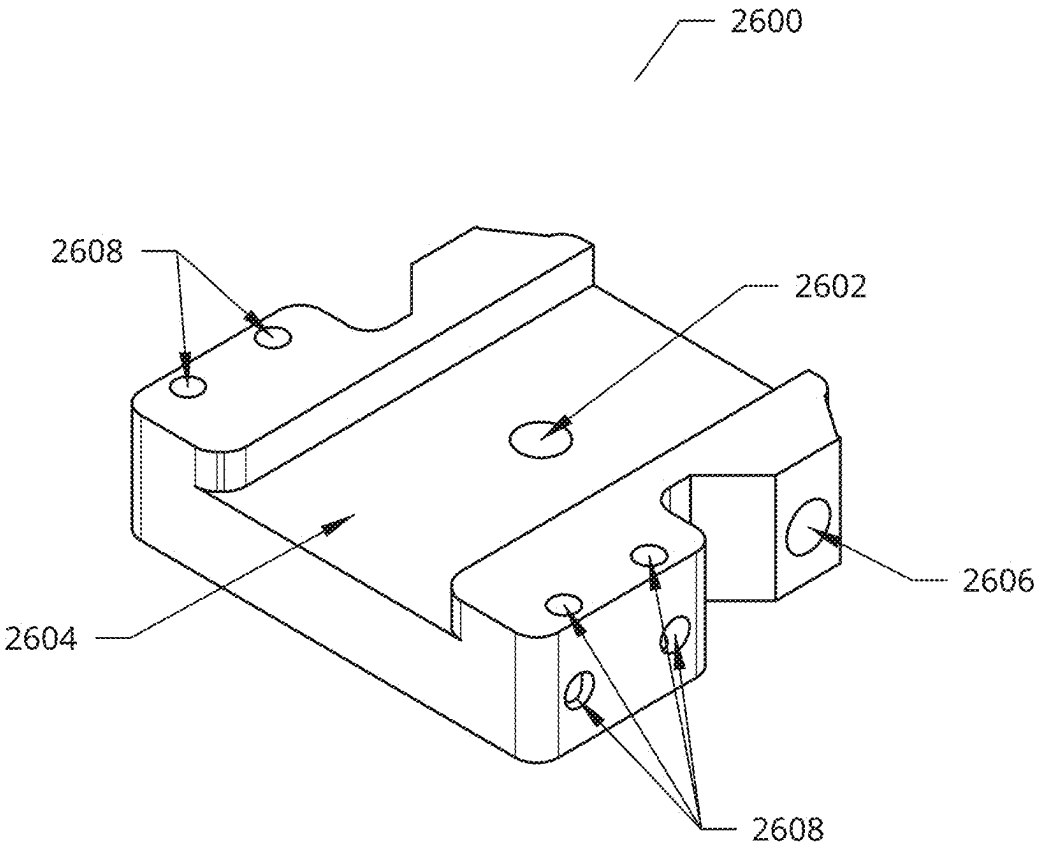


Figure 27A

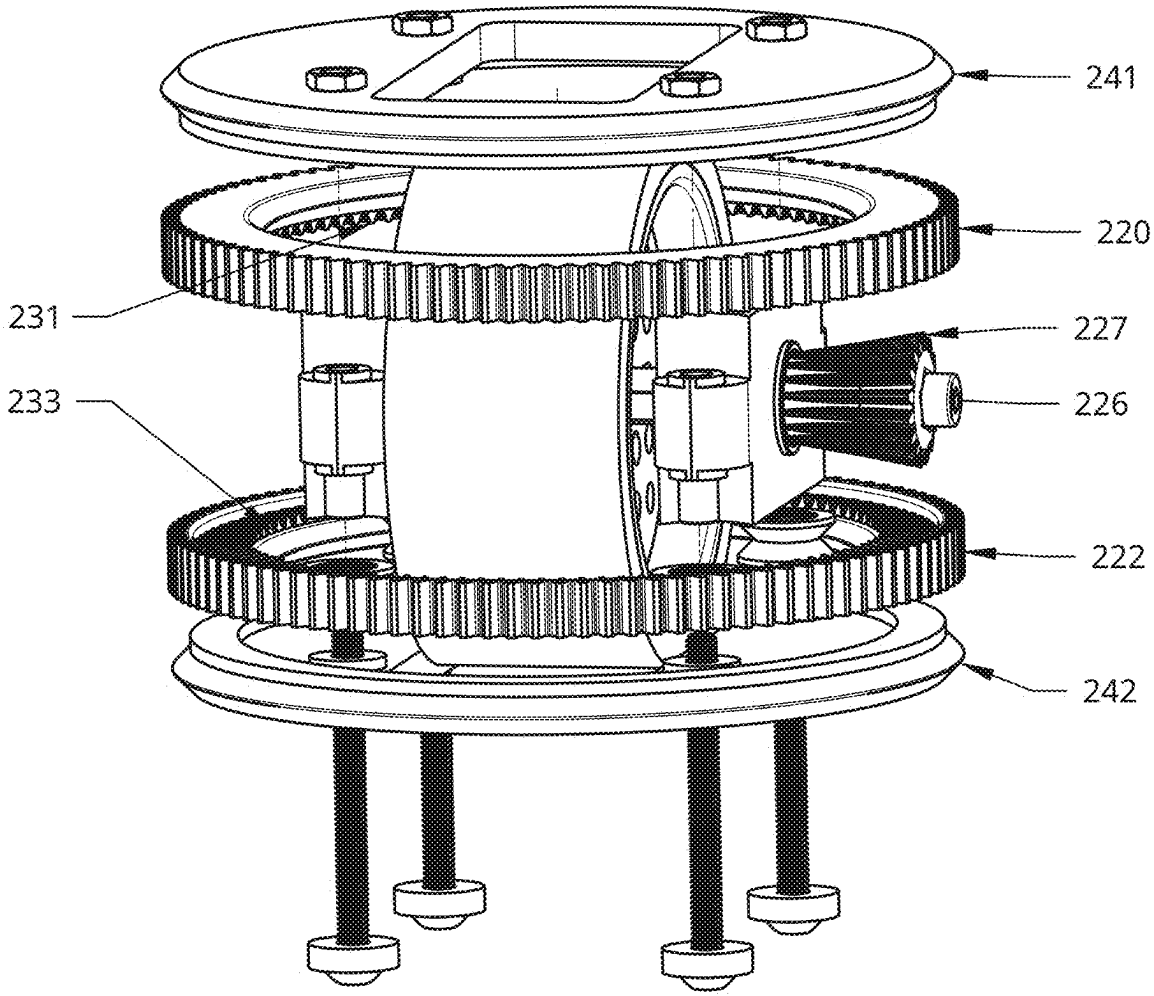
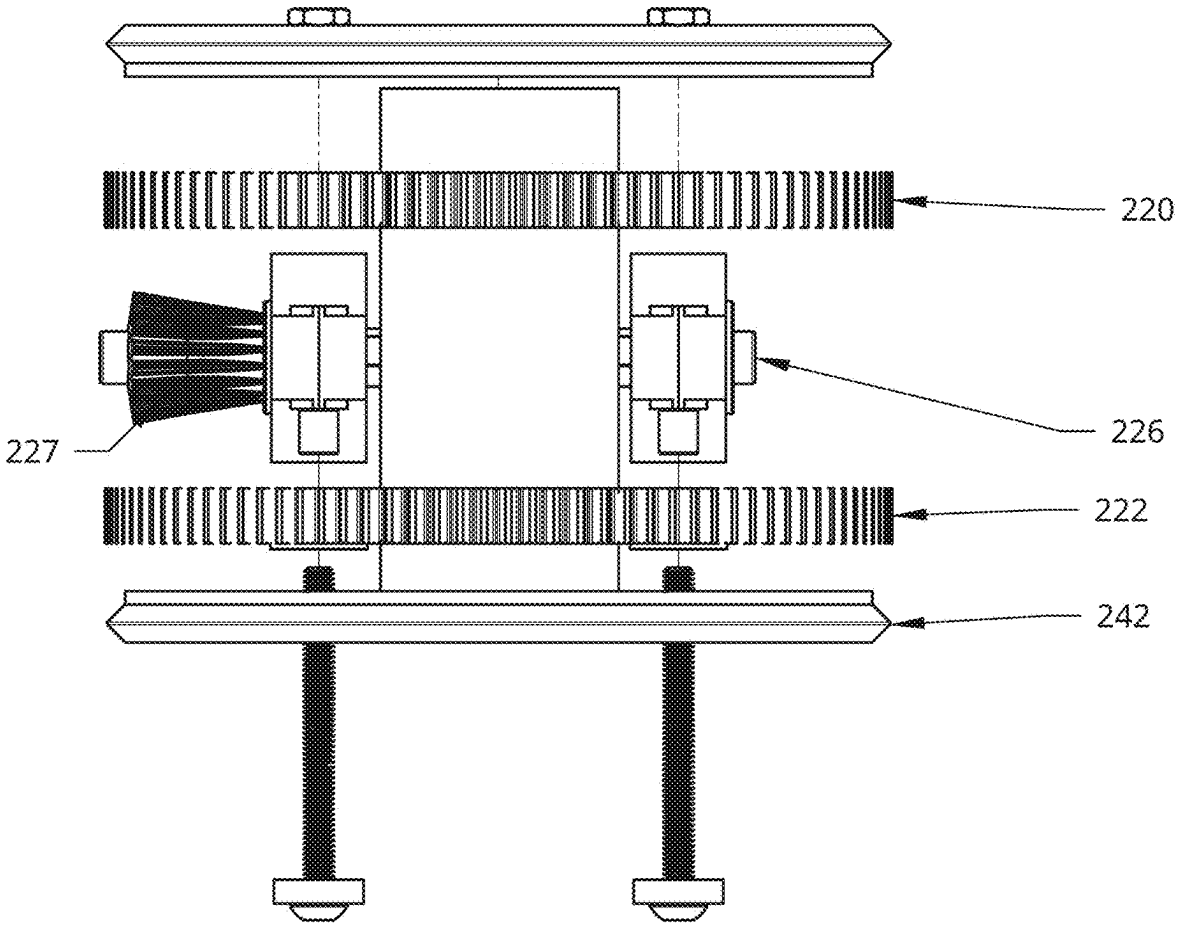


Figure 27B



SINGLE POD DIFFERENTIAL SWERVE DRIVE SYSTEM

FIELD OF THE INVENTION

[0001] The subject matter described herein relates to a novel robot with a single-pod differential swerve drive system. The robot is further equipped with a compact linear slide. This robot may have a particular but not exclusive utility for education, construction, and manufacturing.

BACKGROUND

[0002] The present invention relates generally to mobile robotic systems and, more specifically, to improvements in wheel-based drive mechanisms that enhance traction, maneuverability, and mechanical robustness.

[0003] One known robotic drive system is described in U.S. Pat. No. 8,794,386, which describes a robot equipped with a low-profile base that is movable in a generally horizontal direction. The robot's drive system incorporates a conventional skid-steer chassis driven by paired DC gear-motors acting through rubber-tired wheels on each side. Skid steering simplifies construction yet imposes two familiar limitations. First, turning requires differential wheel slip, so the robot's rubber-tired wheels are necessarily selected to have limited traction. Second, precise odometry is difficult because lateral slip is unmeasured. These restrictions limit the platform's usefulness when accurate navigation or high traction is critical.

[0004] Additional robotic drive systems are described in U.S. Pat. Nos. 9,211,922 and 10,384,338, which describe robots employing four compliant treaded wheels made up of interlinked elastomeric plates wrapped around sprocketed wheel discs. The plates conform to small obstacles and distribute load, giving better grip than smooth tires. Nevertheless, the design requires a relatively large overall wheel diameter, raising the frame and the center of gravity without a commensurate gain in lateral stability. Finally, steering remains skid-based, so the earlier concerns about limited traction and odometric drift persist.

[0005] A unique robotic drive system is described in U.S. Pat. No. 10,647,351, which describes a robot with wheels machined with peripheral scallops sized to hook onto ladder rungs or similar discrete features. The left-and right-side wheels can be re-indexed by a virtual differential so that opposed scallops align with the same rung. On flat ground the wheels behave almost like ordinary tires, but on stepped or caged surfaces the scallops generate positive mechanical interlock. Although the approach markedly increases obstacle-climbing capacity, it does so at the cost of continuous rolling contact. When the scallops are not engaged the wheel alternates between bite and free-roll, producing vibration that limits top speed and complicates closed-loop position control. The virtual differential itself is electronic, not mechanical, so the system still relies on skid turns and retains the tractive power penalty noted above.

[0006] The present robot addresses those shortcomings with a novel drive system that combines high maneuverability, high traction, and high-speed while retaining packaging flexibility.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1***a* is a perspective view of an exemplary robot embodying some principles of the present invention. FIGS. **1***b*-**1***d* are, respectively, side, bottom, and front views of the robot illustrated in FIG. **1***a*.

[0008] FIG. **2**A is a front view of an example embodiment of a swerve pod. FIGS. **2**B-**2**C are, respectively, top and side views of the swerve pod illustrated in FIG. **2**A.

[0009] FIG. **3** is an exploded perspective view of selected components of an embodiment of a swerve pod.

[0010] FIG. **4** is an exploded perspective view of selected components of an embodiment of a swerve pod.

[0011] FIG. **5** is an exploded perspective view of selected components of an embodiment of an omni-wheel subsystem.

[0012] FIG. **6** is an exploded perspective view of selected components of an embodiment of an omni-wheel subsystem.

[0013] FIG. **7** is a bottom view of selected components of an embodiment of a swerve pod.

[0014] FIG. **8** is a perspective view of an embodiment of a pod housing.

[0015] FIG. **9**A is a perspective view of selected components of an embodiment of an omni-wheel subsystem. FIG. **9**B is an exploded perspective view of an embodiment of an omni-wheel subsystem.

[0016] FIG. **10**A is a front view of selected components of an embodiment of a ladder-lift subassembly. FIG. **10**B is a side view of the subsystem illustrated in FIG. **10**A.

[0017] FIGS. **11**A and **11**B are top and side views, respectively, of an embodiment of an extended set of slide stages.

[0018] FIG. **12** is an exploded perspective view of selected components of an embodiment of slide stages.

[0019] FIG. **13** is a partly exploded perspective view of selected components of an embodiment of a continuous string slides subassembly.

[0020] FIG. **14** is an exploded perspective view of one embodiment of a string tensioning insert.

[0021] FIG. **15** is an exploded perspective view of one embodiment of an insert block.

[0022] FIG. **16** is an exploded perspective view of selected components of one embodiment of a driving spool subassembly.

[0023] FIG. **17** is a perspective view of selected components of an embodiment of a pivot base subassembly.

[0024] FIG. **18** is a perspective view of selected components of an embodiment of a robot cover.

[0025] FIG. **19** illustrates an exemplary method to control the rotation of an omni-wheel servo.

[0026] FIG. **20** illustrates an exemplary method to control the engagement of an omni-wheel servo.

[0027] FIG. **21** illustrates an exemplary method to process an image input.

[0028] FIG. **22** illustrates an exemplary method to process an image input.

[0029] FIG. **23** illustrates a perspective view of an exemplary robot embodying some principles of the present invention.

[0030] FIG. **24** illustrates a perspective view of selected components of an embodiment of a claw arm.

[0031] FIG. **25** illustrates a perspective view of selected components of an embodiment of a ladder-lift subassembly.

[0032] FIG. **26** illustrates a perspective view of embodiment of an insert block.

[0033] FIG. **27**A is an exploded perspective view of selected components of one embodiment of a swerve drive pod. FIG. **27**B is an exploded front view of the components illustrated in FIG. **27**A.

DETAILED DESCRIPTION

[0034] For ease of understanding, reference is made herein to the accompanying figures. Identical reference numerals designate identical or functionally equivalent elements throughout the drawings. All dimensional relationships are exemplary and may be varied without departing from the scope of the inventive concepts described.

[0035] FIG. **1**A shows a perspective view of an example embodiment of a robot **100** constructed in accordance with the present disclosure. Additional details of the robot **100** are further illustrated in FIGS. **1**B-**1**D. The robot comprises a chassis **110**, a swerve pod **200** centrally mounted to the chassis, a pair of servo-driven omni-wheel assemblies **300**, **302** located on opposite lateral sides of the swerve pod, an omni-wheel disengagement clutch, a vertical ladder-lift slide subsystem **400**, an articulated arm and wrist assembly **500** coupled to the slide subsystem, a claw end **550**, and a control hub **600**.

[0036] FIGS. **2**A-**2**C and FIGS. **3**-**4** illustrate an example embodiment of the swerve pod **200**. The system includes a differential swerve pod housing **210** (shown in FIG. **3**) secured between two chassis plates **112**, **114**. Two planetary gear motors (M**1**, M**2**) **212**, **214** are arranged vertically and drive independent spur gears **216**, **218**. Each spur gear meshes with a corresponding differential gear stage (**220** upper, **222** lower) that ultimately drives a high-traction drive wheel **225**. As illustrated in FIGS. **27**A and **27**B, the drive wheel **225** is mounted on an axle **226** with a wheel gear **227** that engages with secondary sprockets on the lower face **231** of the upper differential gear stage **220** and the upper face **233** of the lower differential gear stage **222**.

[0037] The drive wheel **225** is preferably a 72 mm diameter traction wheel (such as a Rhino wheel) secured to a hex output shaft (not visible). A through-bore magnetic encoder **230** mounted vertically above the drive wheel **225** on a support bracket **232** provides pod-orientation feedback to the control system. The magnetic encoder **230** measures the rotation, and thus the angle, of a wheel case **234** fixedly mounted over the drive wheel **225**.

[0038] The swerve pod **200** provides a rotatable coupling between the drive wheel **225** and the differential swerve pod housing **210**, and thus, the drive wheel **225** may be rotated to substantially any orientation relative to the chassis **110**. The drive wheel **225** and differential gear stages **220**, **222** are vertically supported by upper and lower pod plates **241**, **242** that ride in v-groove bearings **243** mounted to the differential swerve pod housing **210**. As illustrated, there are six upper v-groove bearings and six lower v-groove bearings, but different v-groove bearing configurations, including either more or less bearings, are possible. The v-groove bearings are preferably equally spaced around the periphery of the upper and lower pod plates (**241**, **242**).

[0039] The orientation and rotation of the drive wheel **225** is controlled by the selective engagement (rotation) of the planetary gear motors. Pod rotation is achieved by commanding planetary gear motors M**1** and M**2** to rotate in the same direction and at the same speed. Because the upper and lower differential gear trains **220**, **222** are mechanically isolated, equal-direction rotation causes the wheel case **234** and drive wheel **225** to yaw without imparting translational ground force. Thus, while the differential swerve pod housing **210** remains substantially still, the drive wheel **225** rotates about a central vertical axis **250**. This rotation is measured by the magnetic encoder **230**. Wheel rotation is achieved by commanding the planetary gear motors M**1** and M**2** to rotate in opposite directions and at the same speed. Operating the motors in opposite directions causes the upper and lower differential gear stages **220**, **222** to rotate in opposite directions. The wheel axle **226** and the drive wheel **225** are thus driven to rotate, propelling the robot linearly without changing pod heading. Fine-grained blending of the speed and direction of the planetary gear motors M**1** and M**2** allows for simultaneous rotation of the drive wheel **225** along both its vertical axis **250** and its axle **226**.

[0040] With only a single ground-contact wheel **225**, the robot **100** would be potentially unstable. One option would be to implement a dynamic balancing mechanism, such as those described in U.S. Pat. No. 7,275,607. The inventors have found that a simpler and more reliable approach—which advantageously does not require continuous powering to maintain the robot's stability—is to provide additional group support points located near the outer periphery of the robot **100**. FIGS. **2**A-**2**C shows a primary support axis formed by the drive wheel **225** and the two laterally-spaced omni-wheels **300**, **302**. FIGS. **1**B and **1**D show roller-ball bearings **260**, **262** mounted fore-and-aft on the chassis sides to provide a secondary support axis. The roller-ball bearings may be attached to the chassis using 3D printed mounts. In some embodiments, there may be more than one roller-ball bearing located at each fore location, aft location, or both locations. Together, the roller-ball bearings **260**, **262** and the omni-wheels **300**, **302** constrain pitch and roll while permitting unrestricted yaw.

[0041] FIGS. **2**A-**2**C further illustrate the two omni-wheel subassemblies. An exemplary single omni-wheel subassembly **350** is illustrated in FIGS. **5** and **6**. Each subassembly comprises:

- **[0042]** A continuous rotation micro-servo motor **310** with a 25-tooth output spline **352**.
- **[0043]** A 40-tooth servo gear **354** coupled to the servo axle.
- **[0044]** A mating 36-tooth pinion gear **356** mounted to a lateral shaft **316** that spins within a first bearing **358** embedded in the differential swerve pod housing **210** and a second bearing **360** secured in a side chassis plate **114**.

[0045] In one embodiment, the side chassis plate **114** is a U-channel, and the shaft **316** is a 40 mm hex shaft. Further attached to the lateral shaft **316** is an omni-wheel **362**. The omni-wheel **362** may be coupled to the lateral shaft **316** using a hub **364**. In one embodiment, the omni-wheel **362** is a 72 mm diameter omni-wheel, and the hub **364** is a sonic hub.

[0046] The resulting 40:36 ratio yields a 1.11× speed increase (in revolutions per minute) from servo to omni-wheel, enabling brisk rotational torque about the primary support axis. When the servo gears are disengaged (as described further below), the omni-wheels free-roll, permitting full translational velocity in the lateral direction. Engaging the omni-wheels creates a torque force on the robot about its central vertical axis, allowing for precise control over the yaw of the robot **100**. This is helpful because, as will be discussed below, the swerve pod **200** is able to yaw freely within the robot **100** chassis, and thus, the swerve pod **200** is generally unable to rotate the robot **100**. Instead, the swerve pod **200** facilitates translational movement of the robot **100** in any direction, irrespective of the robot **100**'s orientation.

[0047] As best seen in FIGS. **7** and **8**, the pod housing **210** presents six recesses (**240** *a-f*) on its upper and lower faces which capture upper and lower pod plates via v-groove ball bearings **243** (shown in FIG. **4**) to enable smooth pod yaw. The pod housing **210** further includes:

[0048] Motor saddles **244** position the gear motors coaxially with the spur gears.

[0049] Omni-wheel axle bores **250** centered on the pod mid-plane.

[0050] Four mounting flanges **252** (two of them shown) for attaching external chassis rails. In one embodiment, the mounting recesses are quad-block mounting flanges spaced 144 mm apart for direct interface with U-channel rails.

[0051] In one embodiment, the overall pod housing **210** footprint is approximately 192 mm×144 mm, allowing easy installation in a compact robotic vehicular design having length, width, and height dimensions of less than approximately 457.2 mm (18 inches).

Omni-Wheel Disengagement Clutch

[0052] FIGS. **9***a*-**9***b* illustrate another embodiment, which incorporates a disengageable clutch mechanism into the driveline between a micro-servo motor and its corresponding omni-wheel. A dual-mode servo motor **902** has its output shaft (not shown) coupled to a 40-tooth output gear **904**. The output gear **904** enmeshes with a floating intermediate 40-tooth gear **906** mounted on a shaft **924** rotatable within two bearings **912** captured in a 3D printed arm **910**. A flexible biasing spring **914** urges the arm **910** upward, creating a small gap between floating intermediate gear **906** and both the output gear **904** and a drive gear **916** mounted on an axle (not shown) with an omni-wheel **920**. The arm **910** is controllably pivoted around shaft **918** and against the biasing spring **914** to lower the floating intermediate gear **906** to enmesh with both the output gear **904** and the drive gear **916**. This controlled movement may be achieved in a variety of ways. In one embodiment, a tensioning cable (not shown) is tied to the end holes on arm **910**. The tensioning cable also couples to a control servo (**902**) so that rotating the control servo pulls the tensioning cable, urging the arm **910** against the biasing spring **914**. Releasing the servo allows the biasing spring **914** to once again urge the arm **910** away from the other drivetrain components. In this way, the omni-wheels **920** are free to rotate about their primary axis, presenting substantially no drag on the robot's free movement.

Continuous-String Vertical Ladder-Lift Slides

[0053] The drive system discussed above, including swerve pod **200** and omni-wheel subassemblies, may be used to provide a controllable drivetrain for a variety of robots and/or vehicles. Additional components may be mounted to a robot **100** to facilitate performing any of a wide variety of tasks. FIG. **1** shows robot **100** equipped with a vertical ladder-lift slide subsystem **400**.

[0054] FIG. **10**A shows a front view of the vertical ladder-lift slide subsystem **400**. FIG. **10**B shows a side view of the same. A set of five slide stages **402** are shown in their retracted position. FIG. **11**A shows a top view of the slide stages **402** in their extended position. FIG. **11**B shows a side view of the slide stages **402** in their extended position.

[0055] FIG. **12** shows two adjacent slide stages, with a first slide stage **404** retracted and a second slide stage **406** extended. Each slide stage comprises an outer slide rail **408** and an inner slide rail **410**. The outer slide rail **408** of the second slide stage **406** is coupled, via a countersunk screw **410** and a button head screw **412**, to the first slide stage **404**. Between the first slide stage **404** and the second slide stage **406** are two inserts **414**, **416**. Each insert is equipped with an extension v-groove bearing **418** and a retraction v-groove bearing **420** on each side for a total of four bearings per insert. As shown in FIG. **13**, for each side of the stages, an extension string **430** is wound around the series of extension v-groove bearings **418** on each of the stacked slide stages **402**. Exerting a pulling force on the extension string **430** at its first end **434** urges together the inserts coupled to opposite ends of adjacent slide stages. Thus, the outer and inner slide rails **408**, **410** of each stage are urged linearly apart, causing the overall slide stages **402** to extend toward their extended (or open) configuration. Similarly, a retraction string **436** is wound around the series of retraction v-groove bearings **420** on each of the stacked slide stages **402**. At the topmost stage **403**, each string **430**, **432** is fixedly tied to a string tensioning insert **440** that is affixed to the inner slide rail **410** of the topmost stage **403**. Exerting a force on retraction string **436** at its first end **436** urges the inserts coupled to opposite ends of adjacent slide stages together. Thus, the outer and inner slide rails **408**, **410** of each stage are urged linearly together, causing the overall slide stages **402** to retract toward their retracted (or closed) configuration. In one embodiment, the slide rails **408**, **410** may be Misumi SAR-240 telescopic rails.

[0056] FIG. **14** illustrates additional details of one embodiment of the string tensioning insert **440**. The string tensioning insert **440** comprises a tensioning block **460** with a recessed channel **462** for mounting to an inner slide rail. Four tensioning screws **464** each couple to a corresponding pair of square nuts **466** embedded within the tensioning block **460**. Mounted on each tensioning screw is a string tie **468** and a locking nut **465**. Each of the extension and retraction strings **430**, **432** is knotted around a corresponding string tie **468**. By rotating the locking nut **465**, the distance between the string tie **468** and the end of a slide rail may be adjusted, thereby allowing for individual calibration of the slack or tension of each string **430**, **432** for best performance.

[0057] FIG. **15** illustrates additional details of one embodiment of insert **414**. The insert **414** comprises an insert block **470** with a recessed channel **472** for mounting to an inner or outer slide rail. On either side of the insert block **470**, a bolt **474** serves as an axle for a pair of v-groove bearings **476** separated by washers **478**. The v-groove bearings **476** allow for both extension and retraction strings to be wound on both sides of the slide stages **402**. This arrangement is preferred as it prevents the extension or retraction actions from generating a lateral torque force that may cause the inner and outer slide rails to bind. In other embodiments, only one extension string **434** and one retraction string **432** are provided, and they may be located either together on one side of the slide stages **402** or on opposite sides. With other embodiments, more than two extension strings **434** and two retraction strings **432** may be employed as well.

[0058] FIG. **16** is a perspective view of the dual-spool drive **500** for pulling the extension and retraction strings **432**, **434**. A 120 mm shaft **522** is inserted into flanged

bearings **524** mounted between two frames **526**, **528** that is itself affixed to the rotating arm pivot shaft **534** (discussed further below). Two slim v-groove spools **530** are bolted to hubs **532** and axially keyed to the shaft **522**. A planetary motor **536** drives the shaft **522** via a belt **538** running on a 16-tooth drive pulley **540** and 24-tooth driven pulley **542**, giving a 3:2 speed reduction. Extension strings (not shown in FIG. **16**) are anchored to the inner grooves of the spools **530**, and retraction strings **452** to the outer grooves of the spools **530**. When the motor **536** turns the spools **530** in one direction, the extension strings are pulled while the retraction strings are let out. When the motor **536** turns the spools **530** in the opposite direction, the extension strings are let out while the retraction strings are pulled. Thus, the extension strings and retraction strings are gathered or released at equivalent rates, ensuring synchronous slide motion and constant string tension.

Arm, Wrist, and Claw Subsystem

[0059] FIG. **17** depicts a main arm **702** affixed to the pivot shaft **534**. A motor **704** drives the shaft through a 5:1 spur gear pair **706** (as further illustrated in FIGS. **10***a*-**10***b*), providing adequate torque to raise the extended slide assembly. A lowest rail of the slide rails **402** is affixed to the arm **702**.

[0060] A second pivot point **710** at the distal end of the highest slide rail mounts a wrist frame assembly **712**. A camera **720** may be attached to the wrist assembly **712** for object location and wrist positioning. The wrist assembly includes a servo motor **714** that actuates the opening and closing of opposing trapezoidal fingers **716**, **718**. The trapezoidal fingers may be 3D printed or fabricated from layers of clear polycarbonate and are controllably opened and closed to act as a claw for grasping an object (not shown).

Sideplates, Covers, and Wire Management

[0061] FIG. **18** shows various cover pieces for enclosing components of the robot **100**. A first side cover **800** and a second side cover **802** provide smooth side surfaces and protect machinery within the robot **100** from unwanted intrusions. A backplate **804** similarly protects the backside of the robot **100**. A first-side top cover **806** and a second-side top cover **808** protect the upper portions of the robot **100**. In some embodiments, some or all covers **802**-**808** may be integrated into a monolithic whole. In other embodiments, the covers **802**-**808** are each independently mounted to the robot chassis. In still other embodiments, not all the covers (**802**-**808**) are present, although in all configurations covers **806** and **808** require **800** and **802** respectively. The second-side top cover **808** preferably has an aperture for a control hub **600** as shown in FIG. **1**A. The first-side top cover **806** preferably has a slot **810** to facilitate passing control wires from the interior space of the robot **100** to the wire management extension **812**, shown in FIG. **1**A. The wire management extension comprises a set of bars interconnected in a scissor lift arrangement. Control wires for powering and controlling components at the end of the vertical ladder-lift slide subsystem **400** a carried in channels that reside in recessions in the scissor lift bars, allowing the wires to passively follow the extension and retraction movement of the ladder-lift slide subsystem **400**. The bars are preferably 3D printed from polylactic acid (PLA), while the channels are preferably a cable sleeve. Rotatable joints couple the bars to one another, composed of a bearing and a 3D-printed v-spring. Screw connections or zip ties may be employed to secure control wires within the recesses during extension and retraction of the scissor lift bars. The rotatable joint v-springs are preferably printed from thermoplastic polyurethane (TPU), allowing them to flex significantly and provide a spring-like tensioning that urges the scissor lift toward its collapsed state.

Control, Vision, and Software Architecture

[0062] Robot **100** preferably includes a control hub **600** providing centralized electrical control of its various motors, sensors, and other electrical components. The control hub **600** may facilitate programming of functionality, such as autonomous operation. Manual control of the robot **100** is preferably provided by a wireless communication link to a handheld user control interface. In one embodiment, the handheld user control interface is a Logitech F310 gamepad. Additional details and examples of providing user inputs may be provided to the robot **100** are in U.S. Pat. No. 12,251,627 to Ozaki, et al., which is hereby incorporated in its entirety for all purposes.

[0063] An input for controlling movement of the robot **100** relative to the field includes a two-dimensional x-y input as may be provided by a gamepad stick. A two by two rotation matrix is created for the target pod orientation and aligned in the direction of the input vector with the lookAt operation. The target pod rotation matrix is then right-multiplied to the inverse of the chassis rotation matrix, resulting in the target local pod rotation matrix, which is in the robot's internal coordinate system. The chassis rotation matrix represents the orientation of the robot in the field coordinate system, and may be obtained from an IMU device mounted to the chassis such as the control hub **600** or a visual odometry sensor (OTOS). An additional rotation matrix, representing the measured local pod orientation, is defined as the identity matrix and rotated by 0, where 0 represents the heading of the drive wheel **225** in respect to the robot **100**'s current heading as derived from information provided by the magnetic encoder **230**. The target local pod rotation matrix is then right-multiplied to the inverse of the measured local pod rotation matrix, and the result is multiplied by the vector (1,0) to obtain the delta vector. The delta vector is then resolved, through assessment of x and y components, into translational and rotational values of the drive pod that dictate differential speeds for motors M**1** and M**2**. As second input, for example a second gamepad stick input, may be used to control the robot's orientation by selectively engaging the omni-wheel servos. A control loop preferably integrates the orientation changes caused by the omni-wheel servos, relative to the translational movement provided by the swerve drive pod, thereby minimizing translation and angular adjustment errors.

[0064] As referenced in the discussion of FIGS. **9**A and **9**B, the omni-wheels may be selectively coupled to the omni-wheel servo motors. This selective engagement may be substantially automatically controlled by monitoring a power magnitude $|P|$ to the omni-wheel servos. When $|P|<$threshold ε, the clutch servo is commanded to lift (disengage) the omni-wheels, preventing unnecessary friction. When $|P|\geq\varepsilon$, the clutch drops (engages) the wheels. Disengaging the clutch also ensures that the servo motors are not back-driven by movement of the omni-wheels.

Vision-Guided Object Acquisition

[0065] The control hub **600** may incorporate programming to facilitate computer-assisted operation of the vertical ladder-lift slide subsystem **400**, articulated arm and wrist assembly **500**, and the swerve drive system. A video input to the control hub **600**, such as from a web camera, may provide visual information about an area generally in front of the robot **100**. There may be various different-colored articles in that area. FIGS. **21** and **22** illustrate example image processing methods for automating control of the robot using such video input data. Upon user selection of a target color (such as via a button input on a gamepad), a processor within control hub **600** may analyze an image from the video input. The image may be resized and converted from RGB to HSV color space. The inventors have found that object detection under variable lighting conditions is more reliable when performed in HSV color space. Noise may be eliminated by blurring the image with a median blur. The image may be modified by drawing a border around its outer edge, which the inventors found improves detection of objects partly located beyond the field of view. An adaptive threshold filter is then applied to outline the edge of each object. Dilation and erosion filters may also be applied to reduce noise and clean up the object edges.

[0066] Each object edge is converted to a contour, and a bounding rectangle is calculated that encompasses the contour. If the bounding rectangle is determined to be valid, an image moment is calculated, and from the moment, the size and centroid of the object is estimated based on the number of pixels within the moment. This overall process is repeated for all detected objects.

[0067] If multiple objects are detected, then their centroid values are used to estimate which object is closest to the robot **100**. The selected object centroid is then used to calculate angular offset from the robot's centerline and a distance to the object. The robot **100**'s claw is commanded to rotate to an orientation equal to the angular offset $+\pi/2$. This orients the claw to a suitable angle for engaging with the object (i.e., picking up the object). If the lateral (left-right) distance to the object exceeds a programmable threshold, the swerve drive subsystem is commanded to maneuver the robot **100** so that the robot **100** is positioned with the object near the robot **100**'s centerline. The arm is lowered, and the ladder-lift slide subsystem **400** is commanded to extend the linear slides by the distance to the object, thus causing contact between the claw end **550** and the object. The claw is commanded to close, grasping the object between its fingers. The arm is then raised slightly and the ladder-lift slide subsystem **400** is retracted.

[0068] The robot **100**'s location may be estimated by starting at a known location and integrating its movements. This approach, however, is subject to accumulating inaccuracies from small errors over time. The robot **100** may also be equipped with a visual odometry sensor (OTOS), such as that commercially available from Sparkfun.

Omni-Wheel Rotational Control

[0069] Commands to control the rotation of the two omni-wheel servos may be provided as illustrated in FIG. **19**. Firstly, a two by two rotation matrix is defined for the target chassis orientation and assigned to the identity matrix. Then a vector, representing the target chassis orientation obtained through user input, is normalized. The rotation matrix is then pointed in the direction of the target chassis vector through the lookAt operation. The target chassis rotation matrix is then right-multiplied to the inverse of the chassis rotation matrix. The resulting delta rotation matrix is in the robot's internal coordinate system. The delta rotation matrix is then multiplied by the vector (1,0) and the inverse tangent of the result, representing the angle to turn the robot, is fed to a PID loop.

[0070] The PID loop calculates the difference between the newly input value and the target position, which provides an error value representative of the angle and distance between the desired orientation and the current orientation. The error is multiplied by a configurable constant value Kp, added to a configurable constant Ki times an integral value, and added to a configurable constant Kd times the error velocity (i.e., change in error divided by change in time) to produce a calculated output power. Finally, the calculated output power value is used to control the speed of the continuous rotation servo motors, if the power value exceeds a configurable threshold.

[0071] Engagement of the omni-wheel servo motors may be controlled using a process as generally illustrated in FIG. **20**. First, the measured and calculated values from the FIG. **19** process are input. These values are then used to determine whether the selectively engageable clutch mechanism between the omni-wheel servo motors and the omni-wheels should be engaged or disengaged. For example, if the calculated output power value exceeds a threshold value, the clutch should be lowered to provide mechanical engagement between the omni-wheel servo motors and the omni-wheels. Alternatively, if the calculated output power value is below the threshold value, the clutch should be raised to disengage the omni-wheel servo motors from the omni-wheels. In that event, the actual output power to the omni-wheel servo motors is also reduced to zero, thereby preventing spurious and wasteful rotation of the omni-wheel servo motors.

Vertical Linear Slides

[0072] FIG. **23** illustrates an example embodiment of a robot **2300** equipped with a claw arm **2302** mounted to vertical linear slides **2304**. The vertical linear slides **2304** may operate similarly to the vertical ladder-lift slide subsystem **400** described previously, however, the vertical linear slides **2304** are mounted in a fixed-vertical orientation. The retraction components are important as to let it reach multiple heights and adjust location even when fully extended.

[0073] FIG. **25** illustrates an example embodiment of vertical linear slides **2502**. Each linear slide **2504** includes an inner slide and outer slide. Mounted between each adjacent pair of linear slides **2504** is an insert **2600**, shown in detail in FIG. **26**. A through-hole **2602** in the insert facilitates attaching the insert **2600** to a linear slide **2504** with a screw (not shown). The insert **2600** also includes a recessed portion **2604** for aligning the insert **2600** with the linear slide **2504**. An axle hole **2606** is provided for an axle (not shown) to which two v-groove bearings (not shown) are rotatably attached, one on either side of the insert **2600**. A variety of screw holes **2608** are also provided for affixing an extension string (not shown). An extension string is threaded through the v-groove bearings on each side of the linear slides **2502** in a "ladder lift" manner. Through this method, each linear slide **2504** has one long string that connects to

the next slide **2504** through the slide inserts **2600**. This allows all the linear slides **2502** to move in unison. This also improves reliability as a slide set can break and the opposite slide set can compensate for it. The use of separate strings at each slide stage also allows for multiple strings to break while retaining some movement functionality for the linear slide overall. Beginning at the top insert, a string is threaded through the top hole **2608** on both sides of the linear insert **2600**. The string then connects to the corresponding lower hole **2608** of the lower insert **2600** of the slide **2504** in front of the initial slide. The string then loops back to the original top insert **2600** through the lower hole **2608** on the top insert **2600**. Two strings per slide insert **2600** are threaded over a v-groove bearing (not shown) and attach to an adjacent slide insert **2600**. The v-groove bearing operates as a mount pulley. Each side of the insert is mirrored which results in two strings per insert **2600**. The pattern is repeated for every slide **2504**. The extension string is preferably Kevlar string.

[0074] FIG. **24** illustrates an example embodiment of the claw arm **2302**. A u-channel base **2402** supports an angle bracket **2404** and horizontal slide support **2406**. At the other end of horizontal slide support **2406** is a servo support bracket **2408**, to which there is mounted a servo motor **2410**. A pinion gear on the servo motor **2410** engages with a rack **2412** extending along the length of a linear slide **2414**. Rotation of the servo motor **2410** thus causes the linear slide **2414** to extend or retract. Mounted to an upper, sliding portion of the linear slide **2414** is a claw mechanism **2416**. The claw mechanism **2416** includes two pinching fingers **2418** whose movement is controlled by a second servo motor **2420**. The design of pinching fingers **2418** may be tailored to improve their gripping capabilities with respect to specific object types. The inventors found that a trapezoidal head configuration of the pinching fingers **2418** to be particularly advantageous.

Materials and Manufacturing Considerations

[0075] The material of various components has been described throughout, but these details are merely exemplary, and any suitable materials may be used. For example, load-bearing components and those potentially subject to friction wear may be steel, stainless steel, aluminum, titanium, other metals, or hard plastic. Printed components may be made from any suitable filament, including PLA, TPU, or Onyx; the infill of printed components may vary from about 20% to about 100%. Shafts may have a circular, D-shaped, or hexagonal cross-section. Some u-channels, linear slides, v-groove bearings, motors, hubs, gears, wheels, screws, shafts, and other components may be commercially available from vendors including goBILDA. For example, shafts may be REX shafts.

[0076] The foregoing detailed description is intended to illustrate, not limit, the scope of the inventive concepts. Variations and modifications within the ordinary skill of the robotic systems engineer are contemplated and fall within the teachings of the present disclosure.

1. An omni-directional drive system for a robotic vehicle, the system comprising:

a chassis having a longitudinal axis and a lateral axis;

a single swerve pod disposed substantially at an intersection of the longitudinal and lateral axes, the swerve pod including

(a) a traction wheel rotatable about a first axis generally perpendicular to the chassis, and

(b) a pod housing supporting the traction wheel for rotation about a second axis generally parallel to the chassis so that the traction wheel can be steered to any azimuth relative to the chassis;

a first electric motor coupled to the traction wheel through a first gear train so as to impart driving torque to the traction wheel;

a second electric motor coupled to the pod housing through a second gear train configured cooperatively with the first gear train to differentially rotate the pod housing relative to the traction wheel, thereby steering the traction wheel without interrupting wheel rotation; at least one chassis support element located remotely from the swerve pod and engaging an underlying surface to stabilize the chassis during motion; and

a controller in communication with the first and second electric motors and operable to (i) command a desired heading by rotating the pod housing to a selected azimuth and (ii) command a desired translational velocity by driving the traction wheel, whereby the robotic vehicle is propelled in any horizontal direction using only the single swerve pod.

2. The drive system of claim **1**, wherein the traction wheel has a diameter of approximately 72 mm and is mounted on a hexagonal-profile shaft received in bearings carried by the pod housing.

3. The drive system of claim **1**, wherein the drive system is mounted to a robot, the robot further comprising a vertical ladder-lift subassembly including at least five linear slides.

4. The drive system of claim **3**, wherein the vertical ladder-lift subassembly is mounted to a chassis of the robot via a pivot mount.

5. The drive system of claim **4**, wherein the robot further comprises:

a claw affixed to a terminal end of the vertical ladder-lift subassembly,

a motor affixed to the terminal end of the vertical ladder-lift subassembly, for controllably opening and closing the claw,

at least one control wire extending from the motor to a control hub on the chassis of the robot that remains stationary when the vertical ladder-lift subassembly pivots via the pivot mount.

6. The drive system of claim **5**, wherein the robot further comprises a passive scissor-lift, wherein the control wire is mounted in a channel on the passive scissor-lift.

7. The drive system of claim **3**, wherein the vertical ladder-lift subassembly is fixedly mounted to a chassis of the robot in a vertical orientation.

8. The drive system of claim **7**, where the robot further comprises a horizontal claw arm.

9. The drive system of claim **1**, further comprising an absolute through-bore encoder coaxially aligned with the second axis and secured to the pod housing for sensing the azimuth of the traction wheel relative to the chassis.

10. The drive system of claim **1**, wherein the chassis support element comprises a pair of omni-wheels positioned on opposite sides of the swerve pod and driven by respective continuous-rotation servos to impart controlled rotation of the chassis about the swerve pod.

11. The drive system of claim **7**, further comprising a selectively engagable clutch that decouples the omni-wheels

from the continuous-rotation servos when the robotic vehicle is translating in a direction parallel to the omni-wheel rollers.

12. The drive system of claim **1**, wherein the pod housing is removably attached to the chassis by a plurality of vertical fasteners passing through upper and lower pod plates and retained by v-groove bearings.

13. The drive system of claim **1**, wherein the controller executes field-oriented control logic that employs feedback from the through-bore encoder and from a visual odometry sensor to coordinate steering of the pod housing and rotation of the traction wheel.

14. The drive system of claim **1**, wherein the first electric motor drives an upper differential spur gear and the second electric motor drives a lower differential spur gear, the upper and lower differential spur gears meshing with a common central spur gear affixed to the traction wheel, thereby effecting simultaneous wheel propulsion and steering.

15. An omni-directional drive system for a robotic vehicle, comprising:

a chassis;

means for supporting a single wheel at a central location on the chassis;

means for rotating the wheel about a first axis to drive the vehicle;

means for steering the wheel about a second axis generally perpendicular to the first axis to select a direction of travel;

means for stabilizing the chassis during motion, the stabilizing means being spaced from the wheel; and

means for controlling the rotating means and the steering means to propel the vehicle in any horizontal direction using only the single wheel.

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