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(54) **COMPONENT CONTROL SYSTEM FOR A VEHICLE**

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B60W 10/20	(2006.01)
B60W 10/18	(2012.01)
B60W 10/04	(2006.01)

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CPC ***B60W 10/00*** (2013.01); ***B60W 10/04*** (2013.01); ***B60W 10/18*** (2013.01); ***B60W 10/20*** (2013.01)

(58) **Field of Classification Search**

USPC 701/20–100; 713/1–50; 700/50–100; 180/50–100

See application file for complete search history.

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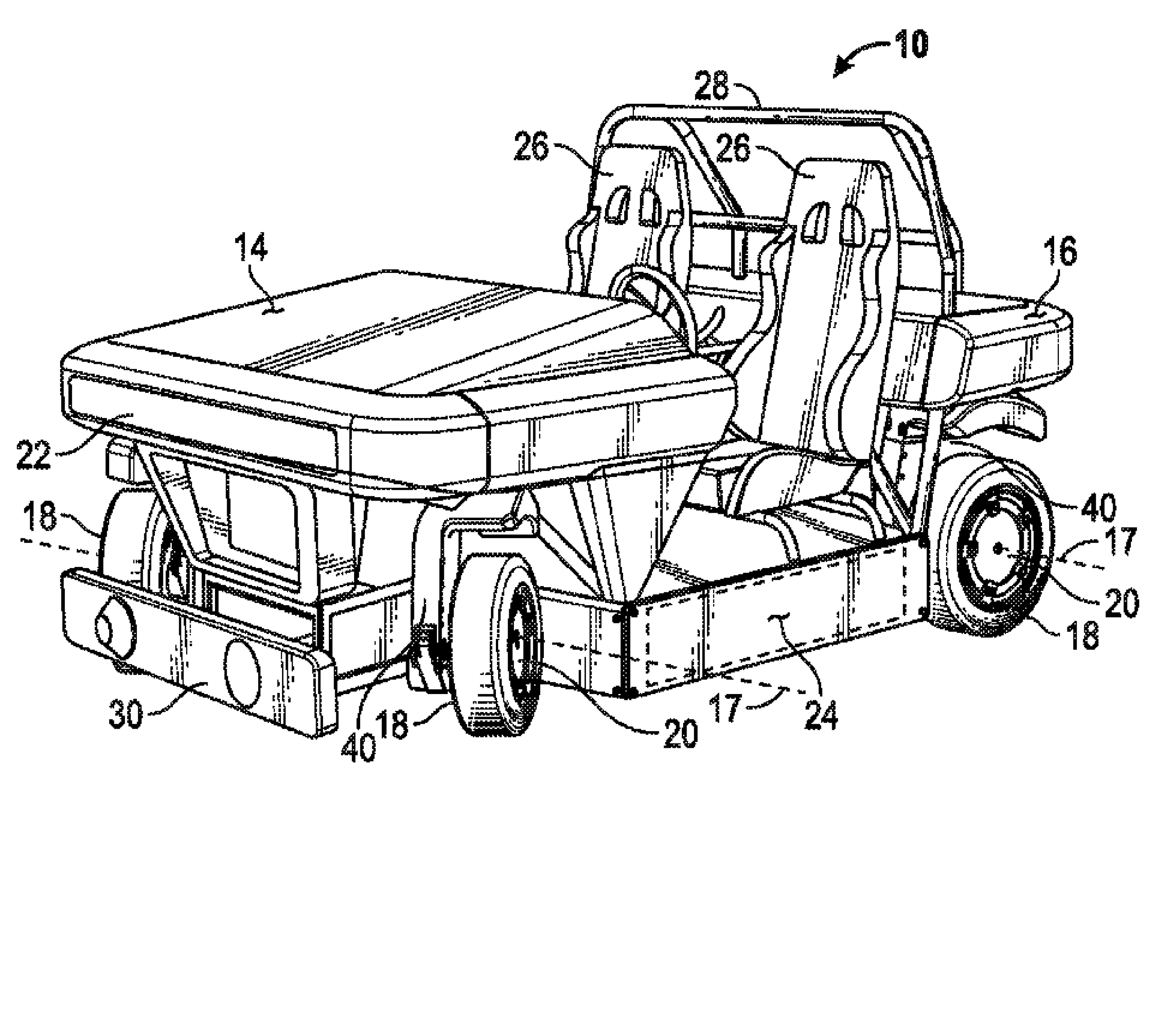
(57) **ABSTRACT**

A vehicle includes a chassis, a modular component, and a central operating system. The modular component is supported by the chassis. The central operating system includes a component control system, a primary master controller, and a secondary master controller. The component control system is configured for controlling the modular component. The primary and secondary master controllers are in operative communication with the component control system. The primary and secondary master controllers are configured to simultaneously transmit commands to the component control system. The component control system is configured to accept commands from the secondary master controller only when a fault occurs in the primary master controller.

20 Claims, 6 Drawing Sheets



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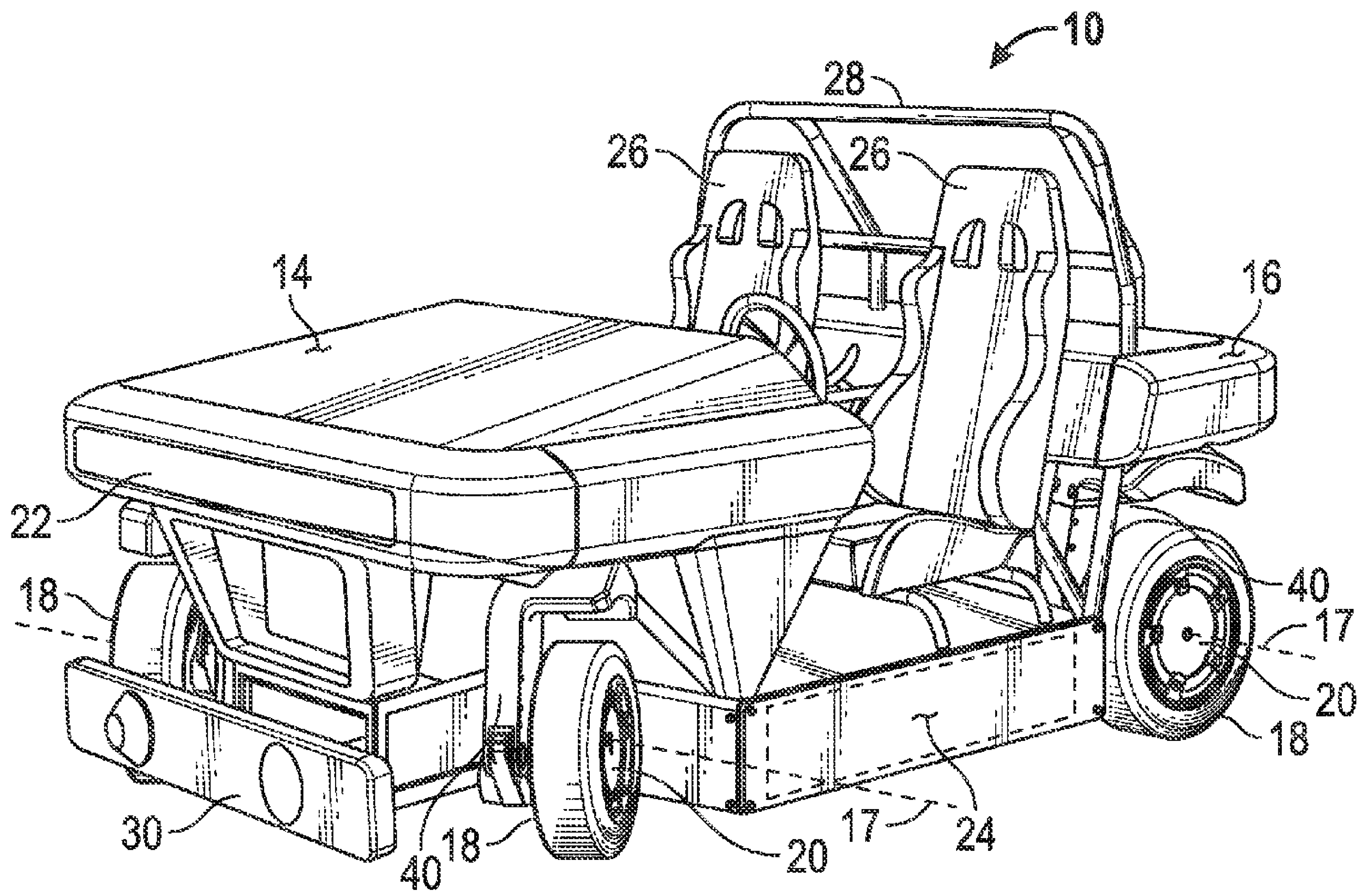
10
28
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26
14
16
22
18
40
17
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18
30
40
18
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17
24

FIG. 1

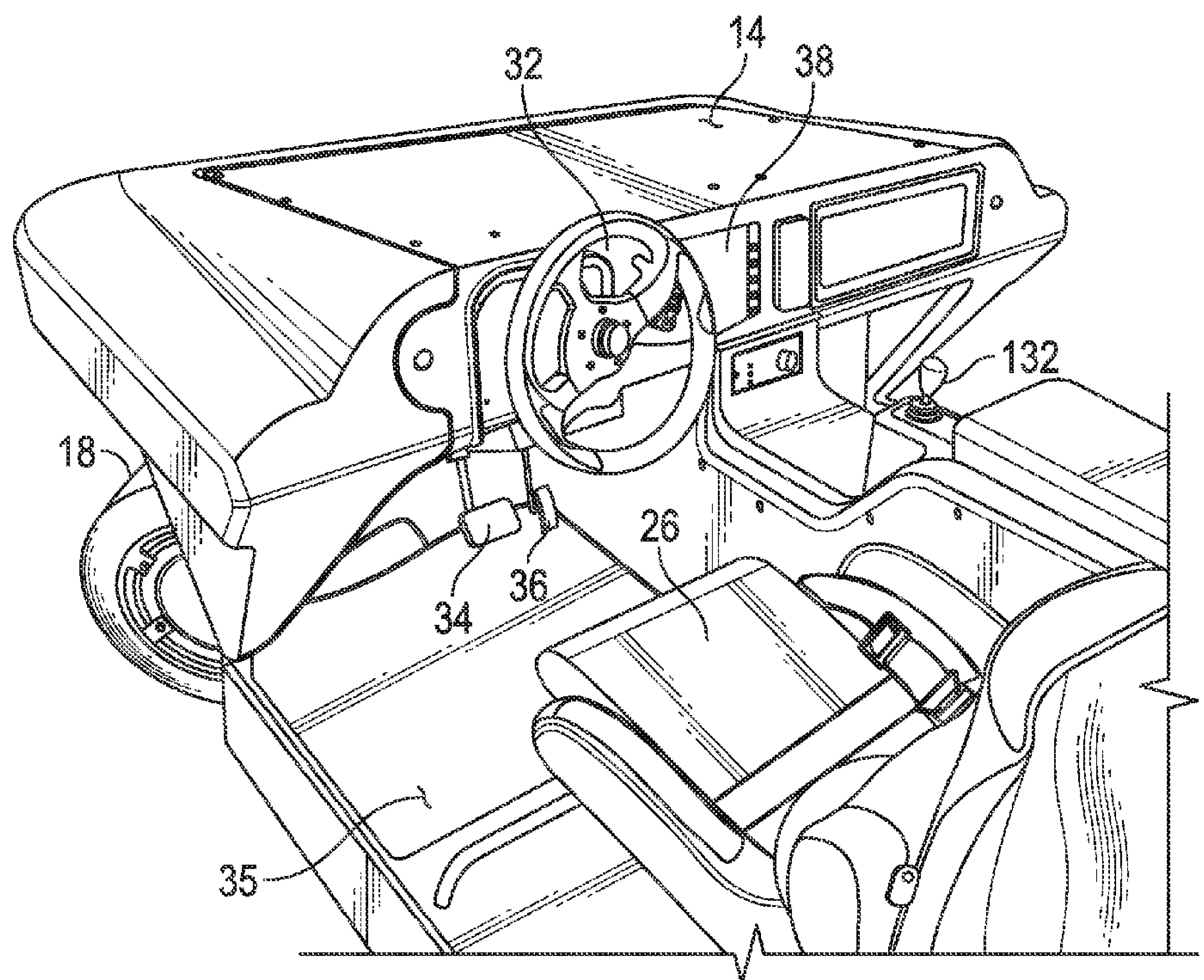

14
32
38
132
18
26
34
36
35

FIG. 2

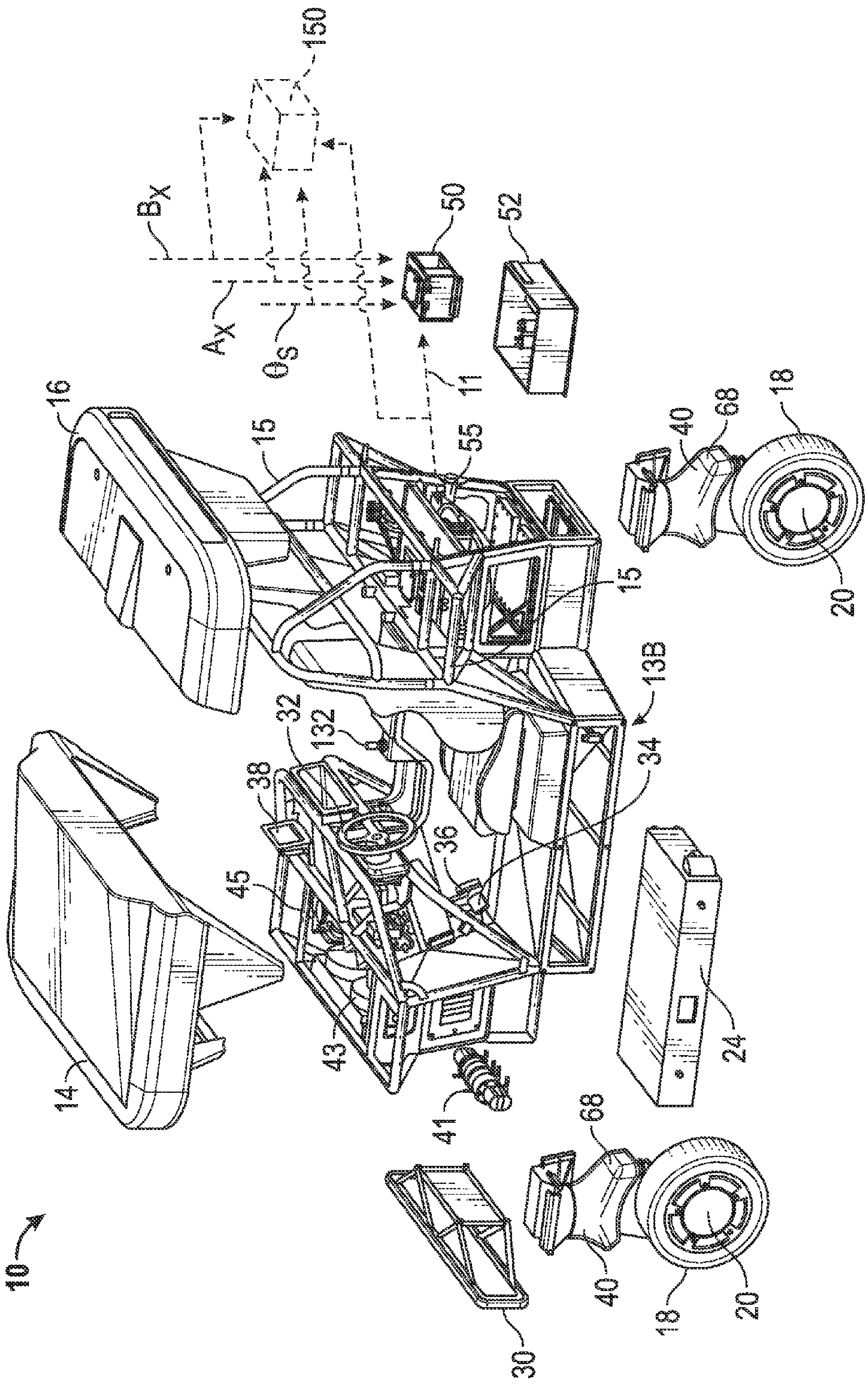

150
B_X
A_X
θ_S
50
52
11
16
15
55
40
68
18
20
15
13B
32
132
38
34
45
36
14
43
41
24
68
40
18
20
30
10

FIG. 3

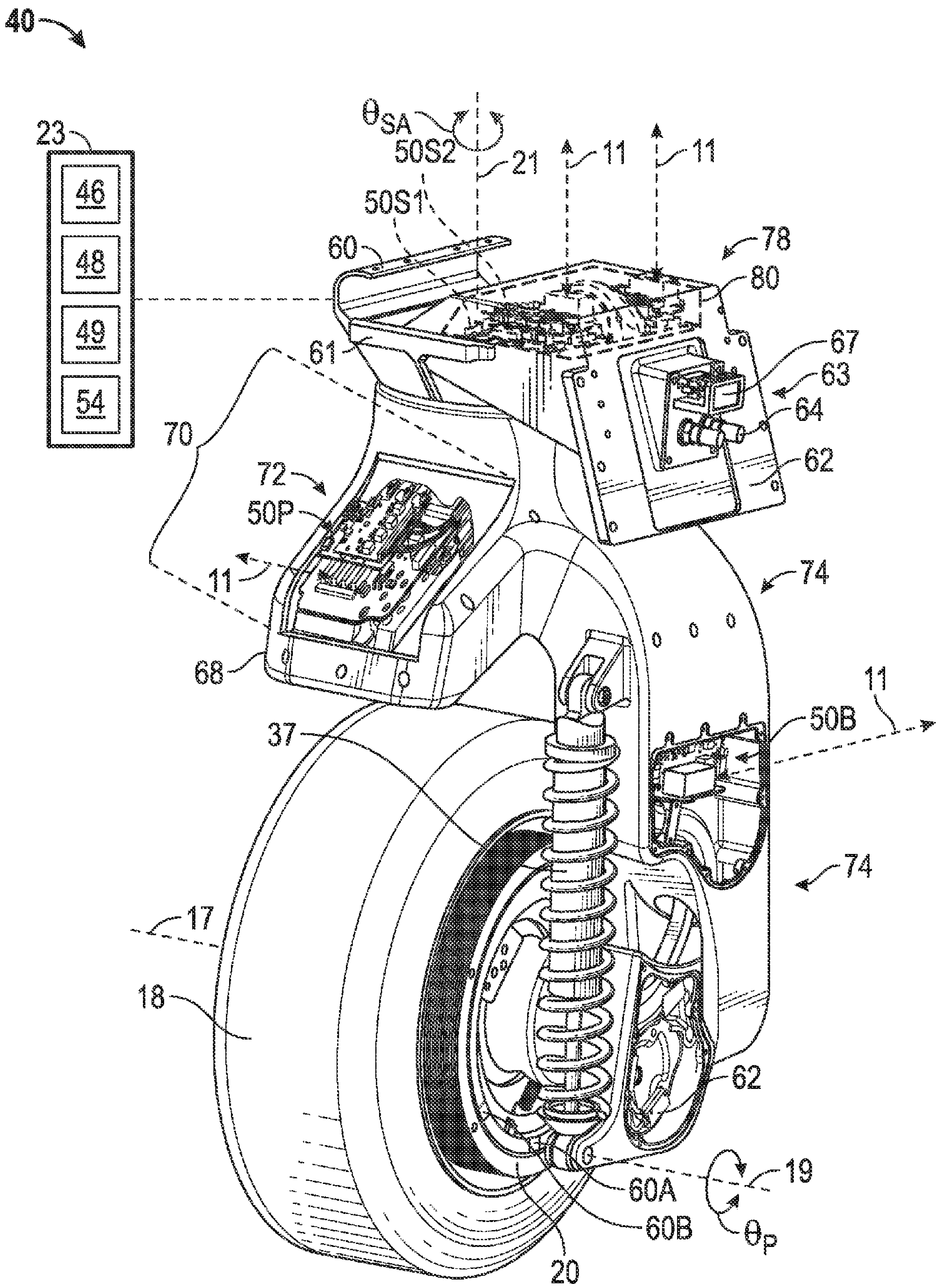

40
23
46
48
49
54
θSA
50S2
21
11
11
50S1
60
78
80
61
67
63
64
62
70
72
50P
11
74
68
37
50B
11
74
17
18
62
19
60A
60B
θP
20

FIG. 4

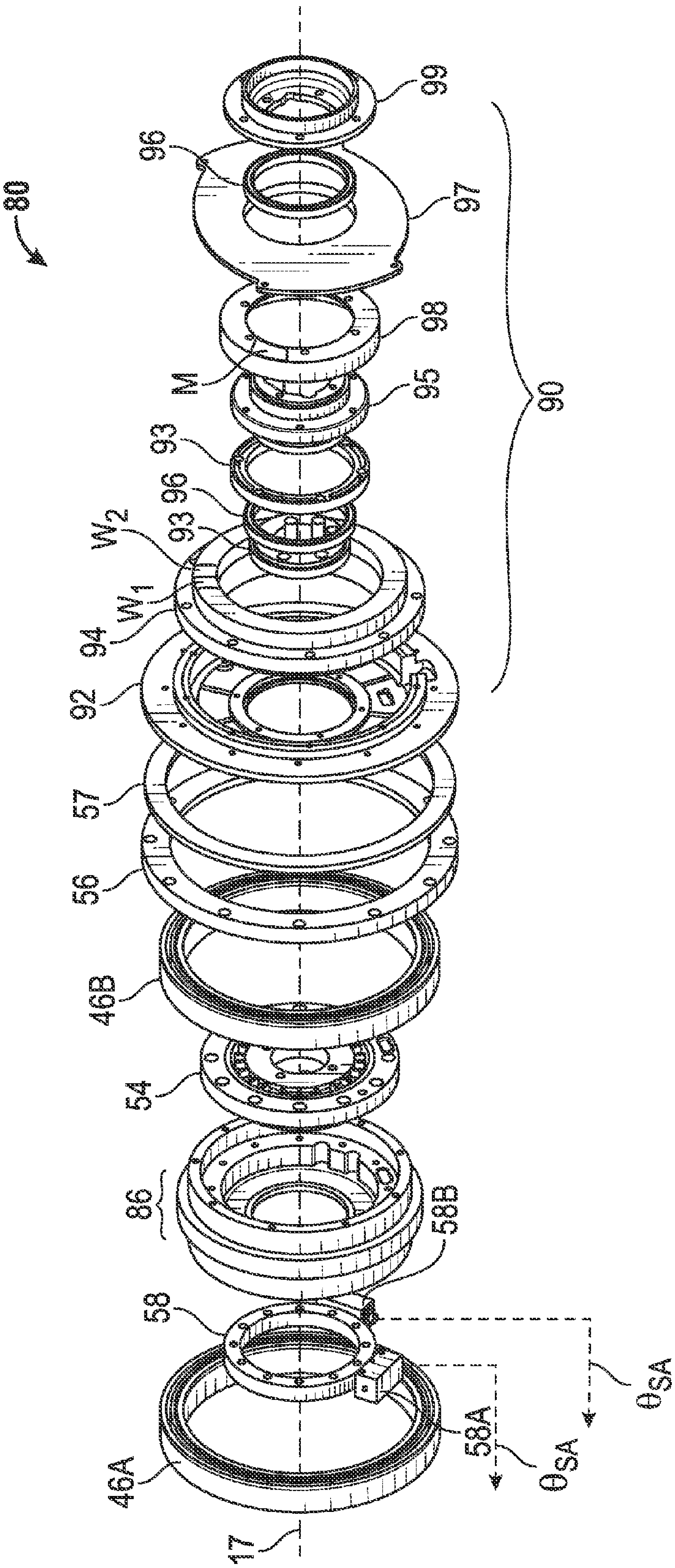
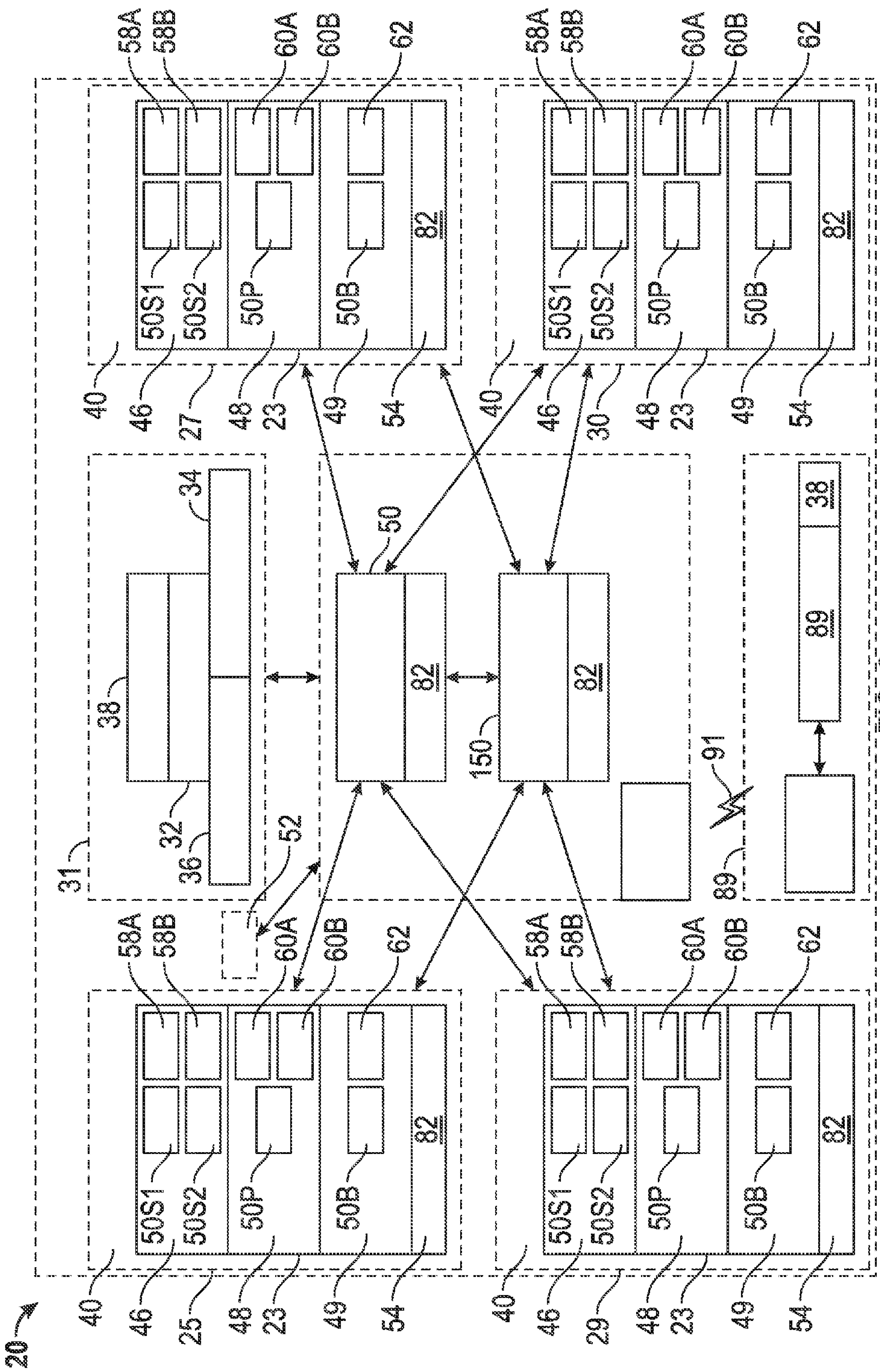

80
99
96
97
98
M
95
90
93
93 96
W_2
W_1
94
92
57
56
46B
54
86
58B
58
θ_{SA}
58A
θ_{SA}
46A
17

FIG. 5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40
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31
32
34
36
38
48
23
49
54
50
52
150
82
89
91
58A
58B
60A
60B
62
50S1
50S2
50P
50B

FIG. 6

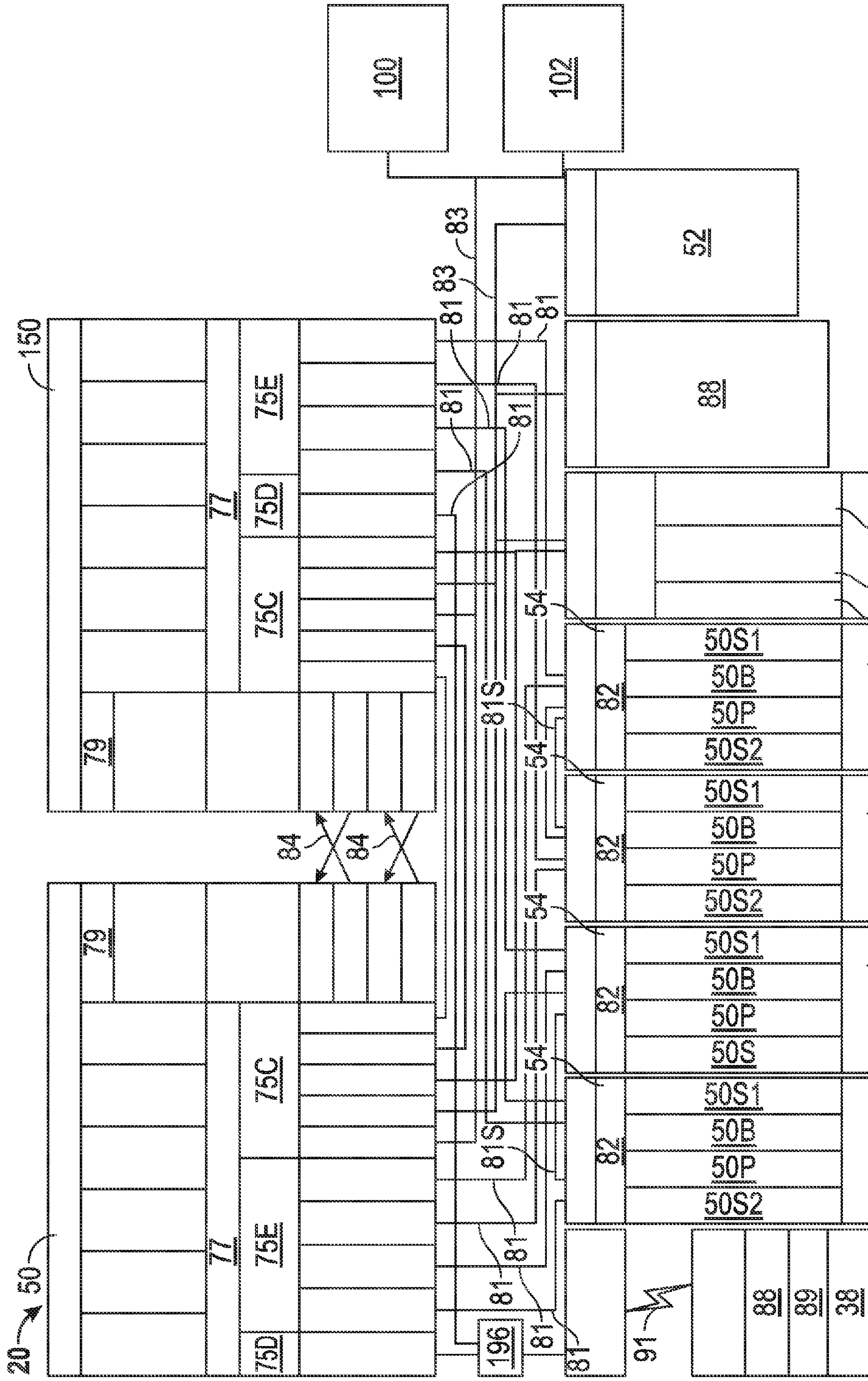
100
102
52
88
83
81
81S
54
82
50S1
50B
50P
50S2
50S
30
25
27
29
40
32
34
36
38
150
77
75C
75D
75E
79
84
196
91
89
20
50

FIG. 7

COMPONENT CONTROL SYSTEM FOR A VEHICLE

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under NASA Space Act Agreement number SAA-EA-10-017. The invention described herein may be manufactured and used by or for the U.S. Government for U.S. Government (i.e., non-commercial) purposes without the payment of royalties thereon or therefor.

TECHNICAL FIELD

The present disclosure is related to a component control system for a vehicle.

BACKGROUND

An ideal vehicle design for a driver who is commuting within a congested area might be a relatively small, fuel efficient vehicle that is easy to maneuver and park. However, on other occasions, the same driver may wish to transport multiple passengers and/or cargo, or may wish to operate in different drive modes. For such a driver, a conventional vehicle chassis and powertrain, having a fixed configuration and mechanically coupled steering, braking, and propulsion systems, may be less than optimal.

SUMMARY

A modular robotic vehicle is disclosed herein. The vehicle is electrically driven, via by-wire commands, using energy from a high-voltage battery pack and an associated power electronics module. The vehicle is controlled by way of a distributed control network having a primary and secondary master controller and multiple embedded control modules, with each control module having a corresponding steering, propulsion, and braking control task for a given corner of the vehicle. Multiple levels of control redundancy are provided, e.g., with multiple control modules used to ensure a "fail safe" backup for operationally critical functions.

Additionally, each corner of the vehicle includes a modular, self-contained "eModule", housing electric steering, propulsion, braking, and suspension subsystems. Independent control of each eModule is supervised by the primary and secondary master controllers, with the various control modules embedded within the eModules communicating as needed with the master controller via Ethernet for Control Automation Technology (EtherCAT) or another suitable high-speed connection.

Driver input commands are received by the master controller from various devices, such as a steering wheel and/or joystick, a brake pedal, an accelerator pedal, and a human machine interface (HMI) screen or touchpad. These electrical input signals are transmitted to the primary and secondary master controllers. The primary and secondary master controllers then issue individual commands to each of the control modules embedded within the eModules that are affected by the driver inputs. The entire control operation is by-wire as noted above, i.e., lacking a direct mechanical linkage between the driver input devices and the steering, propulsion, or braking subsystems being controlled in response to the driver's inputs.

In one possible aspect of the disclosure, a central operating system includes a component control system, a primary master controller, and a secondary master controller. The component control system is configured for controlling a modular component. The primary master controller and the secondary master controller are in operative communication with the component control system. The primary master controller and the secondary master controller are configured to simultaneously transmit commands to the component control system. The component control system is configured to accept commands from the secondary master controller only when a fault occurs in the primary master controller.

In another possible aspect of the disclosure, a vehicle includes a chassis, a modular component, and a central operating system. The modular component is supported by the chassis. The central operating system includes a component control system, a primary master controller, and a secondary master controller. The component control system is configured for controlling the modular component. The primary and secondary master controllers are in operative communication with the component control system. The primary and secondary master controllers are configured to simultaneously transmit commands to the component control system. The component control system is configured to accept commands from the secondary master controller only when a fault occurs in the primary master controller.

The above features and advantages and other features and advantages of the present teachings are readily apparent from the following detailed description of the best modes for carrying out the present teachings when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic perspective side view illustration of an example modular robotic vehicle.

FIG. **2** is a schematic perspective top view illustration of the vehicle shown in FIG. **1**.

FIG. **3** is a schematic exploded view illustration of the vehicle shown in FIGS. **1** and **2**.

FIG. **4** is a schematic perspective side view illustration of an example modular eModule usable with the vehicle shown in FIGS. **1**-**3**.

FIG. **5** is a schematic exploded perspective view of a steering module of the modular eModule.

FIG. **6** is a schematic diagrammatic view of the functional controller architecture of the vehicle.

FIG. **7** is a schematic diagrammatic view of the functional hardware interface of the controllers of the vehicle.

DETAILED DESCRIPTION

Referring to the drawings, wherein like reference numbers refer to like components throughout the several Figures, an example modular robotic vehicle **10** is shown schematically in FIGS. **1**-**3**. The term "modular" as used herein refers to the modularity of design of the vehicle **10** as a whole, i.e., with the vehicle **10** being divided into multiple independently and/or interdependently controlled electromechanical subsystems or modular components, each of which can be disconnected from or connected, to the vehicle **10** as needed to establish a desired functional drive configuration.

A particular modular component providing a foundation to the design set forth herein is a self-contained electric corner assembly or "eModule" **40**, with a first **25**, second **27**, third **29**, and fourth **30** eModule **40**. By way of a non-limiting example, the vehicle **10** may have one eModule **40** being positioned at each corner of the vehicle **10**, i.e., a left front (LF) **25**, a right front (RF) **27**, a left rear (LR) **29**, and a right rear (RR) **30** of the vehicle **10**. Each eModule **40** includes a drive wheel **18**. A typical four-wheel design as shown in FIG. **1** has four eModules **40**. However, it should be appreciated that the vehicle **10** may have more or less eModules **40** than shown and described herein without departing from the intended scope of the disclosure. Further, it should be appreciated that the designation of left, right, front and rear are used descriptively for the figures, and do not represent limitations on the scope of the invention, as defined by the appended claims. The basic design and functionality of the eModules **40** is described in further detail below with reference to FIGS. **4-7**. The vehicle **10** includes a central operating system **20** that includes a component control system **23** for each eModule **40**, a primary master controller **50**, and a secondary master controller **150**. The component control system **23** is configured for controlling the eModules **40**, via the primary and secondary master controllers **50**, **150**. The eModules **40**, as with all components of the vehicle **10**, may be driven solely via electrical power from a high-voltage energy storage system (ESS) **24** and an onboard battery management system (BMS) **52**, shown in FIGS. **3**, **6**, and **7**. Overall control supervision is provided via the primary master controller **50** and/or the secondary master controller **150**, as shown in FIGS. **3**, **6**, and **7**, and explained in more detail below.

Referring to FIG. **6**, the component control system **23** for each eModule **40** includes a steering module **46**, a propulsion module **48**, a braking module **49**, and a communications module **54**. As such, there is a component control system **23** embedded within the LF **25** eModule **40**, the RF **27** eModule **40**, the LR **29** eModule **40**, and the RR **30** eModule **40**.

The steering module **46** is configured for directing steering of the eModule **40**. The steering module **46** includes a first and a second steering controller **50S1**, **50S2** and a first and second steering sensor **58**A, **58**B, i.e., encoder read head. Functional redundancy within the steering module **46** is enabled via the use of the first and second steering controllers **50S1**, **50S2**, as shown in FIGS. **4**, **6**, and **7**. The first and second steering sensors **58**A, **58**B each redundantly measure and output the steering angle (arrow θ_{SA}) to a corresponding one of the first and second steering controllers **50S1**, **50S2**. Therefore, each of these steering controllers **50S1**, **50S2** receives the steering angle (arrow θ_{SA}) from a corresponding one of the first and second steering sensors **58**A, **58**B, e.g., Hall effect sensors. The first and second steering controllers **50S1**, **50S2** are explained in more detail below.

Referring to FIGS. **4** and **6**, the propulsion module **48** is configured for directing propulsion of the eModule **40** and for determining wheel speed of the vehicle **10**. The propulsion module **48** includes a propulsion controller **50**P and a first and a second propulsion sensor **60**A, **60**B or encoder. The first and second propulsion sensors **60**A, **60**B, which are shown schematically in FIG. **4**, provide rotational positional information of the respective wheel **18**. The first and second propulsion sensors **60**A, **60**B may include any suitable sensor capable of providing rotational positional information.

Referring to FIGS. **4** and **6**, the braking module **49** is configured for directing braking of the eModule. The braking module **49** includes a braking controller **50**B and a braking sensor **62**. The braking sensor **62** is shown schematically in FIG. **4**. The braking controller **50**B is used at each eModule **40** to independently control the respective braking at the various eModules **40**. More specifically, with reference to FIG. **4**, the braking sensor **62** may include, but not be limited to, an encoder disc and read head, which are operable to identify a rotational position of an output shaft (now shown) of a brake actuator (not shown). As such, the braking controller **50**B controls the engagement and disengagement of brake shoes (not shown) within the eModule **40**, through all levels of wear of the brake shoes. Accordingly, the brake system does not require any mechanisms for adjusting slack in the brake system caused by wear of the brake shoes.

The communications module **54** is configured for communicating between each of the primary and secondary master controllers **50**, **150** and the corresponding steering, propulsion, and braking modules **46**, **48**, **49**. The communications module **54** may employ an embedded network including, but not limited to, Ethernet for Control Automation Technology "EtherCAT" **82** for communicating between the primary and secondary master controllers **50**, **150** and the corresponding steering, propulsion, and braking modules **49**. EtherCAT **82** is an open high performance Ethernet-based fieldbus system that allows high data throughput. It should be appreciated, however, that other embedded networks may also be used, such as CAN Bus, FlexRay, MLVDS, and the like. Further, the EtherCAT **82** includes an Ethernet connection that is configured to communicate with Ethernet connections on each of the primary and secondary master controllers **50**, **150**, as illustrated in FIGS. **6** and **7**.

Referring briefly to the functional hardware interface diagrams depicted in FIG. **7**, the primary and secondary master controllers **50**, **150** may be embodied as a microprocessor-based computer device having sufficient amounts of tangible, non-transitory memory, e.g., read only memory (ROM), as well as transitory memory such as random access memory (RAM), electrically-programmable read-only memory (EPROM), etc. The primary and secondary master controllers **50**, **150** may also include logic circuitry including but not limited to proportional-integral-derivative (PID) control logic, a high-speed clock, analog-to-digital (A/D) circuitry, digital-to-analog (D/A) circuitry, digital signal processor hardware, and any necessary input/output (I/O) devices and other signal conditioning and/or buffer circuitry. Control functions described herein may be recorded in computer-readable formats in a location accessible by the primary and secondary master controllers **50**, **150**, and executed from such memory in response to changing driver inputs and other conditions such as vehicle speed, battery state of charge, and the like. Further, the primary and secondary master controllers **50**, **150** may also be configured to include command/message handlers **77**, EtherCAT drivers **75**E, CAN drivers **75**C, data distribution service (DDS) **75**D, and the like.

The primary and secondary master controllers **50**, **150** provide redundancy in transmitting commands to the eModules **40**. The primary master controller **50** and the secondary master controller **150** are configured to be in direct operative communication with one another. More specifically, the primary and secondary master controllers **50**, **150** are synchronized via controller area network "CAN" and input/output "IO" interfaces, shown respectively at **83** and **84** in FIG. **7**, so that the primary and secondary master controllers **50**, **150** simultaneously transmit commands to the component control system **23** of each eModule **40**. Synchronization of the primary and secondary master controllers **50**, **150** provides a priority scheme therebetween. As such, each steering, propulsion, and braking controller **50**B disposed within each eModule **40** is configured to prefer commands from the primary master controller **50**, if available. However, the EtherCAT **82** network provides built-in diagnostic features that allow the control architecture to switch command sources on-the-fly, while the system is operating, i.e., from the primary master controller **50** to the secondary master controller or vice versa. As such, each of the primary and master controllers **50**, **150** include a fault detector **79** (e.g., a watchdog circuit) or through some other fault detection means. The component control systems **23** may be configured to only accept commands from the secondary master controller when a fault occurs in the primary master controller **50**. Therefore, at the master controller level **50**, **150**, if a communication fault occurs, the computer software in the master controller may transition into a "degraded mode" and a maximum vehicle **10** speed may be reduced. This arbitration strategy is important because, in the event of a failure, no action is required on the part of the primary or secondary master controllers **50**, **150** for the individual module **46**, **48**, **49** controllers **50S1**, **50S2**, **50**B, **50**P to continue functioning. This is important, because the response time of the system to a failure is typically fast, i.e., about 25 milliseconds (ms), and is thus suitable for controlling a vehicle driving at desired operational speeds.

With continued reference to FIG. **7**, each of the component controllers **50S1**, **50S2**, **50**P, **50**B, i.e., steering, propulsion, and braking controllers, corresponding to the respective eModule **40**, are in operative communication with each of the primary and secondary master controllers **50**, **150** via an Ethernet connection **81**. Further, the component controllers **50S1**, **50S2**, **50B**, **50P** for the LR **29** eModule **40** are in operative communication with the component controllers **50S1**, **50S2**, **50B**, **50P** for the RF **27** eModule **40** and the component controllers **50S1**, **50S2**, **50B**, **50P** for the LF **25** eModule **40** are in operative communication with the component controllers **50S1**, **50S2**, **50B**, **50P** for the RR **30** eModule **40** via a secondary Ethernet connection **81**S. This operative communication between the component controllers **50S1**, **50S2**, **50B**, **50P** provides a daisy-chain ring topology using Ethernet hardware interfaces. Data packets originate from the primary and secondary master controllers **50**, **150** and pass through each EtherCAT slave device **54** before returning back to the primary and secondary master controllers **50**, **150**. Because of the daisy, chain topology, a failure in any network link may prevent communication to the slave devices **54** downstream of the failure. To mitigate this, two physical Ethernet interfaces are used on the primary and secondary master controllers **50**, **150** to enable communication to continue, given any single cable failure. Further, an additional EtherCAT ring network, with slaves in reverse order, is provided to maximize availability. This allows up to three EtherCAT network faults to occur and still maintain full control of the eModules **40**.

Referring again to FIG. **1**, the vehicle **10** of FIG. **1** also includes a chassis **12** to which is attached a front and a rear body shell **14** and **16**, respectively. The chassis **12** may be formed from a lattice of interconnected tubular frame pieces, e.g., steel, aluminum, or fiberglass tubing. The structure of the chassis **12** can also be used to help secure the eModules **40** to the chassis **12**.

Further with respect to FIG. **1**, each drive wheel **18** is individually powered by the corresponding propulsion module **48** and braking module **49** contained within a hub **96** or center structure of the drive wheel **18**. The propulsion module **48** is configured to propel the vehicle **10** by causing the corresponding wheel **18** to rotate about a wheel axis **17**. More specifically, the propulsion controller **50**P is configured to receive a command from the primary and/or secondary master controller **50**, **150** and, in turn, send a signal to energize a corresponding electric wheel motor **85**. While omitted from the Figures for added simplicity, each eModule **40** may include a brake assembly. The brake assembly may include a brake drum that may be used with a pair of diametrically-opposed brake shoes, each of which includes a friction surface that is operable to engage a radial inner surface of the brake drum. An electric brake motor, also omitted, may be used to move the brake shoes into engaged with the drum when braking is commanded by a driver of the vehicle **10**.

The vehicle **10** may also include any necessary vehicle accessory features such as a headlamp **22**, the ESS **24**, seats **26**, and an optional overhead bar **28** or other overhead support structure such as a canopy (not shown).

Referring to FIG. **2**, the vehicle **10** is controlled via driver commands as received by multiple driver interface devices **31**. These devices collectively determine a driver's desired control response, and in turn provide associated control signals to the primary master controller **50**, which is shown schematically in FIG. **3**, for the purpose of establishing reliable, fault-tolerant by-wire control of all steering, propulsion, and braking functions. The noted driver interface devices **31** may include a steering input device, shown here as a conventional steering wheel **32** and an optional joystick **132**, an accelerator pedal **34**, a brake pedal **36**, a human-machine interface (HMI) screen **38**, e.g., a touch screen, and a dashboard display device **88**. Other driver interface devices may be envisioned without departing from the intended inventive scope. In some embodiments, the functions of the steering wheel **32** as well as that of the pedals **34** and **36** may be performed via the joystick **132**. With reference to FIG. **7**, the HMI screen **38** and the dashboard display device **88** may be in operative communication with each other and the primary and secondary master controllers **50**, **150** via a CAN Bus **83**.

The dashboard display device **88** may be configured to display operating characteristics of the vehicle **10** and/or to provide the operator with the ability to select a driving mode of the vehicle. The dashboard display device **88** may be a Murphy PowerView **750** and the like.

With continued reference to FIG. **7**, it should be appreciated that the interface devices **31** are not limited to being disposed on the vehicle **10**, but may reside external to the vehicle **10** on a remote console **89**. The remote console **89** may include the HMI screen **38**, the dashboard display device **88**, and a DDS **75**D. The remote console **89** is configured to communicate with a hub **96** of the central operating system **20** via a wireless Ethernet connection **91**. In turn, the hub **96** is in operative communication with the first and second primary controllers **50**, **150** via an Ethernet connection **81**, as implemented by the respective DDS **75**D. The remote console **89** may be in addition to, or a replacement for, the HMI screen **38** and the dashboard display device **88** resident within the vehicle **10**.

Referring to FIG. **3**, the vehicle **10** is shown in exploded view to illustrate some of the modules and associated components noted above. Sensors (not shown) may be positioned with respect to the accelerator and brake pedals **34** and **36**, respectively, and used to measure the amount of travel and/or force as corresponding accelerator pedal signals (A_X) and brake pedal signals (B_X). Similarly, a steering angle sensor may be positioned with respect to the steering input device **32** and used to measure the steering angle (θ_S). Calculated changes in the measured steering angle over time determine the steering rate (ω_S). Other control inputs (arrow **11**) from the HMI screen **38** such as a selected drive/steering mode and/or heating, ventilation, and air conditioning (HVAC) settings, etc., as well as the various signals A_X, B_X, θ_S, and ω_S, are communicated to the primary and secondary master controllers **50**, **150**, via a CAN Bus, which ultimately coordinates all control actions on board the vehicle **10**. For functional redundancy, as described above, the secondary master controller **150** may be used in conjunction with the primary master controller **50**, with the secondary master controller **150** receiving the same set of signals. As described above, in the event of an unexpected logic fault, for instance, the secondary master controller **150** can continue to provide the core control functionality of the vehicle **10**.

The chassis **12** may define multiple cavities within which the various modules are received and stowed. For example, the ESS **24** may be inserted below a floor pan **35** into a battery cavity **13**B. Other subsystems or modules may include a coolant pump **41** for circulating coolant from a coolant reservoir **45** to a radiator **43**, and/or to each of the eModules **40** for cooling of motor components located therein, all of which may be housed beneath the front body shell **14**.

With respect to propulsion of the vehicle **10** of FIGS. **1-3**, all energy needed for this function is supplied by the ESS **24**, which may be connected to an offboard power supply via a charging port **55** for rapid recharging of the ESS **24**. Thus, the vehicle **10** of FIGS. **1-3** is a battery electric vehicle (BEV) controlled by-wire as noted above, with all available drive and steering modes being electric vehicle (EV) mode variants.

The ESS **24** may be constructed as a high-voltage, multi-cell DC energy storage device, for example a rechargeable solid-cell lithium ion battery having a voltage rating of about 300 VDC to 400 VDC, with 360 VDC being a typical high-voltage rating. In addition to the various cells and connectors of the DC battery, the ESS **24** may include power management circuitry and logic of the type used for balancing and managing the state of charge of the cells, thermal management components, and the like. The ESS **24** in turn may include the necessary solid state hardware for controlling and converting the flow of electrical power to and from the ESS **24** aboard the vehicle **10**.

As is well understood in the art, such power electronics hardware typically includes a power switching module with multiple semiconductor switches, i.e., MOSFETs or IGBTs, for converting DC power from the ESS **24** to AC power suitable for driving the motors positioned within the eModules **40**, and for performing the reverse AC to DC conversion as needed for charging the ESS **24**. The BMS **52** may also include a voltage regulator, a DC-to-DC converter for providing auxiliary power aboard the vehicle **10**, power conditioning/filtering hardware, and the like. The BMS **52** is in operative communication with the primary and secondary master controllers **50**, **150**, the HMI screen **38**, and the dashboard display device **88**, via the CAN Bus.

The central operating system **20** may also be connected to a thermal control system (TMS) **100** and a power distribution unit (PDU) **102** via a CAN Bus. The TMS **100** is configured to regulate the operating temperature of the controllers **50**, **150**. The PDU **102** is a device configured with multiple outputs, designed to distribute electric power to the first and second master controllers **50**, **150**. The ESS **24** also requires communication to the master controllers **50**, **150**.

Referring to FIG. **4**, the eModule **40** is configured to house all of the embedded controllers used for control of that particular corner of the vehicle **10**, i.e., the propulsion controller **50**P, the steering controllers **50S1**, **50S2**, and the brake controller **50**B. To serve this function, the eModule **40** is provided with a housing **68**, having an upper portion **70** and a lower portion **74**, with the controllers **50**P, **50S1**, **50S2**, **50**B disposed therein.

The first and second steering controllers **50S1**, **50S2**, positioned with respect to the upper portion **70**, locally control the steering function of the respective eModule **40**. As described above, the two steering controllers **50S1**, **50S2** may be used for functional redundancy over all steering functions. While omitted for simplicity, the upper portion **70** may include a removable access cover which provides direct access to the steering controllers **50S1**, **50S2**. A suspension assembly having a spring and damper assembly **37** are housed within or connected to the lower portion **74**, e.g., electronics, wiring, conduit, and encoders (not shown) as needed for measuring and communicating information pertaining to the orientation of the drive wheel **18** with respect to a pivot axis **19** (see FIG. **5**). The steering and propulsion controllers **50S1**, **50S2**, and **50**P, respectively, are in communication with the primary and secondary master controllers **50**, **150**, shown in FIGS. **1** and **3**, and programmed and equipped to perform local tasks in response to instructions from the primary or secondary master controller **50**, **150** of FIG. **3**.

Referring to FIG. **5**, each eModule **40** includes a steering control assembly **80**. Each steering control assembly **80** includes a series of annular components arranged along a steering axis **17**. As viewed from left to right in FIG. **5**, the steering control assembly **80** includes a plurality of sequentially stacked components that include a lower support bearing **146**A, an encoder read disc **58**, a steering hub **86**, a speed reducing gear set **154**, an upper support bearing **146**B, a bearing clamp **156**, a seal **157**, and a steering motor stack **90**. The encoder read disc **58** includes a first and a second steering sensor **58**A, **58**B, e.g., Hall effect sensors, each of which measures and outputs the steering angle (arrow θ_{SA}) to a corresponding one of the steering controllers **50S1**, **50S2** of FIG. **4**. In one possible embodiment, the speed reducing gear set **154** shown in FIG. **5** provides a steering speed reduction ratio of at least 100:1, e.g., reducing a 2000 RPM steering input speed to a 20 RPM actual steering speed as transmitted to the drive wheel **18**. This reduction in turn amplifies steering torque, as will be understood by those of ordinary skill in the art.

Still referring to FIG. **5**, the upper support bearing **146**B is disposed adjacent the speed reducing gear set **154**, as shown. The bearing clamp **156** and seal **157** respectively maintain compression on the bearings **146**A, **146**B and provide a fluid seal within the steering control assembly **80**, with the bearings **146**A, **146**B helping to support the load of the vehicle **10** of FIG. **1** at a given eModule **40**.

The seal **157** shown in FIG. **5** seals against the steering motor stack **90**. The steering motor stack **90** includes a motor support race **92** and a dual-wound stator **94** having two sets of windings W**1** and W**2**, with only a portion of the windings W**1** and W**2** shown schematically for illustrative simplicity. The steering motor stack **90** may also include annular motor supports **93** and a pair of motor bearings **96**. A motor hub **95** supports a rotor **98**, on which are epoxied or otherwise secured a series of permanent magnets (M), only one of which is shown for clarity. The steering motor stack **90** is then secured together via a support plate **97** of aluminum or other suitable material and an outer race **99**. Other embodiments of the various supporting elements shown in FIG. **5** may vary with the design. However, to provide functional redundancy to the steering function, the steering control assembly **80** should retain the design of the dual-wound stator **94** and the first and second steering sensors **58**A, **58**B.

Functional redundancy is enabled via the use of the two steering controllers **50S1**, **50S2** shown in FIGS. **4-7**. Each steering controller **50S1**, **50S2** receives the measured steering angle (arrow θ_{SA}) from a corresponding one of the steering sensors **58**A, **58**B. While the dual-wound stator **94** is shown schematically for illustrative clarity, those of ordinary skill in the art will understand that such a device has separately powered parallel windings W**1**, W**2**, and thus two poles. Therefore, the steering control assembly **80** of FIG. **5** has one physical steering motor with a single rotor, i.e., the rotor **98**. Being a permanent magnet-type device, the rotor **98** should have a very low electrical and mechanical fault tendency. However, the dual-wound stator **94** is electrically energized, and thus the built-in functional redundancy allows the steering motor assembly **80** to function even in the presence of an electrical short or other fault in one of the windings W**1** or W**2**.

That is, under steady state conditions the windings W**1** and W**2** of the dual-wound stator **94** may be energized via the ESS **24** of FIGS. **1** and **3**, with each of the dual windings receiving 50% of the required steering power. Should one of the dual windings experience a fault, the primary and secondary master controllers **50**, **150** of FIG. **3** can automatically discontinue power transmission to the faulted winding and increase power transmission to the non-faulted winding. While such a control action may result in additional heat generation, the resultant thermal management concerns may be tolerated in the short term to maintain a threshold level of steering functionality.

Referring again to FIG. **5**, the first and second steering sensors **58**A, **58**B, and other associated hardware (not shown), for a given eModule **40** can be housed with the first and second steering controllers **50**S**1**, **50**S**2**, and configured to properly encode the position and rotational speed of a steering joint within the eModule **40**, as well as to amplify steering torque from such a steering motor. As will be appreciated by those having ordinary skill in the art, such embedded controllers may include printed circuit board assemblies (PCBAs) having local task execution responsibility for the eModule **40** within which the PCBA is embedded with instructions received from the primary master controller **50**. The various PCBAs embodying the individual embedded controllers **50**P, **50**B, **50**S**1**, and **50**S**2** may include a microprocessor, tangible, non-transitory and transitory memory, transceivers, cooling plates, and the like, and programmed to perform specific tasks locally with respect to the eModule **40** in which the PCBA is embedded.

With reference to FIG. **4**, the propulsion controller **50**P may be contained within the upper portion **70** of the housing **68**, thereby securing the propulsion controller **50**P in proximity to the drive wheel **18** being controlled without subjecting the propulsion controller **50**P to the forces typically experienced by the drive wheel **18** as the vehicle **10** travels along a road surface. The brake controller **50**B may be positioned in the lower portion **74**. Any or all of the various controllers **50**, **150**, **50**B, **50**S**1**, **50**S**2**, **50**P provide a level of functional redundancy. For instance, as discussed previously, redundant steering controllers **50**S**1**, **50**S**2**, provide back-up steering control functionality and the secondary master controller **150** provides back-up to the primary master controller **50** for reliable control of the vehicle **10**, in the event the primary master controller **50** and/or one of the steering controllers **50**S**1**, **50**S**2** should experience an unexpected transient logic error or other unexpected hardware or software fault.

With continued reference to FIG. **4**, the three axes of the eModule **40** are represented as the wheel axis **17**, pivot axis **19**, and steering axis **21**. The drive wheel **18** rotates with respect to the wheel axis **17** as noted above, while the mounted eModule **40** rotates through an actual steering angle range indicated by double-headed arrow θ_{SA}. The driver wheel **18** is also allowed to pivot with respect to axis **19** to help absorb shock and road vibration.

Use of the modular, independently-controlled eModules **40** of FIG. **4** enables different steering or drive modes, including two-wheel, four-wheel, diamond, and omni-directional steering modes, as well as a park mode. Two-wheel and four-wheel steering enable steering via two or four of the eModules **40**, respectively. Diamond steering is a particular four-wheel steering mode in which the drive wheels **18** are positioned such that a line passing through their respective centers all pass through a center point of the vehicle **10**. Propulsion in this mode would cause the vehicle **10** to rotate in place around its vertical axis, as will be appreciated by one having ordinary skill in the art.

Omni-directional steering places all of the drive wheels **18** at the same angle with respect to the vehicles longitudinal axis, i.e., the lengthwise axis of the vehicle **10** as shown in FIGS. **1** and **2**, such that the drive wheels **18** are all facing in the same direction. This enables a "crab mode" driving maneuver wherein the vehicle **10** can move at an angle with respect to its longitudinal axis, including at right angles. Such a mode might facilitate difficult parking maneuvers, particularly parallel parking into a tight parking space. Park mode places the front and rear wheels located on the same side of the vehicle, such the front and rear right side, are at the same angle. Thus, in park mode the two front wheels and the two rear wheels would point outward with respect to the longitudinal axis of the vehicle **10**, thereby preventing any forward or reverse motion.

As noted above, the primary and secondary master controllers **50**, **150** are programmed to execute a wide spectrum of different steering modes, including the two-wheel, four-wheel, diamond, and omni-directional or "crab mode" steering noted above. The modular design of the eModules **40**, along with the distributed control network with the primary and secondary master controllers **50**, **150** at its center, enables such flexibility. A driver, using the HMI screen **38** of FIG. **3** or other suitable input device such as a mode selector switch, can pick the steering maneuver for a given drive situation.

Using the vehicle **10** of FIGS. **1**-**3**, independent drive-by-wire control is enabled over multiple steering, propulsion, and braking modules **46**, **48**, **49**, all of which are housed within a corresponding modular eModule **40**. The primary or secondary master controllers **50**, **150** of FIG. **3** supervise the control of each eModule **40**, and combines the eModules **40** into a cohesive system. Full control authority by the primary or secondary master controller **50**, **150** over the functions of each eModule **40** enhances the overall maneuverability of the vehicle **10**.

While the best modes for carrying out the many aspects of the present teachings have been described in detail, those familiar with the art to which these teachings relate will recognize various alternative aspects for practicing the present teachings that are within the scope of the appended claims.

The invention claimed is:

1. A central operating system comprising:

a first component control system configured for controlling a first electric steering, propulsion, braking, and suspension subsystem component (eModule);

a second component control system configured for controlling a second eModule;

a third component control system configured for controlling a third eModule; and

a fourth component control system configured for controlling a fourth eModule;

a primary master controller in operative communication with each of the first, second, third, and fourth component control systems; and

a secondary master controller in operative communication with each of the first, second, third, and fourth component control systems;

wherein each of the first, second, third, and fourth component control systems includes at least one of:

a steering module configured for directing steering of the respective modular component, wherein the steering module includes:

a first and second steering controller; and

a first and second steering sensor;

a propulsion module configured for directing propulsion of the respective modular component, wherein the propulsion module includes:

a propulsion controller; and

a first and second propulsion sensor;

a braking module configured for directing braking of the respective modular component, wherein the braking module includes a braking controller; and

a communications module operatively connected to each of the steering module, the propulsion module, and the braking module, wherein the communications module is configured for communicating with the primary and secondary controller;

wherein the primary master controller and the secondary master controller are configured to simultaneously transmit commands to at least one of the first, second, third, and fourth component control systems; and

wherein the first, second, third, and fourth component control systems are each configured to accept commands from the secondary master controller only when a fault occurs in the primary master controller.

2. A central operating system, as set forth in claim **1**, wherein at least one of the first and second steering controllers, the propulsion controller, and the braking controller of each eModule are in operative communication with each of the primary and secondary master controllers via an Ethernet connection;

wherein at least one of the first and second steering controllers, the propulsion controller, and the braking controller of the third eModule are in operative communication with at least one of the first and second steering controller, the propulsion controller, and the braking controller of the second eModule via a secondary Ethernet connection to provide redundancy in the event the operative communication between the at least one of the first and second steering controllers, the propulsion controller, and the braking controller of each eModule and each of the primary and secondary master controllers via the Ethernet connection is interrupted; and

wherein the at least one of the first and second steering controllers, the propulsion controller, and the braking controller of the first eModule are in operative communication with each of the first and second steering controller, the propulsion controller, and the braking controller of the fourth eModule to provide redundancy via another secondary Ethernet connection to provide redundancy in the event the operative communication between the at least one of the first and second steering controllers, the propulsion controller, and the braking controller of each eModule and each of the primary and secondary master controllers via the Ethernet connection is interrupted.

3. A central operating system, as set forth in claim **1**, further comprising a battery management system (BMS) in operative communication with each of the primary and secondary controllers;

wherein the BMS is configured to control charging of a battery.

4. A central operating system, as set forth in claim **1**, further comprising at least one of a thermal control system and a power distribution unit (PDU) in operative communication with each of the primary and secondary controllers;

wherein the PDU is configured to distribute electric power to the first and second master controllers.

5. A central operating system, as set forth in claim **1**, further comprising a driver interface device in operative communication with each of the first and second primary controllers;

wherein driver interface device is configured to determine a driver's desired control response and provide an associated control signal to the primary and secondary master controllers.

6. A central operating system, as set forth in claim **5**, wherein the driver interface device includes at least one of a human machine interface (HMI) device, a steering wheel, and a brake pedal.

7. A central operating system, as set forth in claim **6**, further comprising a remote console disposed external to the vehicle and in operative communication with the primary and secondary master controllers;

wherein the remote console includes the driver interface device.

8. A central operating system, as set forth in claim **7**, wherein the driver interface device includes a dashboard display device;

wherein the dashboard display device is configured to receive inputs from at least one of the primary and secondary controllers and to provide a display of operational information as a function of the received inputs.

9. A vehicle comprising:

a chassis;

a first, second, third, and fourth electric steering, propulsion, braking, and suspension subsystem (eModule) supported by the chassis; and

a central operating system including:

a first component control system configured for controlling the first eModule;

a second component control system configured for controlling the second eModule;

a third component control system configured for controlling the third eModule; and

a fourth component control system configured for controlling the fourth eModule;

wherein each of the first, second, third, and fourth component control systems include at least one of:

a steering module configured for directing steering of the respective modular component, wherein the steering module includes:

a first and second steering controller; and

a first and second steering sensor;

a propulsion module configured for directing propulsion of the respective modular component, wherein the propulsion module includes a first and second propulsion sensor;

a braking module configured for directing braking of the respective modular component; and

a communications module operatively connected to each of the steering module, the propulsion module, and the braking module, wherein the communications module is configured for communicating with the primary and secondary controller;

a primary master controller in operative communication with each of the component control systems; and

a secondary master controller in operative communication with each of the component control systems;

wherein the primary master controller and the secondary master controller are configured to simultaneously transmit commands to the component control systems; and

wherein the component control systems are each configured to accept commands from the secondary master controller only when a fault occurs in the primary master controller.

10. A central operating system, as set forth in claim **9**, further comprising an interface in operative communication with each of the primary and secondary controllers;

wherein the interface is configured to receive and input from an operator and supply the input to each of the primary and secondary controllers.

11. A central operating system comprising:

a first component control system configured for controlling a first electric steering, propulsion, braking, and suspension subsystem component (eModule);

a second component control system configured for controlling a second eModule;

a third component control system configured for controlling a third eModule; and

a fourth component control system configured for controlling a fourth eModule;

wherein each of the first, second, third, and fourth component control systems include:

a steering module configured for directing steering of the respective eModule;

a propulsion module configured for directing propulsion of the respective eModule; and

a braking module configured for directing braking of the respective eModule;

a primary master controller in operative communication with each of the first, second, third, and fourth component control system; and

a secondary master controller in operative communication with each of the first, second, third, and fourth component control system;

wherein the primary master controller and the secondary master controller are configured to simultaneously transmit commands to each of the first, second, third, and fourth component control system;

wherein each of the first, second, third, and fourth component control systems are configured to accept commands from the secondary master controller only when a fault occurs in the primary master controller.

12. A central operating system, as set forth in claim **11**, wherein the steering module includes:

a first and a second steering controller; and

a first and a second steering sensor.

13. A central operating system, as set forth in claim **12**, wherein the propulsion module includes:

a propulsion controller; and

a first and second propulsion sensor.

14. A central operating system, as set forth in claim **13**, wherein the braking module includes a braking controller.

15. A central operating system, as set forth in claim **14**, wherein at least one of the first and second steering controllers, the propulsion controller, and the braking controller of each eModule are in operative communication with each of the primary and secondary master controllers via an Ethernet connection;

wherein at least one of the first and second steering controllers, the propulsion controller, and the braking controller of the third eModule are in operative communication with at least one of the first and second steering controller, the propulsion controller, and the braking controller of the second eModule via a secondary Ethernet connection to provide redundancy in the event the operative communication between the at least one of the first and second steering controllers, the propulsion controller, and the braking controller of each eModule and each of the primary and secondary master controllers via the Ethernet connection is interrupted; and

wherein the at least one of the first and second steering controllers, the propulsion controller, and the braking controller of the first eModule are in operative communication with each of the first and second steering controller, the propulsion controller, and the braking controller of the fourth eModule to provide redundancy via another secondary Ethernet connection to provide redundancy in the event the operative communication between the at least one of the first and second steering controllers, the propulsion controller, and the braking controller of each eModule and each of the primary and secondary master controllers via the Ethernet connection is interrupted.

16. A central operating system, as set forth in claim **11**, wherein each of the first, second, third, and fourth component control systems include a communications module is configured for communicating with the primary and secondary controller.

17. A central operating system, as set forth in claim **11**, further comprising a battery management system (BMS) in operative communication with each of the primary and secondary controllers;

wherein the BMS is configured to control charging of a battery.

18. A central operating system, as set forth in claim **11**, further comprising at least one of a thermal control system and a power distribution unit (PDU) in operative communication with each of the primary and secondary controllers;

wherein the PDU is configured to distribute electric power to the first and second master controllers.

19. A central operating system, as set forth in claim **11**, further comprising a driver interface device in operative communication with each of the first and second primary controllers;

wherein the driver interface device includes at least one of a human machine interface (HMI) device, a steering wheel, and a brake pedal; and

wherein driver interface device is configured to determine a driver's desired control response and provide an associated control signal to the primary and secondary master controllers.

20. A central operating system, as set forth in claim **19**, further comprising a remote console disposed external to the vehicle and in operative communication with the primary and secondary master controllers;

wherein the remote console includes the driver interface device.

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