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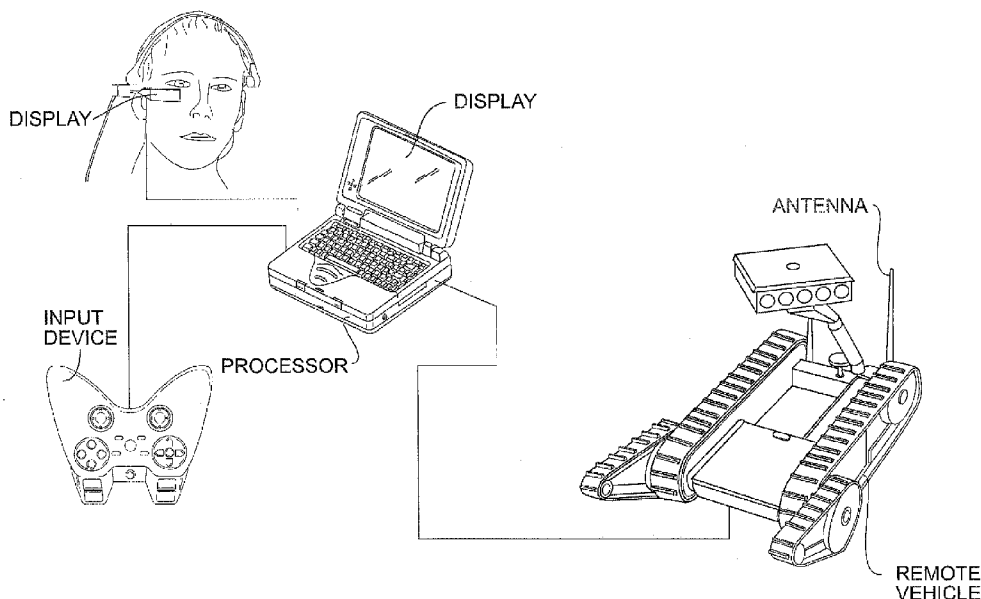
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(54) Title: AUTONOMOUS BEHAVIORS FOR A REMOTE VEHICLE



(57) Abstract: A system and method for allowing an operator to switch between remote vehicle tele-operation and one or more remote vehicle autonomous behaviors, or for implementing remote vehicle autonomous behaviors. The system comprises an operator control system receiving input from the operator including instructions for the remote vehicle to execute an autonomous behavior, and a control system on the remote vehicle for receiving the instruction to execute an autonomous behavior from the operator control system. Upon receiving the instruction to execute an autonomous behavior, the remote vehicle executes that autonomous behavior.

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## **AUTONOMOUS BEHAVIORS FOR A REMOTE VEHICLE**

[0001] This application claims priority to U.S. Provisional Patent Application No. 60/911,785, entitled "Sliding Autonomous Assist for Robotic Platforms," filed April 13, 2007 and U.S. Provisional Patent Application No. 60/828,632, entitled "Autonomous Robot Behaviors," filed October 6, 2006. This application is a continuation-in-part of U.S. Patent Application No. 11/739,590 entitled "Control System for a Remote Vehicle," filed April 24, 2007.

### **Field of the Invention**

[0002] The present invention relates to a method and device for simplifying control of a remote vehicle. The present invention more specifically relates to autonomous behaviors for remote vehicles, and more particularly to switching between tele-operation of a remote vehicle and autonomous remote vehicle behaviors.

### **Background of the Invention**

[0003] Remote vehicles are increasingly being used in military, law enforcement, and industrial applications to provide a tool for a person to perform operations at a safe, remote distance from sites of potential danger or hazard to human beings. Such remote vehicles are being deployed for some tasks by military and civilian forces, such as bomb and ordnance disposal, in which the remote vehicle is remotely navigated to the proximity of the explosives or other potentially dangerous target by an operator located hundred of meters away, so that investigation and disarmament can take place at a safe distance.

[0004] In typical remote vehicle operation, the operator controls the vehicle using a

process known as tele-operation. Conventional remote vehicle tele-operation involves the use of operator control consoles, most commonly having joysticks, trackballs, mouse-type input devices, or some arrangement of physical switches and/or potentiometers and similar manual actuation input devices. Remote vehicles are typically configured with many axes of motion, including motion drive axes, steering axes (either physical or derived virtual steering), manipulation axes, sensor pan-tilt-zoom axes, etc. The axes of the remote vehicle often involve complex mechanical coupling between the drive actuators and the physical motion apparatus, such as wheels, tracks, rudders, heads, etc. Additionally, remote vehicle platforms typically contain many sensors, such as cameras, that can provide multiple streams of video to the operator as visual feedback to aid the operator's control. The electro-mechanical complexity of many remote vehicles has consequently made the manual control of such vehicles complex for human operators in a tele-operation process, requiring many function-specific knobs, joysticks and buttons to perform a task. A significant amount of operator training and experience can be required to develop sufficient manual dexterity and skill to be able to accurately navigate and control a remote vehicle.

[0005] In order for robots to be beneficial in such activities, a method and device are needed to allow remote vehicles to accomplish certain behaviors autonomously, either continuously or upon user commands.

### **Summary of the Invention**

[0006] The present invention provides a system for allowing an operator to switch between remote vehicle tele-operation and one or more remote vehicle autonomous behaviors, or for implementing remote vehicle autonomous behaviors. The system comprises an operator

control system receiving input from the operator including instructions for the remote vehicle to execute an autonomous behavior, and a control system on the remote vehicle for receiving the instruction to execute an autonomous behavior from the operator control system. Upon receiving the instruction to execute an autonomous behavior, the remote vehicle executes that autonomous behavior.

[0007] The remote vehicle executes the autonomous behavior if permitted, and the autonomous behavior is not permitted if one or more of the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior of the remote vehicle, or the remote vehicle's environment are incompatible with the autonomous behavior.

[0008] The control system includes an arbiter, and the autonomous behavior sends a vote to the arbiter requesting control of one or more actuators on the remote vehicle necessary to perform the autonomous behavior. If the voting autonomous behavior has a higher priority than a behavior currently in control of the one or more actuators, the autonomous behavior executes.

[0009] The autonomous behaviors include one or more of ballistic, semi-ballistic, and persistent behaviors. Ballistic behaviors include one or more of stair climbing, preset actions, click-to-drive, click-to-grip, preconfigured poses, retro traverse, self-righting, and autonomous flipper. Semi-ballistic behaviors include one or more of quick brake, speed boost, and cruise control. Persistent behaviors include one or more of retro traverse, self righting, obstacle avoidance, and autonomous flippers.

[0010] The present invention also provides a method for allowing an operator to switch between remote vehicle tele-operation and one or more remote vehicle autonomous behaviors, or for implementing remote vehicle autonomous behaviors. The method comprises inputting

instructions for the remote vehicle to execute an autonomous behavior; evaluating one or more of the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior of the remote vehicle, or the remote vehicle's environment are incompatible with the autonomous behavior; and allowing the autonomous behavior to send a vote to an arbiter if the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior on the remote vehicle, or the remote vehicle's environment are compatible with the autonomous behavior. A vote to the arbiter requests control of one or more actuators on the remote vehicle necessary to perform the autonomous behavior.

### **Brief Description of the Drawings**

FIG. 1 illustrates an embodiment of a control system of the present invention and a remote vehicle;

FIG. 2 is a top view of an embodiment of a hand-held controller of the control system of the present invention;

FIG. 3 is a rear view of the embodiment of FIG. 2;

FIG. 4 is a side view of the embodiment of FIG. 2;

FIG. 5 is a front sectional view of an embodiment of a roller wheel for use with the control system of the present invention;

FIG. 6 is a side view of the roller wheel embodiment of FIG. 5;

FIG. 7 is a top view of an embodiment of a rotary ring switch for use with the control system of the present invention;

FIG. 8 is another top view of the rotary ring switch embodiment of FIG. 7;

FIG. 9 is a side view of the rotary ring switch embodiment of FIG. 7;

FIG. 10 illustrates an embodiment of a quick-release pad of the control system of the present invention;

FIG. 11 is an embodiment of a user interface of the control system of the present invention;

FIG. 12 is another embodiment of a user interface of the control system of the present invention;

FIG. 13 illustrates an exemplary use of the control system of the present invention with a remote vehicle;

FIG. 13A illustrates an embodiment of the invention including a two-piece hand-held controller;

FIG. 13B illustrates another embodiment of the invention including a two-piece hand-held controller;

FIG. 13C illustrates another embodiment of the invention including a two-piece hand-held controller;

FIG. 14 is a block diagram illustrating an exemplary embodiment of autonomous behaviors;

FIG. 15 is a flow diagram illustrating an activation routine used to activate a ballistic behavior and its associated routines;

FIG. 16 is a flow chart illustrating a routine for activating a semi-ballistic behavior used to tune a behavior;

FIG. 17 is a flow chart illustrating a routine to activate or de-activate a persistent behavior;

FIG. 18 illustrates the execution of routines within a persistent behavior;

FIGS. 19A and 19B illustrate an embodiment of a remote vehicle of the present invention;

FIG. 20 illustrates a mobile robot for use with an embodiment of the present invention;

FIG. 21 is a block diagram depicting an embodiment of a mobile robot control system;

FIG. 22 illustrates an embodiment of a chassis assembly;

FIG. 23 illustrates an embodiment of a neck module;

FIG. 24 illustrates an embodiment of a head module;

FIG. 25 illustrates an embodiment of a gripper module;

FIG. 26 illustrates an embodiment of a network installed between a head, a neck, a control system, and a chassis;

FIG. 27 illustrates an embodiment of an Ethernet endpoint block;

FIG. 28 illustrates an embodiment of the invention using the Ethernet endpoint block in the chassis, neck, head and EO/IR payload;

FIGS. 29A and 29B illustrate an embodiment of a robotic arm;

FIG. 30 illustrates an embodiment of a behavior system to be included within a remote vehicle;

FIG. 31 illustrates a listing of behaviors within the behavior system in an exemplary order of priority;

FIG. 32 illustrates an embodiment of a stair climbing behavior;

FIGS. 33A and 33B illustrate positions of a remote vehicle relative to target stairs;

FIG. 34 illustrates an embodiment of a method for performing a stair climbing behavior;

FIG. 35 illustrates an embodiment of a preset action sequence behavior;

FIG. 36 illustrates an embodiment of a control system display for a click-to-grip behavior;

FIG. 37 illustrates an embodiment of a click-to-grip routine;

FIG. 38 illustrates an embodiment of a click-to-drive routine;

FIG. 39 illustrates an embodiment of a technique for moving among preconfigured poses;

FIG. 40 illustrates another embodiment of a technique for moving among preconfigured poses;

FIG. 41 illustrates an embodiment of a waypoint routine;

FIG. 42 illustrates an embodiment of a retro traverse behavior;

FIG. 43 illustrates an embodiment of remote control operation of a remote vehicle in an urban combat zone;

FIGS. 44A and 44B illustrate a retro traverse behavior;

FIGS. 45A – 45C illustrate a retro traverse behavior;

FIGS. 46A – 46D illustrate a retro traverse behavior;

FIG. 47 illustrates a retro traverse behavior;

FIGS. 48 and 49 illustrate an embodiment of speed boost and quick brake behaviors;

FIG. 50 illustrates an embodiment of a cruise control routine included within a cruise control behavior;

FIGS. 51A and 51B illustrate an embodiment of a cruise control behavior;

FIG. 52 illustrates an embodiment of a flow of information in a cruise control behavior;

FIG. 53 illustrates an embodiment of a routine to generate cruise control commands;

FIG. 54 illustrates an embodiment of an interaction between a cruise control behavior and other behaviors;

FIGS. 55A – 55D illustrate an embodiment of an interaction between a cruise control behavior and an obstacle avoidance behavior; and

FIG. 56 illustrates an embodiment of an obstacle avoidance routine for an obstacle avoidance behavior.

### **Detailed Description of Embodiments of the Invention**

[0011] An embodiment of a control system (also called an “operator control system” herein) for use with the present invention includes an unobtrusive, highly mobile control system that provides the user with a remote vehicle operating experience that seamlessly integrates with the user’s other tasks and duties. The control system allows the user to initiate autonomous behaviors for the remote vehicle, and to switch between tele-operation and such autonomous behaviors. Situational awareness is minimally compromised when operating the system, as it is critical for the user to be aware of his surroundings. Basic components of the control system, which are illustrated in FIG. 1, include a display, an input device, a processor, an antenna/radio (for wireless communication), and software. In an embodiment of the invention, a head-mounted display provides video display from one or more remote vehicle cameras. A hand-held controller, preferably having a twin-grip design, includes controls to drive, manipulate, and monitor the robot and its payloads. Audio may additionally be provided via the hand-held controller, the display, or dedicated listening devices such as, for example, Bluetooth headsets commonly used with mobile phones. In an embodiment of the invention, a microphone is provided on the hand-held controller, the processor, the display, or separately from these components, and can be used with a speaker on the remote vehicle to broadcast messages. A button on the hand-held controller or a soft button within the GUI can be used to activate the

speaker and microphone for broadcasting a message.

[0012] The system is preferably compatible with MOLLE packs, ALICE packs, ILBEs, or OTVs commonly worn by users. The system preferably has the following additional characteristics: lightweight (e.g., no more than 7 pounds total, and no more than 2 pounds for the hand-held controller); mobile; small form factor (e.g., able to integrate with existing user gear); wearable or capable of being carried in a backpack; easy to put on/take off; adequate computer processing power; minimal or no external cables; meets mission time thresholds (e.g., 5 hours); rugged to intended environment (e.g., temperature, shock, vibration, water, etc.); able to withstand being dropped (e.g., 3 feet).

[0013] The platform should have standard interfaces for networking, display, wireless communication, etc.

[0014] The control system, as illustrated in FIG. 1, includes a processor such as a rugged laptop computer. The processor could alternatively be any suitably powerful processor including, for example, a tablet PC. The processor communicates with the remote vehicle wirelessly or via a tether (e.g., a fiber optic cable). Although wireless communication may be preferable in some situations of remote vehicle use, potential for jamming and blocking wireless communications makes it preferable that the control system be adaptable to different communications solutions, in some cases determined by the end user at the time of use. A variety of radio frequencies (e.g., 802.11), optical fiber, and other types of tether may be used to provide communication between the processor and the remote vehicle.

[0015] The processor must additionally communicate with the hand-held controller and the display. In a preferred embodiment of the invention, the processor is capable of communicating with the hand-held controller and the display, illustrated in the present

embodiment to be a head-mounted display, either wirelessly or using a tether. To facilitate wireless communication among the various elements of the system, the processor includes a radio and an antenna.

[0016] In addition, the processor includes software capable of facilitating communication among the system elements, and controlling the remote vehicle. In an embodiment of the invention, the software is a proprietary software and architecture, including a behavioral system and common OCU software, which provide a collection of software frameworks that are integrated to form a basis for robotics development. According to an embodiment of the invention, this software is built on a collection of base tools and the component framework, which provide a common foundation of domain-independent APIs and methods for creating interfaces, building encapsulated, reusable software components, process/module communications, execution monitoring, debugging, dynamic configuration and reconfiguration as well as operating system insulation and other low-level software foundations like instrument models, widget libraries, and networking code. In an embodiment of the invention, the processor performs all of the data processing for the control system.

[0017] Referring to FIG. 2, an exemplary embodiment of a twin-grip hand-held controller is illustrated. The hand-held controller includes left and right grips shaped to be held between a little finger, a ring finger, and the ball of a thumb of a respective hand, leaving the index finger, middle finger, and thumb of the respective hand free to manipulate controls. Two joysticks (analog, having 4 degrees of freedom) are provided on the left and right sides of the hand-held controller. The joysticks may be 2-axis analog. In an embodiment of the invention, analog-to-digital resolution of the joysticks is at least 12-bit per axis with the joystick center "dead band" (maximum offset from center on spring return) being less than about 3% of total

resolution. If pressed, the joysticks can function as digital buttons. The present invention also contemplates using pucks (6 degrees of freedom) instead of joysticks.

[0018] In an embodiment of the invention, the left joystick is commonly used to drive the remote vehicle (forward, backward, left, and right). The right joystick controls one or more other functions of the robot depending on a selected button function mode, including a camera (e.g., the attack camera), a weapon, or flipper control.

[0019] A directional pad is located on a left side of the hand-held controller and includes an array of four or five discrete digital buttons for manipulation by the user's left thumb. The buttons are arranged in a diamond shape with an optional button in the center. The four buttons not in the center preferably come to a rounded point at one end to indicate direction. One button points up, one points down, one points right, one points left. In an embodiment, the four buttons not in the center have a generally flat exposed surface and the center button has a generally hemispherical exposed surface and is raised above the surrounding buttons. In an embodiment of the invention, the directional pad is used to navigate among the soft buttons of a GUI displayed by the head-mounted display. The center button of the array, when present, may be used to select a soft button of the GUI.

[0020] A right button array includes an array of four discrete digital buttons for manipulation by the user's right thumb. The buttons are arranged in a diamond shape and are circular with exposed surfaces that may be at least slightly curved. The right button array can be used to control a variety of functions such as camera selection, robot light setting, and robot speed. When no center button is provided on the directional pad, one of the buttons of the right button array may be used to select a soft button of the GUI.

[0021] A center button array is shown to include five discrete digital buttons for

manipulation by the user's thumbs. A first button is generally located in an upper left region of the center area, a second button is generally located in an upper right region of the center area, a third button is generally located in a lower left region of the center area, a fourth button is generally located in a lower right region of the center area, and a fifth button is generally located in the center of the other buttons. The first four buttons are elongated (generally rectangular) and the fifth button is generally hemispherical. In an embodiment of the invention, the center button is larger than the other buttons in the center array.

[0022] In an embodiment of the invention, the upper right button (second) button is the menu button, which brings up a menu within the GUI displayed by the head-mounted display. The menu is preferably a hierarchical menu, such as a drop-down menu, that allows the user to select a screen layout, a robot to control, select a safe mode for the robot (such as observe mode), manage and play video, audio and snap shot recordings, select among other settings such as brightness, and time/date, or review documentation regarding the controller or the robot. In this embodiment, the upper left (first) button acts as a pause or brake button for the robot, ceasing movement of the robot until released. To prevent accidental activation, the pause/brake button may be recessed and/or may require a minimum force for activation.

[0023] A button on the hand-held controller or a soft button within the GUI can be used to switch controllers, so that another hand-held controller or alternative control device can take over control of the remote vehicle. This can allow multiple operators to control the same remote vehicle.

[0024] The pause or brake button may alternatively be designed as a dead man's switch to ensure safe operation of the robot – if the user's finger is released from the switch, the robot ceases to operate. In an embodiment of the invention, the dead man's switch is located under the

user's left index finger, right index finger, left middle finger, or right middle finger.

[0025] Bumper or rocker buttons are located on the shoulders of the hand-held controller, the buttons making up a rocker control. Two rocker buttons make up a first rocker control on the left shoulder and are oriented vertically, and two more rocker buttons make up a second rocker control on the right shoulder and are also oriented vertically. As an alternative to rocker buttons, one-axis switches may be provided on the left and right shoulders (not shown). The rocker buttons, being aligned vertically along the shoulder of the hand-held controller, are thereby located in a pitch plane parallel to the articulated flipper drive. In an embodiment of the inventions, the rocker control on the right shoulder is used for flipper control.

[0026] The directional pad, left joystick, and left shoulder rocker control make up a left control zone. The right button array, right joystick, and right shoulder rocker control make up a right control zone.

[0027] A power button is located between the left and right shoulder areas of the hand-held controller. In the illustrated embodiment, the button is circular with a flat protruding surface. The button may optionally be recessed (to prevent inadvertent actuation) and/or backlit with an LED that indicates the state of the hand-held controller (i.e., on or off). In an embodiment of the invention, the area of the hand-held controller immediately surrounding the power button is smooth to facilitate using electrical tape to cover the power button and its LED as needed. Covering the power button can avoid detection of the hand-held controller. The power button on the hand-held controller may control the state of just the hand-held controller, or of a number of other system components, such as the processor and one or more displays (e.g., the head-mounted display).

[0028] An embodiment of the invention includes a tether zone (see FIG. 3) located

between the left control zone and the right control zone, which includes a tether anchor configured to tether the hand-held controller between the left grip and right grip and permit the hand-held controller to hang in use (see FIG. 13) with the left grip and right grip pointing upward. A tether, or cord, extends from the tether anchor, preferably to the right shoulder of a dismounted operator.

[0029] In an embodiment of the invention, the tether is detachable from the hand-held controller, and connects the hand-held controller to the processor for non-wireless communication between the two. In an embodiment of the invention, the hand-held controller can operate on battery power and communicates wirelessly with the processor, but has the ability to accept a tether when non-wireless connection is preferred.

[0030] In an embodiment of the invention, the tether has a strain relief allowing it to be flexible but also physically support the weight of the hand-held controller and withstand being dropped the a distance equal to the tether's length (e.g., 3 feet) without damage or disconnection.

[0031] In an embodiment of the invention, the tether attaches to the hand-held controller via an environmentally sealed connector, such as push-pull, screw latching, etc. The same environmentally sealed connection may be used where the tether connects to the processor. The tether connectors may be keyed to prevent pin misalignment during connection.

[0032] FIGS. 5 and 6 illustrate an optional roller wheel that may be provided on the hand-held controller. In an exemplary embodiment, the roller wheel is surrounded by a textured tire and sits in a cavity of the hand-held controller. The cavity is formed in the exterior surface of the hand-held controller and includes an interior shell to encase the roller wheel. An axle extends between two sides of the interior shell and allows the roller wheel to rotate within the cavity. Bushings may additionally be provided to reduce friction and wear. The axle extends

into a rotary transducer located on at least one side of the cavity, the rotary transducer measuring rotation of the roller wheel and converting it to a digital output. The location of the roller wheel on the hand-held controller, if provided, may vary, although the wheel is preferable located so that it can be actuated by the user's thumb or forefinger (either left or right). The roller wheel may be used, for example, for camera zoom or to scroll among soft buttons in the GUI.

[0033] FIGS. 7, 8, and 9 illustrate an optional rotary ring switch. In the illustrated exemplary embodiment, the rotary ring switch is located around a joystick and includes three positions on the ring that may be selected by sliding a selector along the ring to one of the positions. In an embodiment of the invention, the rotary ring switch surrounds the left joystick so that selection is made with the user's left thumb. The rotary ring switch may be used to select among button functions modes.

[0034] The present invention contemplates a variety of locations for the ring switch if one is provided, as well as a varying number of positions for selection. For example, the ring switch could surround the right joystick, the directional pad, the right button array, or the center button array.

[0035] The present invention contemplates using labels (not shown) on or near the buttons of the hand-held controller to indicate the functionality of one or more of the buttons.

[0036] It will be appreciated by those skilled in the art that location and shape of the buttons may vary among embodiments of the invention. The present invention contemplates a variety of button shapes and locations. Additional buttons may be added, or buttons may be removed within the scope and spirit of the invention.

[0037] The present invention contemplates additional or alternative functionality for the hand-held controller. For example, the hand-held controller may be able to detect aspects of its

own movement via accelerometers and gyroscopes and translate that movement into remote vehicle control functions such as, for example, scrolling through a GUI menu. While the hand-held controller's movement could be translated into corresponding movement of the remote vehicle, such control may not be advisable in certain situations where precise control of the remote vehicle is critical and/or the controller may be subject to unforeseen jostling with potentially hazardous results in terms of corresponding movement of the remote vehicle.

[0038] An embodiment of the invention provides mode changing software for changing button mapping of the hand-held controller between, for example, driving a robot, manipulating an arm, controlling a camera, etc.

[0039] In an embodiment of the invention, switching among button function modes of the hand-held controller is accomplished by actuating a button or toggle-type switch, preferably using the operator's index finger(s). This can be accomplished using an above-described rotary ring switch, another button on the hand-held controller, or even the optional roller wheel described above. The present invention also contemplates switching button function modes on the left side of the controller which one switch or button, preferably located on the left side, and switching button function modes on the right side of the controller which another switch or button, preferably located on the right side.

[0040] According to an embodiment of the invention, button function modes include:

[0041] Drive Mode - the left joystick is used to steer the robot forward, back, left, and right, the left button array is used to control the attack camera (for a robot having, for example, a drive camera and an attack camera), the right joystick controls a spooler (for example containing fiber optic cable), the right button array controls a variety of functions such as the camera zoom, robot lights, robot speed, an camera choice (allows user to choose one or more cameras as, for

example, primary and secondary), and the right shoulder is for flipper control.

[0042] Manipulate (Gripper) Mode – the left joystick is used to move the gripper forward, back, left, and right, the right joystick is used to move the gripper up and down and to fold or unfold the elbow, and the right shoulder buttons are used to rotate the gripper clockwise and counterclockwise.

[0043] Target (Attack Camera) Mode – The left joystick is used to move the attack camera forward, back, left, and right, and the right joystick is used to move the attack camera up and down.

[0044] Joint Mode – The left joystick folds and unfolds the gripper shoulder (e.g., using the top and bottom buttons), and rotates the turret clockwise and counterclockwise (e.g., using the right and left buttons). The right joystick folds and unfolds two gripper elbows. The left button array controls the attack camera, and the right button array controls a variety of functions such as the camera zoom, robot lights, robot speed, and camera choice. The right shoulder buttons are used to rotate the gripper clockwise and counterclockwise.

[0045] Menu (GUI Navigation) Mode – The left joystick navigates a cursor up, down, right, and left, the left button array moves the menu itself up, down, left, and right, and the right button array includes cancel and select functions.

[0046] Among the above exemplary button function modes, certain buttons may maintain the same functions, such as the top left button of the center button array being a pause/brake button, and the top right button of the center button array being a menu button. In addition, the button to change among the above functional modes may remain the same. In an embodiment of the invention, the left joystick is always used to drive the remote vehicle and the directional pad is always used to navigate soft buttons of the GUI. It is the other buttons that change

functionality among modes.

[0047] It should be understood that the present invention contemplates a variety of button mapping scenarios, and a variety of single and combined function modes that allow the operator to control one, two, or more payloads of the remote vehicle with the same hand-held device by manipulating the buttons on the hand-held controller.

[0048] In an embodiment of the invention, the weight of the hand-held controller, including the cord, is less than or equal to two pounds. In a preferred embodiment, the weight of the hand-held controller itself is less than one pound, and the dimensions are no larger than 4.5" x 2.5" x 6.5".

[0049] According to an embodiment of the invention, the hand-held controller is ruggedized. For example, the casing and switch plate may comprise aluminum, and the unit or parts thereof may be coated in plastisol or another suitable coating. In addition, the tether connection may be environmentally sealed, and the buttons may additionally be made waterproof as is known to those skilled in the art, particularly in the area of waterproof cameras.

[0050] For adhering the hand-held controller to the user's gear, an embodiment of the invention includes a quick-release system. An embodiment of the quick-release system includes a quick release pad, an embodiment of which is illustrated in FIG. 10. The quick-release pad preferably comprises Velcro® on an outer-facing side thereof, and has a size suitable to allow releasable but stable attachment of the hand-held controller to the pad. The pad is attached to a loop on the user's gear. In the embodiment of FIG. 10, the loop is a horizontal loop such as those provided on an OTV. A strap connected to the quick-release pad circles through the OTV loop to attach the quick-release pad to the OTV. An additional quick-release mechanism (not shown) may be used to releasably fasten the tether (which connects the hand-held controller to

the processor) to the user's gear. Complementary material is located on an underside the hand-held controller to mate with the quick-release pad. In an embodiment of the hand-held controller including protrusions extending from a bottom thereof (see FIGS. 3 and 4), the complementary material is located on the protrusions. In an alternate embodiment with, for example, a flat bottom, at least a portion of the bottom would include complementary material. Because Velcro® can wear out and become less effective, the present invention contemplates the Velcro in the quick-release system being easily replaceable.

[0051] The head-mounted display illustrated in FIG. 1 generally indicates a display device worn on a user's head or as part of a helmet, which has a display optic in front of one or both eyes. A typical head-mounted display has one or two displays with lenses and semi-transparent mirrors embedded in a helmet, eye-glasses, or a visor. The display units are miniaturized and may include cathode-ray tubes (CRTs), liquid crystal display (LCD), Liquid Crystal on Silicon (LCos), or an organic light-emitting diode (OLED).

[0052] The head-mounted display allows the remote vehicle operator to see what the remote vehicle sees through one or more cameras, so that the remote vehicle can be controlled when it is not within the operator's line of sight, and also allows the operator to maintain situational awareness. In an embodiment of the invention, the head-mounted display is an Icuiti tactical display.

[0053] The head-mounted display displays a GUI with views from the robot's camera(s) and information about the robot such as battery life, payloads, communication status, etc., and also displays soft buttons that are mapped to the hand-held controller buttons and allow the user to more intuitively control the robot using the hand-held controller.

[0054] The present invention contemplates using one or more head-mounted displays

with a single control system. In addition, the video stream from the robot camera(s) can be multi-casted for use by multiple clients. Indeed, the multiple clients need not only be multiple head-mounted displays, but may alternatively or additionally include a variety of displays and/or recoding devices in a variety of locations.

[0055] The head-mounted display is preferably capable of either wireless or tethered communication with the hand-held controller through the processor.

[0056] As stated above, a menu mode of the hand-held controller allows the user to navigate among soft buttons or icons displayed by the head-mounted display. Exemplary embodiments of the GUI display are illustrated in FIGS. 11 and 12.

[0057] As illustrated in the embodiment FIG. 11, the head-mounted display provides the user with a variety of information in what is indicated as a “max camera” layout. In this illustrated embodiment, the main image is a video stream from the robot’s attack camera and the smaller image in the lower right corner is video stream from the robot’s drive camera. As an alternative to video streams, a series of snapshots can be displayed at predetermined time intervals. The status of the attack camera (e.g., front zoom) is displayed in the upper left corner, and certain camera control icons or soft buttons are presented under the camera status. In this embodiment, the icons include zoom in, zoom out, IR filter on/off, IR light off/low/medium/high, camera default position (designated in this embodiment as a V in a sun shape), camera setting choices, audio choices, snap shot, and video record on/off. In this embodiment, upon choosing (by pressing the soft button or icon by manipulating the hand-held controller in the menu mode) camera settings and audio, the GUI pops up a screen to select among a variety of setting options. In an embodiment of the invention, the icons can be minimized. Above the status of the camera, the robot’s name can be displayed (illustrated herein

as “Name567890123456”).

[0058] The camera may be returned to its default position, or otherwise controlled, via the soft button mentioned above, or a button on the hand-held controller.

[0059] Additional icons or soft buttons may be displayed, for example on the right side of the head-mounted display view. In this embodiment, the icons or soft buttons include, from top to bottom, status of communication link (with robot), battery charge level (of the robot and the OCU), speed toggle (wherein the snail icon indicates that the robot is in a slow range of speed within the available scalable range of speed), robot heading, two icons indicating the robot’s position and heading, and a variety of autonomous assist options such as predefined poses (described in detail below).

[0060] Another embodiment of the system’s GUI, indicated as a “quad” layout, is illustrated in FIG. 12. The larger, upper left image is a video stream from the robot’s attack camera and the smaller image in the center of the display is video stream from the robot’s drive camera. As an alternative to video streams, a series of snapshots can be displayed at predetermined time intervals. The status of the attack camera (e.g., front zoom) is displayed in the upper left corner, and certain camera control icons or soft buttons are presented under the camera status, as set forth for the prior embodiment. In an embodiment of the invention, the icons can be minimized. Above the status of the camera, the robot’s name can be displayed (illustrated herein as “Name567890123456.” Under the camera controls is a map icon allowing the user to select additional information from the system’s mapping function. To the right of the map icon and under the video stream from the attack camera, mapping information regarding one or more of the robot’s prior mission movements can be displayed. Alternatively, the missions of a number of nearby robots are displayed.

[0061] Additional icons or soft buttons may be displayed, for example on the right side of the head-mounted display layout. Similar to the previous embodiment, the icons or soft buttons include, from top to bottom, status of the communication link (with robot), battery charge level (of OCU), speed toggle wherein the snail icon indicates that the robot is in a slow range of speed (within the available scalable range of speed), and a variety of autonomous assist options such as predefined poses. In this embodiment, the poses are indicated by name rather than a graphical representation of the pose itself. Payload icons under the pose icons allow the user to activate a payload or bring up a control menu for that payload. They can also display information regarding selected payloads. Possible payloads include cameras, chemical detection devices, sniper detection devices, cable spools, batteries, etc. In the illustrated embodiment, payload 3 is an Explorer extension added to the chassis of the robot, and payloads 4 and 5 are batteries.

[0062] To the right of the video stream from the robot's attack camera is a representation of the robot's position and heading, including any tilt. Under the positional representation is an identification of the payloads and information regarding the payloads, such as an indication of remaining battery life.

[0063] In accordance with the present invention, the user may choose among a variety of GUI layouts, such as the "max camera" and "quad" layouts described above.

[0064] In the above illustrative embodiments of the GUI, the icons or soft buttons may be displayed continuously for the user, who navigates among them using a dedicated set of buttons on the hand-held controller (e.g., the directional pad), or may be displayed only when the hand-held controller is in a menu mode. Additional soft icons or buttons may be displayed as desirable. In an embodiment of the invention, the illustrated icons are displayed continuously for

the user, and selection of a menu mode on the hand-held controller brings up an additional hierarchical menu of functions through which the user can navigate, for example, using the directional pad.

[0065] In an embodiment of the control system of the present invention, audio is provided on one or more of the processor, the hand-held controller, the head-mounted display, or a separate headset.

[0066] The control system of the present invention preferably has two states (on and off) and three modes: (1) training mode; (2) operation mode; and (3) maintenance mode. The modes of the control system are distinct from the button function modes of the hand-held controller. After being powered on, the system may default into an operation mode, default to the last mode selected, or may initially prompt the user to choose among the three modes. Most system functions, including the exemplary functions listed in the table below, are preferably performed in all three modes.

#### Power

On/off

Status

#### Communicate

communicate with robot

status of communications

tethered and wireless communication

## Control

drive/stop

brake engage/release

speed control

flipper control

head/neck control

pose selection

camera selection

camera zoom

camera control options including

aperture/exposure/resolution/black and white/color/etc.

microphone control on/off/speak

speaker control on/off/volume

request information/status/data

illumination on/off/other

select options

select robot

payload control

map controls (autonomous robots or assistance)

autonomy controls

## Display

display video

display health and status (system)

display options

GPS location/navigational information

#### Audio

Emit

Send

adjustment options

#### Process

process data/audio/video

[0067] The system is intended for use by a dismounted operator, dismounted means that the operator is freely moving about outside of the remote vehicle(s). However, the system may additionally be used by an operator that is not dismounted. The system of the present invention may be useful to an operator that is not dismounted in an instance where the operator has difficulty reaching all of the controls needed to operate the vehicle and its payloads, or the vehicle and other remote vehicles.

[0068] The system of the present invention should be capable of controlling remote vehicle mobility, executing operator tasks with one or more remote vehicles, and supporting maintenance functions.

[0069] FIG. 13 illustrates a soldier using the control system of the present invention to control a robot. Although the robot is illustrated to be in the soldier's line of sight, the present

invention is directed to non-line-of-sight operation as well, with the soldier using the head-mounted display to see what the robot sees and thereby effectively control the robot.

[0070] FIG. 13A illustrates an embodiment of the invention including a two-piece hand-held controller that functions substantially similar to the one-piece hand-held controller described above. This embodiment of the invention allows the left portion of the controller to be attached to the user's gun, so that one hand can remain on the gun while controlling the remote vehicle.

[0071] FIGS. 13B and 13C illustrate another embodiment of the invention including a two-piece hand-held controller. In this embodiment, the right hand controller is mounted to the gun and the left hand controller can be secured to a quick-release pad. The left hand controller would preferably hang from the user's left shoulder. This embodiment would be preferably where a user is trained to or tends to keep his firing hand on the gun.

[0072] The controller may have a variety of shapes and sizes to facilitate ease of gripping and actuation by a user. For example, the one or both pieces of the controller may include a grip portion shaped to be held between a little finger, a ring finger, and the ball of a thumb of a respective hand, leaving the index finger, middle finger, and thumb of the respective hand free to manipulate controls. One or both pieces of the controller may include a joystick to be manipulated by the user's thumb. The two-piece hand-held controller may include the same number of buttons as the one-piece controller above, or may include a more limited number of buttons.

[0073] In an embodiment of the two-piece hand-held controller, the two pieces may be mated to form a one-piece hand-held controller for use as described above. In this embodiment, the two pieces may look more like halves of the one-piece hand-held controller illustrated in

FIG. 2.

[0074] As in the prior disclosed embodiments, the hand-held controller communicates with the display via a processor (not shown).

[0075] Remote vehicles can utilize a number of autonomous behaviors that can be implemented automatically or via the control system, such as via the GUI icons described above. Such behaviors, illustrated in FIG. 14, can be categorized as: (1) ballistic behaviors that autonomously execute once within a defined operating period; (2) semi-ballistic behaviors that execute once within a defined operating period and that operate autonomously while allowing for manual control during execution; or (3) persistent behaviors that execute continuously and autonomously while allowing the operator to manually control other behavior(s) of the remote vehicle. In an embodiment of the present invention, the autonomous behavior(s) may begin by either responding to sensor output and autonomously starting the behavior, responding to operator input via the depression of a key, soft key, or other actuator included the control system described above, or by responding to other behavior output.

[0076] An embodiment of the present invention provides the operator with varying levels of autonomy so that the operator may control the remote vehicle at times and choose to allow the remote vehicle to operate autonomously at times or concurrently. Autonomous behaviors that execute one-time operations simplify operator manipulation of the remote vehicle when such operation includes monotonous or difficult tasks.

[0077] FIG. 14 is a block diagram illustrating an exemplary embodiment of autonomous behaviors available to an operator and included within the remote vehicle's control system. Included within the control system manipulated by the operator is a software array of behaviors organized under a main autonomous behavior 7050 and fanning out into the various subtypes of

autonomous behavior. In particular the main autonomous behavior 7050 identifies in memory three main subtypes of behaviors: ballistic behaviors 7065, semi-ballistic behaviors 7092 and persistent behaviors 7053. An embodiment of the present invention includes the capability to provide all three types of behaviors, but the present invention also contemplates providing only one or two types of behaviors. Ballistic behaviors 7065 comprise a particular behavior routine that executes for a finite period of time when the behavior is activated. Activation of a ballistic behavior 7065 causes that particular behavior's status to indicate that the behavior is active, and further causes that behavior to put in a vote to the actuator to gain control of its associated actuators. Exemplary ballistic behaviors 7065 include: stair climbing 7068, preset action sequence 7071, click-to-drive or click-to-grip 7074, custom pose presets 7077, autonomous flipper routine 7078, retro traverse 7080, and self-righting 7083.

[0078] FIG. 15 is a flow diagram illustrating an activation routine used to activate a ballistic behavior and its associated routines. To activate the behavior, the operator must actuate a control system button, switch, etc. to generate an associated signal, and the signal is transmitted 802 to the control system. The control system then calculates a command 804 representative of the actuated button, switch, etc. and sends the command to the remote vehicle via a communication connection. Once the command is received by the remote vehicle, the remote vehicle's control system 1155 (see FIG. 21) executes a routine to determine if the behavior is compatible 806 with the remote vehicle's current state. This means that the executed routine will evaluate all sensor output to determine whether or not the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior on the remote vehicle, or the remote vehicle's environment are incompatible with the chosen behavior. If the behavior is not okay to run (not permitted), the remote vehicle generates

feedback information 808 that is sent to the user, alerting the user to the behavior's incompatibility. The ballistic behavior activation routine is then exited 824.

[0079] If the behavior is compatible (permitted), the remote vehicle changes the start condition of the chosen behavior to a positive value 810, causing the behavior to turn on. Once turned on, the behavior sends a vote to the arbiter 812 requesting control of its associated actuators. If the behavior has a higher priority than the behavior currently in control of the actuators 814, the remote vehicle will gain control of the actuators and wait for a second start condition (explained further below). If the behavior doesn't have a higher priority than the behavior currently in control of the actuators 814, the behavior will wait 816, and send another vote 812 to the arbiter. The behavior will continue to do this until it gains control of the actuator. Should the behavior have control of the actuator, and its second start condition is true 818, then the software routines included within the behavior will execute 822. When finished executing, the routines will alter the behavior's start conditions to a false or stop status effectively halting the behavior 824.

[0080] If the remote vehicle's second start condition 818 is not true, the behavior will wait 820 until such a condition is true. A second start condition check 818 is included to accommodate those behaviors that may be in a perpetual start mode, but that are not activated until they receive particular sensor information. Alternatively, the second start condition check 818 could be used to activate routines within behaviors that are currently in an "on" state. An example of the above routine includes starting the stair climbing behavior which can be accomplished by, for example, depressing a soft button included on the screen, which in turn creates 800 and sends 802 a signal to the control system. The control system interprets the signal as indicating the start of stair climbing, and creates and sends a command 804 to the remote

vehicle indicating that the stair climbing behavior should be activated. A routine within the remote vehicle's control system 1155 then determines whether or not the remote vehicle is able to execute stair climbing 806.

[0081] In response to an allowance of execution of stair climbing, the routine will then alter the stair climbing behavior's first start condition 810 to a positive or true value and the stair climbing behavior will begin to send votes to the arbiter requesting control over the drive motors, tilt sensor, and other actuators and circuits involved in stair climbing. When the arbiter determines that stair climbing has the highest priority 814, stair climbing will then check to see if its second start condition is true. Such a start condition could include such input as the positioning of a target location over the stair case using a selection graphic included on the display screen. Once the target location is input, a message could be sent to the remote vehicle indicating that the second start condition is true 818 and further causing the routines within the stair climbing routine to execute 822. During the time period between gaining actuator control and realizing a second start condition, the stair climbing behavior will wait 820. Once the robot has reached the top of the stairs, as indicated by the tilt sensor, an end condition is reached and the stair climbing behavior resets its flags to a stop or negative start condition which effectively halts and stops 824 the stair climbing behavior.

[0082] Activation of a semi-ballistic or interactive behavior 7092, on the other hand, can cause one of either an alternative version of a pre-existing behavior to execute, or a one-time tuning behavior to execute. For example, a behavior or routine that starts a fire-and-forget process for a limited time (or stopped by a particular detection) but that permits user interaction or partial tele-operation during its course (in contrast to what is referred to herein as a "ballistic" behavior, which generally proceeds for a specific time period or until finished but would be

interrupted and terminated by tele-operation intervention. Similar to ballistic behaviors 7065, alternative embodiments of the invention can include more or less semi-ballistic behaviors in the semi-ballistic set, or can not include a semi-ballistic behavior set 7092 within the autonomous behaviors 7050. Semi-ballistic behaviors 7092 may include, for example, quick brake 7089 and speed boost 7086. In an embodiment where the semi-ballistic behavior 7065 is used to fine tune another behavior, the behavior chosen to be fine tuned can either be selected by the operator via pressing a button, selecting a behavior on the display via soft keys, a mouse, or controller, or there could be a behavior pre-associated with a particular semi-ballistic behavior. Fine tuning a behavior preferably includes altering calculations within a routine included within a behavior, or altering variables included within the behavior.

[0083] FIG. 16 is a flow chart illustrating a routine for activating a semi-ballistic behavior used to tune a behavior. To activate the behavior, the operator actuates a control system button or switch, which generates a signal associated with that particular button or switch 830. The signal is transmitted 832 to the control system, which calculates a command 834 representative of the actuated button or switch and sends the command to the remote vehicle via a communication connection. This command includes information indicating that the semi-ballistic behavior should be activated, along with information indicating which behavior the semi-ballistic behavior should be applied to. Once the command is received by the remote vehicle, its control system 1155 executes a routine to determine if the behavior is compatible 836 with the remote vehicle's current state. This means that the executed routine will evaluate all sensor output to determine whether the remote vehicle's position within its environment, its current internal state, its current operational behavior, or its environment are incompatible with the chosen behavior.

[0084] If the behavior is not okay to run (not permitted), the remote vehicle generates feedback information 838 that is sent to the user, alerting the user to the behavior's incompatibility, and the ballistic behavior activation routine is exited 850. Should the behavior be compatible (permitted), the remote vehicle changes the start condition of the chosen behavior to a positive value 840, effectually causing the behavior to turn on. Once turned on, the behavior sends a vote to the arbiter 842 requesting control of its associated actuators. If the behavior has a higher priority than the behavior currently in control of the actuators 844, then the remote vehicle will gain control of the actuators. If the behavior doesn't have a higher priority than the behavior currently in control of the actuators 844, then the behavior will wait 846, and send another vote 842 to the arbiter. The behavior will continue to do this until it gains control of the actuators. Once the behavior has control of the actuator, the routine within the behavior 848 will execute.

[0085] The routine selects the chosen behavior to be altered and tune variables or routines included within the behavior according to the routine within the semi-ballistic behavior. Once the routine within the semi-ballistic behavior finishes altering the chosen behavior, the routine alters the semi-ballistic behavior's start conditions to a false or stop status, effectively halting the semi-ballistic behavior 824. An example of a semi-ballistic behavior is the speed boost behavior 7086 which has a chosen behavior already associated with it, the drive behavior. When an operator actuates the button or switch associated with speed boost, a signal is created 830 and sent 832 to the control system, where the signal is converted into a command that is sent to the remote vehicle via a communication link 834. Once the remote vehicle's control system 1155 receives the command, a routine included in the remote vehicle's control system determines whether or not speed boost is compatible with the remote vehicle's current state. For example, should the remote vehicle currently be climbing stairs, the routine may alert the user

that speed boost cannot be activated. When speed boost is okay to activate 836, the start condition in the speed boost behavior is set to a positive start value 840, and speed boost begins sending in votes 842 to an arbiter (see FIG. 31) to gain control of the actuators associated with the drive behavior. Once speed boost is determined to be the highest priority behavior, the routine within speed boost will then alter 848 any one of a speed range or velocity value within the drive behavior. Upon completing the change, the routine within speed boost alters speed boost's start condition to a negative value and the speed boost behavior halts and turns off speed boost 850.

[0086] Also included within the autonomous behaviors 7050 are persistent behaviors 7053, which include behaviors that can be turned on and kept on via an always true first start condition. A persistent behavior is activated via a proper second start condition. Persistent behaviors 7053 start when the remote vehicle is powered up and can be stopped by actuating a control system button, switch, etc. An embodiment of the invention includes a persistent behavior set 7053 including an obstacle avoidance 7059 behavior. While shown as a semi-ballistic behavior in FIG. 14, cruise control can alternatively be a persistent behavior.

[0087] FIG. 17 is a flow chart illustrating a routine to activate or de-activate a persistent behavior. To de-activate a currently activated persistent behavior, the operator actuates a control system button, switch, etc. generating a signal that is transmitted 857 to the control system. The control system then calculates a command 859 representative of the actuated button, switch, etc. and sends the command to the remote vehicle via a communication connection. According to an embodiment of the invention, the command either includes a start or stop command that causes the persistent behavior to have an on or off state. When on, the behavior will execute in response to sensor and system input. When off, the behavior will not execute.

[0088] Once the command is received by the remote vehicle, the remote vehicle's control system 1155 relays the command to the proper behavior, which causes the behavior's first start condition to be altered. When the command indicates that the persistent behavior should be turned on, the start condition will be changed to a positive or on condition. When the command indicates that the persistent behavior should be turned off, the start condition will be changed to a negative or off condition. Depending on whether the condition was made positive or negative, the persistent behavior will either start or stop 865. In an embodiment where persistent behaviors have an initial positive start condition, an operator will need to turn off the behaviors after the remote vehicle is powered up to keep the persistent behaviors from executing in response to system and sensor output.

[0089] FIG. 18 illustrates the execution of routines within a persistent behavior when the routines' second start condition is activated by system or sensor output. The flowchart in FIG. 18 assumes that the persistent behavior's first start condition is true, and has been true as a function of its "always on" characteristic. To initiate the execution of the persistent behavior, sensor or system output must be sent 867 to the persistent behavior by the remote vehicle's control system 1155. If such output is of the type that will cause the remote vehicle's second start condition to become positive, the persistent behavior's second start condition flag will be changed 871 to a positive or start value and the persistent behavior will begin to send votes 873 to the arbiter to gain control of the behavior's associated actuators and manipulators. If the behavior has a higher priority than the behavior currently in control of the actuators 873, then the behavior will gain control of the actuators. If the behavior doesn't have a higher priority than the behavior currently in control of the actuators 875, then the behavior will wait 878, and send another vote 873 to the arbiter. The behavior will continue to do this until it gains control of the

actuators or manipulators. Should the behavior have control of the actuator, the routine within the behavior will execute 879. The routine will continue to execute until it loses control over the actuators 885, in which case one of the first or second start condition flag is changed to a negative or stop value 887 which causes the behavior to stop 883. If the first start condition flag changes to a negative or stop value, the behavior is disabled. In an embodiment of the invention, the behavior can thereafter be restarted using the routine displayed in FIG. 17. If the second start condition flag is changed to a negative or stop value, the behavior will stop until it detects sensor or system output that causes the behavior to start again.

[0090] An example of a persistent behavior is obstacle detection (avoidance) 7059, which is always on unless an operator actuates a control system button, switch, etc. for altering the first start condition of the obstacle detection behavior. When actuated, a signal is generated and sent 857 to the control system, where a representative command is sent 859 to the remote vehicle. Once received by the remote vehicle, the command is relayed to the obstacle detection behavior where it changes the first start condition flag 861 to a negative value. This change of value causes the obstacle avoidance behavior to be disabled. If the obstacle detection behavior remains on, and a sensor detects an obstacle, the sensor output is sent to the obstacle detection behavior 867, where it causes the obstacle detection behavior's second start condition flag to change to a positive or on state 871. Upon the second start flag's change in state, the obstacle detection behavior sends votes 873 to the arbiter to gain control of the drive assembly, actuators, and assemblies needed to avoid obstacles. When the arbiter determines that obstacle detection has the highest priority 875, obstacle detect then executes its routines 879. While executing, the behavior checks to make sure that it has control of the actuators 885, and halts the routines and behavior 883 when it loses control. The behavior also checks to see if the second or first start

conditions have changed, and if they change from positive to negative, then the routines and behavior halt 883.

[0091] The above description of ballistic, semi-ballistic and persistent behaviors is exemplary. The present invention contemplates implementing other versions of the behaviors. For example, steps 879 through 887 of FIG. 18 may be substituted into the ballistic and semi-ballistic routines for steps 848 and/or 822.

### **Tutorial Routines**

[0092] In an embodiment of the invention, the software included in the control system also includes tutorial routines able to perform the characteristics of a training system. The tutorial routines could include a storage bank for providing cells of storage to each mission for which the operator indicates that training information should be recorded. The training information can more aptly be called macros in that it records, according to a timeline, an environmental set of variables, a command set, and a set of system variables. Preferably, the command sets include both commands sent by the operator and commands generated and sent by routines within the remote vehicle's control system 1155. The command sets and variables are recorded as use routines able to recreate the recorded action according to a proper timeline. When a recorded mission is replayed, the use routines included in the macro are executed, which causes the control system to display information to the user as though it were sensing the recorded environmental and system sensor information, and further causes the remote vehicle to mobilize according to the recorded commands. The result is a replaying of the events of the mission. The routines can be stored and used later as a pre-defined action sequence, and they may further be used to train operators on the proper use of the control system and remote vehicle. When routines are used as a pre-defined action sequence, the replay routines call additional use

routines that suppress environmental and system variable information and execute only the stored commands.

### **Robot Structure**

[0093] FIGS. 19A and 19B illustrate an embodiment of a remote vehicle of the present invention. A mobile robot 10 has a head 122 that includes a drive camera 127 mounted thereon to provide visual information regarding the environment of the mobile robot 10, an electro-optic infrared (EO/IR) module 4165 which uses LIDAR to map the environment and detect possible obstacles, main drive treads 110 for propelling and steering the mobile robot 10, and robot-mounted antennae 131 for communicating with an operator via the control system. The mobile robot 10 also includes rotatably extensible, treaded flippers 115 that can be deployed to augment traction and to overcome obstacles, and a robotic gripper 150 for grasping or manipulating objects in the mobile robot's environment. The mobile robot 10 further includes an attack camera 151 to aid in navigation of the mobile robot and the robotic gripper 150.

[0094] FIG. 20 illustrates a mobile robot with both its robotic gripper 113 and attached upper arm 112 and lower arm 111 extended. Further shown is the extension of an arm 118 connected to the head 117, and the extension of the head 117 from the arm 118. Also shown is the advantage of having an attack camera 114 attached to the gripper's upper arm 112. The attack camera 114 is able to display the gripper's position within its environment in relation to the position of the gripper's upper arm 112. Using this information, the user can adjust the upper arm 112 to reposition the gripper 113 in its environment. Further shown is an extended flipper 116 which shifts the mobile robot's center of gravity.

[0095] FIG. 21 is a block diagram depicting an embodiment of a mobile robot control system. Included in the control system 1155 is a single board computer (SBC) 1110 such as, for

example, a Freescale MPC5200. A microprocessor can be used in lieu of the single board computer 1110. Connected to the single board computer 1110 is a global positioning system (GPS) module 1135, a radio module 1150, and a wireless Ethernet transmitter and receiver 1140. A radio module 1150 is connected to the single board computer 1110 via an Ethernet switch 1190, and is further connected to a radio antenna 1145. The user can control the control system 1155 using a radio communicating over a secure connection created by the radio module 1150 and the radio antenna 1145.

[0096] Further included in the control system 1155 in the illustrated embodiment is a power supply 1115 and memory 1125 including any combination of ROM, volatile, and non-volatile memory. Also connected to the single board computer are network 1 transmitter and receivers 1120, 1121, 1122 and a network 2 switch 1130. The network 1 transmitter and receivers 1120, 1121, 1122 provide communication between the control system 1155 and an actuator assembly 1165 via a first connection wire 1187 installed between the first network 1 transmitter and receiver 1122 and second neck 1191 and a second connection wire 1186 installed between the second network 1 transmitter and receiver 1120 and first neck 1194. The network 1 transmitter and receivers 1120, 1121, 1122 also provide communication between the control system 1155 and the chassis 1160 via a third connection wire 1181 installed between the third network 1 transmitter and receiver 1121 and the chassis 1160. The network 2 switch 1130, on the other hand, provides communication between the network 2 switch 1130 and each of the chassis 1160, the first neck 1194, and the second neck 1191 via a first connection link 1180, a second connection link 1188, and a third connection link 1180, between the chassis 1160, first neck 1194, and second neck 1191, and the network 2 switch 1130.

[0097] In an embodiment of the invention, the network 1 transmitter and receivers 1120,

1121, 1122 include an RS485 transmitter for transmitting data over an RS485 network using a point-to-point configuration between each N1 (network 1) transmitter and receiver and a corresponding N1 transmitter and receiver. For example, the communication between the control system 1115 and the head 1195 is achieved by establishing a communication link between an N1a transmitter and receiver 1122 connected to the control system 1115 and an N1 transmitter and receiver 4315 connected to the neck's field programmable gate array (FPGA) 4330. A connection is then made between the N1 transmitter and receiver 4360 connected to the neck's FPGA 4330, and the N1 transmitter and receiver 4120 connected to the head's FPGA 4125. Thus, a network is created between the SBC 1110 and the head's FPGA 4125 via the nodes created by the N1 transmitter and receivers included in the control system 1155, the first neck 1194, and the head 1195. In an embodiment of the invention, the network has a two-wire configuration providing half duplex communication.

[0098] On the other hand, the network 2 (N2) transmitter and receiver 1130 of the illustrated embodiment includes an Ethernet switch for receiving and routing data over an Ethernet network. An example of this includes communication between the SBC 1110 and the head 1195, created by the N2 switch 1130 being connected to the SBC 1110 to establish a connection with the N2 switch 4320 connected to the neck's FPGA 4330 via a communication link 1188. A connection is then made between the N2 switch 4320 connected to the neck's FPGA 4330 and the N2 switch 4130 connected to the head's FPGA 4125. The connections made create a network between the SBC 1110 and the head's FPGA 4125. In an embodiment of the invention, the network is a full duplex communication implemented via Ethernet cable.

[0099] Connected to the control system 1155 is a chassis assembly 1160 as well as an actuator assembly 1165. In an embodiment of the invention, the actuators included in the

actuator assembly 1165 are a first neck 1194 connected to a head module 1195, and a second neck 1191 connected to a third neck 1192 which is further connected to a gripper module 1193. Also preferred is that each of the necks 1194, 1191, 1192, include a substantially similar hardware circuit and software routine architecture 4301. In an embodiment of the invention, both of the actuator modules within the actuator assembly 1165 are connected to the control system 1155 via connection wires 1187, 1186, and connection links 1189, 1188. The chassis 1160 is connected to the control system 1155 via a connection wire 1181, and a connection link 1180. The present invention contemplates allowing the control system 1155 to communicate with the actuator assembly 1165 and the chassis 1160 via connection links only, wherein connection links include Ethernet, wire, wireless, radio, or any other link that provides communication between circuits. The present invention also contemplates allowing the control system 1155 to communicate with the actuator assembly 1165 and the chassis 1160 via connection wires only.

[00100] An embodiment of a chassis assembly 1160 is further described in the block diagram shown in FIG. 22. Included within the chassis 4001 base circuit 4055 is an FPGA 4035 connected to a network 1 transmitter and receiver 4050, and a network 2 switch 4045. In an embodiment of the invention, the FPGA 4035 is a Xilinx XC3S1000. Further included within the base circuit 4055 are power regulators 4015 including circuits configured to manage power within the chassis 4001. Additionally, included in the base circuit 4055 for motion control are motor drivers 4030, motor encoders 4025, and a motor battery charger 4020. The chassis 4001 also includes a number of motion control components connected to the base circuit 4055, including incremental encoders 4060, drive motors 4065, a brake 4070, thermistors 4075, and hall sensors 4080.

[00101] A block diagram of an embodiment of a neck module 4301 is shown in FIG. 23. The neck module 4301 includes a base circuit 4305 having an FPGA 4330 connected to a first network 1 transmitter and receiver 4315, a second network 1 transmitter and receiver 4360, and a network 2 switch 4320. Included within the base circuit 4305 are power regulators 4340 that are circuits configured to regulate power within the neck module. The first and second network 1 transmitter and receivers 4315, 4360 are connected to a payload connector 4310, 4355. The payload connectors 4310, 4355 are plugs configured to mate with a corresponding plug on a payload such as an additional neck module 1191, 1192, a head module 1195, or a gripper module 1193. Further included within the base circuit 4305, to aid in motion control, are a clavical encoder 4345, a tilt 1 encoder 4350, half-bridge drivers 4365, and h-bridge drivers 4370. Additional motion control components included within the neck module 4301 and connected to the base circuit 4305 are brushless motors 4385, hall sensors 4380, and a thermistor 4375.

[00102] The neck module 4301 is also connected to a pan module 4390 and a tilt module 4395. The pan module 4390 allows the user to pan the distal portion of the neck about the neck's pivot point, while the tilt module 4395 allows the user to tilt the distal portion of the neck about the neck's pivot point. A slip ring and magnet assembly for the connections between the pan module 4390 and the neck module 4301, between the pan module 4390 and the tilt module 4395, and between the tilt module 4395 and a further connection.

[00103] A block diagram of an embodiment of a head module 4100 is shown in FIG. 24, and includes a base circuit 4105 with a centrally located FPGA 4125. Connected to the FPGA 4125 are a network 2 switch 4130, and a network 1 transmitter and receiver 4120 which is further connected to a payload connector 4190. In an embodiment of the invention, the payload

connector 4190 is a plug configured to mate with a corresponding plug on a neck module 4301 such as neck module 1 1194. Additionally, included in the base circuit 4105 are power regulators 4110 that are circuits configured to manage power within the head module 4100. The base circuit 4105 is connected to a set of video decoders 4150 via a CCIR-656 video communication bus 4145 and a serial bus 4140. Input to the video decoders 4150 includes: (1) the output from a drive camera 4160; (2) the output from a differential NTSC receiver 4155 which is further connected to the head module connector 4156; and (3) the output from the electro-optic infrared (EOIR) module 4165. Output from the EOIR module 4165 includes a near infrared (NIR) 4170 camera, a long wave infrared (LWIR) 4175 camera, and a laser range finder 4180.

[00104] An embodiment of a gripper module 1193 is shown in the block diagram of FIG. 25. Located within the base circuit 4210 of the gripper module 4201 is a FPGA 4240 connected to a network 2 switch 4245, and network 1 transmitter and receiver 4235 that is further connected to a payload connector 4230. The payload connector 4230 is preferably a plug configured to mate with a corresponding plug on neck module 3 1192. Also included within the base circuit are power regulators 4220 including circuits for regulating power within the gripper module 4201, and the following components for motion control: gripper encoders 4215; half-bridge drivers 4255; and h-bridge drivers 4260. Additional motion control components connected to the base circuit 4210 and included within the gripper module 4201 are brushless motors 4285, hall sensors 4280, and a thermistor 4275. A video decoder 4265 is also connected to the base circuit 4210. An attack camera 4270 located proximate to the gripper 4201 creates input to the video decoder 4265 so that the user can view the gripper 4201 actions.

### **Network Configuration**

[00105] FIG. 26 illustrates an embodiment of a network installed between the head 4401 and the control system 4409 and the chassis 4406. There are two sub-networks included within the network: (1) the Ethernet network created by the Ethernet switches 4427 included within each module and the communication link 4415 that connects each Ethernet switch to a corresponding switch; and (2) the RS485 network created by the RS485 transmitter and receivers 4430 and the connection wires 4412 that connect each RS485 transmitter and receiver to a corresponding transmitter and receiver. An alternative network may include RS422 transmitter and receivers in lieu of RS485 transmitter and receivers. Such an embodiment would provide full duplex communication, meaning each transmitter and receiver could simultaneously receive and transmit data packets.

[00106] The RS485 network embodiment illustrated in FIG. 26 includes master nodes and slave nodes. A master node includes the node created by the single board computer 4436, the node created by the head 4401 and the node created by the chassis 4406. Such nodes are master nodes because they provide a central point to which other nodes, slave nodes, communicate. An example of such communication includes the communication between the single board computer 4436, the chassis 4406, and the head 4401. The single board computer can receive information from the head 4401 representative of a drive command and pass such information onto the chassis 4406. This configuration would consider the single board computer 4436 a master node, and the chassis 4406 and the head 4401 slave nodes.

[00107] The network includes a control system 4409 with a single board computer 4436 for processing information transmitted to the computer 4436 by each network. To gather such information, the single board computer 4436 is connected to a single Ethernet switch 4427

which in turn is linked to an Ethernet switch 4427 within the neck 4403 via a communication link 4415 and an Ethernet switch 4427 within the chassis 4406 via a communication link 4415. The single board computer 4436 connects to two RS485 transmitter and receivers 4430, one transmitter and receiver 4430 is connected to a RS485 transmitter and receiver 4430 in the neck 4403 via a connection wire 4412, and a second transmitter and receiver 4430 is connected to a RS485 transmitter and receiver 4430 in the chassis 4406 via a connection wire 4412. While an embodiment of the invention includes both an Ethernet network and a RS485 network, an alternative embodiment can include only an Ethernet network. Such a network would provide a full duplex communication network requiring less infrastructure than a RS485 network. The inclusion of both an RS485 network and an Ethernet network is advantageous because it provides two networks, including an Ethernet network capable of communicating from one far node to another, thus bypassing the token ring configuration of the RS485 network which requires passage of data through intermediate nodes.

[00108] Each actuator assembly includes a core circuit capable of implementing an alternative network that includes only an Ethernet network. The core circuit includes a field programmable gate array 4418 with a media access controller 4433, where the FPGA is capable of managing multiple digital input 4421 and is further programmed to interface with the media access controller (MAC), which includes information or commands generated either by the FPGA or the digital I/O 4421 to generate frames of data to be sent to other modules within the robot via packets sent by the Ethernet switch 4427. Furthermore, the MAC is able to parse frames of data included within packets it receives from the Ethernet switch and extract information or commands that are either processed by routines included within the FPGA or relayed to the digital I/O 4421. Due to the full duplex communication network created by the

Ethernet switch 4427, the MAC is able to simultaneously transmit and receive packets of data. The RS485 transmitter and receiver 4430, on the other hand, is half duplex communication meaning that the transmitter and receiver 4430 cannot transmit data and receive data simultaneously. “Actuator assembly” refers to the head 4401, the neck 4403 or the chassis 4406. “Module” refers to a component within the head 4401, the neck 4403, the control system 4409, or the chassis 4406.

[00109] Each Ethernet switch 4427 is also connected to a payload 4424, wherein payload can include a drive assembly, an EO/IR, or other assembly. Use of an Ethernet switch 4427 allows for simultaneous communication between the payload 4424 and other modules within the network including the head 4401, neck 4403, and chassis 4406. An example of this would include video information transmitted from a payload 4424 such as the video decoders 4150. The form of such information is a constant stream of video feedback from the drive camera 4160. The example network created using the Ethernet switch 4427 allows for simultaneous receiving of video information from the drive camera 4160 and transmitting and receiving of information from the single board computer 4436.

[00110] FIG. 27 illustrates an embodiment of an Ethernet endpoint block 4439 including an FPGA 4418 configured to include a MAC and connected to an Ethernet switch 4427. The Ethernet switch 4427 is connected to the MAC included on the FPGA 4418 via a medium independent interface bus that provides a logical interface with a communication protocol selecting the line speed and whether the connection is in a half or full duplex mode. The MAC parses the I/O ports 4445 included on the FPGA and generates frames of data to be included in packets. The packets are transmitted out through the Ethernet switch 4427 to the rest of the modules in the network. Included on the Ethernet switch 4427 are physical devices or line

interfaces that handle the transfer of data from the Ethernet cable to the Ethernet switch 4427. An oscillator 4442 is included to facilitate the exchange of information between the MII buses.

[00111] FIG. 28 illustrates an embodiment of the invention using the Ethernet endpoint block in the chassis, neck, head and EO/IR payload. Further shown is the connection of various payloads to the Ethernet endpoint block as well as the running of Ethernet to other modules. Advantages of an Ethernet endpoint block include: low EMC footprint, noise/bounce tolerant, modularity, can uniformly read/control each endpoint. In addition, an Ethernet network can handle far node-to-far node communication.

[00112] Referring to FIG. 26, both the RS485 network and the Ethernet network can be used for communication. As an example, the Ethernet network can be used for quick data transmission of video output from the EO/IR module to the single board computer 4436, while the RS485 network is used to transmit drive commands from the computer 4436 to the head 4401 via the neck. Such a transmission would include the creation of video output by the EO/IR module 4424, the video output would then be relayed to the Ethernet switch 4427 where it would be transmitted directly to the single board computer 4436 in the central control system 4409. The video data would be transmitted via a cable 4415 connected at one end to the Ethernet switch 4427 and at the other end to an Ethernet switch in the neck 4403, and via a cable 4415 connected at one end to the Ethernet switch 4427 in the neck 4403 and at the other end to an Ethernet switch 4427 in the control system 4409. The Ethernet switch 4427 in the control system 4409 is connected to the single board computer 4436 included in the central control system 4409. Although the video information must pass through two additional Ethernet switches, such information can pass through each switch without the need for additional signal processing by the intermediary Ethernet switches.

[00113] If the RS485 network is used to send a drive command from the single board computer 4436 to the head 4401, the data must first be sent to an RS 485 transmitter and receiver included in the control system 4409, which then transmits the data over a wire 4412 connected at the other end to an RS485 transmitter and receiver located in the neck 4421. The data must then be processed by the FPGA 4418 included in the neck 4403 and then passed on to a second RS485 transmitter and receiver 4430 included in the neck 4403. The second RS485 transmitter and receiver 4430 then transmits the data over a wire 4412 to an RS485 transmitter and receiver 4430 included in the head 4401 which is further connected to an FPGA 4418 included in the head 4401. The RS485 network processes the data at the intermediary node (in the neck 4403) between the head 4401 and the control system 4409. The Ethernet network, on the other hand, is able to send the data through the neck 4403, or intermediary node, without requiring additional signal processing. Including both an RS485 and Ethernet network can prevent bottlenecks created by the passage of large amounts of data over a single network, and further allows for faster transmission time due to the inclusion of multiple networks. Alternative embodiments of the system can include one or more Ethernet networks, or one or more RS485 networks. Further embodiments include a full duplex RS485 network implemented using RS422 transceivers and receivers.

### **Gripper Manipulator**

[00114] FIGS. 29A and 29B illustrate an embodiment of robotic arm 900 for functioning as a gripper affixed to the mobile robot 10. The robotic arm 900 preferably includes a base 925 with circuitry required to control the arm. Additionally, the arm 900 includes a pair of actuators 920 installed toward the end of the arm and able to grip and manipulate objects. Further included near the actuators 920 are joints 915, 910 which may be mobilized to alter the

position of the actuators 920 in space, and a camera 905 installed proximate the actuators 920 so that the operator may control actuator 920 movement based on video feedback. The actuators are connected to a secondary arm 930 which pivots at a joint 901, and which is connected to a main arm that pivots at a joint 940.

[00115] The joint 940 connected to the arm base 925 and the primary arm 935 can be controlled by the operator via the control system outlined above. When drive commands are sent to the mobile robot 10 indicating that the joint 940 should be actuated, a drive command is sent to the drive assembly located proximate the joint 940 which in turn causes a motor located in the drive assembly to mobilize actuators connected to the joint 940 via gears and subsequently mobilize the primary arm 935. Similarly, drive commands sent to the drive assembly located proximate the joint 901 connecting the primary arm 935 to the secondary arm 930 can cause a motor located in the drive assembly to mobilize actuators connected to the joint 901 via gears and subsequently mobilize the secondary arm 930. Joints 915, 910, capable of mobilizing the manipulators 920 located on the gripper, can also be actuated via drive commands sent to a drive assembly proximate the joint 915 and including a motor. Additionally, the camera 905 installed near the gripper actuators 920 can input video data regarding the gripper's environment and further transmit such data to the control system 1155 where it is further transmitted to the control system to be displayed on a screen so that the operator may view the gripper's environment.

### **Software Architecture**

#### **Behavior System Overview**

[00116] In accordance with the present invention, a remote vehicle (such as the mobile robot 10 described above) has included within its control system 1155 a behavior system comprising software routines and circuits. FIG. 30 illustrates an embodiment of a behavior

system to be included within a remote vehicle. At the heart of the system are behaviors 715 including different behavior software routines that further include behavior software subroutines. The behavior software routines are the main routines and are referred to as the individual behaviors, for example the stair climbing behavior software routine is referred to as the stair climbing behavior. The individual behaviors 715 include within them sub-routines, which are routines that implement the actions associated with each behavior. An example would include the stair climbing behavior which includes within it a stair climbing routine, a maintain alignment routine, as well as other routines necessary to fully implement the stair climbing behavior.

[00117] In an embodiment of the invention, each behavior includes a status check routine that constantly checks sensor input to determine a change in start condition. When the start condition is a positive value, the behavior initiates a routine, included within the behavior that begins sending software commands to an arbiter (coordinator) 710 included within the behavior system. The commands sent to the arbiter 710 are votes that tell the arbiter 710 that the behavior would like control of the actuators used by the routines included within the behavior. An example of this would include the stair climbing behavior, that responds to a positive change in its start condition by sending votes to the arbiter 710 indicating that stair climbing would like control over the tilt sensor, the drive assembly, the drive and attack cameras, and all other actuators and manipulators needed to implement the stair climbing behavior. Each behavior could have its own specific set of routines, or some or all behaviors 715 may be able to share a common set of routines included within the behavior system.

[00118] Also included within each behavior is a priority. FIG. 31 illustrates a listing of behaviors within the behavior system in an exemplary order of priority. As shown, a

behavior such as the obstacle avoidance behavior 7059 has a higher priority than the stair climbing behavior 7068 as it is more important that the remote vehicle avoid an obstacle than climb a stair. This practicality can be displayed in a situation where there is a bomb located on a set of stairs, and the behavior system stops the stair climbing behavior 7068 on detection of an obstacle by a sensor, so that the higher priority obstacle avoidance behavior 7059 may control the remote vehicle's drive assembly to drive away from the obstacle which in this case is a bomb. Were the obstacle avoidance behavior 7059 is not a higher priority than the stair climbing behavior 7068, the remote vehicle would have continued to drive toward the bomb, likely hitting it and causing injury to the remote vehicle and those humans present in the surrounding environment.

[00119] The arbiter 710 included within the system is a software routine that manages the votes and priorities of the individual behaviors 715 in conjunction with the scheduler 730, to determine when and in what order the behaviors 715 will gain control over the actuators and manipulators within the remote vehicle. To accomplish this, the arbiter 710, at any point in time, reviews all the behaviors 715 currently voting for control. To determine which behavior 715 will gain control, the arbiter 710 reviews each voting behavior's priority level, and the scheduler's 730 indication of which behavior should gain control based on the length of time that the current behavior or a past recorded behavior, has or had control of the actuators and manipulators. An embodiment of the invention includes a scheduler 730, but alternative embodiments may include a system with a single arbiter 710 that determines the controlling behavior based on priority level and votes.

[00120] To input sensor output to the behaviors 715 and their corresponding routines, the system has a set of virtual sensors 720 in communicative connection with a set of

sensors 725. The sensors 725 can include sensor components and related circuitry and software routines that provide feedback representative of the remote vehicle's current external and internal environment. An example includes a wireless receiver providing feedback regarding detectable wireless signals within the remote vehicle's external environment, and a brake that uses an electrical switch to provide feedback about the state of the brake within the remote vehicle's internal environment via an electrical signal generated when the electrical switch is closed. Output from the sensors 725 is further conditioned by virtual sensors 720 which include circuits and software able to input sensor 725 signals and process the signals to provide outputs representative of each signal, but in a form able to be processed by the routines within the behaviors 715.

[00121] In an embodiment of the invention, each of the sensors 725 has a corresponding virtual sensor 720 configured to the requirements of that sensor. An example is the brake sensor which outputs an electrical signal in response to the actuation of the brake. The virtual sensor 720 associated with the brake sensor may be configured to input the raw analog signal into a signal processing circuit that further conditions the analog input and outputs a digital signal which is further processed by a software routine that outputs a logic value representative of the brake's status. Output from the virtual sensors 720 is inputted to the behaviors 715 where it is used in behavior routines to mobilize the remote vehicle and further respond to raw sensor output.

[00122] Included within the behavior system are actuators 705 able to respond to output from virtual actuators 701 by mobilizing and performing actions. To control the actuators 705 within the robot 10, the behaviors 715 output control commands which can include drive commands, communication commands, and other commands able to control actuators included

on the robot 10. Each actuator is able to receive drive commands in a particular format. The virtual actuators 701 include software routines and circuits able to input the software control commands from the behaviors 715, and convert them into control commands able to be received by the actuators 705. In particular, the motors included within the chassis can take drive commands in a format that preferably includes an electrical signal. The virtual actuator 701 associated with the motors within the chassis are able to take the software command generated by the behaviors 715 and convert the command into a signal that is then transmitted to the motors within the chassis.

### **Autonomous Remote Vehicle Behaviors**

[00123] In an embodiment of the invention, these behaviors are included on the remote vehicle in memory, and are executed by the single board computer. There are three types of behaviors: Ballistic, Semi-Ballistic, and Persistent. The descriptions below refer to mobile robot 10 described above. The present invention contemplates employing autonomous behaviors on a variety of remote vehicle types as would be appreciated by one of ordinary skill in the art.

### **Ballistic Behaviors**

#### **Stair Climbing**

[00124] The stair climbing behavior drives the mobile robot 10 to traverse a set of stairs in an autonomous manner, after receiving a command to initiate the behavior and information indicating the location of the stairs from the operator. The mobile robot 10 may include a pitch/roll sensor that indicates whether the mobile robot 10 is tilted relative to the ground, which is used by the stair climbing behavior to decide whether the mobile robot 10 should continue climbing the stairs.

[00125] The mobile robot 10 can be positioned in the vicinity of a staircase 920,

and the user may initiate the autonomous stair climbing behavior by simply identifying the location of the stairs 920 and inputting a command to activate the stair climbing behavior. The mobile robot 10 can then ascend or descend the stairs 920 without requiring further input from the operator.

[00126] Referring to a control system console illustrated FIG. 32, an embodiment of a stair climbing behavior is initiated when the operator navigates the mobile robot 10 to within a threshold distance of the stairs, such that the stairs are visible in the image data displayed both in a drive camera window 261 and an attack camera window 262. The operator positions a first selector 267 to enclose or abut a region of the window 261 corresponding to the stairs, and similarly positions a second selector 268 to enclose or abut a region of the window 262 that also corresponds to the stairs.

[00127] With the target stairs 920 identified by the first and second selectors 267, 268, the operator can then trigger the stair climbing behavior by clicking an on-screen button or otherwise inputting a command that causes transmission of a control signal that activates the stair climbing behavior. In accordance with an embodiment of the invention, the operator further inputs whether the mobile robot 10 should climb up the stairs or descend the stairs. In another embodiment, the mobile robot 10 includes a routine for autonomously determining whether the target stairs 920 are ascending or descending relative to the mobile robot 10, and informs the stair climbing behavior accordingly.

[00128] FIGS. 33A and 33B illustrate positions of the mobile robot 10 relative to the target stairs 920 as the mobile robot ascends or descends the stairs 920 in accordance with the stair climbing behavior. The mobile robot 10 may initially extend the flippers 115 to a predetermined angle to facilitate the stair climbing operation. FIG. 33A illustrates an

embodiment of the invention wherein the flippers 115 may rotate out to a 180° angle relative to the main treads 110 to ensure contact with the stairs 920 and to raise the front end of the mobile robot 10 up onto the stairs 920. When descending, the mobile robot 10 may instead extend the flippers to an angle 77 that is approximately 45° relative to the main treads 110 (see the embodiment of FIG. 33B).

[00129] When the tilt sensor of the mobile robot 10 indicates that the angle of tilt of the mobile robot 10 is zero relative to the horizon, the stair climbing behavior may stop and navigation authority may be resumed by another routine.

[00130] FIG. 34 illustrates an embodiment of a method for performing the stair climbing behavior. At step 2901, the behavior initializes internal variables (by setting the initial turn rate and roll rate to zero, for example), and then determines at step 2902 whether the mobile robot 10 should ascend the stairs. If so, the mobile robot positions the flippers 115 to the appropriate angle for ascending the stairs at step 2903, outputs a speed value for ascending the stairs at step 2904, and proceeds to traverse the stairs at step 2907. The mobile robot 10 may ascend the stairs at a predetermined speed while under control of the stair climbing behavior. The predetermined speed may be, for example 0.2 meters per second.

[00131] If the mobile robot 10 is determined at step 2902 not to be intended to ascend the stairs, then the behavior positions the flippers 115 to an angle appropriate for descending the stairs, sets a speed appropriate for descending stairs, and proceeds to navigate the stairs at step 2907. Thereafter, the behavior may optionally perform steps to maintain the mobile robot's alignment with the stairs at step 2908 (for example, to prevent the robot falling off the side of unprotected stairs), and then determines at step 2909 whether the tilt sensor indicates the existence of tilt.

[00132] If tilt exists, the behavior continues to ascend the stairs 920 autonomously by returning to step 2907. Otherwise, step 2910 stops the mobile robot 10 from proceeding further, and returns the flippers 115 from the ascending or descending position back to the neutral, undeployed position at step 2911.

[00133] To ascertain whether there are more stairs to traverse, the stair climbing behavior may use a median pitch filter routine to integrate tilt sensing information from multiple sources, and to reduce false positive determinations of being level. In one embodiment, the median pitch filter routine tracks pitch information from the tilt sensor and uses only those values that fall within the median of all previously recorded values. Accordingly, the routine can reduce the detrimental impact of transient values on the determination of whether the stair traversal is complete.

[00134] According to an embodiment of the invention, the median pitch filter routine stores native pitch/roll sensor output in memory. An on-board timer then increments and the routine periodically checks whether it has been incremented by a full half second. If so, then the routine moves on to the next step. Otherwise, the routine stores the tilt sensor output, and increments the timer. The median pitch filter routine then examines the pitch/roll sensor native output over the full half second and determines the respective highest and lowest frequencies of the signal. Using this information, the median pitch filter routine then calculates the median frequency. The median pitch filter routine outputs this calculated median frequency as the pitch/roll sensor output to the robot's control assembly.

[00135] The maintain alignment routine may be used by the stair climbing behavior to keep the mobile robot 10 moving in a consistent direction with respect to the vertical axis of movement, and allows the mobile robot 10 to ascend or descend stairs with a turn rate

magnitude of zero. While moving forward with a zero turn rate, for example, the routine simultaneously samples the roll angle as determined by the pitch/roll sensor output and subsequently calculates a turn rate magnitude from the output. In an embodiment of the invention, the equation by which the turn rate magnitude is calculated may be approximately  $k \cdot X$  degrees per second, in which  $k$  is a constant having a value within the range of 1/10 to 3 and  $X$  represents the roll angle. Other embodiments may use differing formulas. At one step, the routine checks the roll angle to determine whether it has a value other than zero. If so, the routine returns to the first step and moves forward with a roll angle of zero. Otherwise, the routine re-aligns the mobile robot 10 by turning the mobile robot 10 by the calculated turn rate magnitude. Once the mobile robot 10 is re-aligned, the process goes back to the first step and continues to climb forward with a roll angle of zero.

[00136] This embodiment of the stair climbing behavior utilizes a tilt sensor allowing the robot 10 to position itself without the need for walls. Alternative embodiments may include the use of a SICK LIDAR sensor to detect walls to position the robot as the robot moves up the stairs, or the use of SONAR to detect walls and position the robot as it moves up the stairs. Other alternative embodiments include a fully autonomous version of stair climbing that is implemented upon the detection of stairs. Such a version may include a sensor placed toward the outer rim of the robot's lower chassis to detect negative obstacles such as downward stairs, or may require multiple sensors to indicate that there is an obstacle within the allowed height, meaning that software routines within the robot would associate certain dimensions with stairs. Still other alternative embodiments include a routine that commands the robot to re-position its arms to 180° when it reaches the top of the stairs, or a robot that utilizes a magnetic compass or IMU in addition to or in lieu of a tilt sensor.

### **Preset Action Sequence**

[00137] FIG. 35 illustrates an embodiment of a preset action sequence behavior by which an operator can create a custom action sequence routine that is an aggregation of user-chosen routines and behaviors. An action sequence routine may consist of a combination of available robot behavior routines and events. Alternatively, the operator can include actions and movements available to the mobile robot 10 but not defined by a pre-existing behavior or routine. An exemplary method for constructing the preset action sequence behavior using a console as illustrated in FIG. 35 includes depressing soft keys 253 either by moving a mouse over the button image on the screen 261 and then depressing a mouse button, or by contacting and applying a force to the area on the screen 261 that corresponds to the button image 253. Once the button is actuated a command is sent to the control system 1155 to include the action or behavior routine in the preset action sequence behavior. Further methods of input include actuating buttons or switches of the control system described above, or by any other suitable method. Alternatively, a software routine of the preset action sequence behavior can be loaded directly into the mobile robot memory 1125, for example via an external memory device inserted into the mobile robot 10. Furthermore, the preset action sequence behavior can be created by recording a macro of the actions of the robot while the user is driving the robot and actuating various autonomous behaviors. Additionally, the present action sequence can be created using any combination of the methods described above.

[00138] Once the preset action sequence behavior is initiated by the operator, the operator can then input the desired sequence of behaviors, actions, and events in step 3901. Such a sequence can be any combination of autonomous behaviors, actions, and events available on the robot, and manual behaviors, actions, and events available on the mobile robot 10. Upon

entering step 3901, a routine included within the preset action sequence behavior routine determines if the combination of behaviors, actions, and events chosen by the user is allowed in step 3902. Such a determination is made by evaluating the requirements for each behavior, action, and event and then inputting the determined results against a series of error checking routines that evaluate whether the selected combination is allowed per requirement vectors stored in memory. Should a combination not be allowed, the routine included in step 3902 will either alert the user of the error and perhaps require them to choose an alternative sequence, or exit the preset action sequence behavior routine step 3907.

[00139] An example of a combination action sequence that might be precluded would be the use of Speed Boost in addition to the Stair Climbing behavior. A Boolean value representative of whether the chosen action sequence is allowed is outputted. Should the value not be allowed, then the behavior routine either re-displays the initial action entry screen and perhaps instructs the user to enter a different action sequence step 3901, or exits the preset action sequence behavior. Alternatively, if a speed value is selected in the Speed Boost behavior that is incompatible with the Stair Climbing behavior, then the behavior routine may re-display the initial action entry screen and instruct the user to enter a different value for the speed. Other embodiments may make substitutions for the forbidden actions and proceed with the behavior's subsequent steps. In an embodiment of the invention, the screen also relays to the operator the conflicts present in the previous list of chosen actions. Alternatively, the screen may request that the operator change only the actions that are not allowed.

[00140] Further referring to FIG. 35, upon identification of an allowed action sequence, the behavior routine stores the selected sequence step 3903 in memory 1125. Once an allowed sequence is stored, the control system 1155 executes the preset action sequence starting

in order from the first action chosen by the operator in step 3904. The step of initiating an action step 3904 is followed by a check to see if operator input is needed for the action to perform properly in step 3905. In an embodiment of the invention, a need for operator input is only indicated in absolute cases so that efficiency and autonomy is preserved. In an embodiment of the invention, autonomy is enhanced by allowing the mobile robot 10 to determine the value of operator input based on prior operator data and environmental data. In other embodiments, the mobile robot 10 may refrain from inputting data for operator inputs and should indicate when operator input is needed. If the mobile robot 10 determines that operator input is needed, it should prompt the operator to input the required data and then perform the action in step 3909. Example user input may include any one of a speed value, time duration of an autonomous behavior, a direction heading, or other value needed to execute any one of the included behaviors, actions, or events. Should the initiated action need no further user input, the behavior routine will then continue to execute autonomously and perform the action in step 3909.

[00141] Once the action has been performed in step 3909, the mobile robot 10 checks to see if there are further actions listed in the sequence step 3906. In the event that additional actions remain, the next action in the sequence is initiated and the operator input check is done before the action is performed. Otherwise, if no additional actions remain, the mobile robot 10 exits the preset action sequence behavior in step 3907. An embodiment of the invention allows the mobile robot 10 to enter another behavior or event when no additional actions remain.

[00142] An alternative routine may substitute the portion of the behavior routine associated with the execution of an action 3910, with a single step of executing the behavior routine as recorded. Such a step would not allow the user to input additional data, but would rather execute the actions in the order in which they were chosen.

**Click-to-Drive and Click-to-Grip**

[00143] In an embodiment of the invention, the robot includes two “fire and forget” behaviors allowing an operator to choose a destination pixel displayed to the operator via the above-described control system and either drive toward the destination or move toward the destination and grip an item. Both of these behaviors are intended for one-time use and allow the operator to accomplish complex actuation and driving with less intervention. The click-to-grip behavior also utilizes image data from first and second cameras displayed in respective first and second windows 261, 262 to identify a target object for the behavior. The embodiment of FIG. 36 illustrates that the robot’s gripper can be manipulated to move toward an object and grip the object in response to a user clicking on the object within an image of the environment. To accomplish gripping, the operator positions the first and second selectors 267, 268 to identify the target object 3010 in both the drive camera display 261 and the attack camera display 262. In an embodiment of the invention, the operator has already actuated a button or switch to actuate the click-to-grip behavior. Alternatively, the operator may additionally actuate a “begin behavior” button or switch, which transmits a control signal to the mobile robot 10 that activates the click-to-grip behavior.

[00144] Once the object is chosen in both displays 261, 262, the position of the object within those displays is used to calculate its coordinates. FIG. 37 illustrates an embodiment of a click-to-grip routine executed during the click-to-grip behavior. Upon selection of the object by the operator, the routine stores the image coordinates from the attack camera video display 8103 and the drive camera video display 8106. Using these image coordinates and stored values corresponding to the resolution of the attack camera and the drive camera, the routine calculates the destination point 8109. The coordinates are projected into the

robot's current environment 8112 and from the projected coordinates, a set of rays are calculated 8115 that are representative of travel vectors from the robot's current position to the destination position. The rays are then corrected 8118 and a check is done to ensure that the gripper is on the correct side of the turret 8121. If the gripper is not on the correct side of the turret, the robot moves the gripper 8124. Once the gripper is correctly positioned, a check is done to ensure that the drive camera is synched up with the object to be gripped 8130. If the camera is not synched up, then the robot can move the camera 8127 which may include moving the camera to a position included within the newly calculated travel vector. Once the drive camera is synched up with the destination object, the robot moves the gripper toward the destination point 8133 grips the object 8136 after arriving at the destination point.

[00145] Similarly, click-to-drive uses video feed from the attack and drive cameras to determine a destination point. FIG. 38 illustrates an embodiment of a routine included on the robot for implementing click-to-drive. The routine responds to activation of the click-to-drive behavior and selection of a destination pixel by storing the selected coordinates from the attack and drive camera video displays 8153. Once the coordinates are stored, the routine calculates a destination point 8156 and projects the destination point onto the robot's current ground plane 8159 so that directional rays can be calculated 8162. Once calculated, the rays are corrected 8165 and used by the robot to drive toward the destination point 8168. Like click-to-grip, click-to-drive is a fire-and-forget behavior and therefore will terminate once the robot reaches the destination point. In an embodiment of the invention, the click-to-drive and click-to-grip behavior include fail safe routines where the behavior will terminate and reset when the robot is powered down, loses communication with the control system, or is interrupted by a behavior with a higher priority.

[00146] The present invention also contemplates an embodiment where the click-to-grip and/or the click-to-drive behavior are operable in two modes: (1) a high degree of precision mode and (2) a low degree of precision mode. The high degree of precision mode allows the operator to choose the object's corresponding pixel image on the display screen and responds to the actuation of a button triggering a gripping sequence that takes the precise pixel location and converts it to a destination point. The low degree of precision mode, on the other hand, allows the operator to choose a heading direction and responds to actuation of button triggering a sequence that flies the gripper in the general direction of the objects included within the heading. An embodiment of the invention includes a robot with the ability to choose a path within an approved heading that provides the most direct route and avoids obstacles. In both modes, the gripper moves using a "fly in motion," which actuates all joints in a fluid motion. Fly-in motion moves the claw forward in a single fluid motion actuating all necessary joints to keep the direction of movement uniform. The gripper will stop if it encounters unexpected obstacles, and will move forward 50% of the estimated distance to reduce the risk of over-travel. An alternative embodiment of the invention moves forward 100% of the estimated distance. After moving 50% of the estimated distance, the operator may reposition the gripper and then trigger the click-to-grip behavior again. Both modes can also move away from the object using the same path that was used to move the gripper forward. Further alternatives include a robot that:

- uses sensors to identify the basic shape of the object and orient the wrist joint of the manipulator arm accordingly;
- has motors that can fine tune the manipulator arm;
- has a pre-programmed manipulator arm motion routine;

- uses analysis of the object's dimensions to close the gripper's fingers until the aperture is the required size or until torque sensors in the gripper indicate that the fingers have a required amount of resistance;
- has a gripper that grips the object until the grip routine exits;
- has an emergency halt routine that halts the gripper and awaits instructions if an unexpected obstruction is encountered;
- uses camera triangulation, camera depth-of-field, and object size estimation to estimate the range to the target; and/or
- has a distance sensor to provide distance feedback used by the routine to adjust movement toward the object to be gripped.

### **Custom (Preconfigured) Poses**

[00147] As shown in FIGS. 39 and 40, once a preconfigured pose available via a GUI, soft button, dedicated button, switch, toggle, or other selection device has been selected, the robot must move some or all of the flippers, neck, and head with respect to the robot main body and main drive in order to move from the present pose to the preconfigured pose (e.g., prairie dog P16, stowed P10, driving on a flat surface P14, driving on a bumpy or angled surface P20, stair climbing). Some robot configurations may use symmetric flipper arm and body (each the same size), providing alternative poses (e.g., inverted Y in which the body and/or head is positioned directly above a steeped symmetric flipper and body, inverted arrow in which body and/or head are positioned above V-oriented symmetric flipper and body - which may further require inverted pendulum gyroscopic AKA "Segway" balancing). Only a few exemplary poses are shown in FIGS. 39 and 40. Actions by the robot or in which "the robot moves" mean that the actuators of the robot are driven under motor control and amplification as directed by the

controller circuit on the robot itself.

[00148] Changing or returning to a preconfigured pose from any arbitrary pose may require determining the current position and orientation of the robot's body, drive or flipper arms, neck, and/or head. In an embodiment of the invention, the robot's movement is determined through the use of motor encoders (relative or absolute) and the robot's camera (with camera lens) is mounted at a controllable height above the robot's body, as controlled by the movement of the neck. A pan/tilt head with a camera is mounted at the top of the neck. The neck may contain a physical neck index switch allowing the system to reset the neck location in an absolute sense as the neck's movement passes through a specified location. By using the starting angle of the neck and motor encoders, the angular location of the neck at any given time can be calculated. Likewise, the pan and tilt position of the head camera can be calculated using the start locations. Alternatively, some or any of the flipper arm angle, neck angle, head angle (tilt), and head turn (pan) may use absolute encoders.

[00149] By using the current locations of each of the robot elements (body, flipper arm, neck, head pan & tilt) via motor encoders or other proprioceptive sensing, the static geometry of the robot itself (for example, the length of the neck and its arc of travel, the distance from the center of rotation to the base of the neck, known x, y, z locations of the center of mass of each of the body, flipper arms, neck, head) and on-board orientation sensors in any robot element (accelerometers, tilt sensors, gyroscopes, and/or horizon detection), it is possible to produce a frame of reference for each robot element. Each frame of reference is represented by a matrix giving the x, y, z location of the robot element and the rotation vectors for forward, left and up.

[00150] A similar frame of reference can alternatively be created for each element

in turn using well-known Denavit-Hartenberg Parameter computations, e.g., going from the robot base toward the head and camera location. For example, the frame of reference for the neck can be computed using the body frame of reference, Denavit-Hartenberg Parameters describing the neck geometry, and the current neck angle of rotation. Using these three inputs, a new frame of reference can be computed for the neck. Similarly, the pan frame of reference is calculated, followed by the tilt frame of reference. In an embodiment where the camera is attached to the head, the frame of reference for the head is the frame of reference for the camera itself.

Such calculations from sensor data, performed on the robot itself, permit the robot's starting state to be determined, e.g., including the robot's location and vector (frame of reference) and the camera's location and vector (frame of reference). Embodiments of the invention may not require all of the calculations. For a particularly robust robot, merely the element configurations as expressed by the relative position of the body, flipper arms, neck, and head may be sufficient.

[00151] FIG. 39 illustrates an embodiment of a technique for moving between positions - by mapping necessary states between preconfigured poses and current states, including necessary states P24. This state diagram shows that for some robot configurations, a loop among the states is not necessarily formed, and the path between intervening states may be limited to passing through particular sequences of intervening states. For example, a robot in stowed pose P10 (solid lines indicating a preconfigured pose), with head and neck retracted and flippers aligned along the main tracks, may be placed in any of three exemplary preconfigured poses (prairie dog P16, bumpy travel P20, and flat travel P14).

[00152] In order to move to prairie dog pose P16, in which the robot is stably elevated on the flipper tracks with the neck elevated to a substantially maximum height, the robot

must begin by lifting the body, by turning the flipper tracks counterclockwise F-CCW (from the side shown in FIG. 39). As the robot moves through intervening poses P12, the center of mass/gravity of each of the body, neck, and head are maintained above the midpoint of the flipper arms. As shown in FIG. 39, this may be accomplished by specifying predetermined intervening states and actuations for the robot to pass through (e.g., where "CW" is clockwise from the side shown in FIG. 39 and "CCW" is counter clockwise, first arranging the body and head above the arms by moving the body only via the flippers F-CCW, then by elevating the neck N-CCW and head H-CW, then by unfolding all at once vertically flipper F-CCW, neck N-CCW, and head H-CW).

[00153] To return to the stowed position P10, or as shown in FIG. 39 to move to either of the driving positions P20 or P14, the robot moves back through the necessary states in the opposite order and with the opposite CW or CCW motions.

[00154] In order to move to, e.g., bumpy driving pose P20, in which the robot is stably positioned to be driven at slower speeds on the main tracks with the flipper tracks up to handle small obstacles, the neck and head being positioned behind the main body to provide a driving view but maximum static stability, the robot must begin by turning the flipper tracks clockwise F-CW (from the side shown in FIG. 39). As the robot moves through intervening poses P22, the flipper arms move to a ready-for-driving (or potentially climbing) position. As shown in FIG. 39, this may be by specifying predetermined intervening states and actuations for the robot to pass through (e.g., first arranging the flipper by moving only the flippers F-CW, then by elevating the neck N-CCW and head H-CW).

[00155] In order to move to, e.g., flat driving pose P14, in which the robot is stably positioned to be driven at higher speeds on the main tracks with the flipper tracks also in contact

with the ground, the neck and head being positioned behind the main body to provide a driving view but maximum moment about the leading end to resist flipping forward upon sudden stops or braking, the robot continues from the bumpy driving pose P20 by moving the flippers F-CW, elevating the neck N-CCW and tilting the head H-CW (from the side shown in FIG. 39). In order to "return" to any of the previous preconfigured poses, the robot must pass through the intervening preconfigured poses and intermediate poses.

[00156] As discussed, FIG. 39 demonstrates a model in which intervening and intermediate poses are predefined states on a closed, not necessarily looping, state map, in order to ensure that the robot does not tip over, self collide, or inappropriately lose balance or pose in transitioning from a present pose to a preconfigured pose. This is a methodical, but less flexible approach than having the robot actively maintain balance using proprioception, tilt, acceleration, and rotation (gyro) sensors.

[00157] FIG. 40 shows an embodiment in which the robot, although passing through similar states, constantly monitors balancing proprioception (position encoders), tilt, acceleration, and/or rotation (gyro) sensors. This system may deal more successfully with uneven ground (shown in FIG. 40) than a system using predefined positions. As shown in FIG. 40, a robot on level, tilted, or uneven ground in the stowed position P30 may be moved into, e.g., prairie dog pose (on uneven ground P32), flat driving pose (on uneven ground P34), and bumpy driving pose P36 by monitoring position encoding, calculating the overall center of gravity of the robot over that portion of the robot in contact with the ground (either the main body, the main body and flipper tracks, or just the flipper tracks), maintaining the individual centers of gravity of the body, flipper arms, neck, and head in positions over a stable center of ground contact, and monitoring and/or controlling acceleration and movement of the elements to obtain relative tilt,

orientation to terrestrial gravity, and/or static and/or dynamic stability. As shown in FIG. 40, because the preconfigured poses are reached by active monitoring and control of balance, the robot need not pass through all preconfigured intermediate pose states, but will pass through arbitrary, yet stable and balanced poses P40, on its way from one pose to another (e.g., from bumpy driving P36 to prairie dog P32 without passing through the stowed configuration P30). As such, the state map P38 will permit direct transition from one preconfigured pose state to another through a continuously changing, but continuously balanced pose transition, and from arbitrary current poses P42 directly to preconfigured poses P30 via a continuously changing, but continuously balanced pose transition (or a succession of continuously balanced pose transitions). The robot may also seek preconfigured poses by moving only from a present position into a confined solution space of next positions that includes only balanced poses.

[00158] In an embodiment of the invention, the robot may display to the user a representation of itself within its environment (see FIGS. 11 and 12) based on current information from the robot to the control system. Upon the user selecting a pose, the robot flippers and body move to angle themselves using accelerometers that input a direction of gravity reference. To achieve, for example, a prairie do position, accelerometer input is used by the robot to position its body at about  $55^\circ$  plus or minus about  $2^\circ$  from the horizontal (with respect to gravity). The robot tries to position its body at this orientation even on non-level ground. The robot is kept balanced during pose transitions by monitoring its body position relative to the horizontal. As can be seen from the illustrated prairie dog position, the neck may be set at about  $130^\circ$  relative to the body.

[00159] In an embodiment of the invention, the prairie dog pose may need to be deactivated to tilt the robot head, but no to pan it.

[00160] In an embodiment of the invention, the robot returns from the prairie dog pose to a driving position quickly, if not gracefully, to facilitate expedient withdrawal or other movement.

[00161] In an embodiment of the invention, the robot can be controlled to actively return to a preconfigured pose set when disturbed via the continuously balanced pose transition, including a self-righting routine intervening before the robot seeks the last set preconfigured pose. For example, if the robot is temporarily forced into a different pose, or is tipped over or otherwise disturbed, using tilt sensors, proprioceptive encoders, accelerometers, and/or gyro sensors, it may detect this and initiate seeking of the predetermined pose. In moving to and from preselected poses, an embodiment of the invention further includes an inherent collision avoidance behavior or system that uses a geometric model of the robot in its environment to ensure that the robot parts will not collide with each other when moving to and among poses.

### **Autonomous Flipper Behavior**

[00162] Autonomous flipper behavior allows an operator to operate the robot manually while the flippers are in an autonomous mode. The behavior autonomously identifies surface conditions and can use this data to trigger the autonomous flipper behaviors. When constantly running in the background, autonomous flipper behavior is considered a persistent behavior. Possible terrains to identify include: (1) soft terrains which may include snow and sand; (2) hard smooth terrains such as building interiors or roadways; and (3) firm broken terrain such as fields or dirt roads. For each terrain, there is a corresponding flipper position that works best. For example, flippers rotated into the retracted position work best on soft terrains, and flippers extended upwards works best on hard smooth terrains. Other inputs that could trigger autonomous flipper behavior include the robot being lifted high off the ground by an object

which the robot traversed. In an embodiment of the invention, autonomous flipper behavior draws upon data flows already present - operator drive commands, accelerometer spectral density, and load on the drive motors. More experienced users may disable the automated behaviors and manually control the flippers as needed.

[00163] An embodiment of the invention determines terrain type using spectral density of the vehicle's onboard accelerometer readings to identify the amount and type of vibration the robot is encountering. This data is correlated with other inputs to identify conditions requiring flipper position modification. For example, high centering shows negligible accelerometer vibration and rough terrain shows large jolts. Alternative or addition sensor input to consider includes video jitter and flow, comparing odometry to an external reference such as GPS, and tracking the fiber optic control line's feed-out speed. High centering a situation where the treads do not make solid contact, resulting from an encounter with an obstacle high enough to lift the robot's chassis. The ideal configuration for driving over unknown terrain for instance is with the flippers in front and raised at 30 to 45 degrees relative to the surface.

[00164] In an embodiment of the invention, operation in soft terrain causes the autonomous flipper behavior to maximize the amount of driven surface contacting the ground. To accomplish this, the flippers are lowered in front of the vehicle or tucked along the side of the vehicle. When the flippers are extended, there is a possibility that a flipper will dig into the soft ground.

[00165] In high center events, an embodiment of the invention directs the vehicle to mobilize the tracks in a swimming motion, continuously rotating the flippers overhead and driving the tracks only when the flipper is in contact with the surface. When engaged, tracks are propelled at the same rate that the flipper is expected to pull the vehicle forward. In swimming,

the optimal speed of flipper rotation is based not on the absolute length of the flippers but on their effective length (the area in effective contact with the ground), which changes as the surface density changes. By measuring the changes in angle of the vehicle as the flippers rotate, it is possible to calculate optimal speeds.

### **Retro Traverse**

[00166] In an embodiment of the invention, a retro traverse behavior autonomously navigates the mobile robot 10 back along a return path interconnecting various previously traversed coordinates. The retro traverse behavior may be activated by user request or automatically when trigger conditions are detected by the mobile robot 10, such as when no control signal has been received after a threshold period of time; or may be activated explicitly by the operator inputting an activation command. If automatically triggered, retro traverse acts as a persistent behavior.

[00167] To perform retro traverse according to an embodiment of the invention, the mobile robot 10 records waypoints at intermittent times when the mobile robot 10 is moving. FIG. 41 illustrates an embodiment of a waypoint routine. At step 2101, the routine receives the values for variables `min_dist` (the minimum distance by which successive waypoints should be separated), `wait_interval` (the period of time the routine should wait before recording a next waypoint) and `pres_coord` (the present coordinates of the mobile robot 10, as provided by a position reckoning system), and step 2102 initializes several variables, setting `init_time` (the initial timestamp) and `pres_time` (the current time of the present execution cycle) to zero, and `prev_coord` (the coordinates ascertained for the previous execution cycle) and `pres_coord` (the currently ascertained coordinates of the mobile robot 10) to zero, as well.

[00168] It is determined at step 2103 whether the robot is moving and, if not, the

process loops back to step 2103. Otherwise, step 2104 gets the current time (such as from a clock or cycle counter) and stores it to the variable `pres_time`. It is then determined at step 2105 whether sufficient time has passed since the initial time and, if not, the process returns to step 2103. If sufficient time has passed, then step 2106 assigns the value of `pres_time` to the variable `init_time`; step 2107 ascertains the present coordinates of the mobile robot 10 and stores them to the variable `pres_coord`; and step 2108 calculates the distance between the mobile robot's current position and the position of the mobile robot 10 ascertained at the immediately previous cycle.

[00169] If step 2109 determines that not enough distance has been traversed since the previous cycle, then the process returns to step 2103. Otherwise, step 2110 appends the values of `pres_coord` (as a positional record) and `pres_time` (as the corresponding timestamp) to the list of recorded waypoints; step 2111 sets the value of `prev_coord` to the same value as `pres_coord`; and step 2112 updates the variable `wait_interval`, if necessary or appropriate, before returning to step 2103.

[00170] Accordingly, the waypoint routine maintains a list of recorded waypoints separated by at least minimum permitted differences in time and distance. The retro traverse behavior can then utilize the list of recorded waypoints to generate a return path interconnecting the waypoints, in reverse order of timestamps.

[00171] FIG. 42 illustrates an embodiment of a method for performing a retro traverse behavior. At step 2201, it is checked whether the behavior is active and, if so, the behavior proceeds to step 2202 (otherwise looping back to step 2201). Step 2202 sets the values of `retro_start` and `prev_retro_start` to zero; step 2203 erases any previously used waypoints; and step 2204 ascertains the current position of the mobile robot 10 and the current time, which are prepended to the list of recorded waypoints.

[00172] At step 2205 it is determined whether a control signal has been properly received. If so, then step 2212 proceeds to navigate the robot based on the instructions received from the operator. Otherwise, step 2206 sets the value of `prev_retro_start` to `retro_start`, and `prev_retro_end` to `retro_end`; step 2207 sets the value of `retro_start_time` to the current time; and step 2208 navigates the mobile robot 10 toward the next previous waypoint retrieved from the list of recorded waypoints for one execution cycle. If step 2209 determines that communication has not been restored, the behavior returns to step 2208 and continues navigating toward the waypoint; otherwise, step 2210 sets `retro_end_time` to the current time and step 2211 inserts a new entry (comprising the values of `retro_start_time` and `retro_end_time`) into a list of retro traverse intervals before proceeding to step 2212.

[00173] By maintaining a list of previously-performed retro traverses (for example, by recording a list of start/end time pairs for each period of time the retro traverse behavior is activated and deactivated), the retro traverse behavior can ignore any waypoints that are recorded during retro traverse operation, as these are spurious for future retro traverse purposes. That is, after the mobile robot 10 has finished a retro traverse, it records the range of timestamps on the points it retraced and that it created on its path back. On its next retro traverse, it may ignore those points.

[00174] An embodiment of remote control operation of the mobile robot 10 in an urban combat zone is shown in FIG. 43. An operator 5 is positioned within a sandbag-enclosed bunker 9012 adjacent a roadway. The mobile robot 10 proceeds out from the bunker 9012, under control of the navigation commands transmitted, preferably wirelessly, by the operator. As shown by the curved dotted line, the mobile robot 10 then traverses a path between various buildings 9011.

[00175] At various times during navigation of the mobile robot 10, waypoints A through J are recorded. Each recorded waypoint includes information regarding the position of the mobile robot and a timestamp indicating when the position was sampled. The waypoints may be recorded in the electronic memory of the mobile robot 10 in a suitable data structure (e.g., as a doubly-linked, indexed list, sorted chronologically by timestamp) to permit forward and reverse list traversal as well as indexed access to the waypoints, for example.

[00176] As the mobile robot 10 proceeds further away from the operator, or when an obstacle such as the buildings 9011 sufficiently impede wireless communication, the mobile robot 10 may fail to receive the control signal transmitted by the operator. Therefore, as an example of a persistent autonomous behavior, the retro traverse behavior may be activated by the robot 10 when it determines that communication is lost.

[00177] Another embodiment of a retro traverse behavior is illustrated in FIG. 44A, in which the robot traverses either forward or backward along a single line 2300. First the mobile robot 10 proceeds out along the line 2300 during a first outbound leg 2301. In this case, the waypoint routine records waypoints A and C at positions  $x = 3$  and 7. When the mobile robot 10 starts retro traversing, it uses these waypoints because no previous retro traverse has yet been performed.

[00178] In the embodiment of FIG. 44A, the first outward leg 2301 stops just after  $t = 8$  (at which time the mobile robot 10 may have lost radio contact with the operator or received instructions to stop, *inter alia*). The first retro traverse leg 2302 then begins at  $t = 8.1$  and continues until  $t = 12$ , at which time the mobile robot 10 stops retro traversing and resumes outbound traversal along the second outbound leg 2303 (e.g., after regaining communications with the operator). During the first retro traverse leg 2302, the mobile robot 10 again travels

over points B and A, but does not proceed all the way back to  $t = 0$ . Also during the first retro traverse leg 2302, the waypoint routine generated waypoints at  $t = 9$  and  $t = 11$ .

[00179] So the retro traverse interval  $t = 8.1$  to 12, representing the start time ( $t = 8.1$ ) and end time ( $t = 12$ ) of the retro traverse leg 2302 is added to the list of retro traverse intervals, and any waypoints having a timestamp within this range (in this case, the waypoints at  $t = 9, 11$ ) are excluded on any subsequent retro traverse.

[00180] FIG. 44B illustrates an embodiment of the invention that continues from the example shown in FIG. 44A. The mobile robot 10 proceeds along the second outbound leg 2303 until  $t = 18$ , when retro traverse is activated again. When this second retro traverse leg 2304 starts, the retro traverse behavior retrieves the list of waypoints having timestamps  $t = 17, 11, 9, 7, 3, 0$ .

[00181] From the list of waypoints, the behavior removes from consideration all recorded waypoints having a timestamp within the interval  $t = 8.1$  to 12, resulting in a pruned list  $t = 17$  (corresponding to C),  $t = 7$  (corresponding to B),  $t = 3$  (corresponding to A) and  $t = 0$  (an implicit, unnamed timestamp corresponding to the beginning of the robot's movement). This pruned list corresponds to the desired straight path back to the beginning of the journey. Following the second retro traverse leg 2304 ending at  $t = 26$ , a second retro traverse interval  $t = 18$  to 26 is appended to the list of recorded retro traverse intervals (resulting in a list of intervals comprising the two entries  $[8.1, 12]$  and  $[18, 26]$ ) and the third outbound leg 2305 then starts (resulting in a third waypoint D recorded at  $t = 36$ ).

[00182] If a third retro traverse leg (not shown) were to start, it would accordingly ignore all waypoints with timestamps within the intervals 8.1 to 12 and 18 to 26.

[00183] To ensure smooth navigation and avoid abrupt veering or swerving in the

vicinity of corner points along an intended path of travel, the mobile robot 10 may base its navigation on a lookahead vector. A lookahead vector can be defined in the following way: a starting point lies at the closest point on the path to the mobile robot 10, and an ending point is a point farther along the path that is either at a maximum distance away, or at a shorter distance as determined by the curvature of the path and/or other factors. For example, the mobile robot 10 may continuously drive toward a virtual point approximately 1 meter in front of it along the intended path. In some implementations, the distance that the mobile robot 10 looks ahead may be variable, depending upon the geometry of the lookahead vector.

[00184] In addition, rather than always manipulating the  $x$ - $y$  coordinates of points directly, navigation of the mobile robot 10 may utilize a line-segment abstraction of the intended path. First, when retro traversing, the return path can be represented as a set of piecewise continuous, conjoining line segments rather than a set of points. The mobile robot 10 may perform most of its calculations in terms of the tangent and perpendicular to the line segment the mobile robot 10 is traversing instead of based on the vector difference to the next waypoint. Accordingly, the mobile robot 10 may reduce or eliminate sharp turning when it approaches waypoints conjoining two path line segments at acute angles.

[00185] Secondly, once the robot has pre-computed the tangents and lengths of the line segments, a point can be expressed as a distance along the path. For example, letting  $\lambda$  represent the tangent unit vector to the  $i^{\text{th}}$  line segment, then a point  $r$  with path length  $l$  has a position

$$r = \sum_{i=0}^n a_i \lambda$$

where  $a_i$  represents the length of the  $i^{\text{th}}$  segment for  $i = 0$  to  $n-1$  and  $a_n = l - \sum_{i=0}^{n-1} a_i$ .

[00186] Further, the retro traverse behavior may implement a predetermined cycle of calculations to follow a return path:

- Determine on which line segment the robot is currently traversing;
- Calculate the end of the lookahead vector; and
- Calculate motion commands.

The calculations may be done in the listed order during a cycle of the behavior system because the mobile robot 10 moves after all of the calculations have been completed.

[00187] The retro traverse behavior may use a radius of interception to determine whether the mobile robot 10 has reached a waypoint, or a perpendicular plane to determine when the mobile robot 10 has passed a waypoint. Preferably, however, the mobile robot 10 keeps track of which line segment of the return path it is traversing. Since the lookahead vector keeps track of the local area that the robot's motion is based on, the only line segments of the retro traverse path that the robot needs to consider are those spanned by the lookahead vector. The retro traverse behavior then determines the closest of these line segments and sets that as its reference.

[00188] FIG. 45A illustrates an embodiment of the invention where the lookahead vector 2410 extends from the mobile robot 10 along a linear return path including a first line segment 2401 and second line segment 2402 interconnecting waypoints A, B and C. The mobile robot 10 computes its distance to all the line segments between the beginning and the end of the lookahead vector 2410. The line segment closest to the mobile robot 10 is the one it associates with. In the embodiment of FIG. 45A, the robot associates to the first line segment 2401 via the perpendicular line 2411.

[00189] In an embodiment illustrated in FIG. 45B, third and fourth line segments 2403, 2404 interconnecting waypoints D, E and F, form an angle with waypoint E as the corner. Here, on the previous iteration, the mobile robot 10 determined it was closest to the third line segment 2403, and thus the lookahead vector 2410 starts there for the present cycle. However this time it finds that it is closest to the fourth line segment 2404, meaning it has passed waypoint E.

[00190] FIG. 45C illustrates a situation similar to the arrangement of FIG. 45B; however, in FIG. 45C, the lookahead vector—which is rooted in the fifth line segment 2405—does not extend all the way out to the closest point on the sixth line segment 2406. In this case, the mobile robot 10 should not associate with the sixth line segment 2406 because then the mobile robot 10 would short cut the desired path. Accordingly, the lookahead vector preferably gets shortened in order to avoid taking short cuts that bypass waypoints. To achieve proper paths without shortcutting, the retro traverse behavior does not accept any line segments for which the closest point to the mobile robot 10 is beyond the end of the lookahead vector.

[00191] In the embodiment of FIG. 45C, the mobile robot 10 stays on the fifth line segment 2405 despite it being farther away than the sixth line segment 2406. Once the mobile robot 10 has determined which line segment it is on, it calculates the closest point to the mobile robot 10 on that line segment. This point is then used as the origin of the lookahead vector for the subsequent iteration.

[00192] After determining the beginning of the lookahead vector, the retro traverse behavior next determines where the end of the lookahead vector is. Referring to an embodiment of the invention illustrated FIGS. 46A through 46D, the lookahead vector 2510 may have a length established by default to a predetermined value (*e.g.*, one meter long). However, the retro

traverse behavior may be implemented so as to ensure that the mobile robot 10 drives at least within a maximum permitted distance of each waypoint. If the lookahead vector 2510 were to always stay at its full default length, the mobile robot 10 might traverse a route with all the curves excessively smoothed out in some circumstances.

[00193] In view of this, the embodiment of FIGS. 46A through 46D demonstrate a system for determining when and how to shorten the lookahead vector 2510 to keep the mobile robot 10 aligned with the intended path. FIG. 46A shows a straight-line path comprising first and second line segments 2501, 2502. In this case, the path of mobile robot 10 passes well within the permitted distance from waypoint A and accordingly, the lookahead vector 2510 may remain at its full default length.

[00194] In FIG. 46B, the mobile robot 10 has moved farther along the path to a section where it angles slightly at waypoint E between the third line segment 2503 and fourth line segment 2504. Because the mobile robot 10 will attempt to drive toward the end of the lookahead vector 2510, the appropriate approximation of the mobile robot's path is the vector extending from the mobile robot 10 to the end of the lookahead vector 2510.

[00195] To ascertain whether the mobile robot's route will lie within the permitted distance from a waypoint, the retro traverse behavior checks whether the perpendicular distance from a waypoint to is less than the maximum permitted distance (which may be a predetermined, constant value—such as one meter, for example). The mobile robot 10 repeats this check for every waypoint disposed orthogonally to the lookahead vector (i.e., waypoints for which there exists an orthogonal projection onto the lookahead vector). Alternatively, the mobile robot 10 may repeat the distance check for every waypoint that is associated with any of the retro traversal path line segments intersected by the lookahead vector 2510, to simplify the calculation of

whether a waypoint “lies along” the lookahead vector 2510. In the example shown in FIG. 46B, the distance is within the permitted range; therefore, the lookahead vector 2510 extends to its full length.

[00196] FIG. 46C shows a similar situation; however, the full-length lookahead vector 2510 does not lead to a path that is within the permitted distance of one of the waypoints (waypoint I) that projects orthogonally onto the lookahead vector 2510. The mobile robot 10 therefore sets the end of the lookahead vector 2510 (which will be used in the subsequent cycle) to be the mean of the current end point and the end point of the previous lookahead vector 2511 used in the preceding cycle of the behavior. The retro traverse behavior running on the mobile robot 10 will continue to decrement the length of the lookahead vector 2510 for several iterations in a similar manner until it either finds an acceptable end point or performs a maximum threshold number of iterations without success. Because the end point of the lookahead vector 2510 should always be on a line segment in the intended path, the mean of the old and new end points are preferably calculated in terms of the respective path lengths of the two and then transformed into x-y coordinates, rather than averaging the x-y coordinates of the two points.

[00197] FIG. 46D illustrates a situation with a sharp angle between the seventh and eighth line segments 2507, 2508. The waypoint K does not project orthogonally onto the lookahead vector 2510 shown in FIG. 46D. Accordingly, the retro traverse behavior preferably ensures that the closest point is actually within, to obviate this situation.

[00198] FIG. 47 illustrates an embodiment of a relationship between two output values,  $v_{\text{rotate}}$  and  $v_{\text{translate}}$ , that may be issued by the retro traverse behavior. The translational ( $v_{\text{translate}}$ ) and rotational speeds ( $v_{\text{rotate}}$ ) are calculated based on the angle by which the mobile robot 10 needs to turn to be heading toward at the end of the lookahead vector.

The rotational speed may be determined as a PID loop on the function  $v\_rotate$  shown in FIG. 47, for example. The function characteristics may be adjusted to ensure the mobile robot 10 does not overshoot waypoints.

[00199] Also, in another embodiment, there are three different modes in which the mobile robot 10 can operate:

“always drive forward;”

“always drive backward;” or

“drive in which ever direction requires the least rotation.”

[00200] For “always drive forward,” the speeds are calculated based on the angle between the mobile robot’s heading and the direction to the end of the lookahead vector. For “always drive backward,” they are based on  $\theta_2$ , and the translational speed is multiplied by  $-1$ . For “driving the direction of least rotation,” when  $\theta$  in between  $\theta_1$  and  $\theta_2$  then the mobile robot 10 drives forward; otherwise, it drives backwards.

[00201] Retro traverse can be implemented in the following exemplary manners:

- the robot will either track odometry and determine position based on that;
- will maintain a global map and place the coordinates within a global map;
- will maintain a far off destination point within a global map and adjust its heading to move towards that point;
- will use some sort of navigation point (i.e. GPS, or other satellite or landmark easily detected from most points within the environment); or
- will communicate with navigation beacon points (signal repeaters, etc.) and use those to determine position within the environment.

[00202] Alternative methods of implementing retro traverse include: (1) following

a reduction in chemical scent, or following a chemical scent; or (2) following a trail left by the robot – i.e. a fiber optic cable, a line of spray paint, setting a destination point in a global map and traveling towards that destination point.

[00203] Two alternative methods of implementing retro traverse include:

- Collecting odometric data and using it to calculate the return path;
  1. Example Data – heading and approximate distance of travel for each stage of retro traverse.
- GPS waypoint collection
  1. GPS approximations can be collected.
  2. Tie these approximations to the odometry data.
  3. Use Kalman Filter based algorithms to provide confidence in the return path.

### **Self-Righting**

[00204] Self-righting behaviors can also be persistent, in a sense that it may constantly be running in the background to right the robot if it is up-ended. Robots traveling over very rough terrain or through opposing fire can end up flipped on their sides or even upside down. Self righting behavior allows the remote vehicle to turn itself back over and onto its tracks so it can continue with its mission objective or return back to the operator, as desired. When self righting, the robot senses its orientation and determines a strategy for turning itself upright. The robot will perform a progression of increasingly complex arm and flipper motions until it has levered itself back onto its tracks.

[00205] Self righting has two modes. In the first mode, it will be autonomously initiated when the robot detects that it has flipped upside down. In the second mode, the operator

explicitly commands the robot to start or stop self righting. The advantage of enabling persistent autonomous self righting is that should communications be degraded because the antennae are beneath the unit to the point where the operator cannot directly command it, the robot can rescue itself without explicit direction, and without the need for hands-on human intervention.

### **Semi-Ballistic Behaviors**

[00206] Semi-ballistic behaviors allow the operator to manually operate the remote vehicle. Semi-ballistic behaviors can quit when certain actuators are actuated such as stop a speed boost behavior when the operator actuates a stop button or switch, the drive control, or a quick brake.

### **Speed Boost and Quick Brake**

[00207] In an embodiment of the invention, activating speed boost or quick brake behavior allows the operator to quickly increase or decrease the current drive speed of the mobile robot 10. Once activated, the mobile robot 10 will continue to drive with the new drive speed until a new behavior, action, or event occurs. An example of this is the execution of the speed boost behavior while the mobile robot 10 is driving forward at a current drive speed. Upon execution, the mobile robot 10 then drives forward at a speed equivalent to the current drive speed increased by a preset speed value stored in memory.

[00208] FIGS. 48 and 49 illustrate an embodiment of speed boost and quick brake behaviors. These behaviors are initiated by activating a switch or button of the control system described above. Activating the button or switch multiple times in a row will result in multiple and successive executions of the chosen behavior. The end result is a new drive speed equivalent to the current drive speed increased or decreased by a factor of the preset speed value multiplied by the number of times the button or switch was activated.

[00209] The speed boost behavior stores the current drive speed 8001 and the current drive heading 8002. The behavior then calculates a new drive speed value by increasing the current drive speed value by a factor equivalent to a preset speed value 8004 stored in memory 1125. A speed check 8006 is done to ensure that the new drive speed is compatible with behaviors or routines that may be active on the mobile robot 10. If the speed check 8006 allows for the new drive speed, the mobile robot 10 drives forward at the new drive speed 8010 and the speed boost behavior ends 8012. Otherwise, if the speed check 8006 does not allow for the new drive speed, then the mobile robot 10 drives forward at the current drive speed 8008 and the speed boost behavior ends 8012.

[00210] The quick brake behavior embodiment shown in FIG. 49 is similar to the speed boost behavior embodiment in that it stores the current drive speed 8014 and the current drive heading 8016 and performs a speed check 8020 once the new drive speed is calculated. The quick brake behavior differs in that the new drive speed is calculated by decreasing the current drive speed by a factor equivalent to the preset speed value 8020. Like the speed boost behavior, if the new drive speed is allowed, then the mobile robot 10 drives forward at the new drive speed 8024 and the quick brake behavior ends 8026. Alternatively, if the new drive speed is not allowed, then the mobile robot 10 drives forward at the current drive speed 8020 and the quick brake behavior ends 8026.

[00211] Alternate embodiments of speed boost and quick brake may include:

- A speed boost behavior that sets a zone of acceptable speeds that is greater than the normal zone (e.g., typically the robot can drive at a speed between 2 and 20 MPH, but with speed boost it can drive between 15 and 50 MPH);
- A speed boost behavior that provides a quick boost of speed for a period of time –

then returns to the previous drive speed;

- A quick brake that lowers the zone of acceptable speeds (e.g., zone is now 0 to 5 MPH from 2 to 20 MPH); and/or
- A quick brake that for a period of time quickly reduces the speed of the robot, then returns to the previous drive speed after the period of time.

### **Cruise Control**

[00212] A cruise control behavior receives information from the control system regarding an intended constant speed and heading for the mobile robot 10. In an embodiment of the invention, the information sent from the control system includes an acceleration value and a rotational velocity, both of which are used by the mobile robot 10 to determine a drive velocity and heading. The cruise control behavior allows the operator to drive the robot 10 for a distance without necessary intervention by the operator. In an embodiment of the invention, the operator uses a left and right joystick or puck of the control system to control the robot's movement. In this embodiment, the left joystick or puck can be dedicated to the cruise control behavior such that when the left joystick or puck is actuated, the cruise control behavior commences, and when the right joystick or puck is actuated, the cruise control behavior halts. Alternatively, the cruise control behavior could commence following the actuation of a button or other actuator of the control system. Alternatively, a third joystick or puck may be included in the control system that is dedicated to cruise control.

[00213] In an embodiment of the invention utilizing pucks, each puck has the ability to rotate about a vertical axis, translate forward and backward about a horizontal axis, and tilt away from the vertical axis. Furthermore, when the puck is translated, rotated or tilted, it is the movements correspond to different movements of the robot. In particular, driving the robot

in a forward or backward direction is preferably controlled by the translation of the puck about a horizontal axis, alteration of the robot's heading is controlled by the rotation of the puck about a vertical axis, and actuation of the flippers included on the robot are controlled by tilting the pucks. An example of the movement of a robot in response to puck movement is one in which the puck is rotated about the vertical axis  $30^\circ$  in a clockwise direction, and the puck is moved forward a distance of a half inch. In response, a robot at rest will adjust its heading by turning  $30^\circ$  in a clockwise direction, and driving forward at a velocity equivalent to a pre-determined value associated with movement of the puck a half inch. Should the puck be tilted to the right  $15^\circ$  from the normal, the robot's flippers would respond by rotating towards the ground an angle equivalent to  $15^\circ$ .

[00214] FIG. 50 illustrates an embodiment of a cruise control routine 3200 included within a cruise control behavior. When in control of its corresponding actuators, the cruise control behavior executes the cruise control routine 3200, which commences by scanning for a new set of cruise commands 3212 from the operator. Should the routine sense a new set of cruise commands, the routine inputs the commands as an absolute heading 3215. There may be a time lag between when the robot's cameras record video information and the time that such information is displayed to the operator. If the robot 10 is moving at a particular speed and particular heading, and a new heading and/or speed is chosen by the operator and sent to the robot, the robot will have moved a certain distance during the time between when the robot's camera detected the image and when image was displayed to the operator. The latency of the system can cause discrepancies when sending the robot cruise commands.

[00215] In an embodiment of the invention, to eliminate the possibility of these discrepancies, the operator sends the robot 10 an absolute heading and velocity. When the robot

10 receives the absolute heading and velocity, the robot then calculates its new heading and velocity using the absolute heading and velocity and the positional and velocity values at the time the robot's camera detected the image, rather than the current real-time positional and velocity values. Upon calculating the new travel velocity and heading, the robot 10 uses real-time positional and velocity values to calculate a new travel vector 3218.

[00216] Once a travel vector is calculated 3218, the robot will then drive at the specified velocity using the specified heading 3201. While driving, the cruise routine gathers real-time positional and velocity values from the sensors 3203 and compares these values to the chosen travel vector 3206. Should there be a significant difference between the current travel vector and the chosen travel vector, the routine will instruct the robot 10 to adjust its heading and velocity 3221 using past odometry values. Otherwise, if there is little difference between the current travel vector and the chosen travel vector, the routine will instruct the robot 10 to continue driving 3201.

[00217] Further illustrative of an embodiment of cruise control, FIGS. 51A and 51B display a robot 3444 that responds to new heading commands to change direction. The robot 3444 moves forward in a particular direction 3440. Once the operator retrieves video feedback of the robot's position, the robot's position has changed from its position at the time the video information was captured 3446 to its current position 3444. Thus, the robot has continued along its current path 3440 during the time between when the robot collects video information of its position at that time 3446 and the time when the robot receives new heading commands from the operator. When the operator sends the heading information to the robot 10, the heading information 3442 is relative to the robot's previous position 3446. FIG. 51B shows how the robot uses the heading 3442 generated in relation to the robot's previous position 3446 to

determine a new heading 3452 calculated in relation to the robot's current position 3444.

[00218] FIG. 52 illustrates an embodiment of a flow of information in the cruise control behavior. Input from the control system is received and processed to produce an updated current intended heading and speed  $\theta_n, v_n$ . In the equations displayed,  $\theta_{n-1}$  is the intended heading of the preceding cycle,  $t_n$  is the time of the current cycle,  $t_{n-1}$  is the time of the preceding cycle,  $\theta(t_n - t_{n-1})$  is the angular difference between the heading of the current cycle and the heading of the preceding cycle,  $v_{n-1}$  is the intended speed of the preceding cycle, and  $(v_n - v_{n-1})$  is the difference between the speed of the current cycle and the speed of the preceding cycle.

[00219] Simultaneously, input from position reckoning systems (such as a compass, IMU, or GPS) are fed to a motion tracking system, which updates the reckoned actual heading and speed. The reckoned actual heading and speed of the mobile robot 10, as well as the updated intended heading and speed, are passed to a comparator, which generates an appropriate output (such as turn rate and drive motor current) to control the drive system.

[00220] Activation of the cruise control behavior includes first actuating an actuator of the control system. As discussed above, the actuator may be a puck, button, lever, soft button, or any other actuator that initiates the cruise control behavior. FIG. 53 illustrates an embodiment of a routine carried out by the control system (using a puck for cruise control activation) to generate cruise control commands. The routine scans a puck designated for activating and controlling the cruise control behavior 3251. Upon detecting a change in the position of the puck 3253, the routine determines whether the change included a rotation of the puck about a vertical axis 3256. If not, the routine will continue to scan the puck's position. If the change included a rotation of the puck about a vertical axis 3256, the routine calculates a

rotational velocity proportional to the rotation of the puck and indicative of the direction the puck was rotated 3259, and the control system sends the new drive heading to the robot 10, where the heading is relayed to the cruise control behavior.

[00221] The routine then determines whether or not the puck was translated about a horizontal axis 3265. If this has occurred, the routine calculates an acceleration/deceleration command 3268 representative of the puck's movement, and the control system sends the acceleration/deceleration command 3271 to the robot 10 where the acceleration/deceleration command is relayed to the cruise control behavior. In the illustrated embodiment, if the routine detects a tilting of the puck 3274, the routine exits 3277 because such a movement of the puck indicates flipper movement which is controlled by a behavior other than the cruise control - activation of another behavior causes cruise control to halt. If the routine does not detect a tilting of the puck 3274, the routine continues to scan the puck's position 3251.

[00222] FIG. 54 illustrates an embodiment of the interaction between the cruise control behavior and other behaviors installed on the robot's single board computer. When the cruise control behavior has control of the robot's actuators, it executes its cruise routine 3301. However, when the coordinator indicates that another behavior has been activated 3303 and that behavior has a higher priority 3306 than the cruise control behavior, the cruise control behavior is halted and the cruise routine exited 3318. Otherwise, if the coordinator does not indicate that another behavior has been activated 3303, or if a behavior has been activated but that behavior does not have a priority 3306 greater than the cruise control behavior, the cruise control routine will continue to execute 3301. In an embodiment of the invention, when a behavior with a higher priority than cruise control is activated, the coordinator checks whether this behavior is the obstacle avoidance behavior 3309, and if true, allows the obstacle avoidance behavior to have

control of the actuators without halting the cruise control behavior. Otherwise, if the obstacle avoidance behavior is not identified and the behavior has a higher priority than the cruise control behavior, the cruise control behavior will exit the cruise routine and halt 3318.

[00223] Should the obstacle avoidance behavior gain control of the actuators, an obstacle avoidable routine is executed 3312 by the obstacle avoidance behavior. Once the obstacle avoidance behavior is executed and exited, cruise control may regain control of the actuators 3321. Once in control of the actuators, the cruise control will pick up where it left off and begin executing the cruise control routine 3301. Within the cruise routine 3200 (see FIG. 50), a check is made of the robot's real-time travel vector 3203. Since the obstacle avoidance routine caused the robot to veer away from the chosen travel vector, the cruise control routine will detect the change in travel vector and correct the robot's heading and velocity 3221 using past odometry values so that the robot returns to the chosen travel vector.

[00224] An embodiment of the interaction between the cruise control behavior and the obstacle avoidance behavior is illustrated in FIGS. 55A – 55D. Obstacle avoidance can be a persistent behavior, but is discussed here based on its interactions with cruise control. FIG. 55A shows the robot's 3458 movement along the chosen travel vector 3456 dictated by the cruise control behavior, where the vector 3456 points the robot toward an obstacle 3454. FIG. 55B illustrates the robot's response to the obstacle 3454 by commanding the robot to drive to a position 3460 not included within the chosen travel vector, which is the result of an avoidance travel vector 3462 instituted by the obstacle avoidance behavior to cause the robot 10 to avoid the obstacle 3454.

[00225] Once the obstacle 3454 is avoided, the cruise control behavior re-assumes control of the actuators and, as shown in FIG. 55C, begins to adjust the robot's direction of travel

so that the robot returns to a path included within the chosen travel vector 3456. To do this, the cruise control behavior alters the robot's heading so that the robot drives along a path included within a translational vector 3462 calculated to cause the robot 3460 to return to the chosen travel vector 3456. FIG. 55D displays the final effect of the translational vector 3462. The robot 3458 moves from a path included within the avoidance travel vector 3462 to a path within the chosen travel vector 3456.

[00226] The obstacle avoidance behavior can include an embodiment of an obstacle avoidance routine as illustrated in FIG. 56. Once an obstacle is detected 3520 and the obstacle avoidance behavior has retained control of the actuators, the obstacle avoidance routine begins to execute. The routine first inputs camera video output of the obstacle detected 3522 and uses the camera's resolution to determine the dimensions of the obstacle. To ensure proper clearance, the routine bloats the obstacle by a pre-determined value so that an avoidance vector can be calculated 3518. The avoidance vector allows the robot 10 to drive along a path that avoids the obstacle 3528. As the robot 10 drives forward 3528, the routine continually checks for obstacles 3530. If an obstacle is detected, the robot 10 then inputs the video image of the obstacle 3522, determines its dimensions 3524, bloats the obstacle 3526 and calculates a new avoidance vector 3518. These steps occur until no obstacle is detected, at which point the obstacle avoidance routine is exited 3532 and the cruise control behavior regains control of the actuators.

[00227] In an embodiment of the invention, the cruise control behavior assumes that the robot is moving at a velocity of 0 m/s, and considers the robot's position to be the normal position. Subsequent rotational velocities and accelerations/decelerations are an alteration of the robot's 0 m/s velocity and normal position. Alternatively, the cruise control behavior could

include cruise routines that allow for acceleration and/or deceleration of a robot with a velocity other than 0 m/s. In such an embodiment, an additional actuator may be included in the control system so that the user can control activation of cruise control with an actuator separate from the puck.

[00228] Other possible features of the cruise control behavior include fail safe conditions that cause the cruise control behavior to halt. These conditions include: (1) actuating brakes included within the drive system; (2) actuating a button, switch, puck, or other input device not designated to control the cruise control behavior; (3) depressing a stop actuator included of the control system; (4) changing the drive mode; or (5) dropping communication between the control system and the robot 10. Additionally, there is a maximum speed at which the robot can go and the robot is configured not to drive at a speed higher than the maximum speed.

[00229] Alternative embodiments of the implementation include:

- Setting a point far in the distance and driving toward that point so that when a behavior like obstacle detection interrupts, the cruise control behavior can do one of calculating a path from the robot's current position back to the original cruise path and calculating a new path from the robot's current position to the destination point
  - Tracking odometry and adjusting the robot's current path using a translational vector calculated from the odometry values so that when obstacle detect interrupts, the cruise control behavior calculates a translational vector from the past odometry values and applies the vector to the robot's current path – so that the robot will return to the cruise path.
- Set a start waypoint and end waypoint when a behavior like odometry interrupts cruise, meaning that two waypoints are stored while the robot is still on the cruise

control path and at the point in time when obstacle detection is initiated, the first waypoint being representative of the robot's position when obstacle detect interrupts and the second waypoint being representative of a point much farther down the path from the first waypoint (far enough that the point will exist at a position beyond the obstacle). After obstacle detection finishes, the cruise control behavior uses the two waypoints to calculate a path back to the original cruise control path.

[00230] In an embodiment of the invention, the cruise control behavior sends an "operator attention required" alert to the operator. Alert conditions may include:

- Hard bump to the manipulator arm, indicating contact with a solid object.
- Repeated drifting off course, indicating uneven ground.
- Tilt or roll approaching tip-over limits.
- Increased motor torque indicating the presence of an obstruction.
- Time-out situations to prevent over-travel.

[00231] Other embodiments of the cruise control behavior include a cruise behavior that can be used while drive is in control, the user actuating a cruise control button of the control system. The cruise control behavior can also be activated such that the robot will cruise for a predetermined period of time, or a predetermined distance. Alternatively, the cruise control behavior could include a hybrid where such an action would happen unless the user instructs the normal cruise to take over indefinitely.

### **Obstacle Avoidance**

[00232] An embodiment of an obstacle avoidance behavior is described above. Ways of implementing the obstacle avoidance behavior include:

- Path Planning – the robot detects obstacles & avoids them, then calculates a path around the obstacle. Path planning may be carried out while the robot is traversing the path to

ensure that the robot remains on the path.

- Continuous obstacle detection where there are obstacle detection sensors installed along the sides of the robot. The robot turns a predetermined angle and moves a predetermined distance in response to a forward obstacle detection. Once the forward sensor no longer detects the obstacle and if the side sensors detect the obstacle, obstacle detect moves forward until the side sensors no longer detect the obstacle.

**CLAIMS**What is claimed is:

1. A system for allowing an operator to switch between remote vehicle tele-operation and one or more remote vehicle autonomous behaviors, comprising:

an operator control system receiving input from the operator including instructions for the remote vehicle to execute an autonomous behavior;

a control system on the remote vehicle for receiving the instruction to execute an autonomous behavior from the operator control system;

wherein, upon receiving the instruction to execute an autonomous behavior, the remote vehicle executes that autonomous behavior.

2. The system of claim 1, wherein the remote vehicle executes the autonomous behavior if permitted.

3. The system of claim 2, wherein the autonomous behavior is not permitted if one or more of the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior of the remote vehicle, or the remote vehicle's environment are incompatible with the autonomous behavior.

4. The system of claim 1, wherein the control system comprises an arbiter, and wherein the autonomous behavior sends a vote to the arbiter requesting control of one or more actuators on the remote vehicle necessary to perform the autonomous behavior.

5. The system of claim 4, wherein, if the voting autonomous behavior has a higher priority than a behavior currently in control of the one or more actuators, the autonomous behavior executes.
6. The system of claim 1, wherein the autonomous behaviors comprise one or more of ballistic, semi-ballistic, and persistent behaviors.
7. The system of claim 6, wherein ballistic behaviors comprise one or more of stair climbing, preset actions, click-to-drive, click-to-grip, preconfigured poses, retro traverse, self-righting, and autonomous flipper.
8. The system of claim 6, wherein semi-ballistic behaviors comprise one or more of quick brake, speed boost, and cruise control.
9. The system of claim 6, wherein persistent behaviors comprise one or more of retro traverse, self righting, obstacle avoidance, and autonomous flippers.
10. A method for switching between remote vehicle tele-operation and one or more remote vehicle autonomous behaviors, comprising:
  - inputting instructions for the remote vehicle to execute an autonomous behavior;
  - evaluating one or more of the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior of the remote vehicle, or the remote vehicle's environment are incompatible with the autonomous behavior;

and

allowing the autonomous behavior to send a vote to an arbiter if the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior on the remote vehicle, or the remote vehicle's environment are compatible with the autonomous behavior,

wherein a vote to the arbiter requests control of one or more actuators on the remote vehicle necessary to perform the autonomous behavior.

11. The method of claim 10, further comprising executing the autonomous behavior if the voting autonomous behavior has a higher priority than a behavior currently in control of the one or more actuators.

12. The system of claim 10, wherein the autonomous behaviors comprise one or more of ballistic, semi-ballistic, and persistent behaviors.

13. The system of claim 12, wherein ballistic behaviors comprise one or more of stair climbing, preset actions, click-to-drive, click-to-grip, preconfigured poses, retro traverse, self-righting, and autonomous flipper.

14. The system of claim 12, wherein semi-ballistic behaviors comprise one or more of quick brake, speed boost, and cruise control.

15. The system of claim 12, wherein persistent behaviors comprise one or more of retro traverse,

self righting obstacle avoidance, and autonomous flippers.

16. A system for implementing remote vehicle autonomous behaviors, comprising:

an operator control system receiving instructions for the remote vehicle to execute an autonomous behavior;

a control system on the remote vehicle for one or more of executing a persistent autonomous behavior and receiving the instruction to execute an autonomous behavior from the operator control system;

wherein, upon receiving the instruction to execute an autonomous behavior, the remote vehicle executes that autonomous behavior.

17. The system of claim 16, wherein the remote vehicle executes the autonomous behavior if permitted.

18. The system of claim 17, wherein the autonomous behavior is not permitted if one or more of the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior of the remote vehicle, or the remote vehicle's environment are incompatible with the autonomous behavior.

19. The system of claim 16, wherein the control system comprises an arbiter, and wherein the autonomous behavior sends a vote to the arbiter requesting control of one or more actuators on the remote vehicle necessary to perform the autonomous behavior.

20. The system of claim 19, wherein, if the voting autonomous behavior has a higher priority than a behavior currently in control of the one or more actuators, the autonomous behavior executes.

21. The system of claim 16, wherein the autonomous behaviors comprise one or more of ballistic, semi-ballistic, and persistent behaviors.

22. The system of claim 21, wherein ballistic behaviors comprise one or more of stair climbing, preset actions, click-to-drive, click-to-grip, preconfigured poses, retro traverse, self-righting, and autonomous flipper.

23. The system of claim 21, wherein semi-ballistic behaviors comprise one or more of quick brake, speed boost, and cruise control.

24. The system of claim 21, wherein persistent behaviors comprise one or more of retro traverse, self righting obstacle avoidance, and autonomous flippers.

25. The system of claim 16, wherein the persistent autonomous behavior is executed continuously, upon input from one or more sensors of the remote vehicle, or upon being activated by another behavior.

26. A method for implementing remote vehicle autonomous behaviors, comprising:

inputting instructions for the remote vehicle to execute an autonomous behavior;

evaluating one or more of the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior of the remote vehicle, or the remote vehicle's environment are incompatible with the autonomous behavior; and

allowing the autonomous behavior to send a vote to an arbiter if the remote vehicle's position within its environment, the current internal state of the remote vehicle, the current operational behavior on the remote vehicle, or the remote vehicle's environment are compatible with the autonomous behavior,

wherein a vote to the arbiter requests control of one or more actuators on the remote vehicle necessary to perform the autonomous behavior.

27. The method of claim 26, further comprising executing the autonomous behavior if the voting autonomous behavior has a higher priority than a behavior currently in control of the one or more actuators.

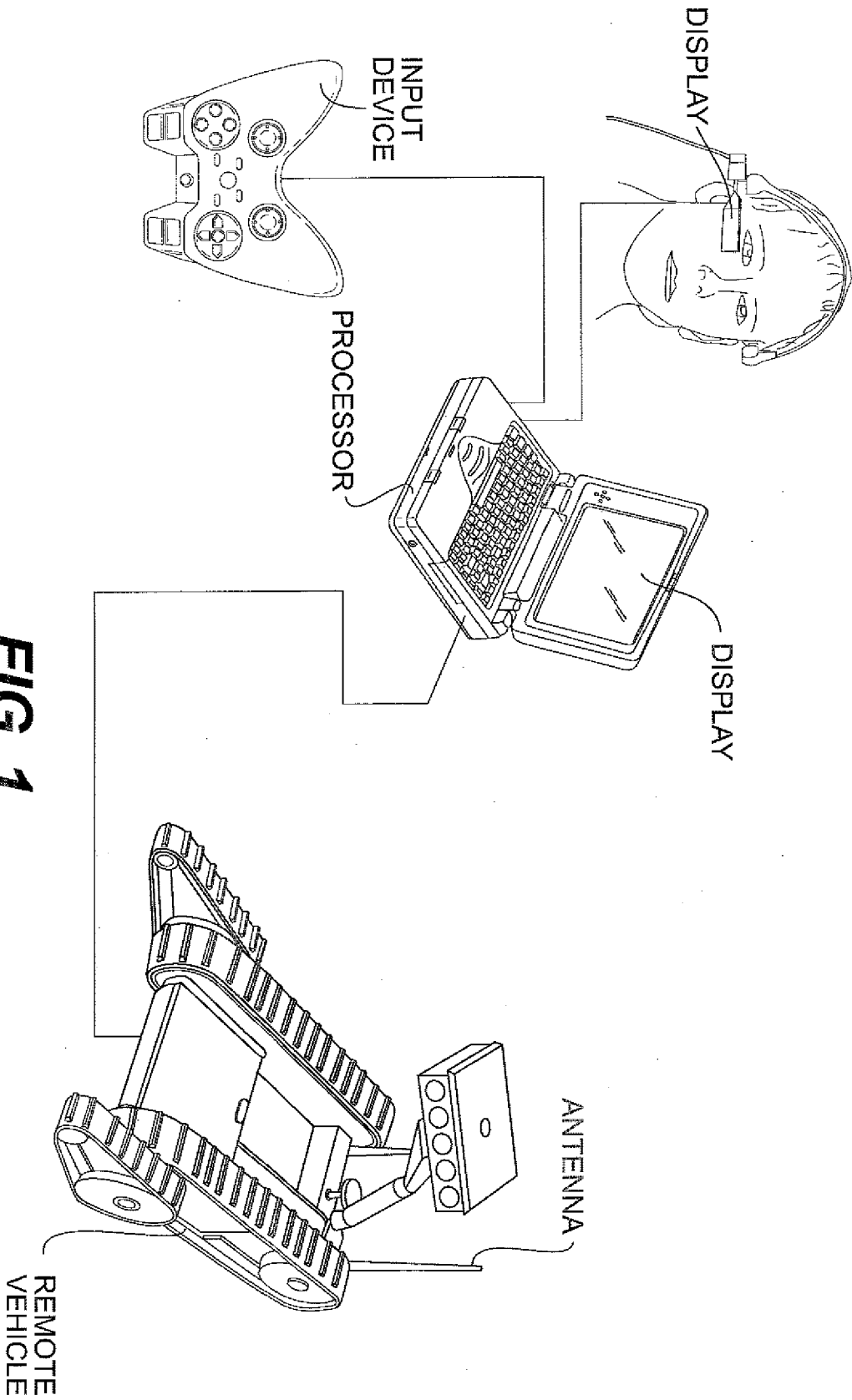
28. The system of claim 26, wherein the autonomous behaviors comprise one or more of ballistic, semi-ballistic, and persistent behaviors.

29. The system of claim 28, wherein ballistic behaviors comprise one or more of stair climbing, preset actions, click-to-drive, click-to-grip, preconfigured poses, retro traverse, self-righting, and autonomous flipper.

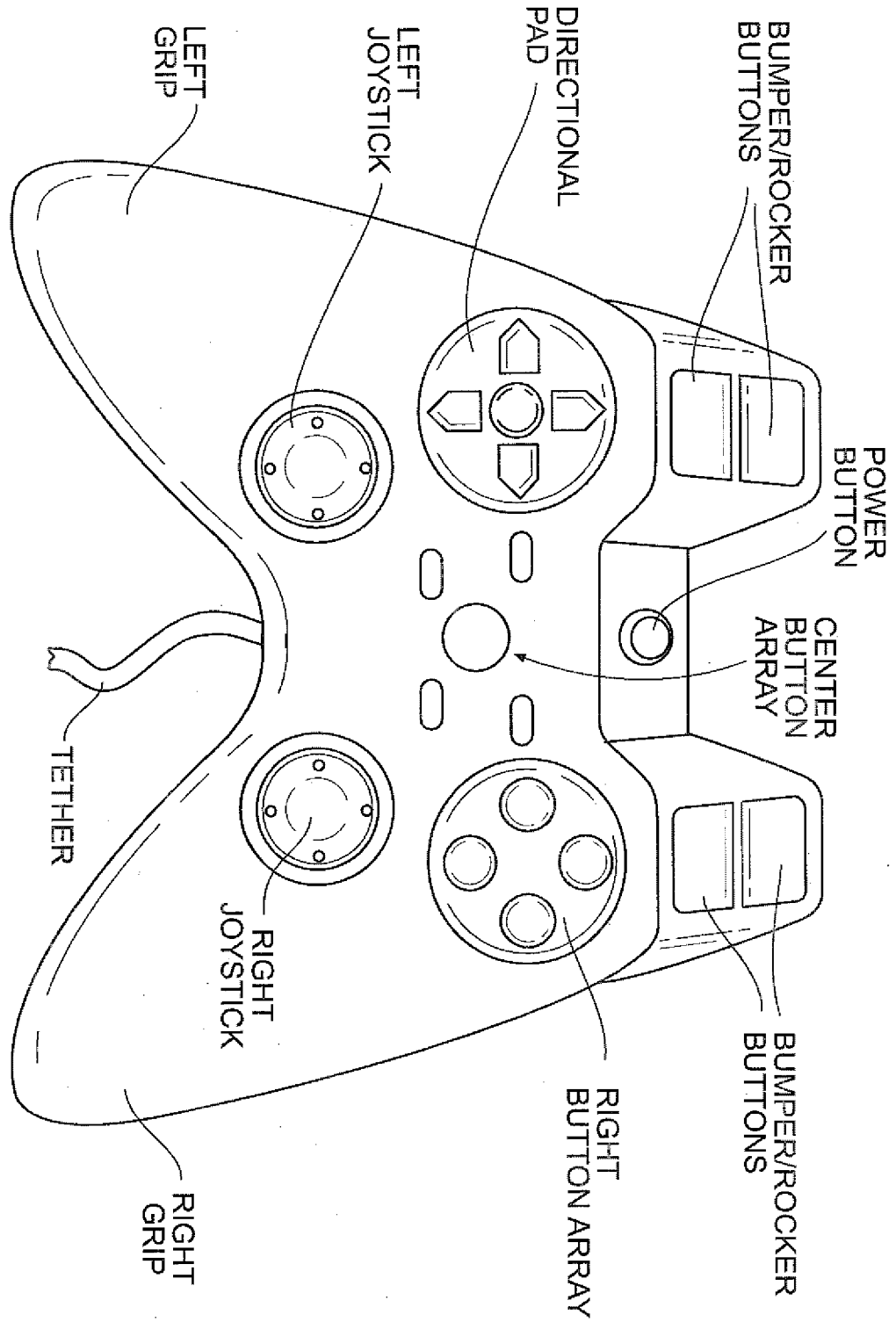
30. The system of claim 28, wherein semi-ballistic behaviors comprise one or more of quick

brake, speed boost, and cruise control.

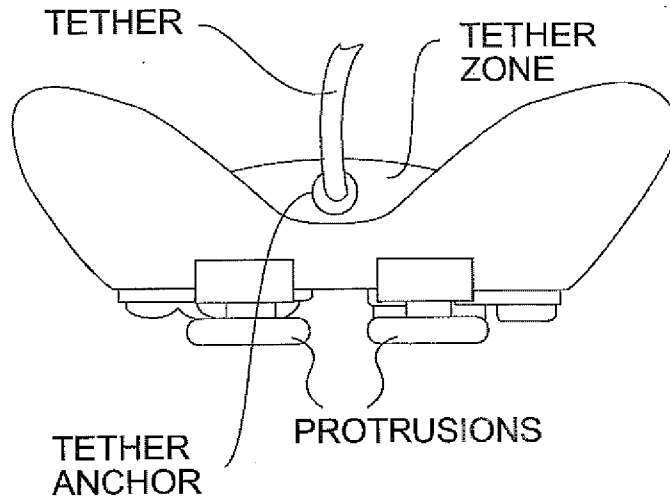
31. The system of claim 28, wherein persistent behaviors comprise one or more of retro traverse, self righting obstacle avoidance, and autonomous flippers.



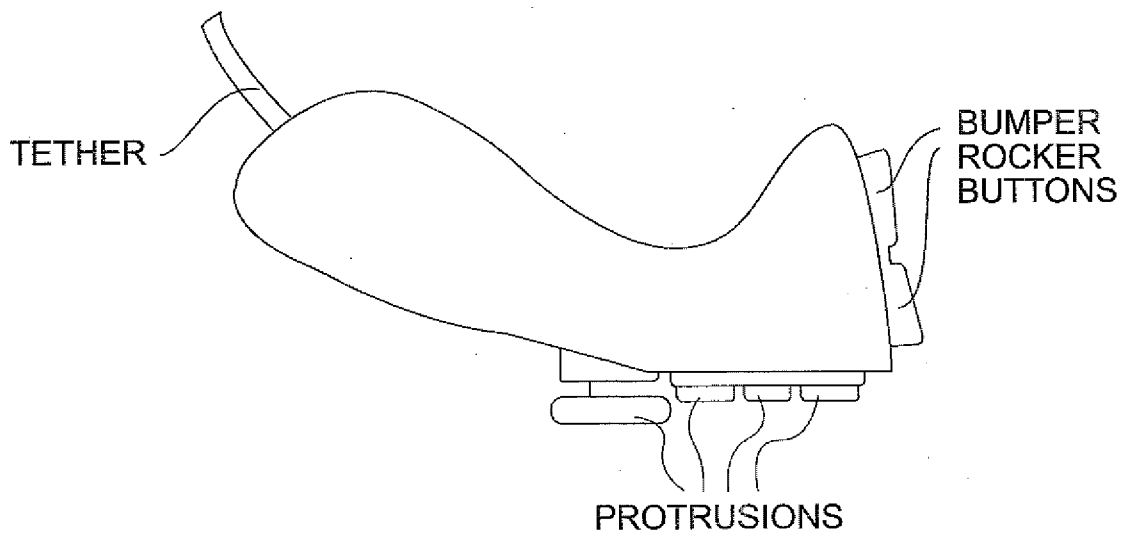
**FIG. 1**



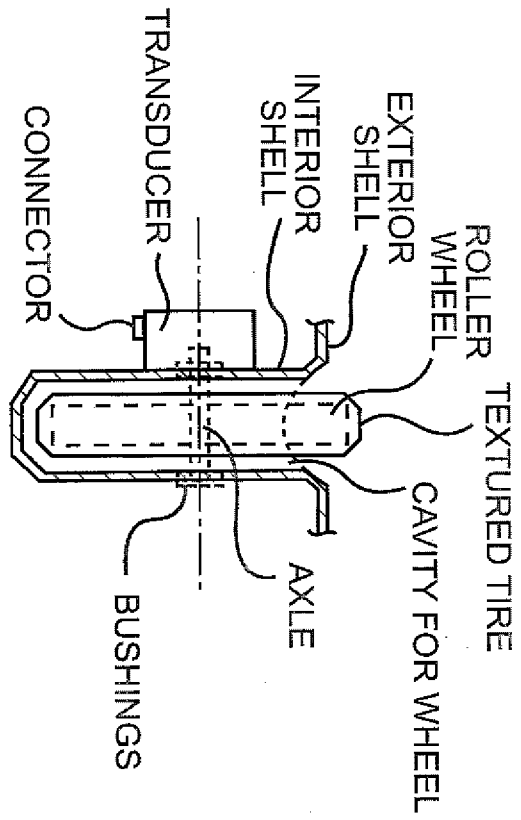
**FIG. 2**



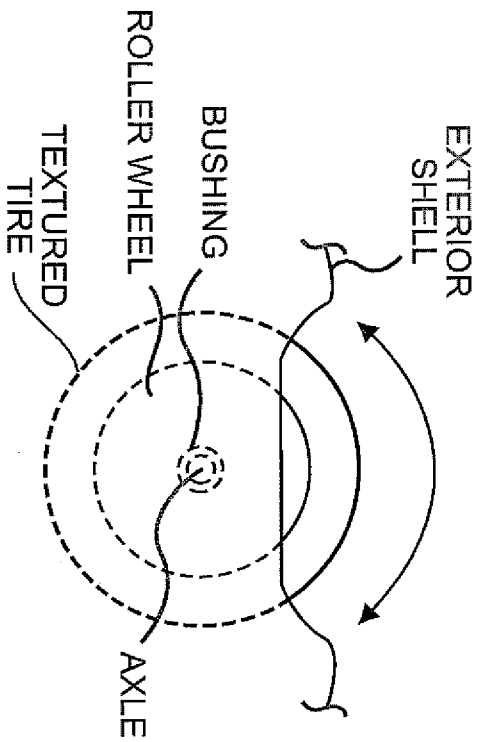
**FIG. 3**



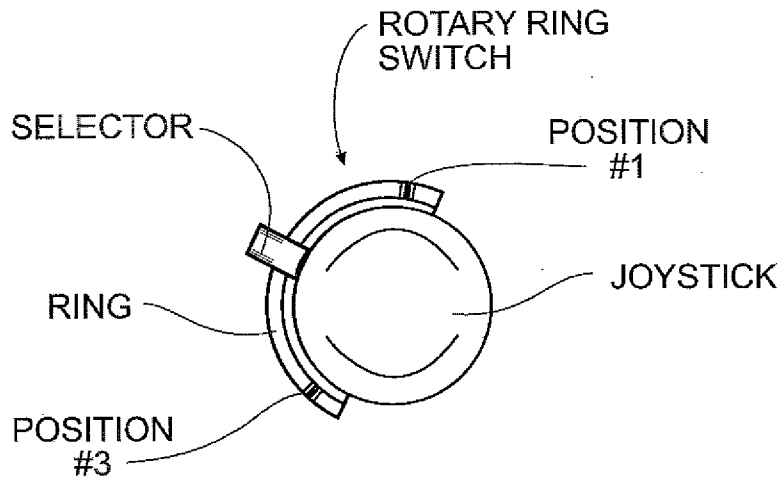
**FIG. 4**



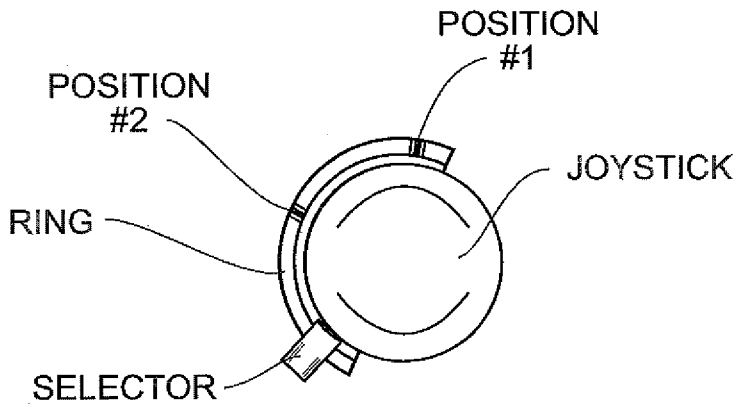
**FIG. 5**



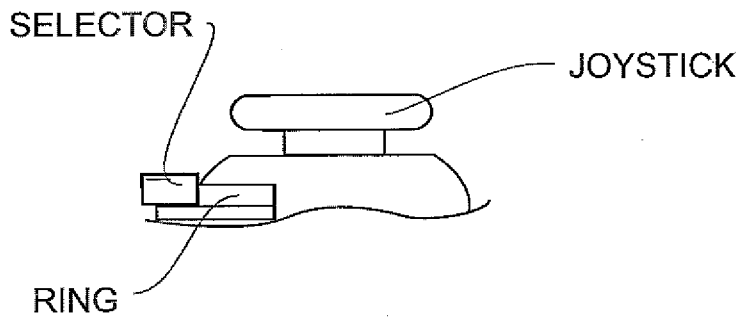
**FIG. 6**



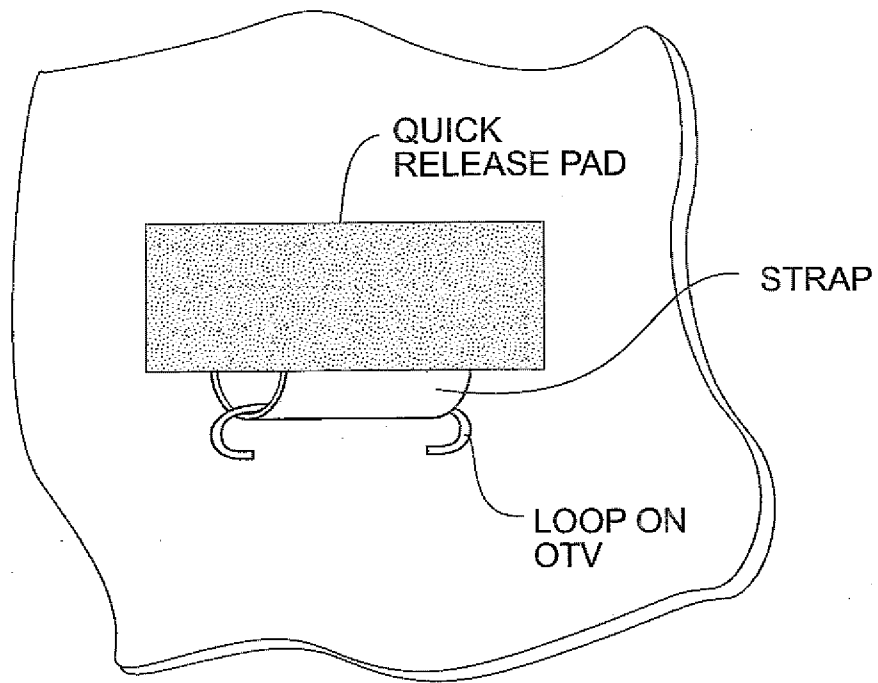
**FIG. 7**



**FIG. 8**



**FIG. 9**



**FIG. 10**

Max Camera Layout: Zoom Camera

“Name567890123456”  
(XXX.XXX.XXX) 1 of 3

(Feedback Here)

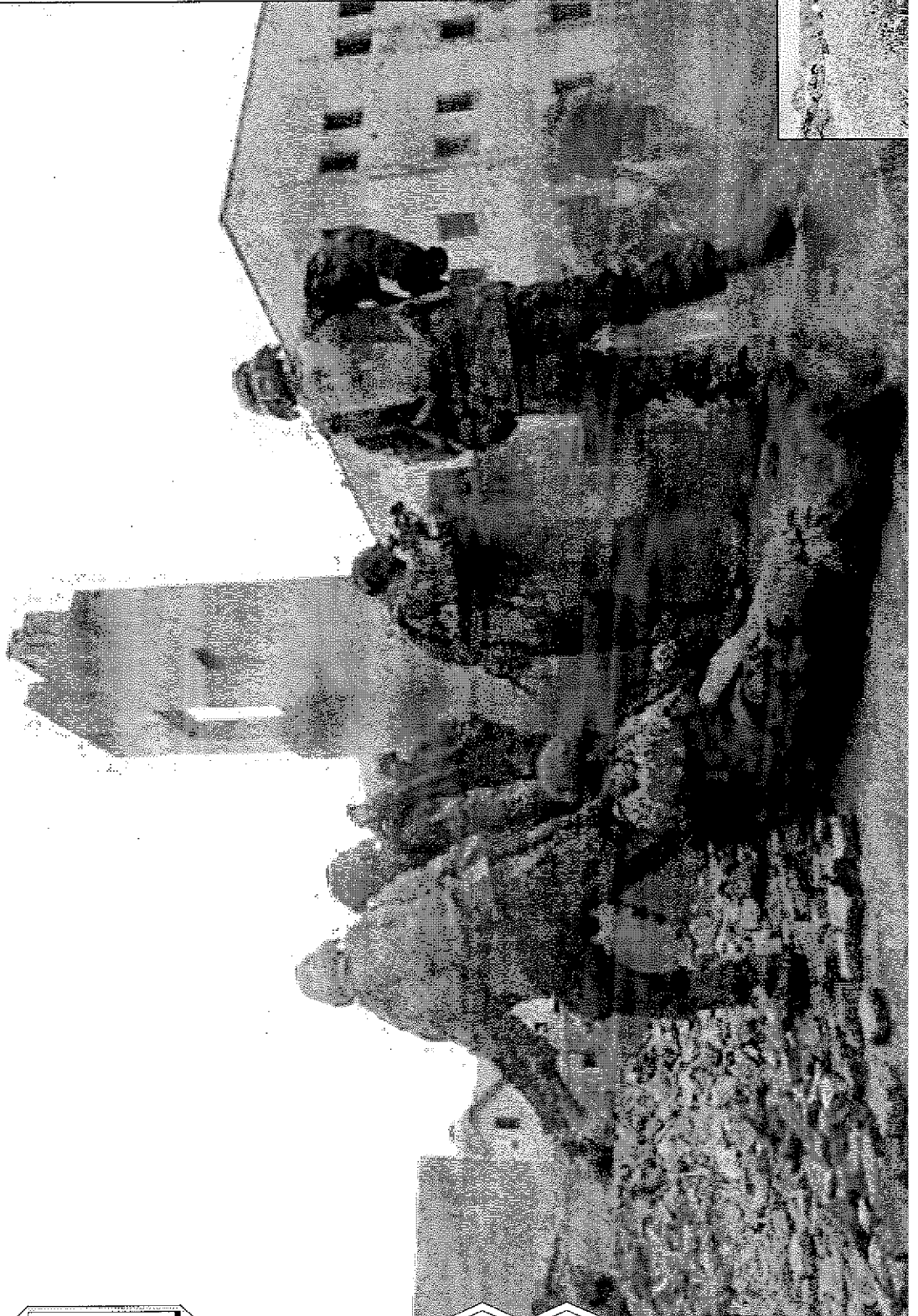
Front Zoom

2007/04/05 09:34:52

88%

**Controls**

- Zoom In
- Zoom Out
- IR Filter On/Off
- IR Light Off/L/M/H
- 
- Camera Settings
- Audio
- Snap Shot
- Record Video or STOP



Quad Layout: Zoom Camera

"Name567890123456" <sup>1</sup> of <sup>3</sup>  
(XXX.XXX.XXX)

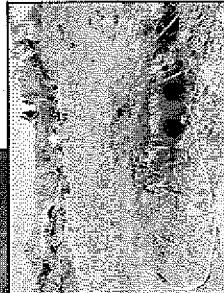
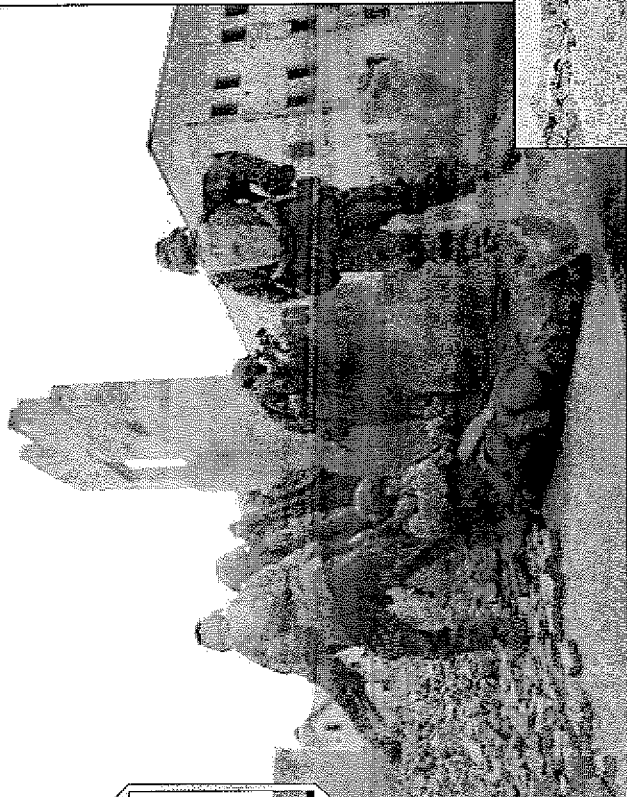
88% 

 0x01 


(Feedback Here)

2007/04/05 09:34:52

Front Zoom

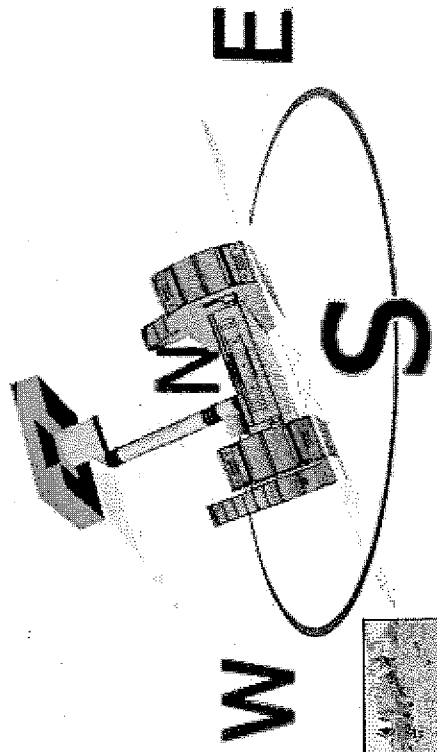


**Controls**

- Zoom In
- Zoom Out
- IR Filter On/Off
- IR Light Off L/M/H
- 
- Camera Settings
- Audio
- Snap Shot
- Record Video or STOP
- Map
- More Info

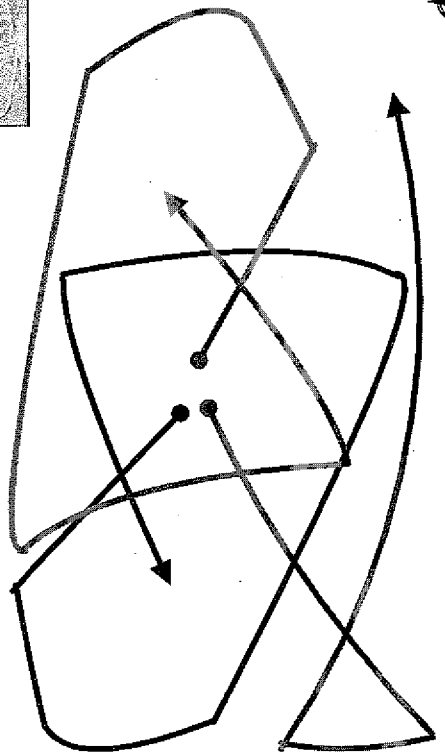
**Poses**


- Deploy or Stow
- Center Camera
- Drive
- Decline
- Stand



**Payload**

- 3
- 4
- 5




6  4

3 Explorer 0

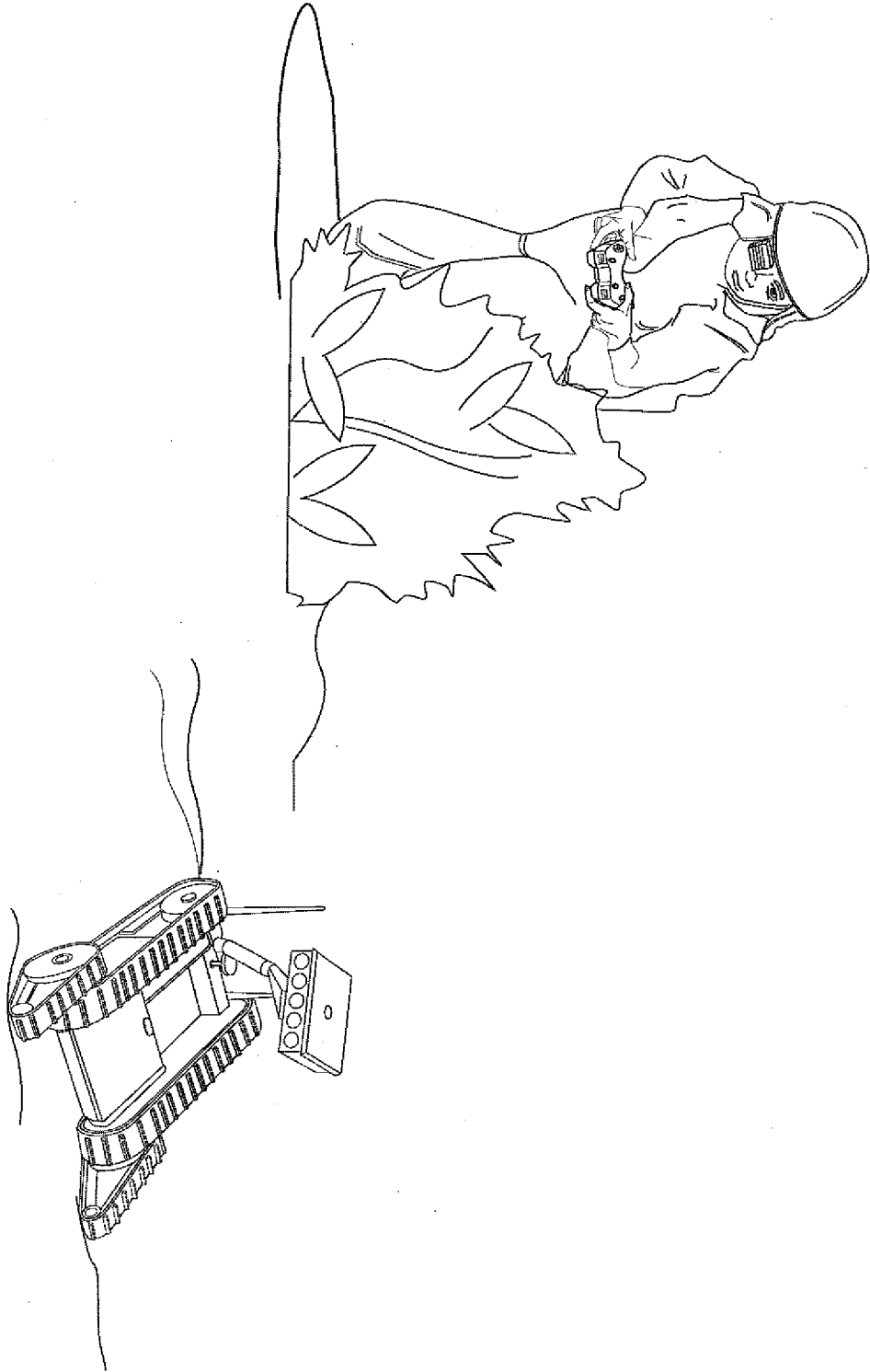
2

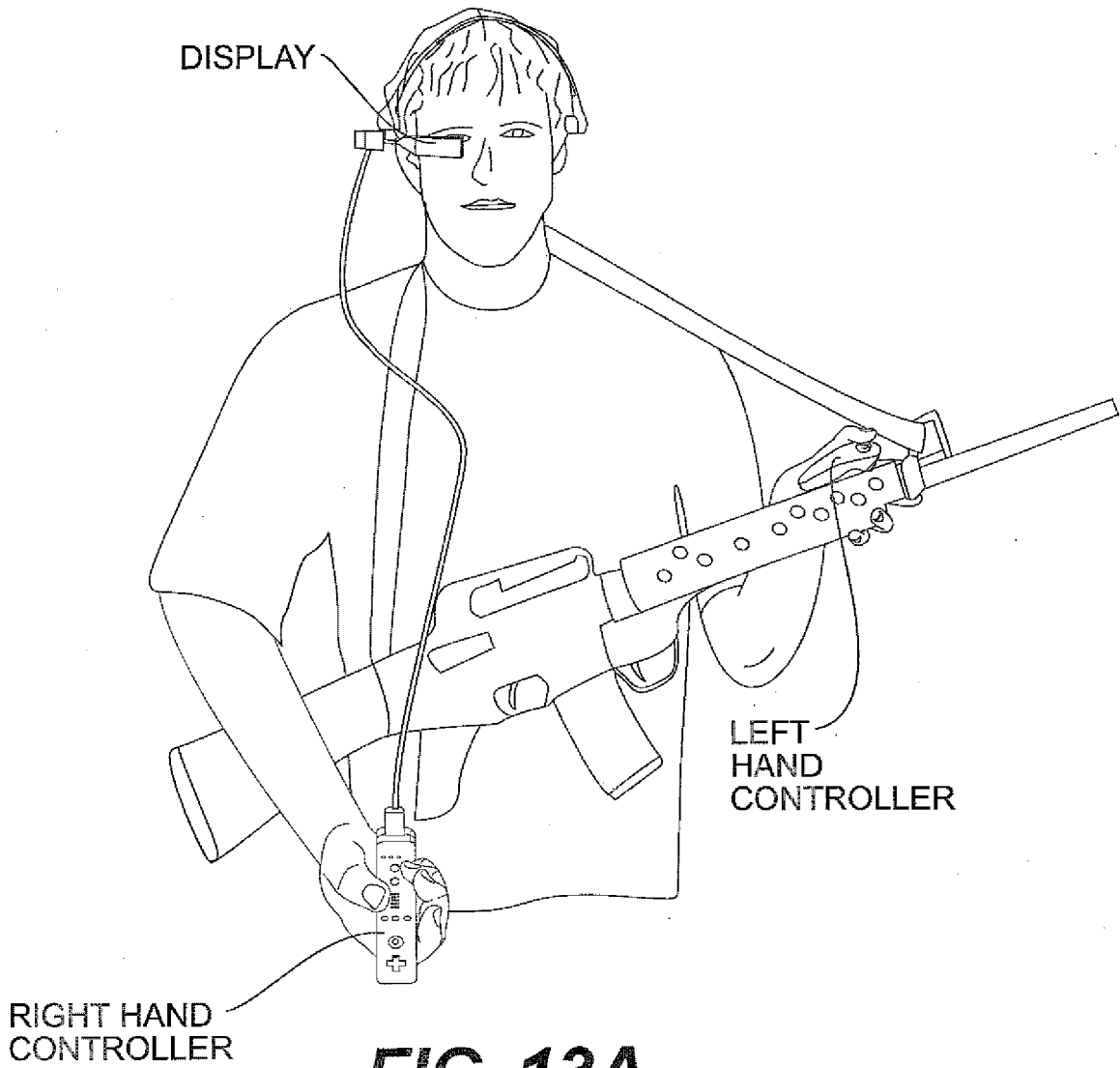
1

7  5

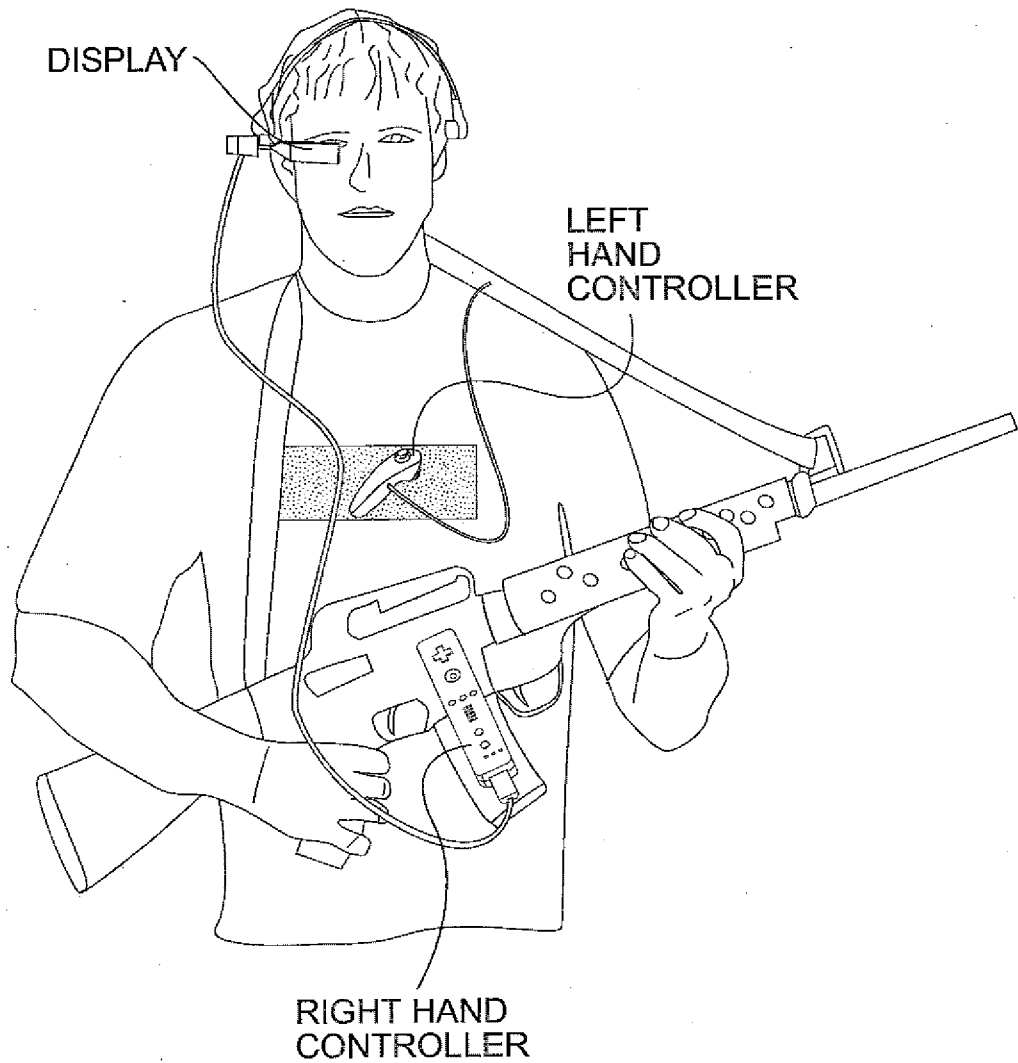


**FIG. 13**

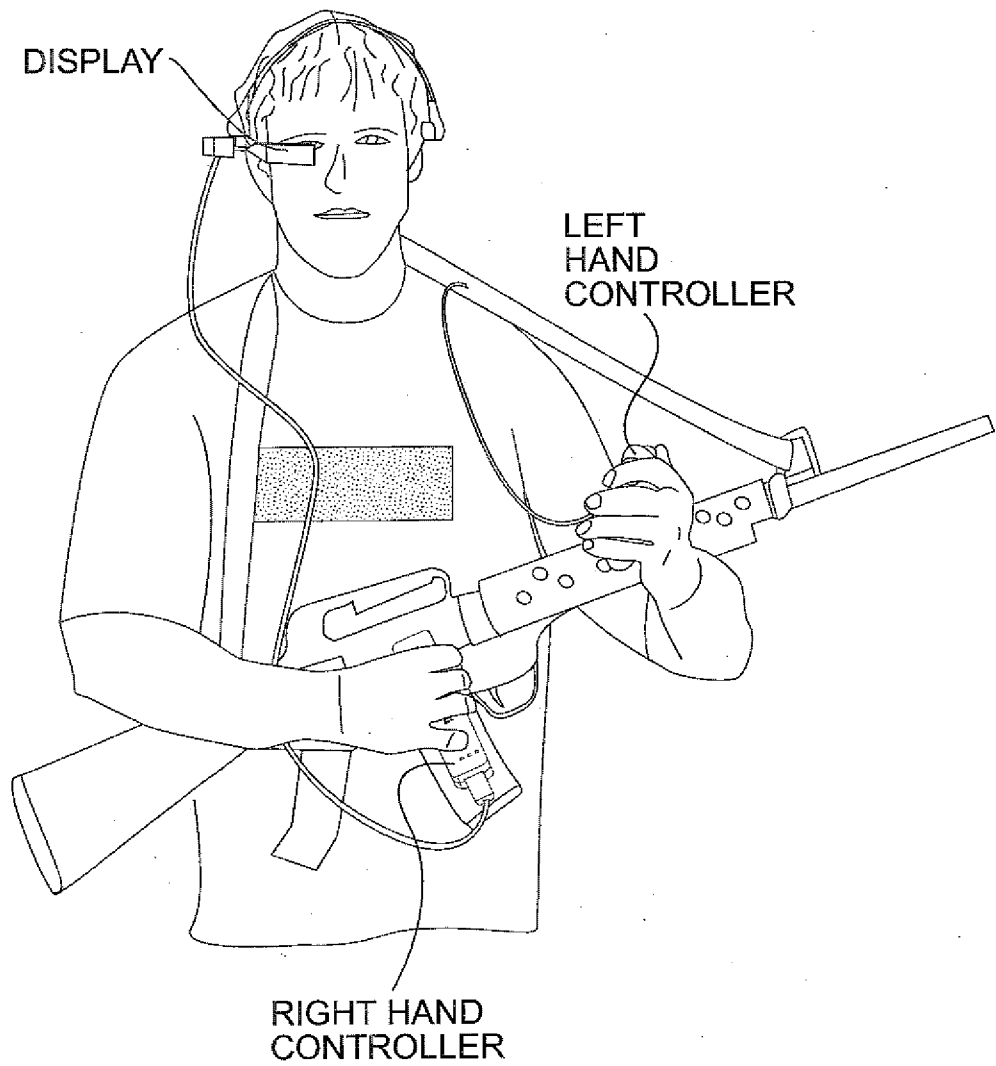




**FIG. 13A**



**FIG. 13B**



**FIG. 13C**

FIG. 14

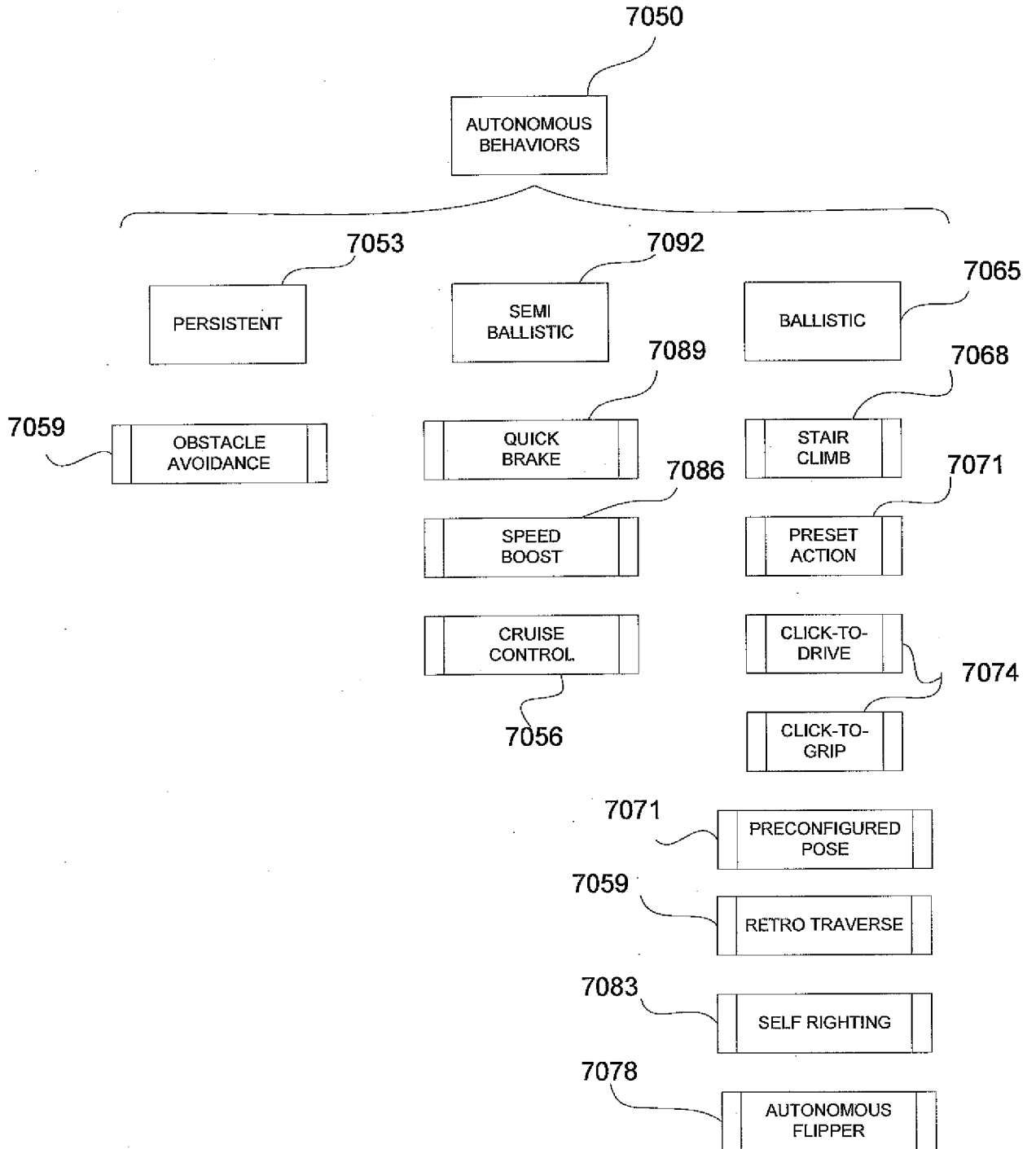


FIG. 15

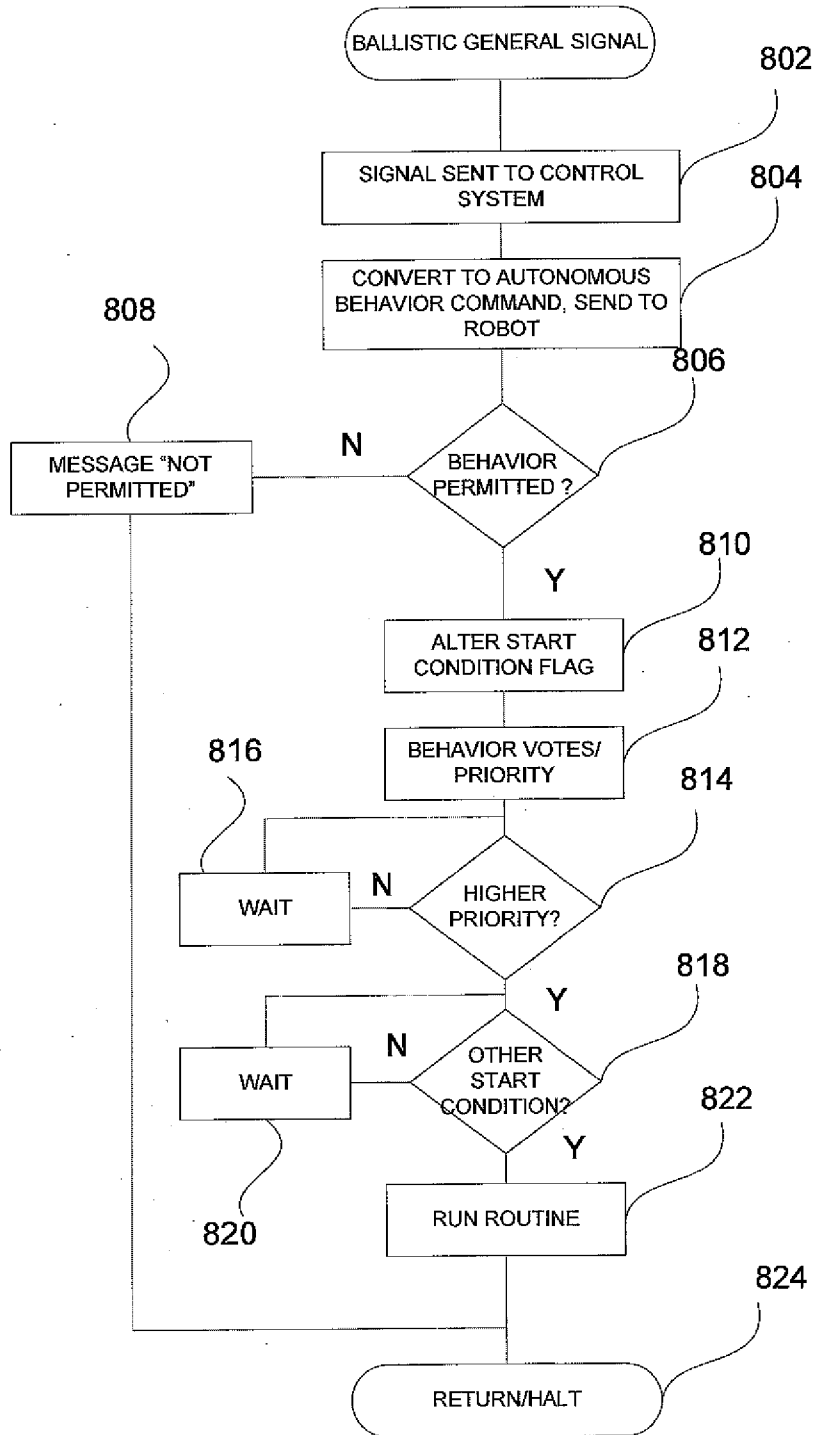


FIG. 16

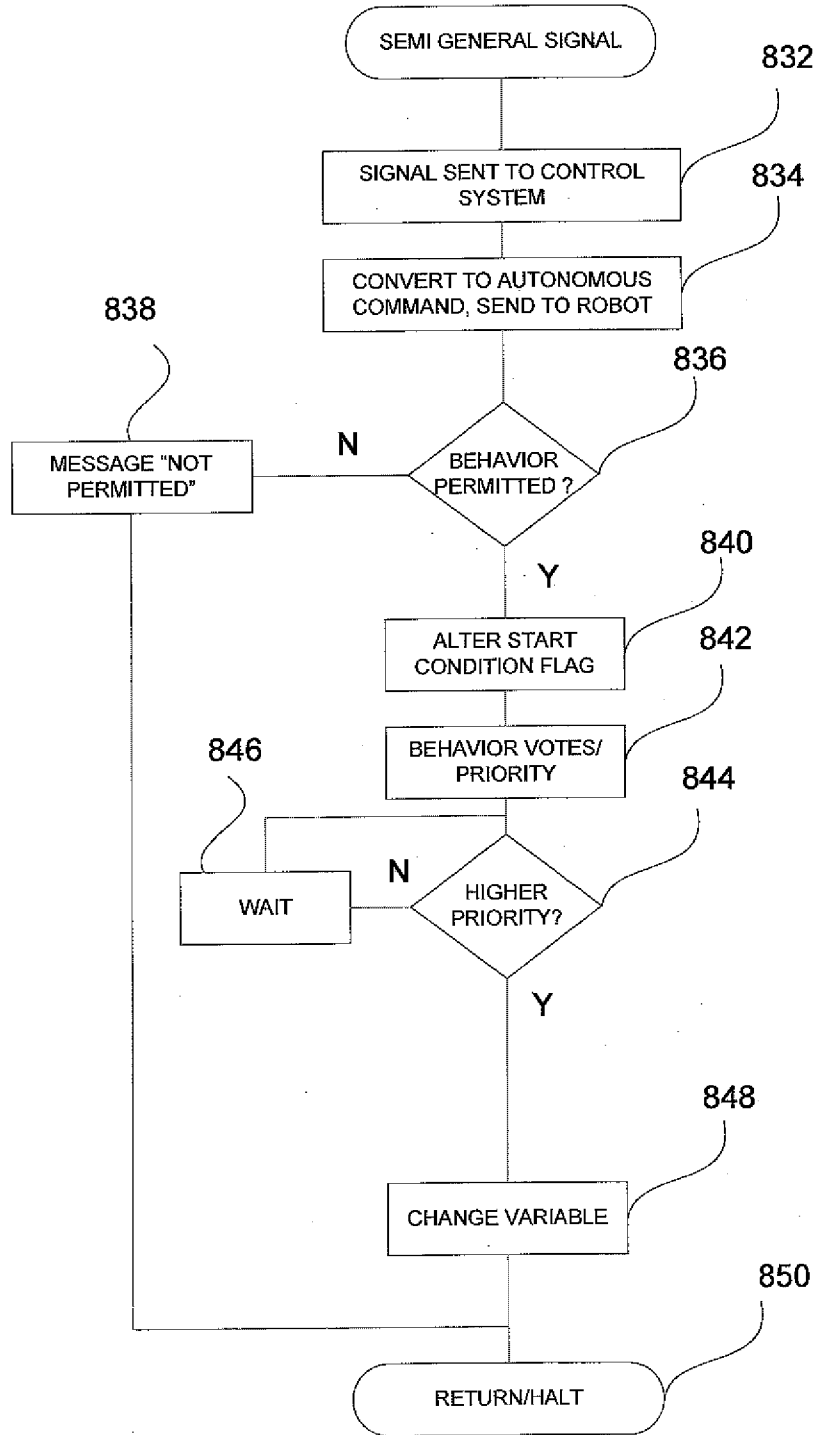


FIG. 17

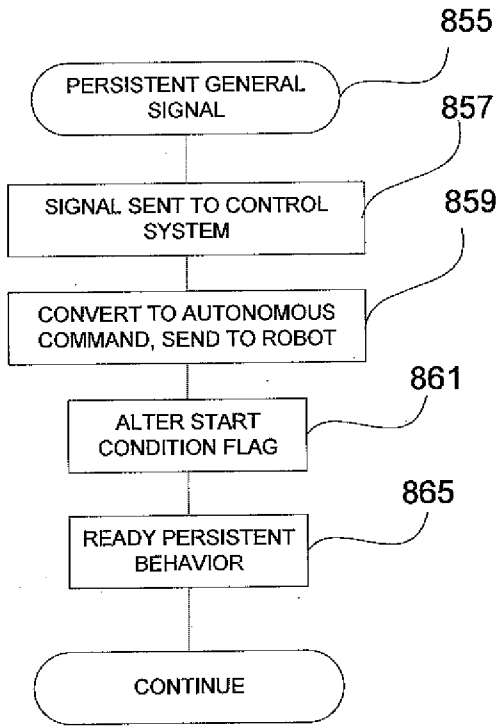
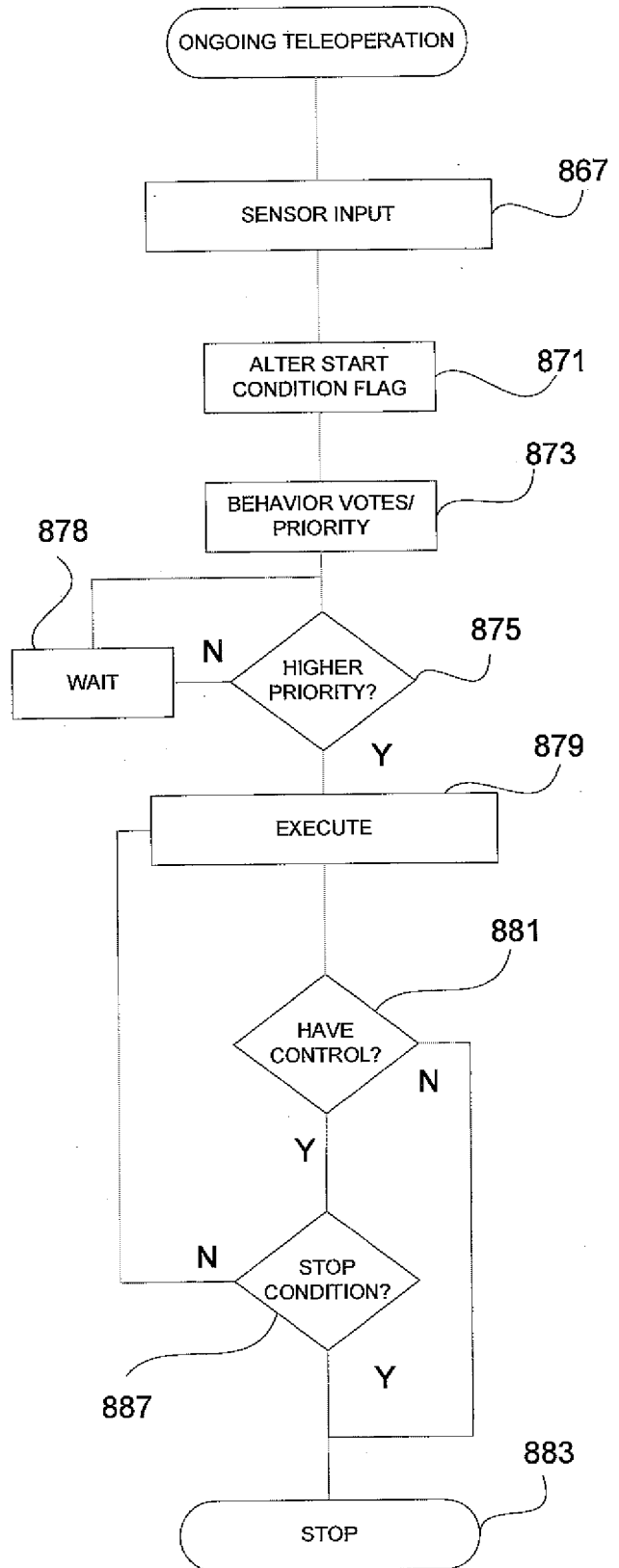


FIG. 18



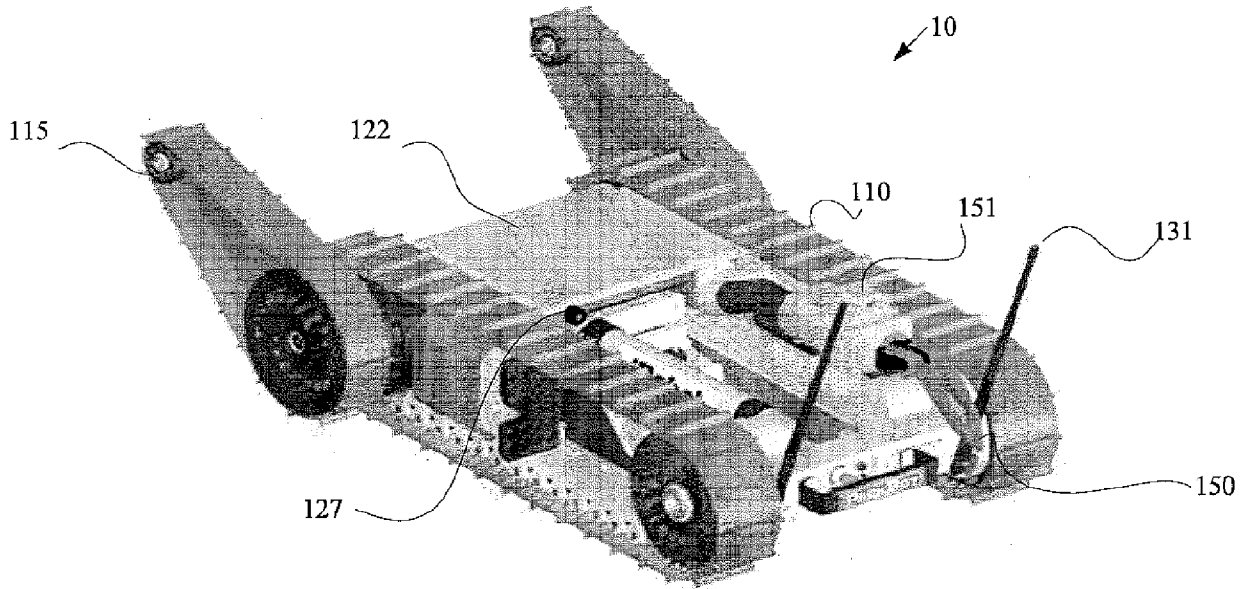


FIG. 19A

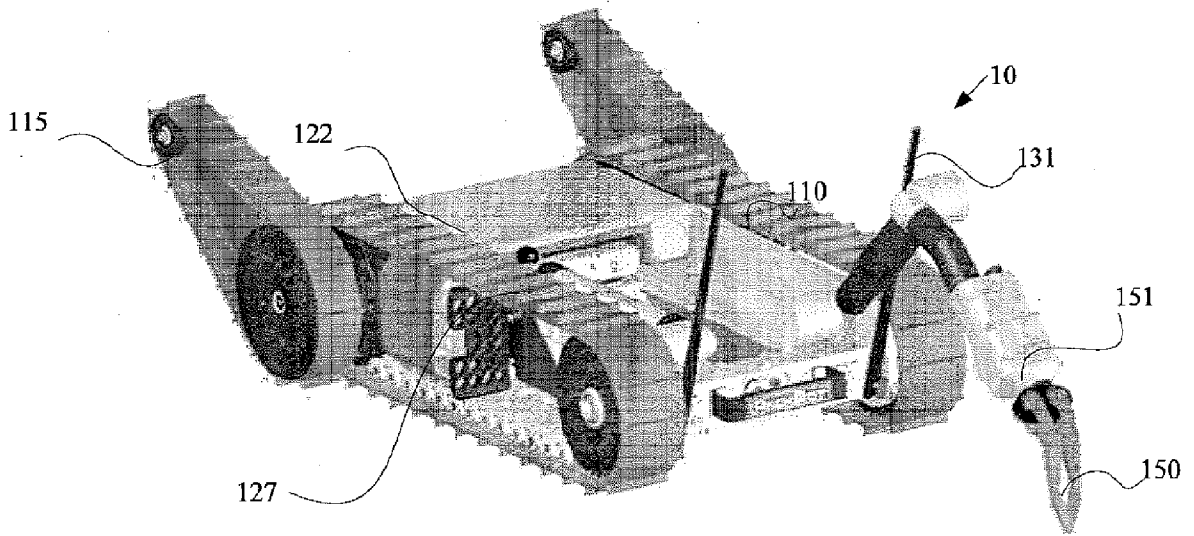


FIG. 19B

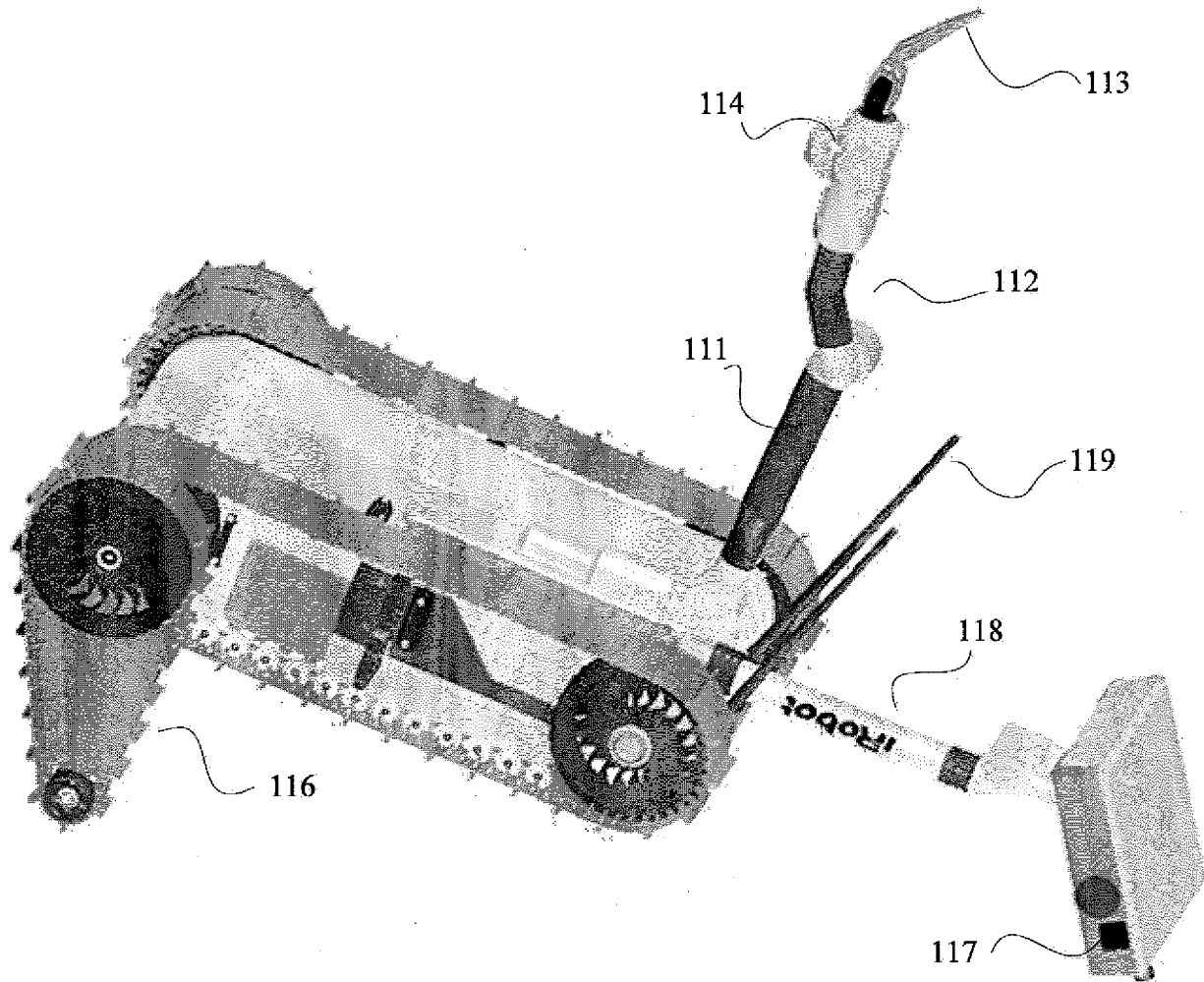


FIG. 20

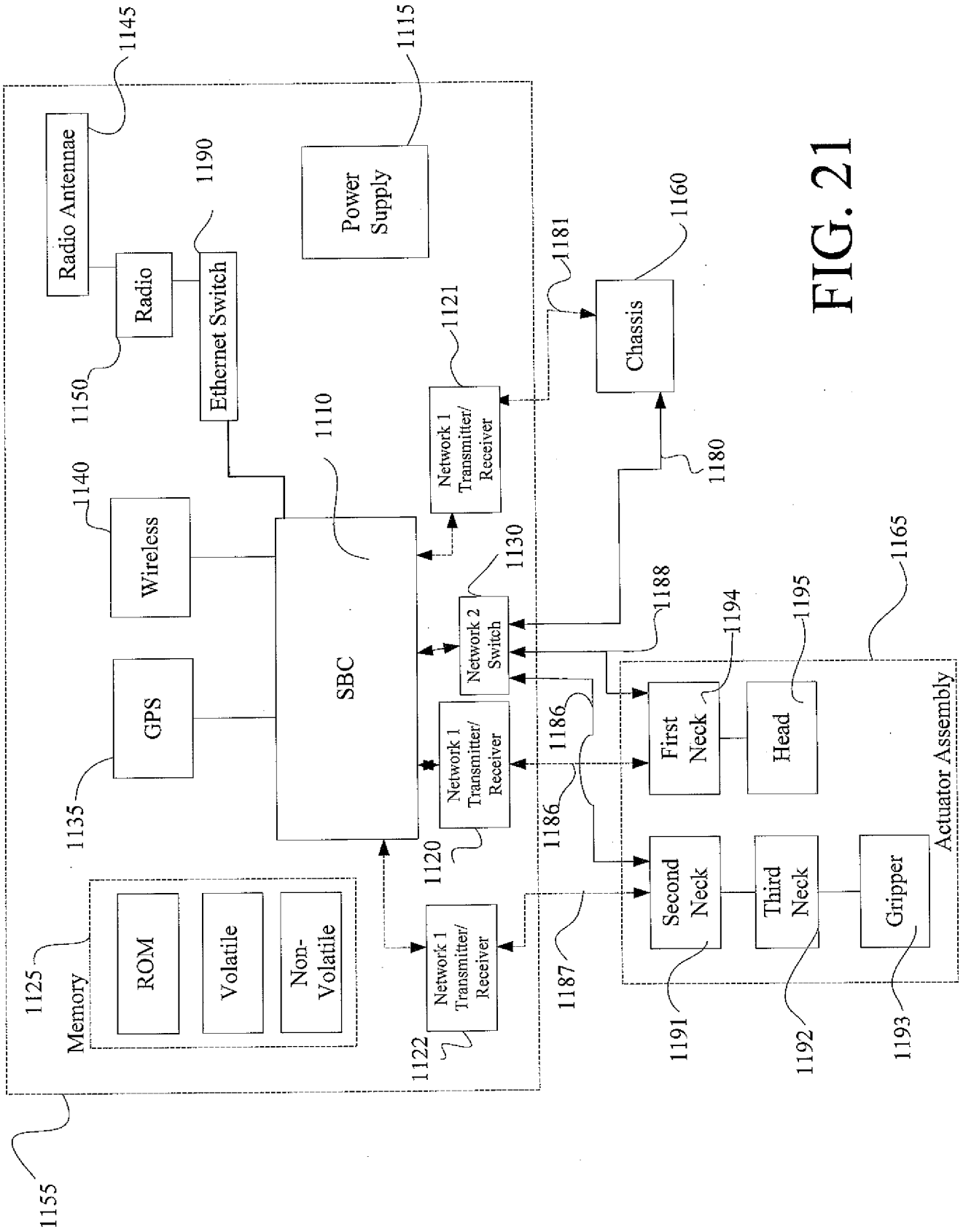


FIG. 21

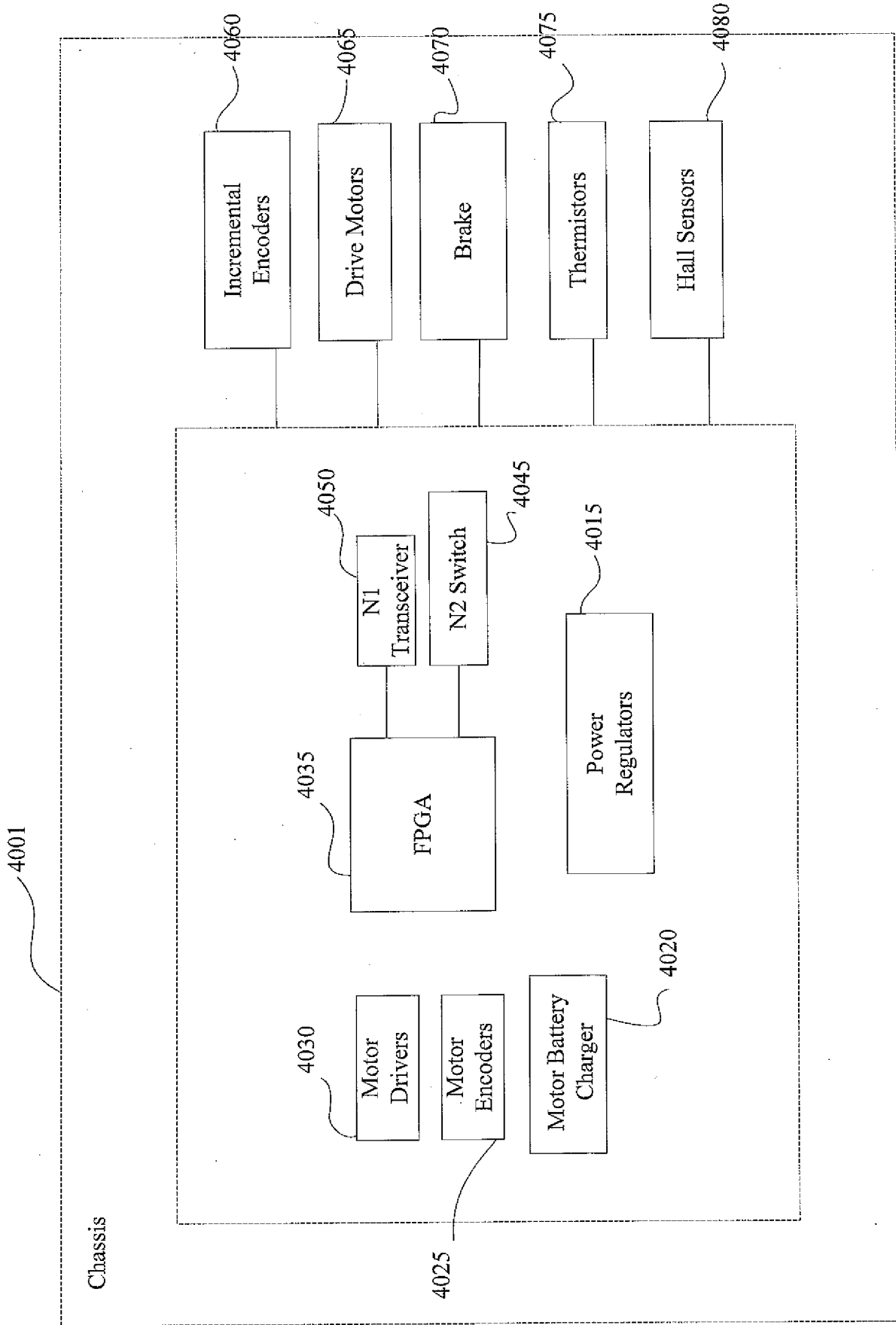


FIG. 22

FIG. 23

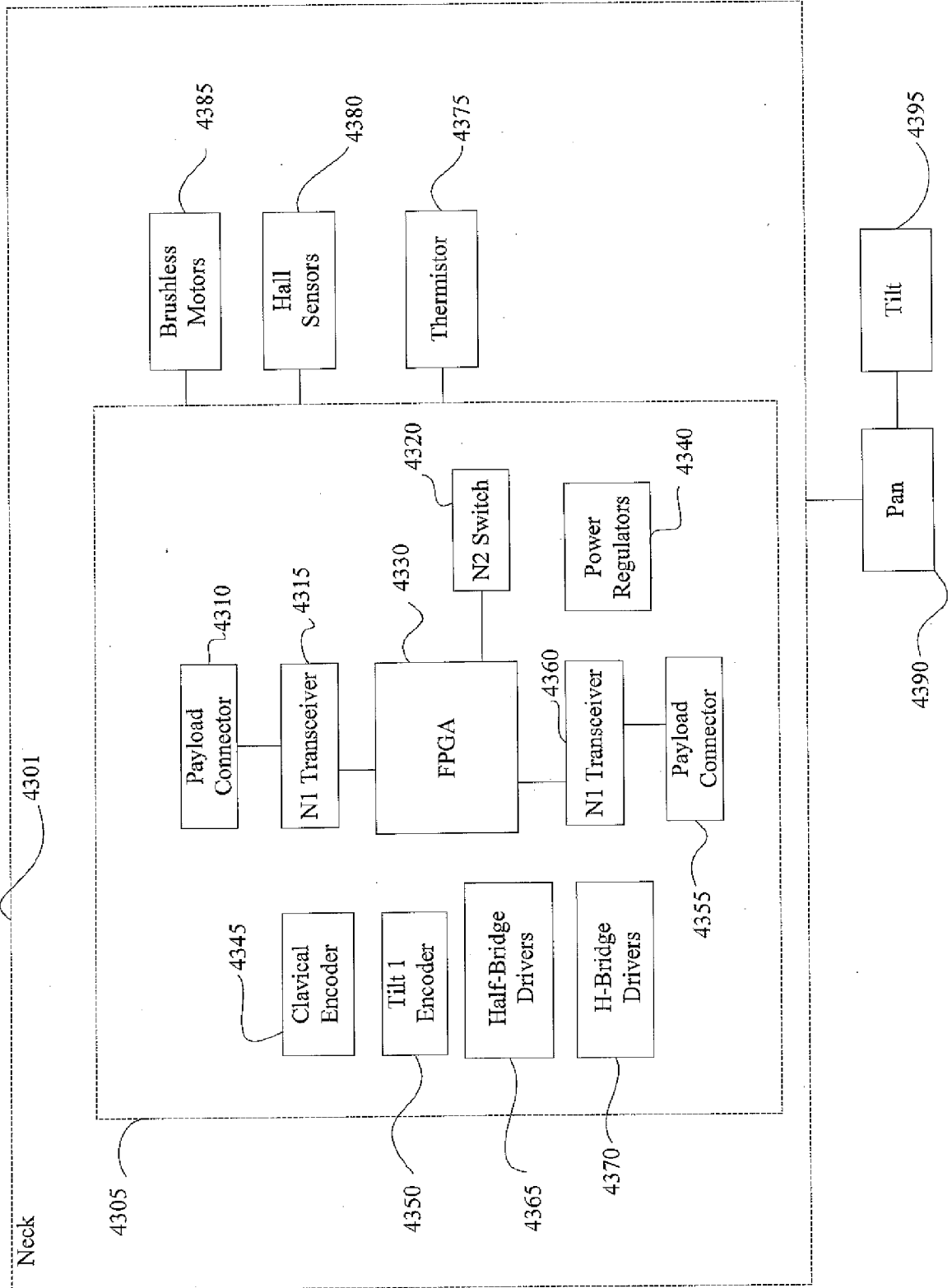


FIG. 24

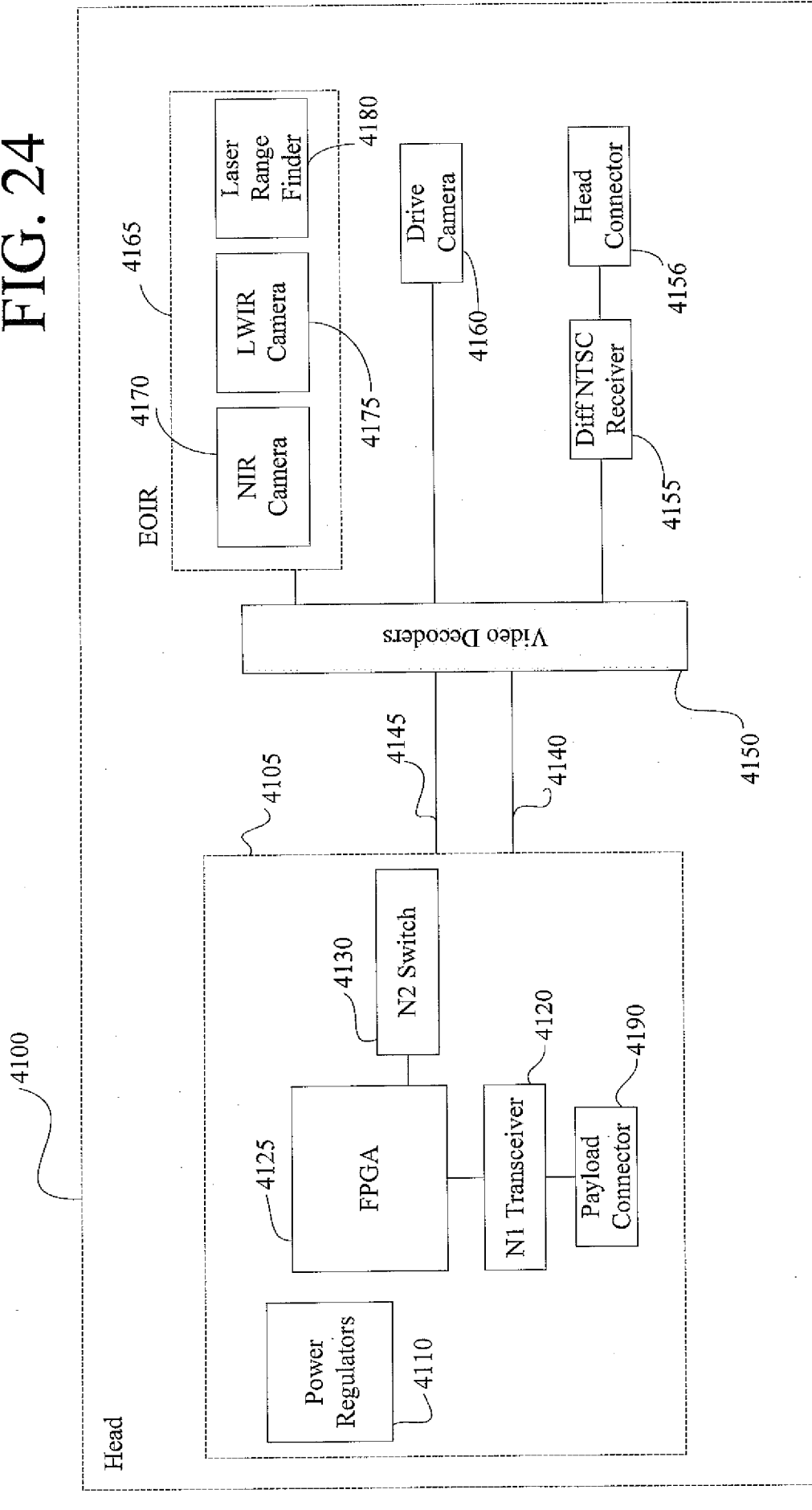
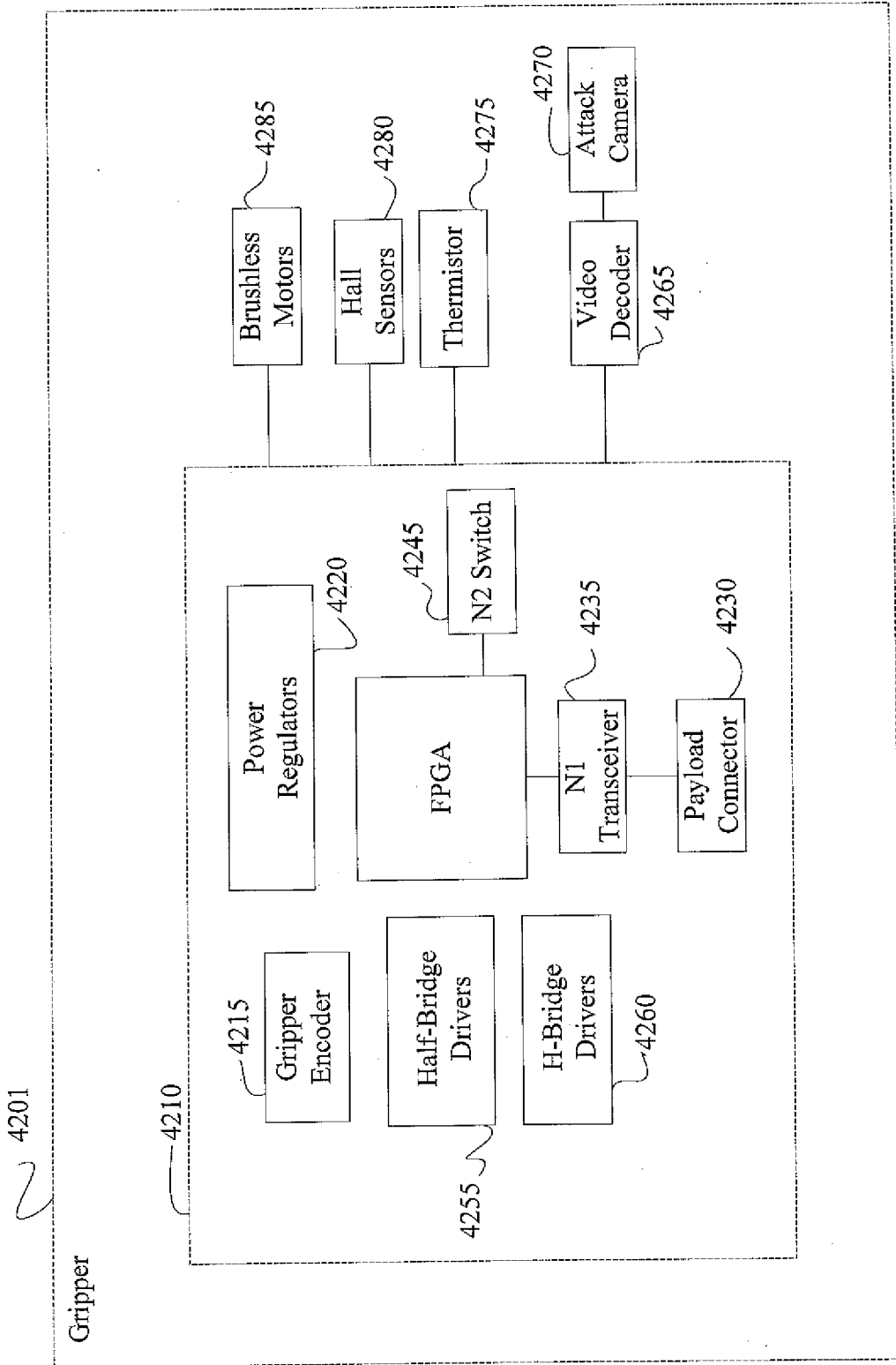


FIG. 25



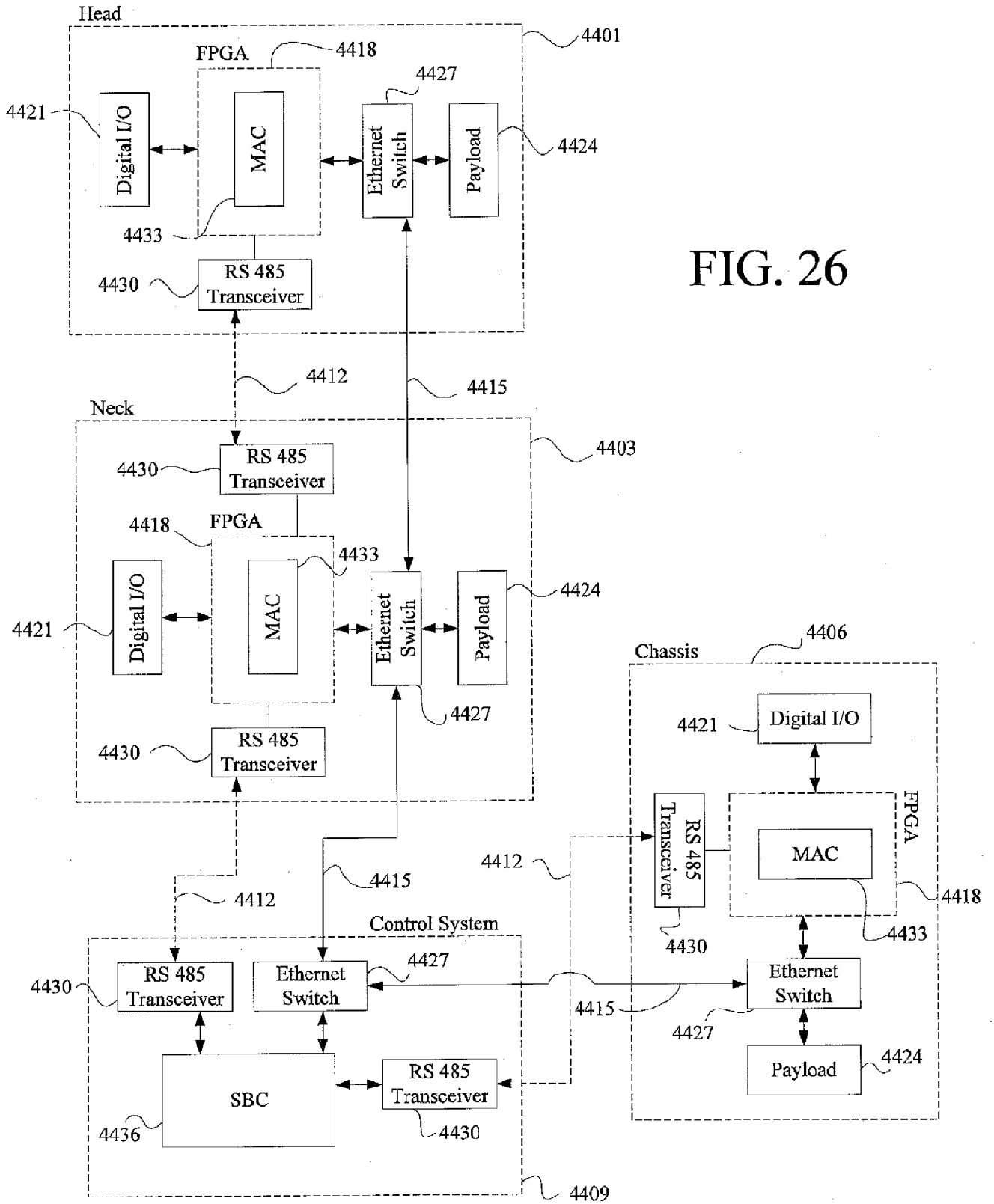
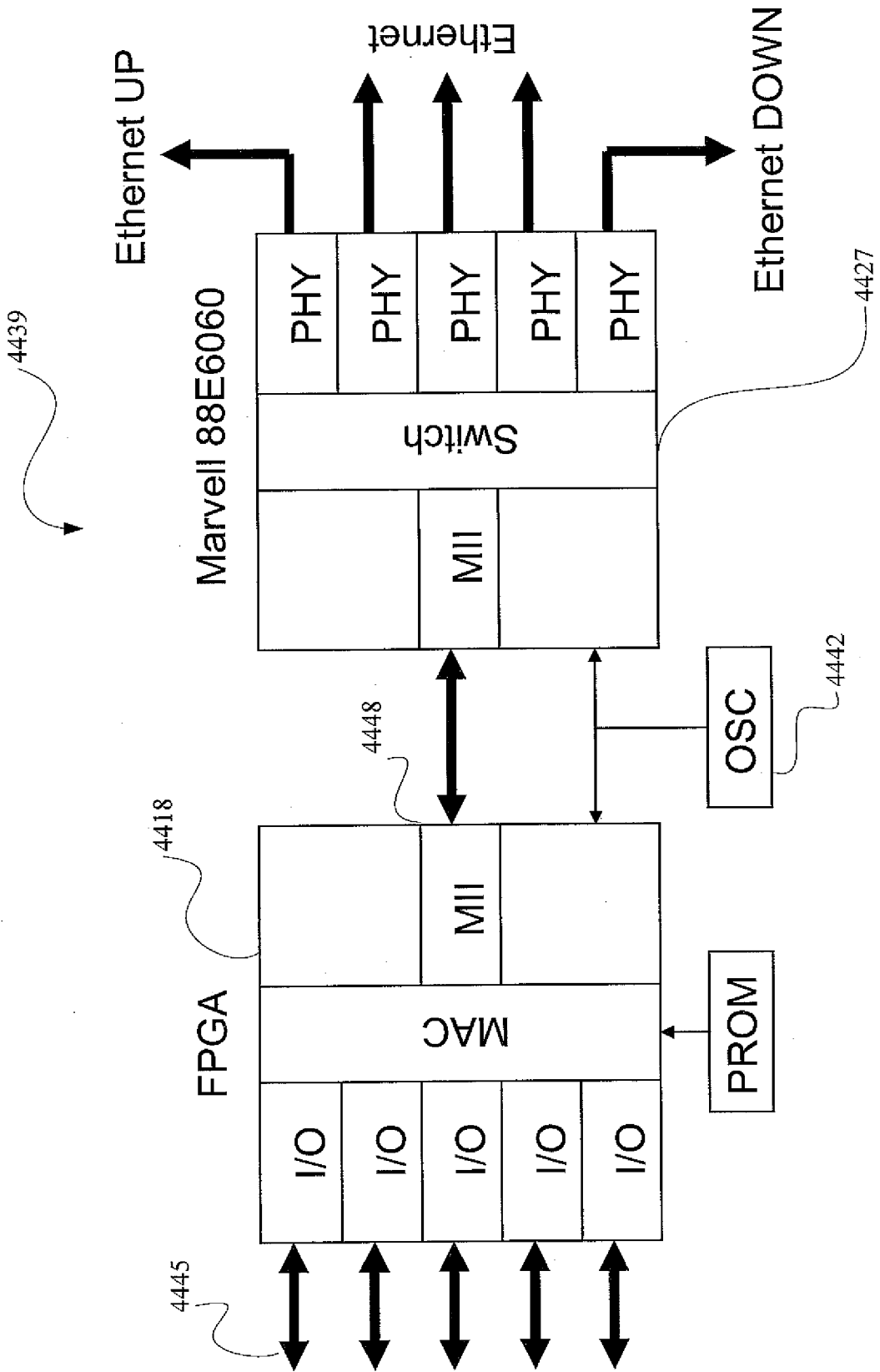
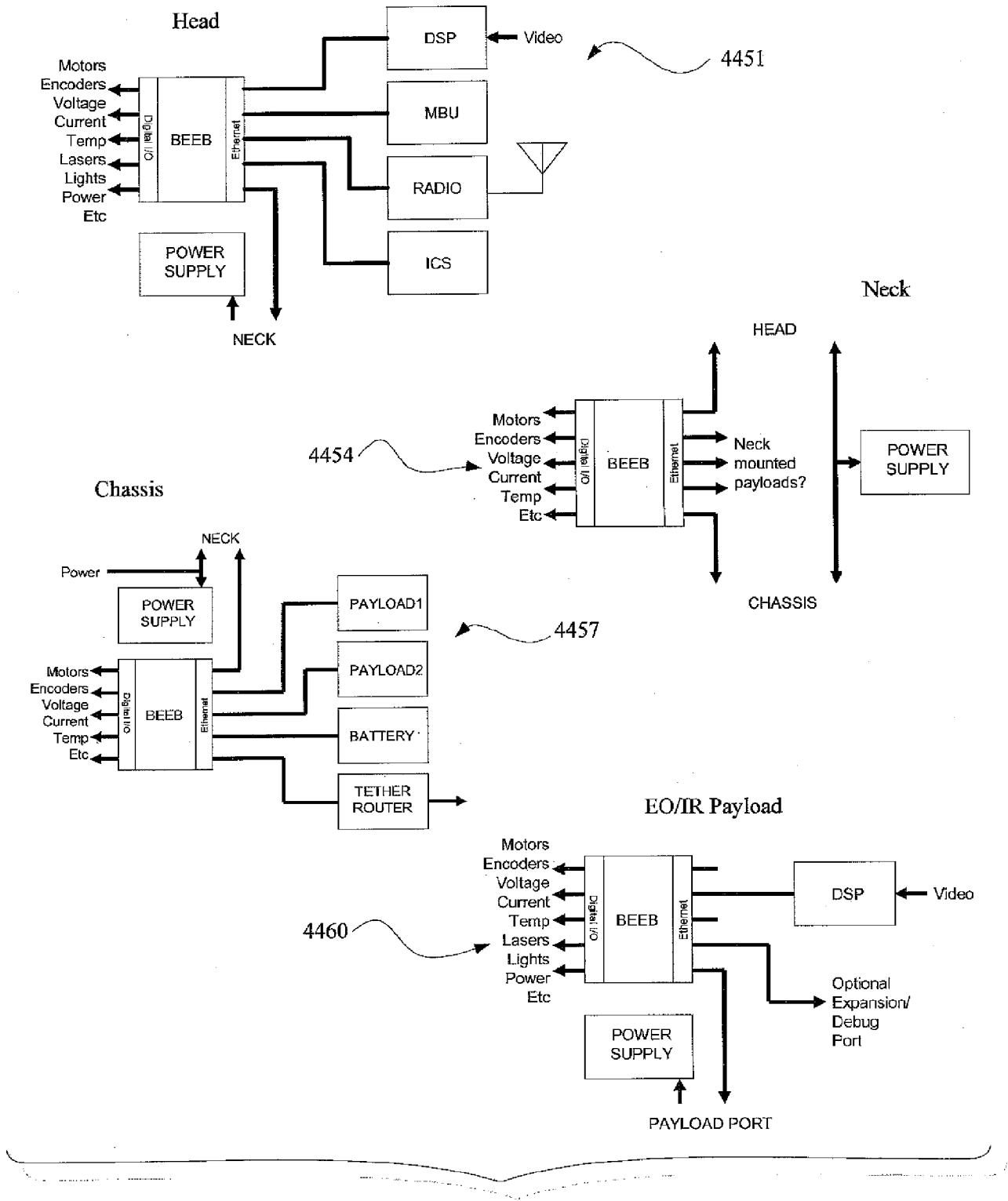


FIG. 26

FIG. 27





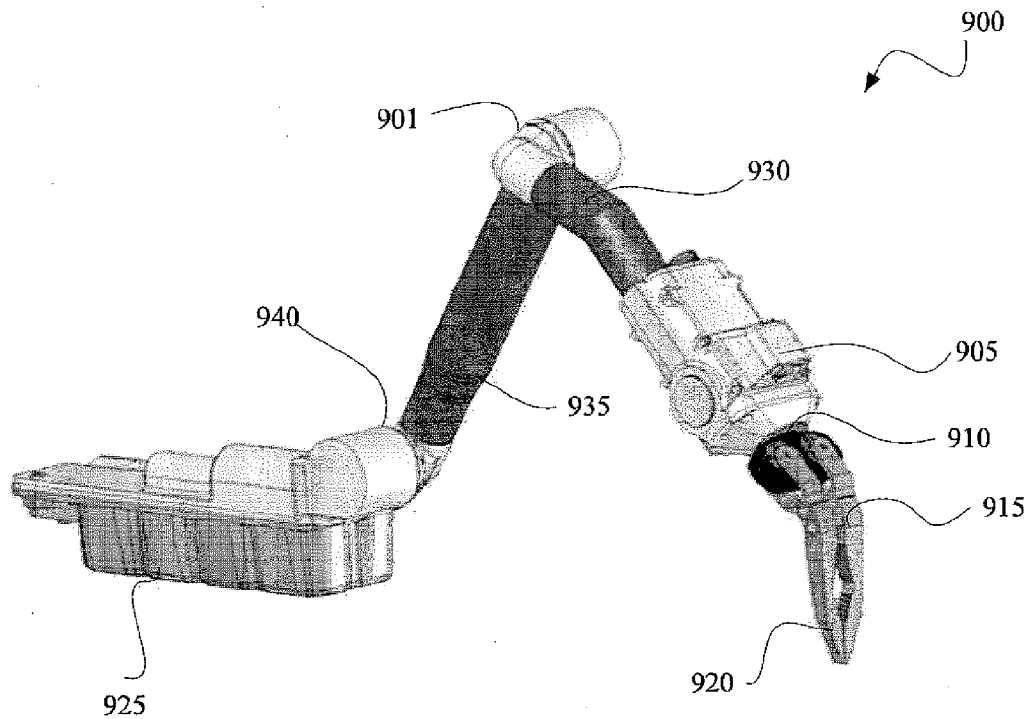


FIG. 29A

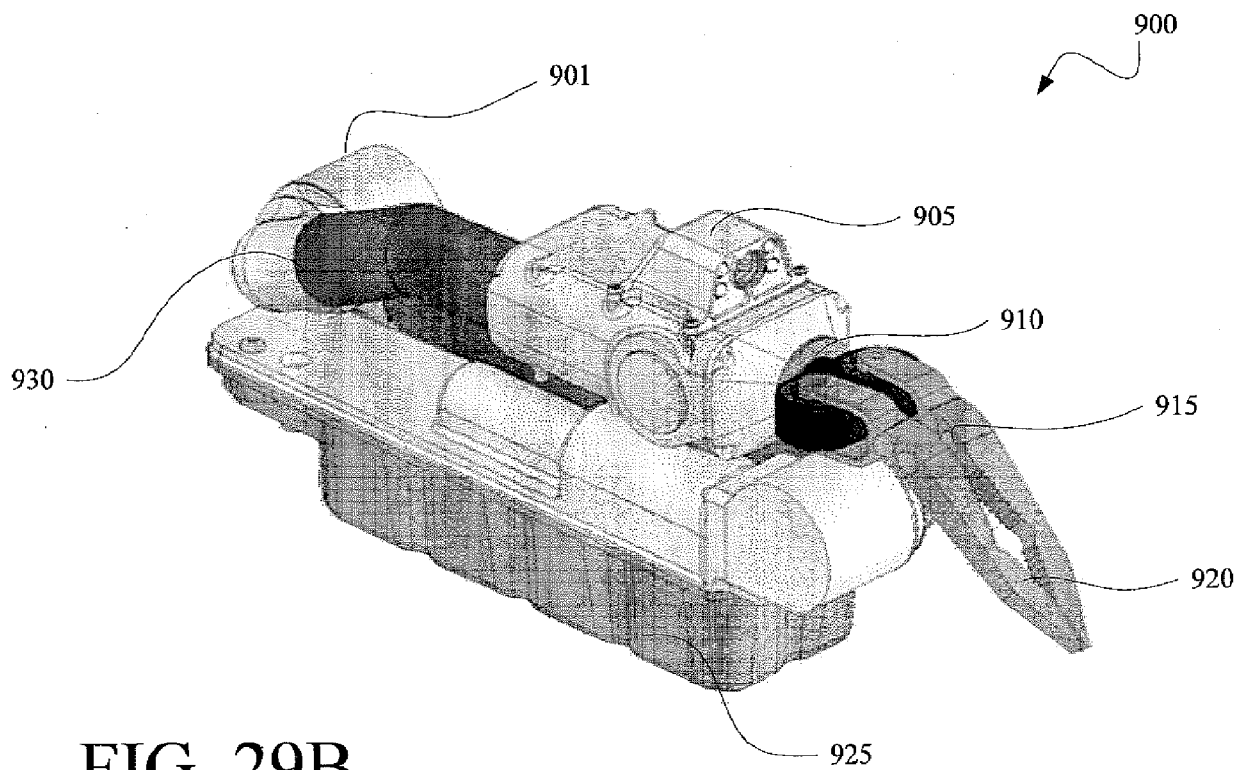


FIG. 29B

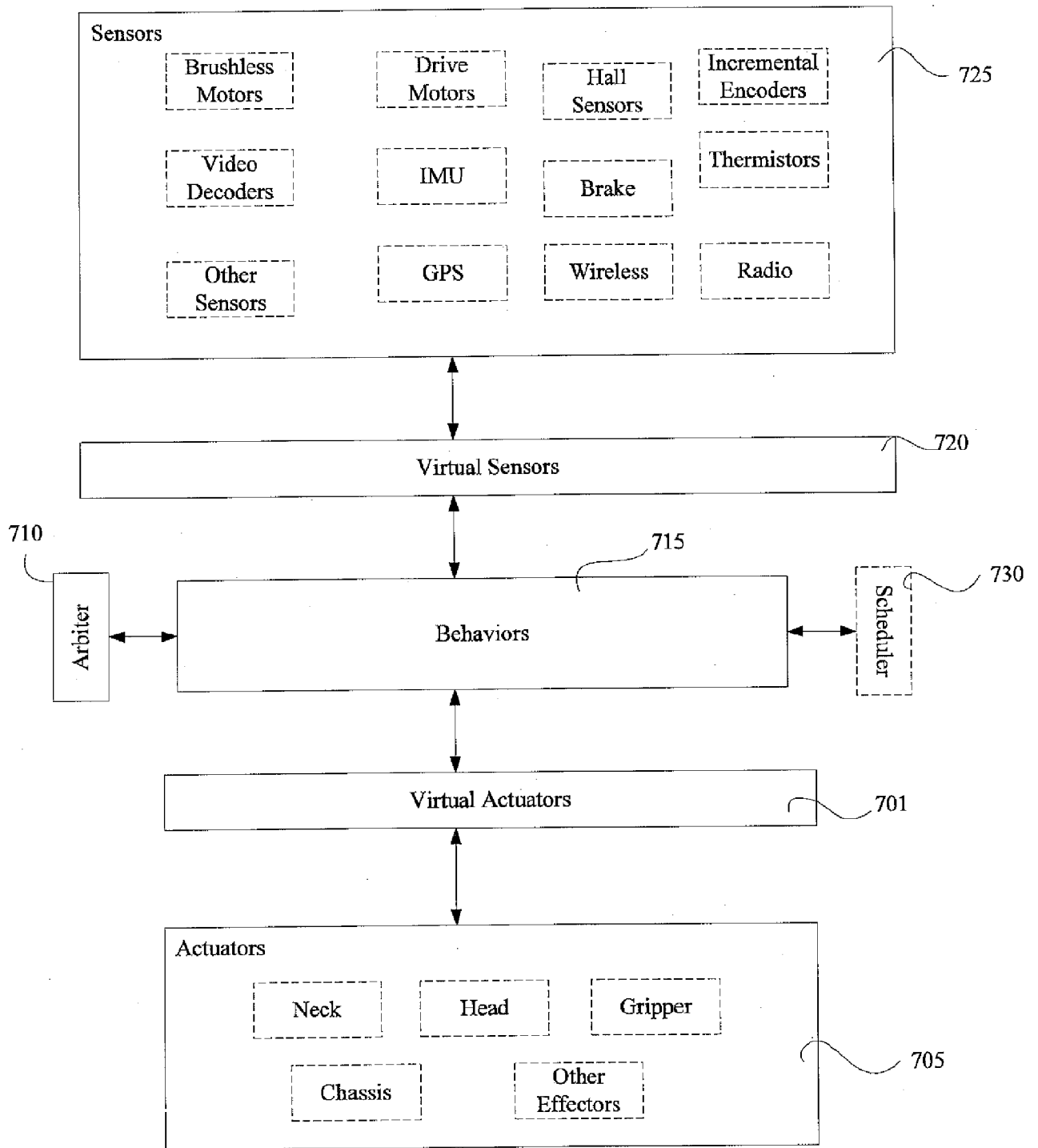
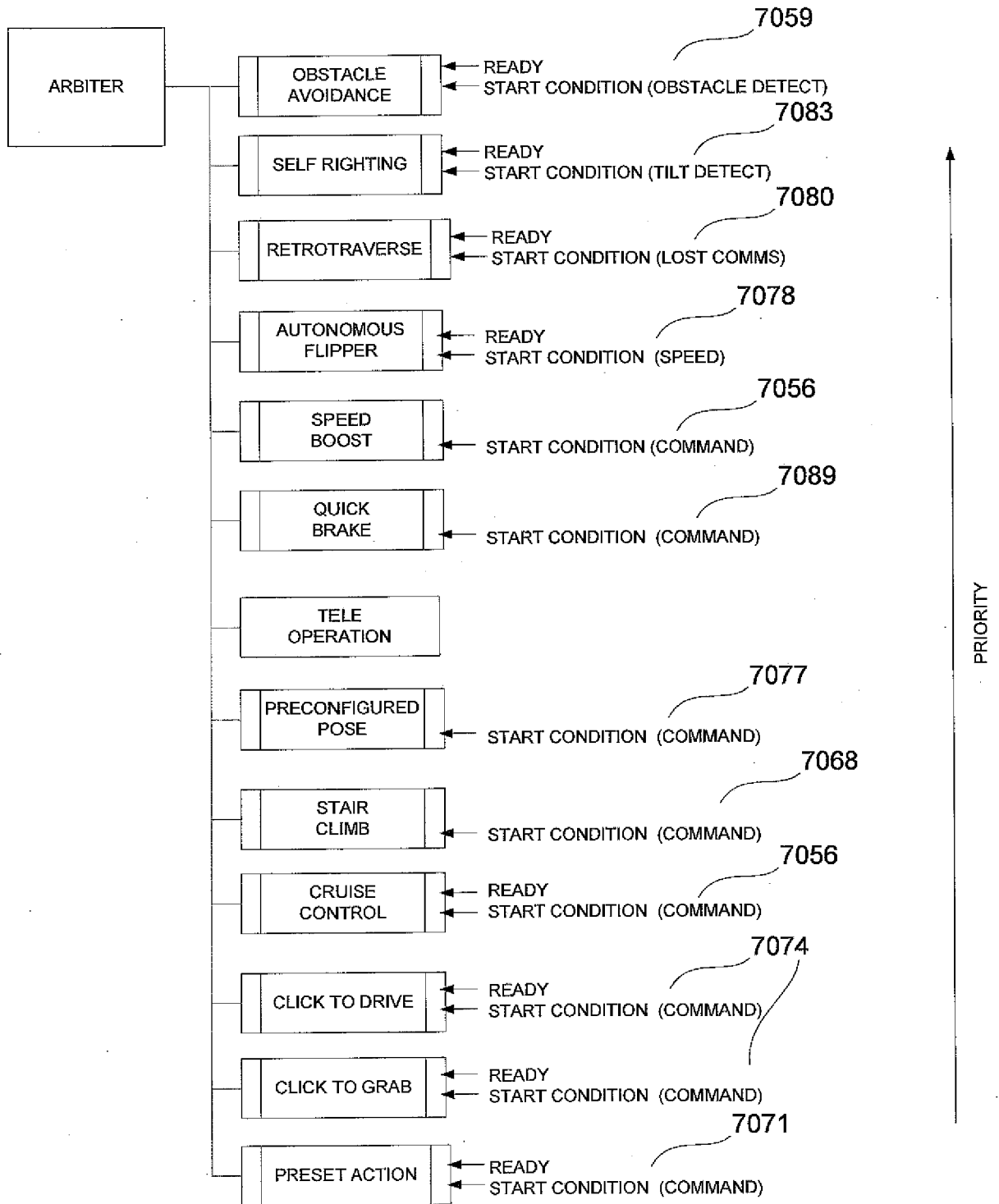


FIG. 30

FIG. 31



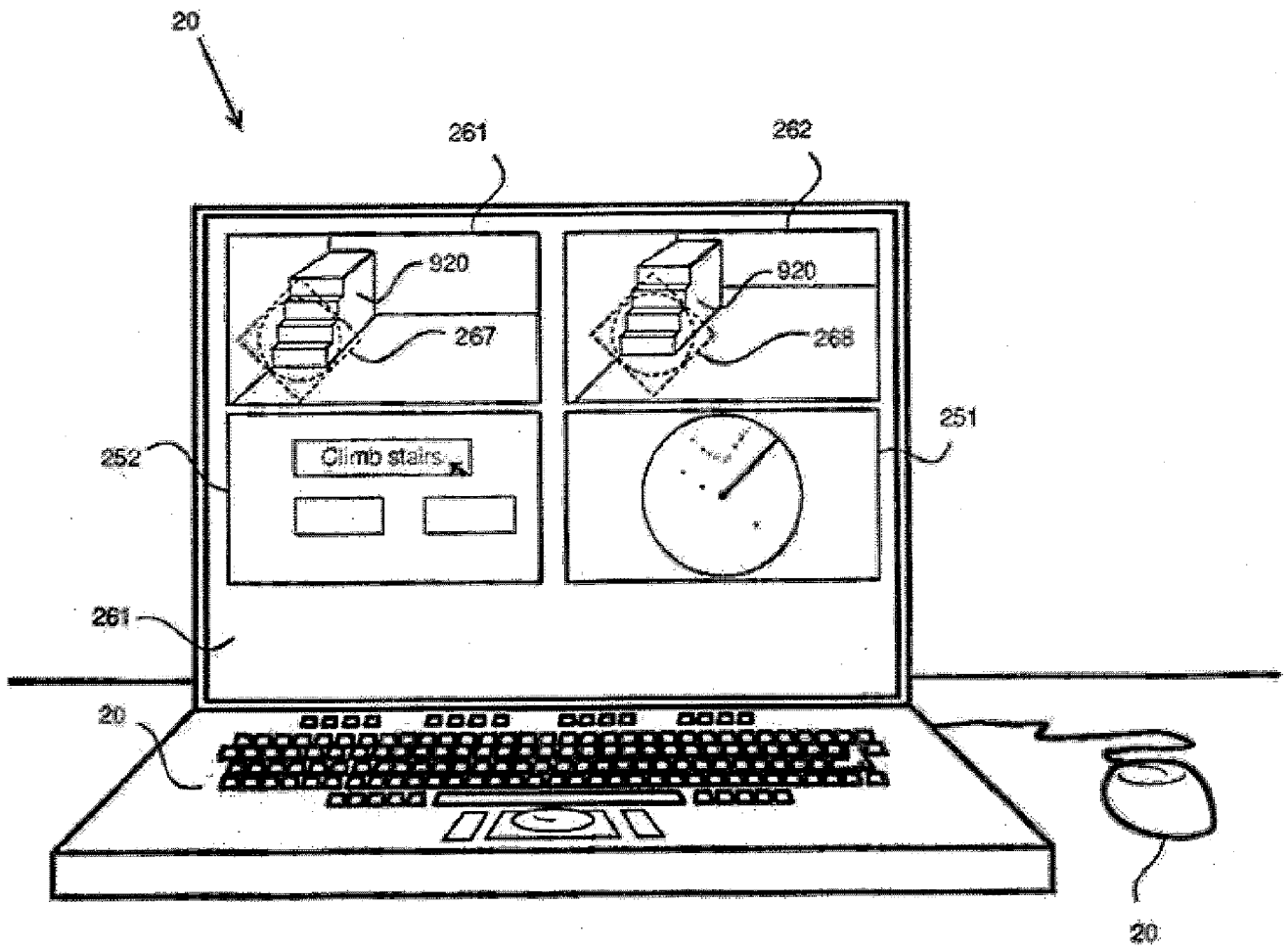
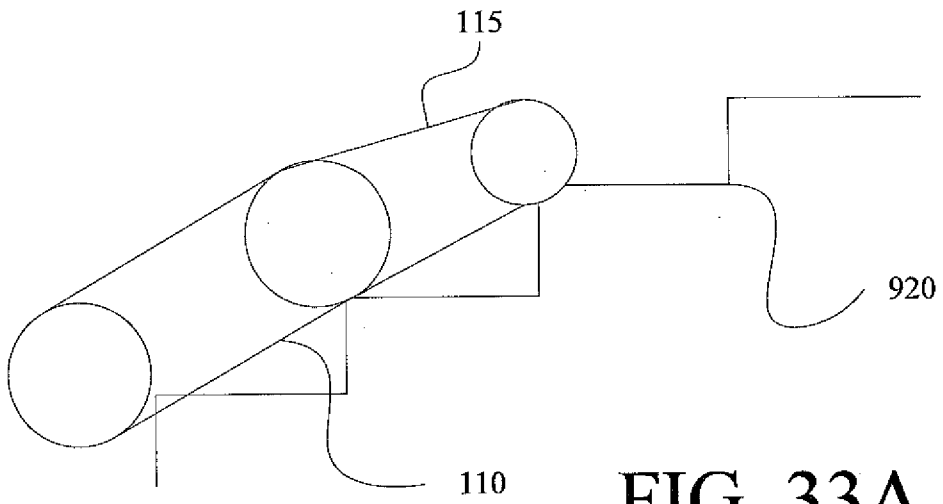
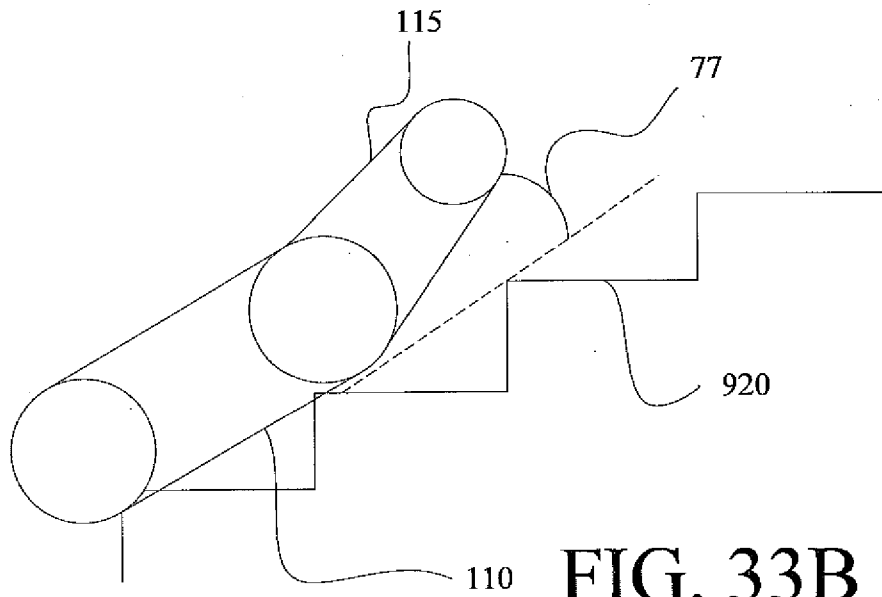


FIG. 32



**FIG. 33A**



**FIG. 33B**

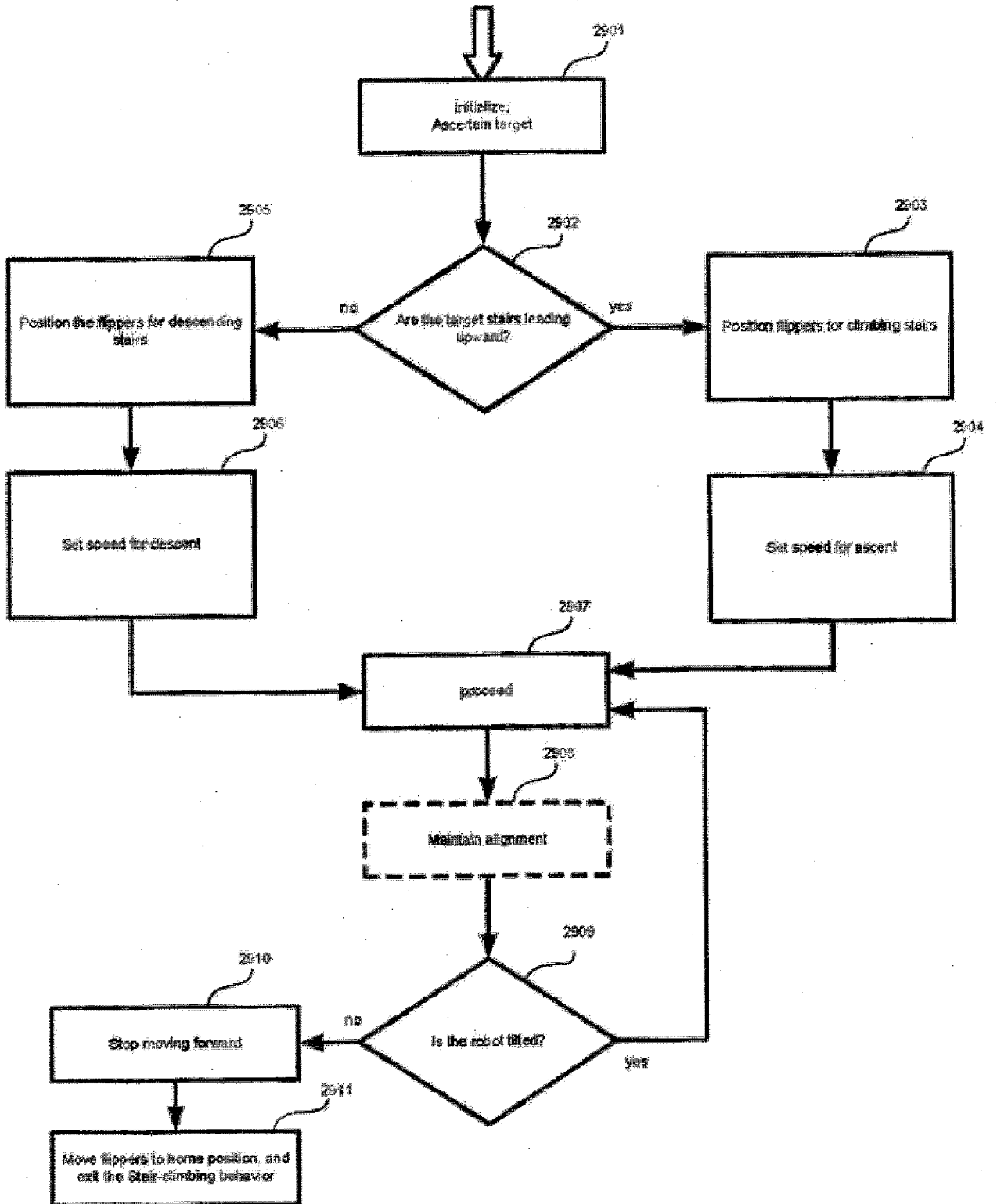
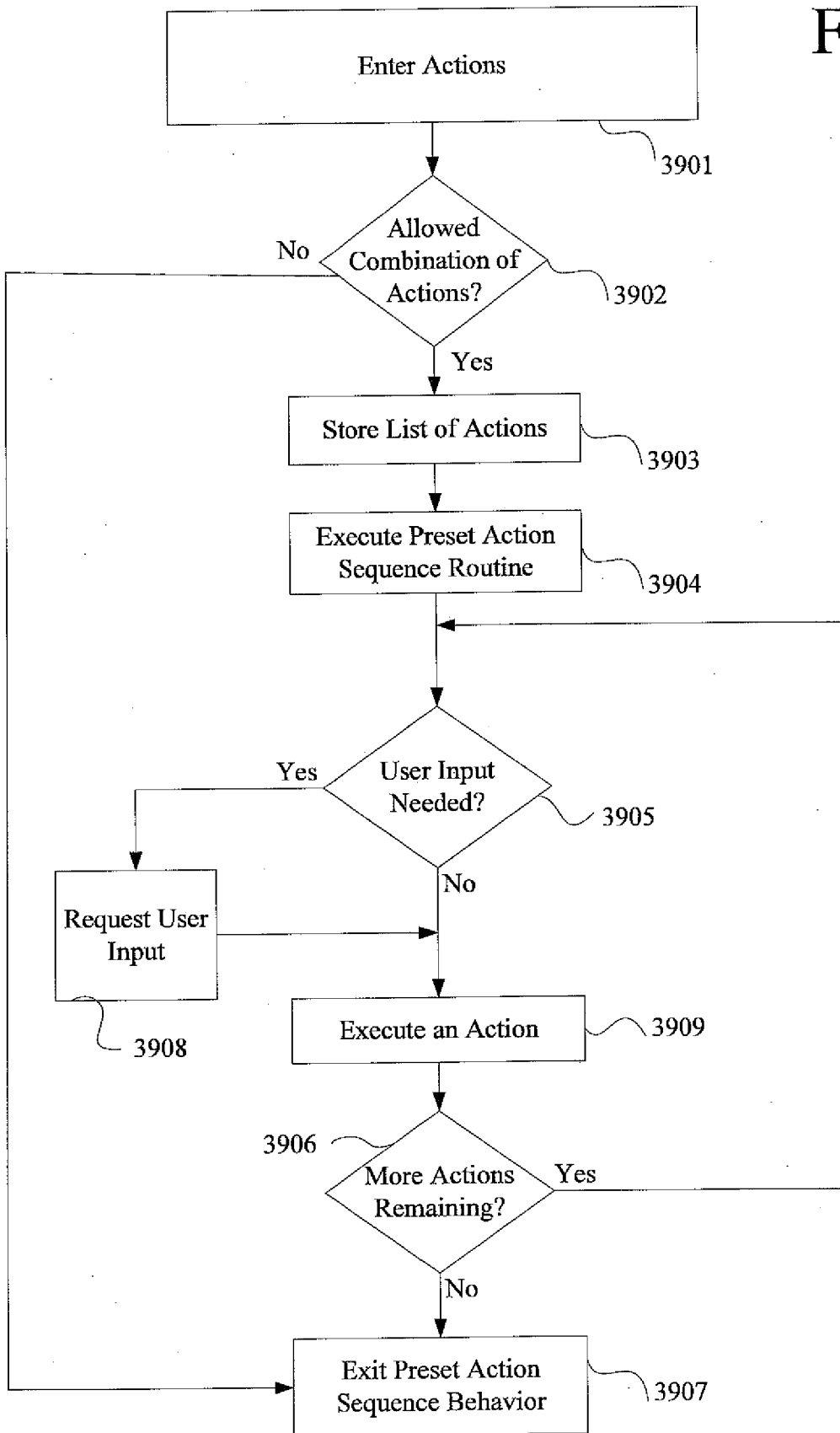


FIG. 34

FIG. 35



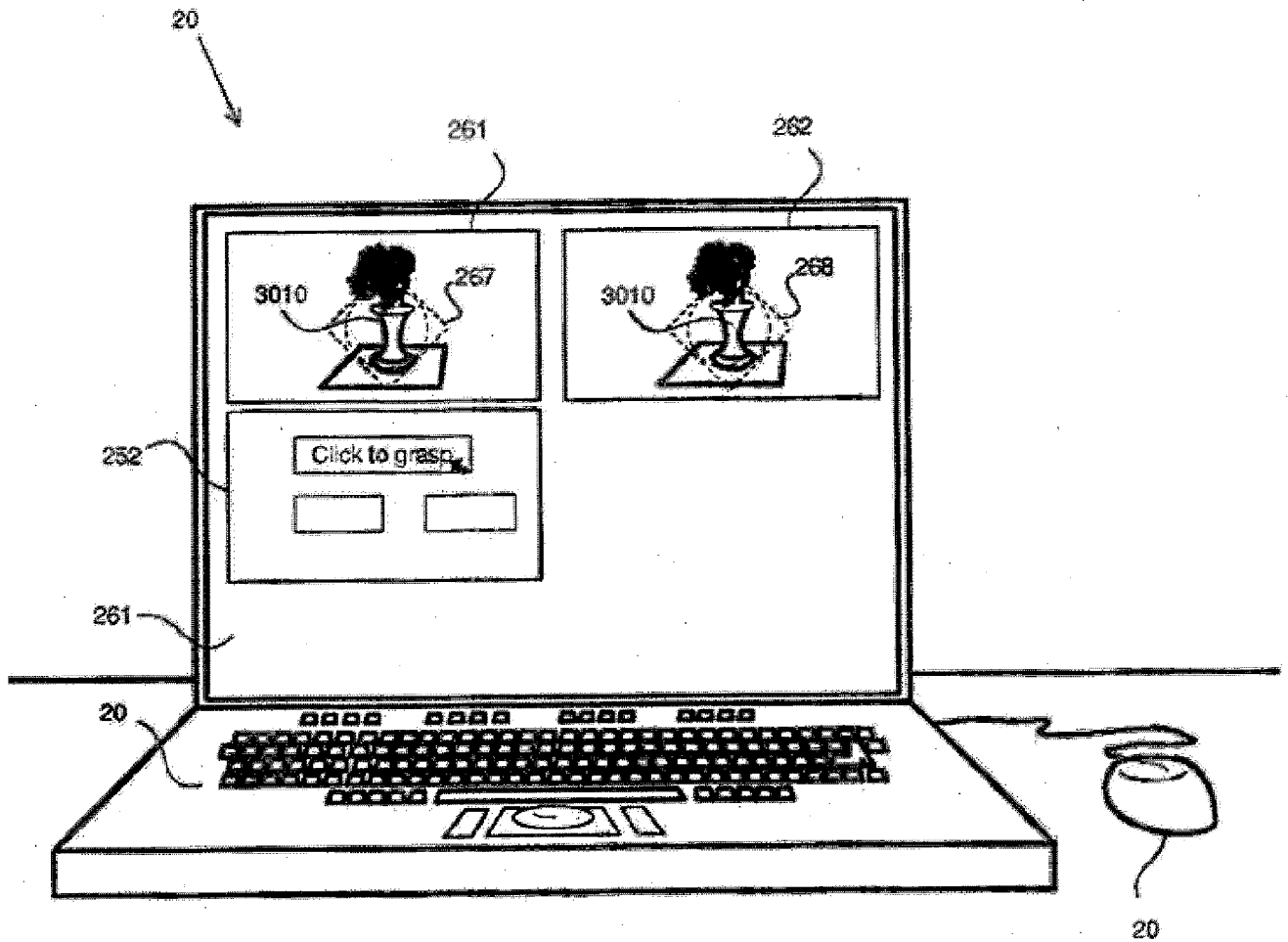


FIG. 36

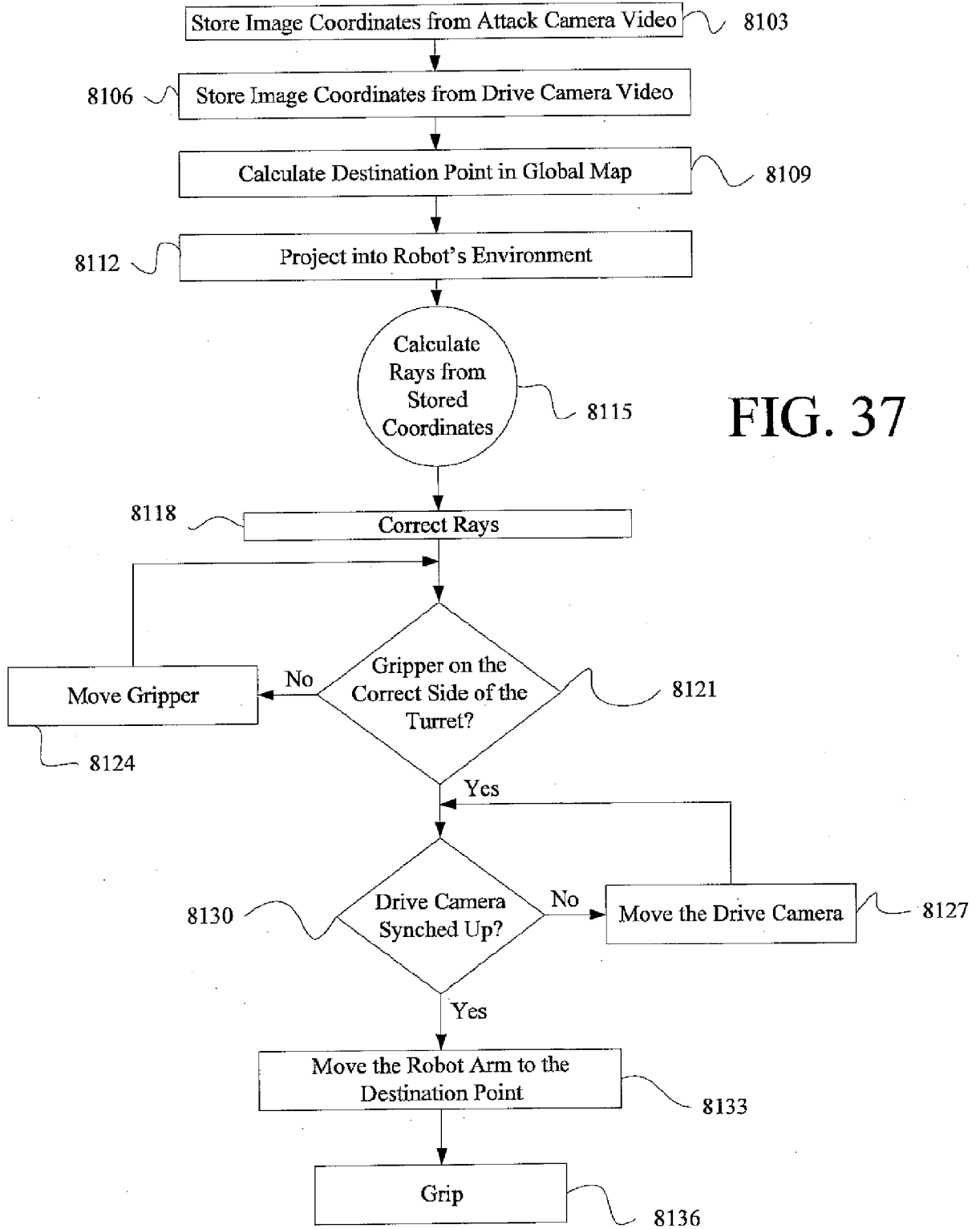


FIG. 37

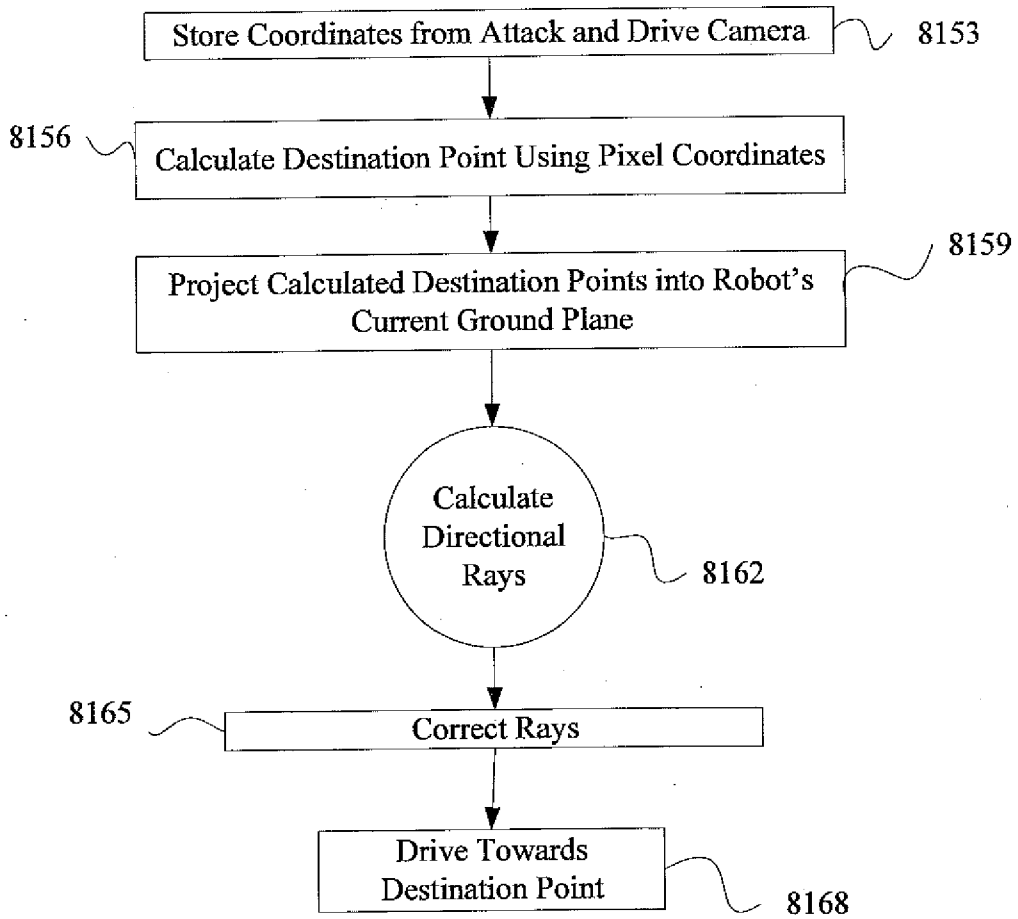


FIG. 38

FIG. 39

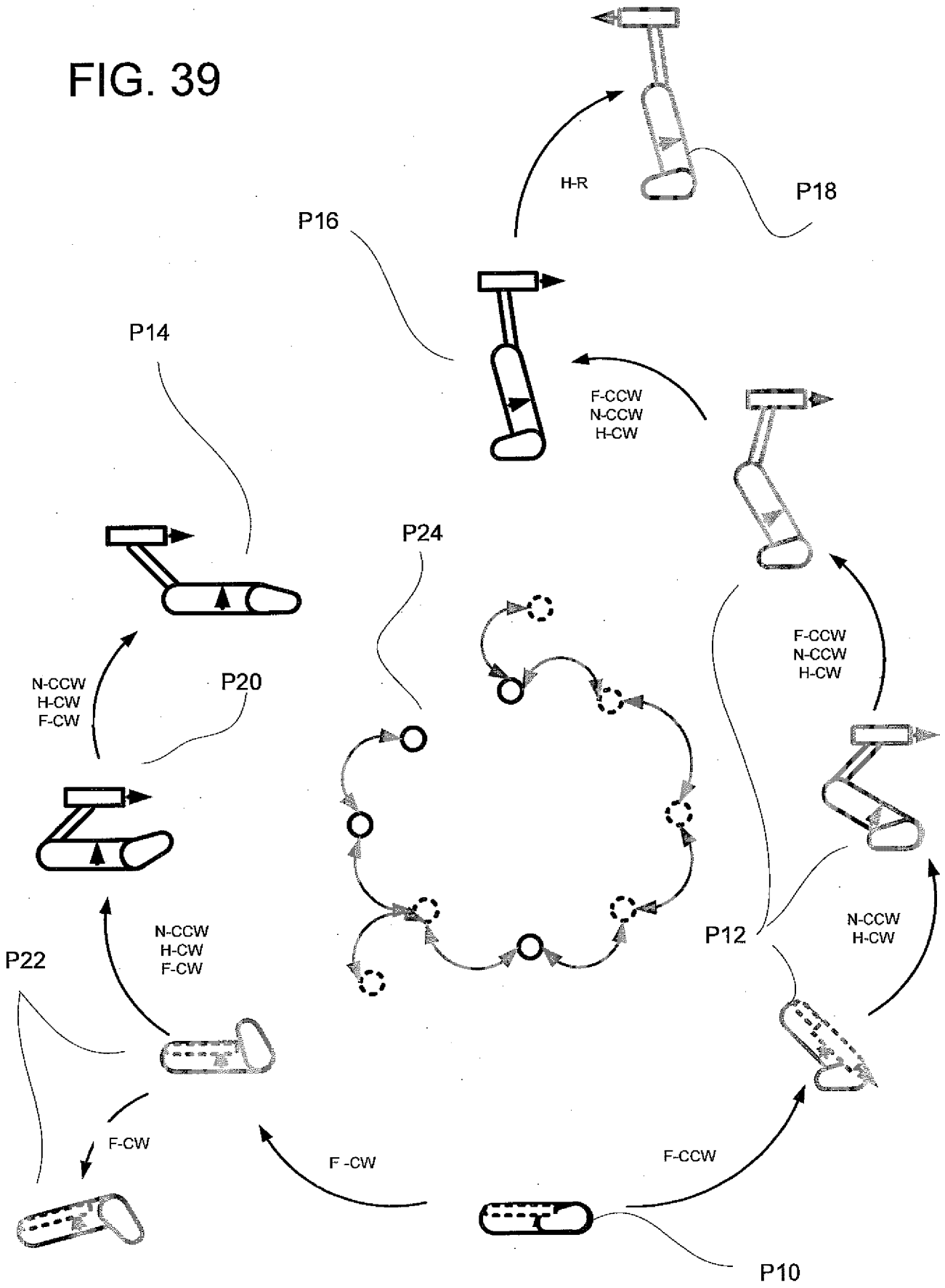
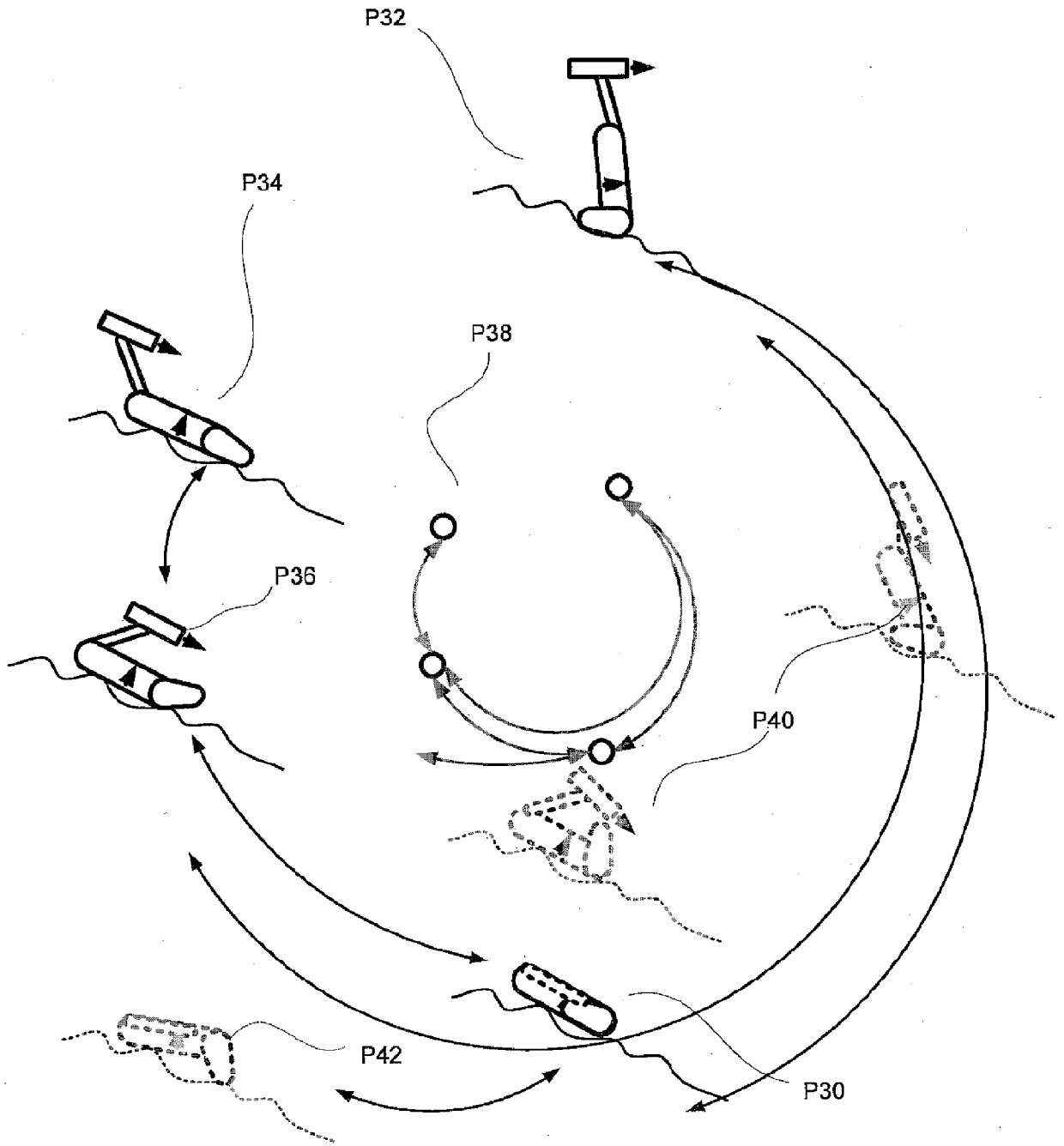


FIG. 40



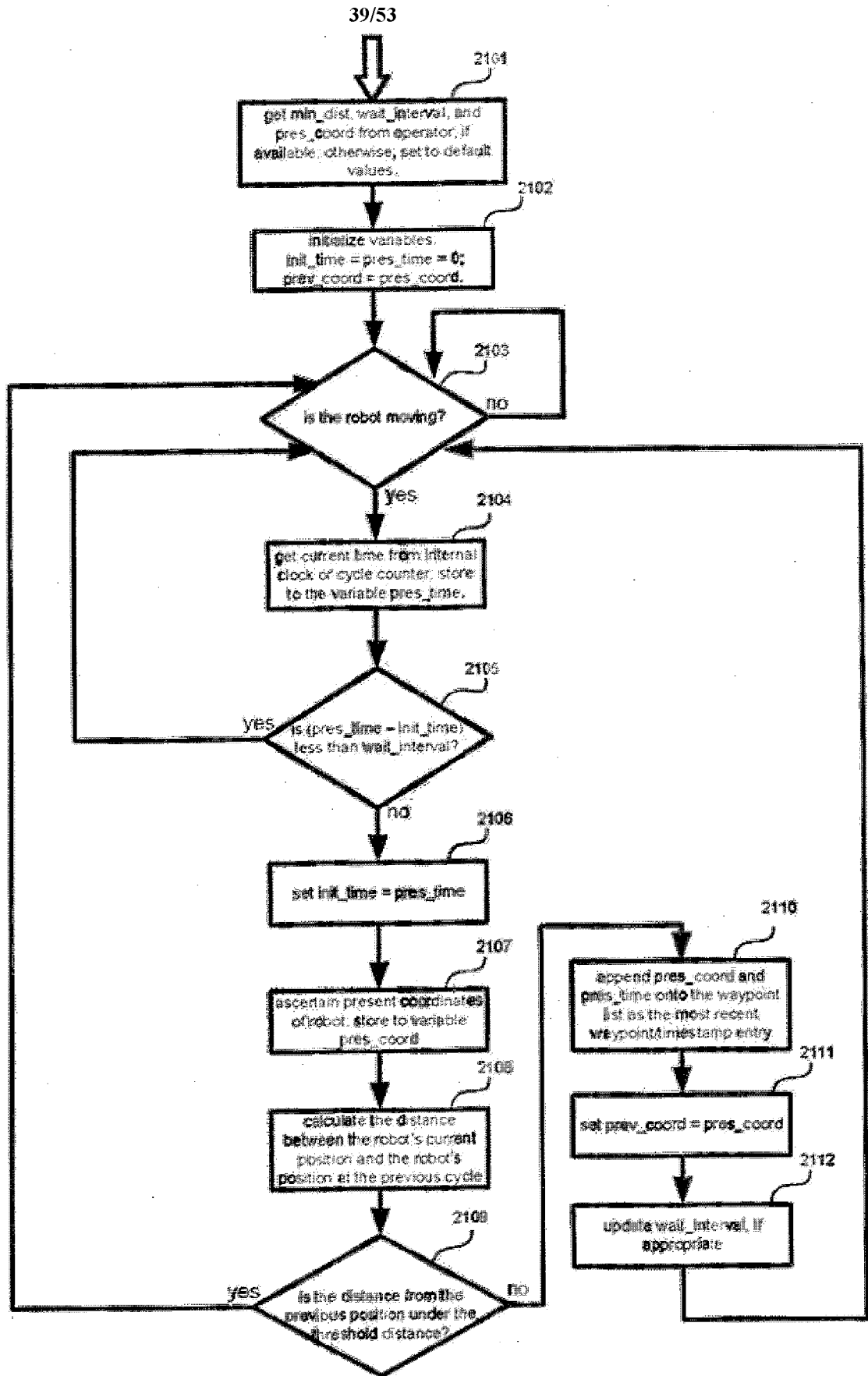


FIG. 41

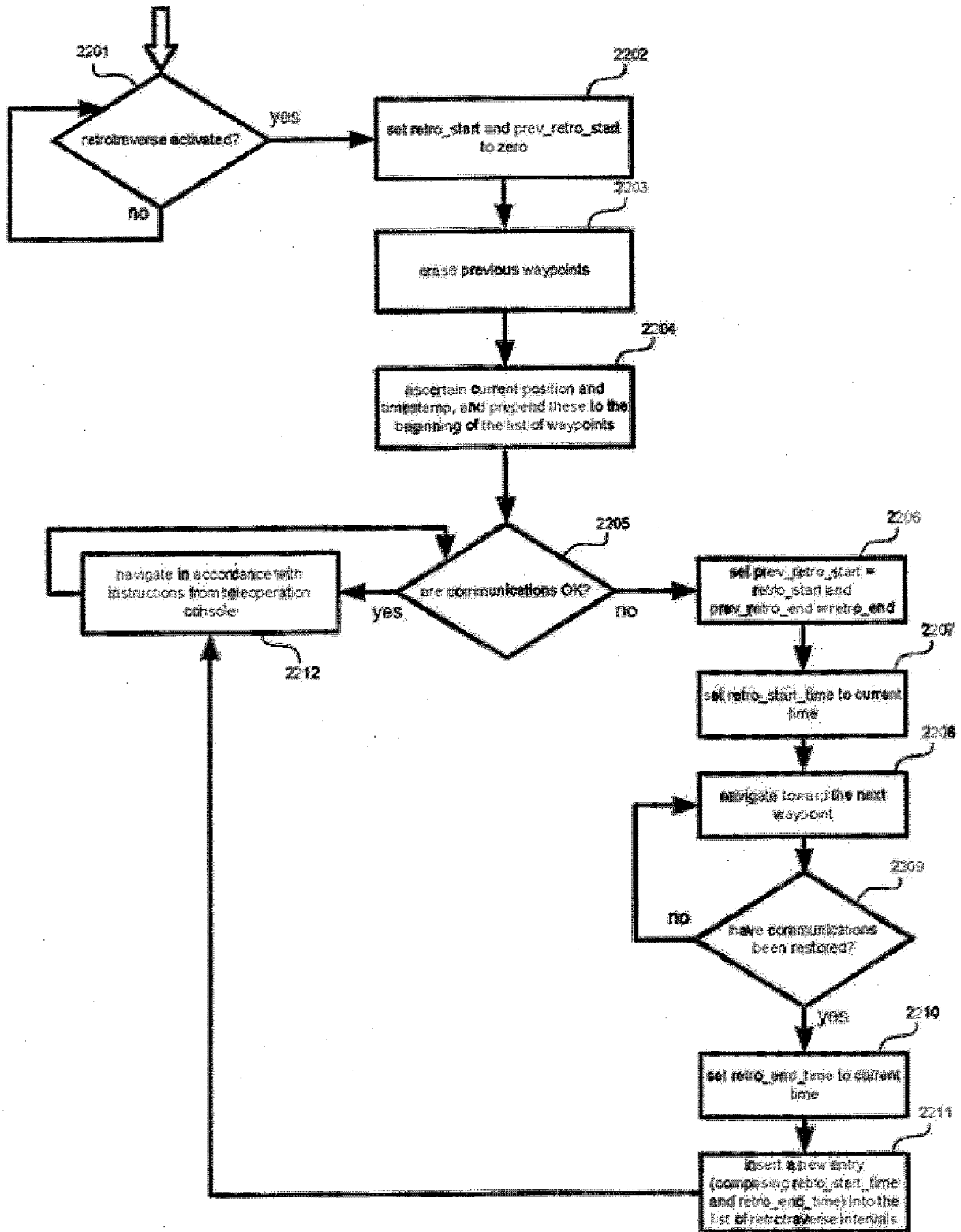


FIG. 42

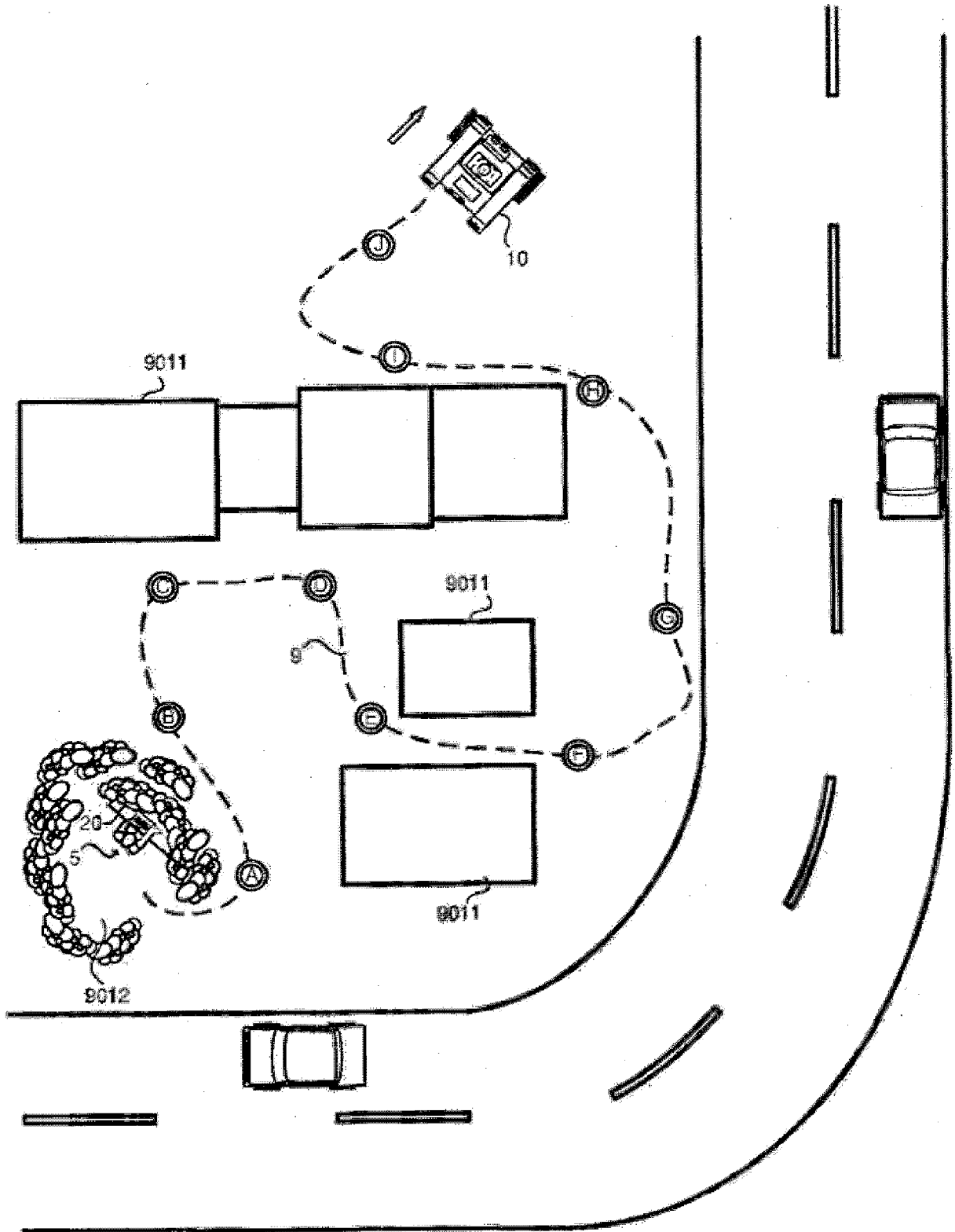


FIG. 43

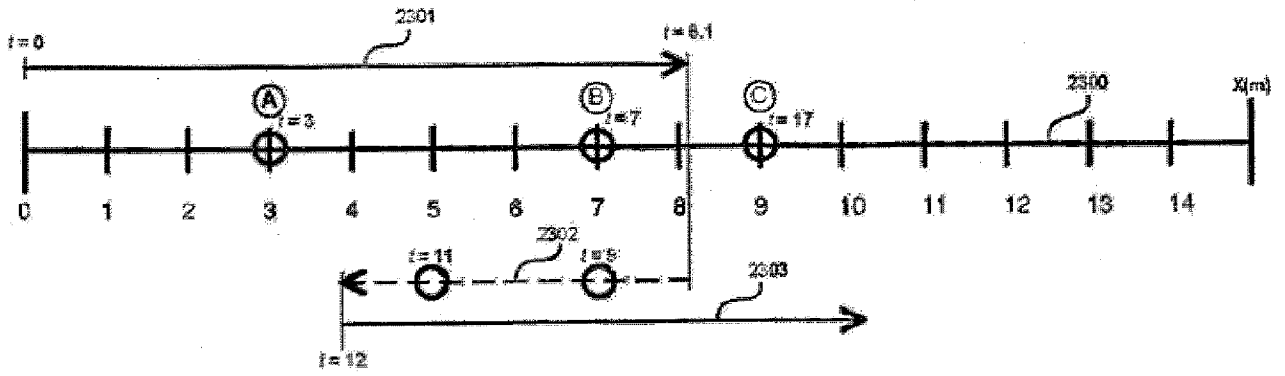


FIG. 44A

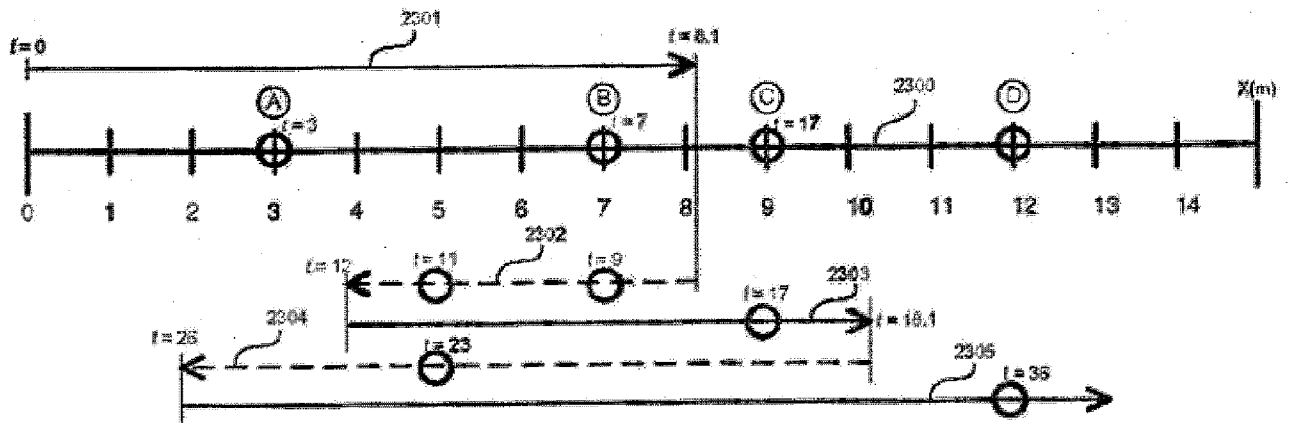


FIG. 44B

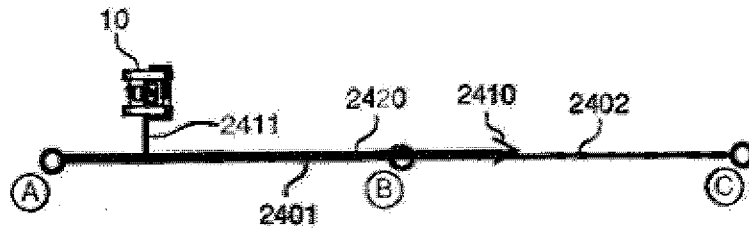


FIG. 45A

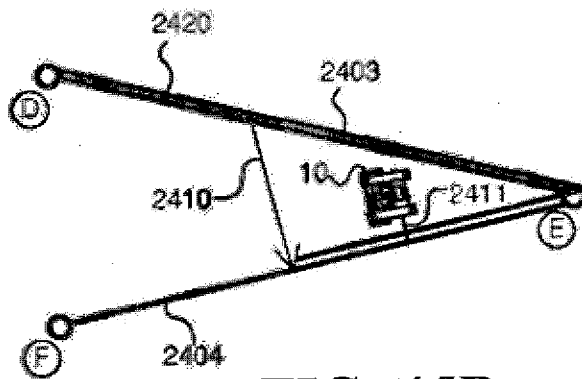


FIG. 45B

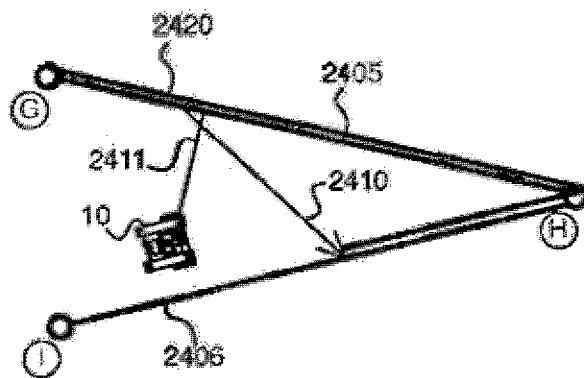


FIG. 45C

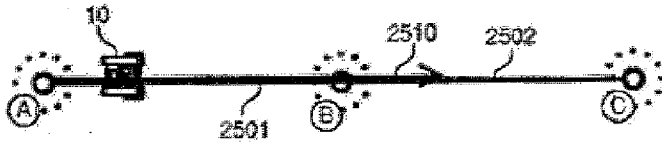


FIG. 46A

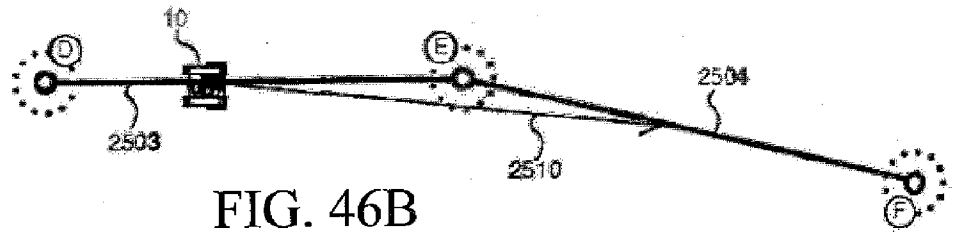


FIG. 46B

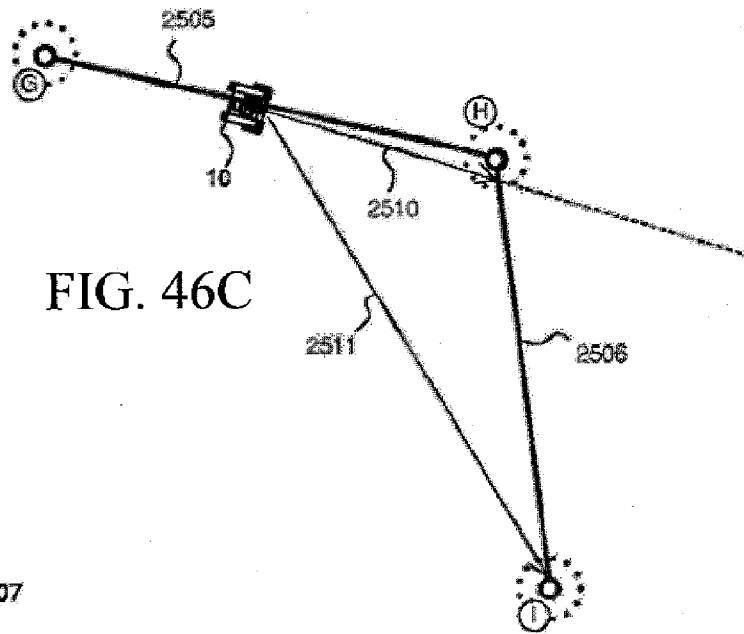


FIG. 46C

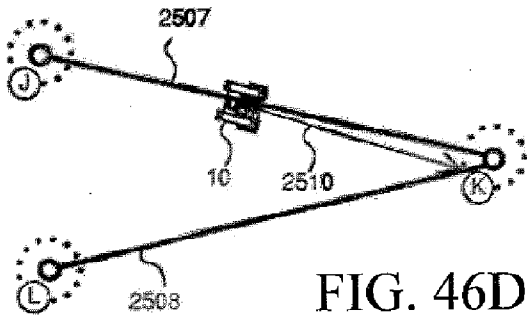


FIG. 46D

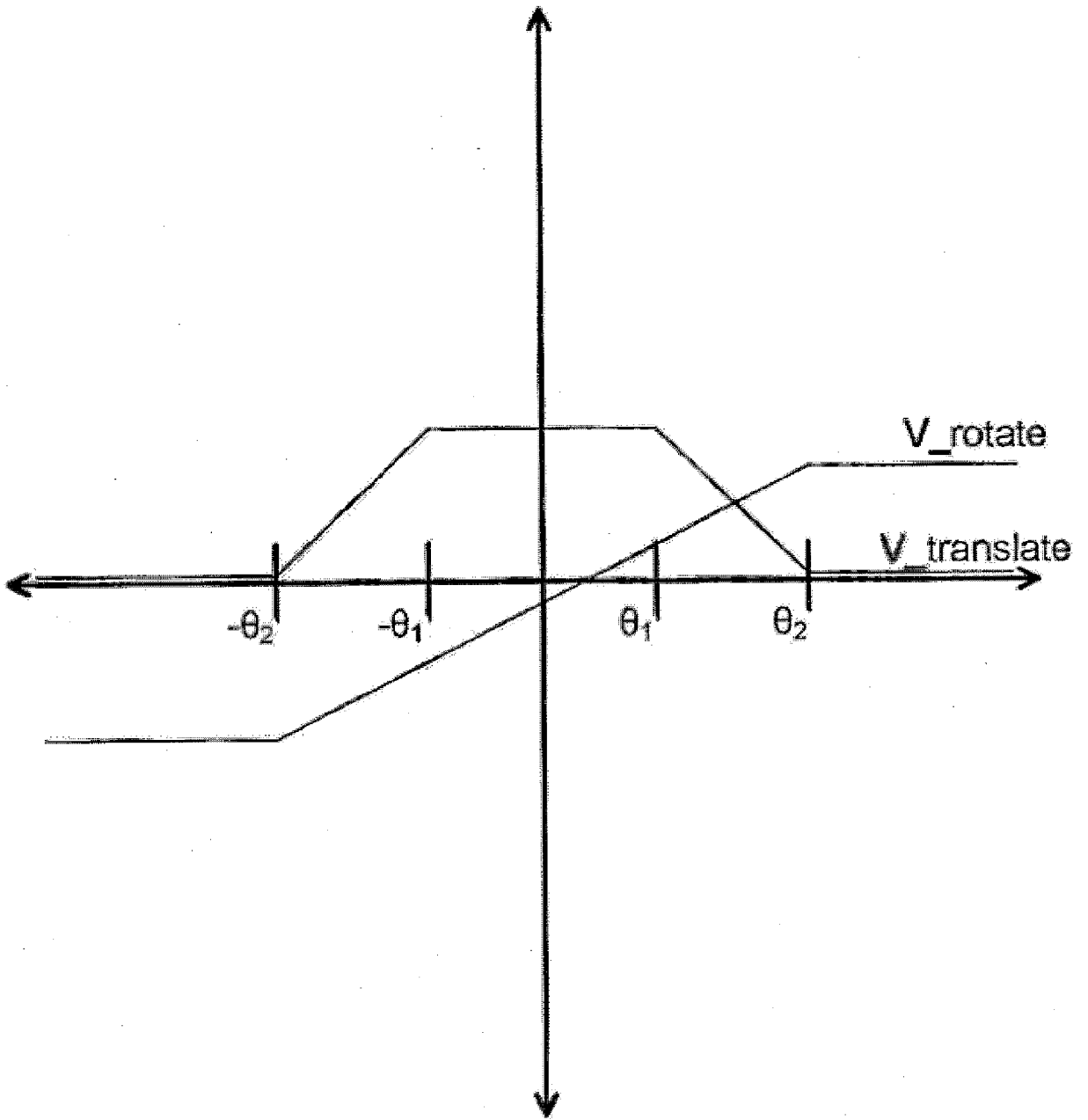


FIG. 47

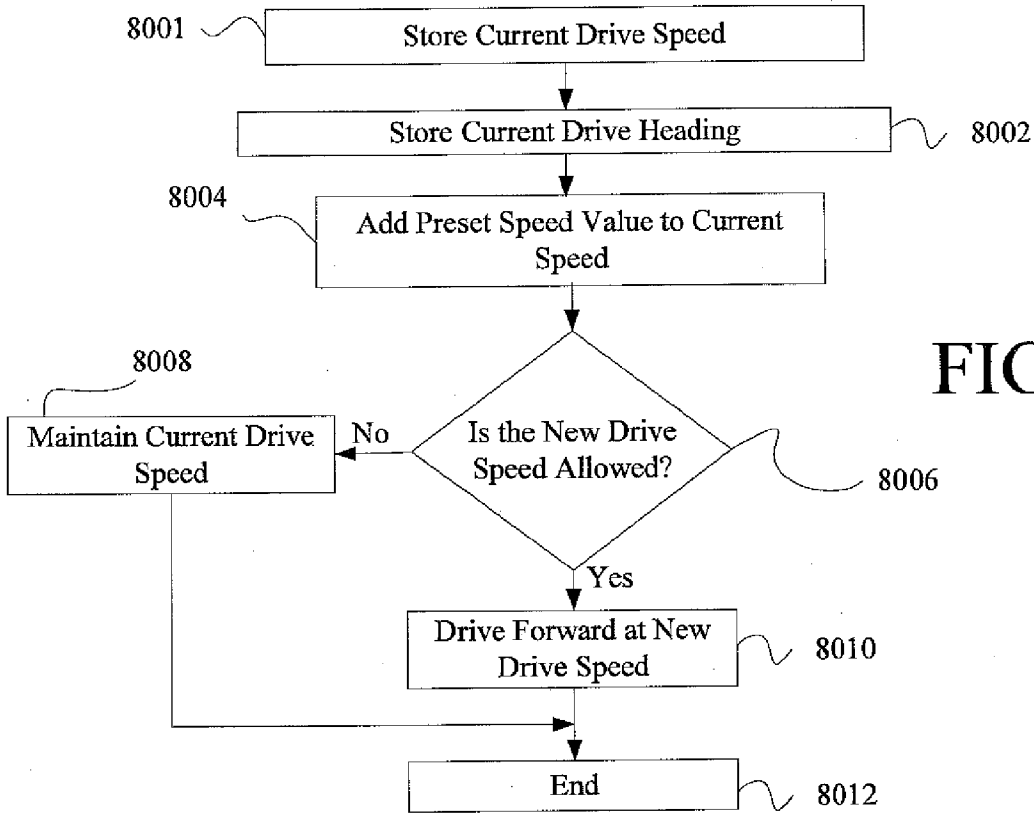


FIG. 48

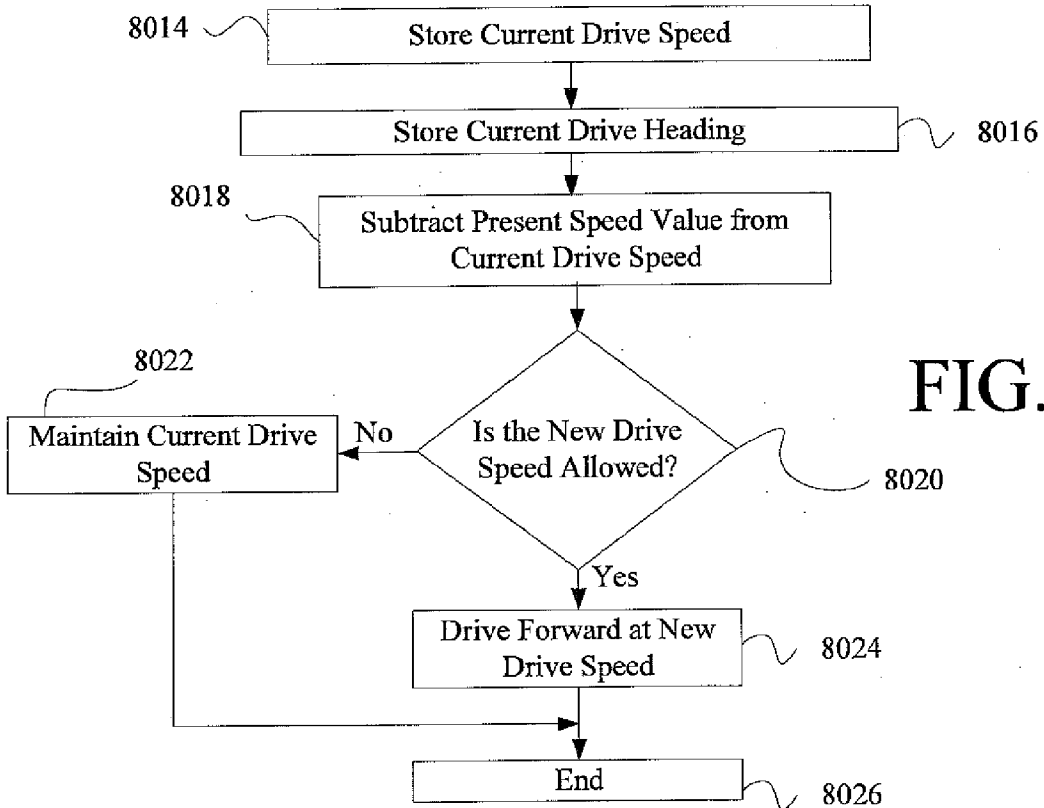
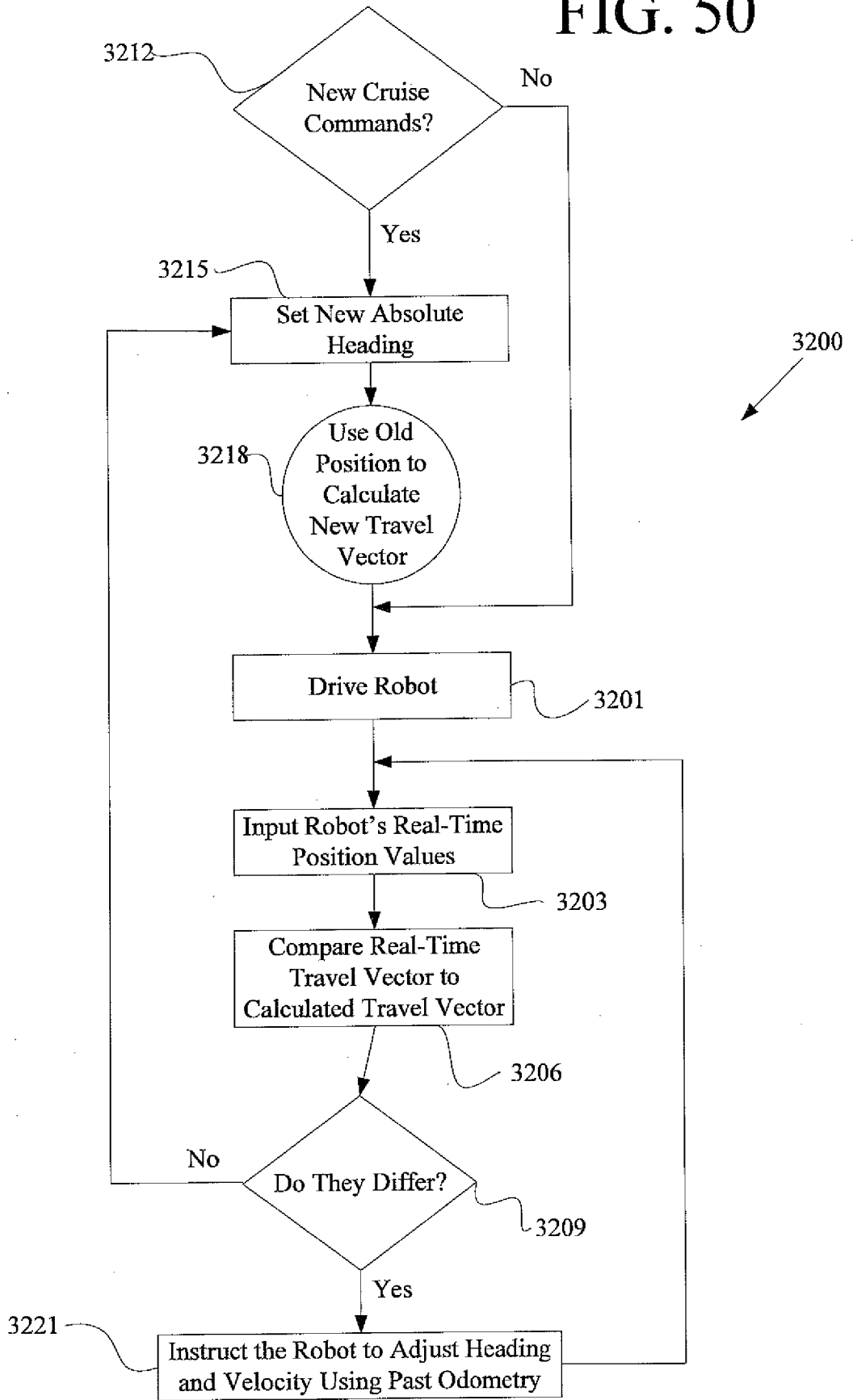


FIG. 49

FIG. 50



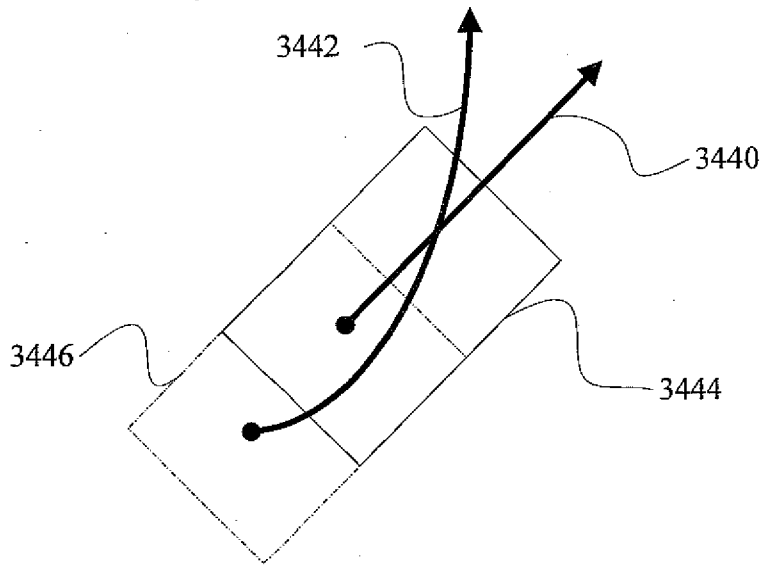


FIG. 51A

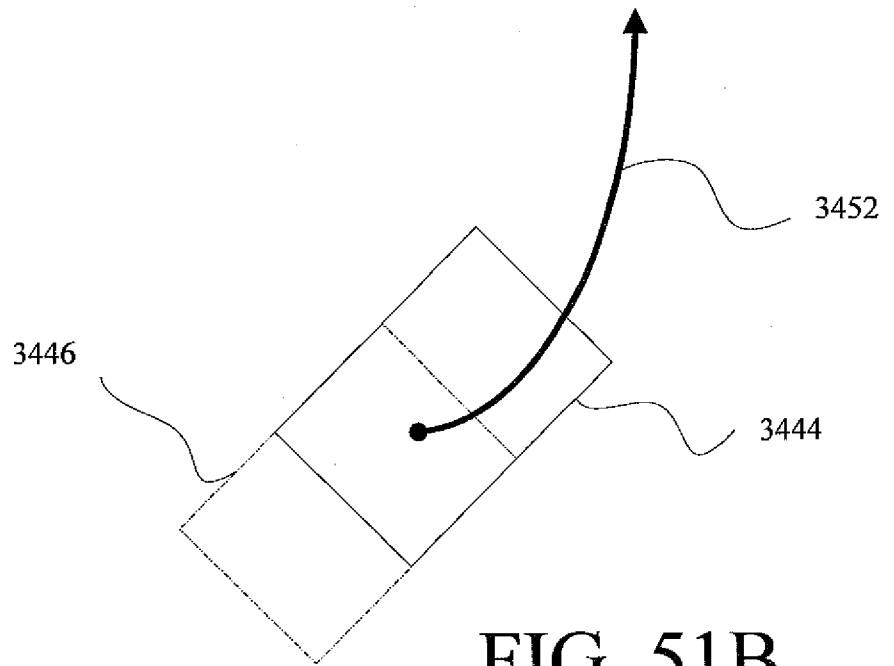


FIG. 51B

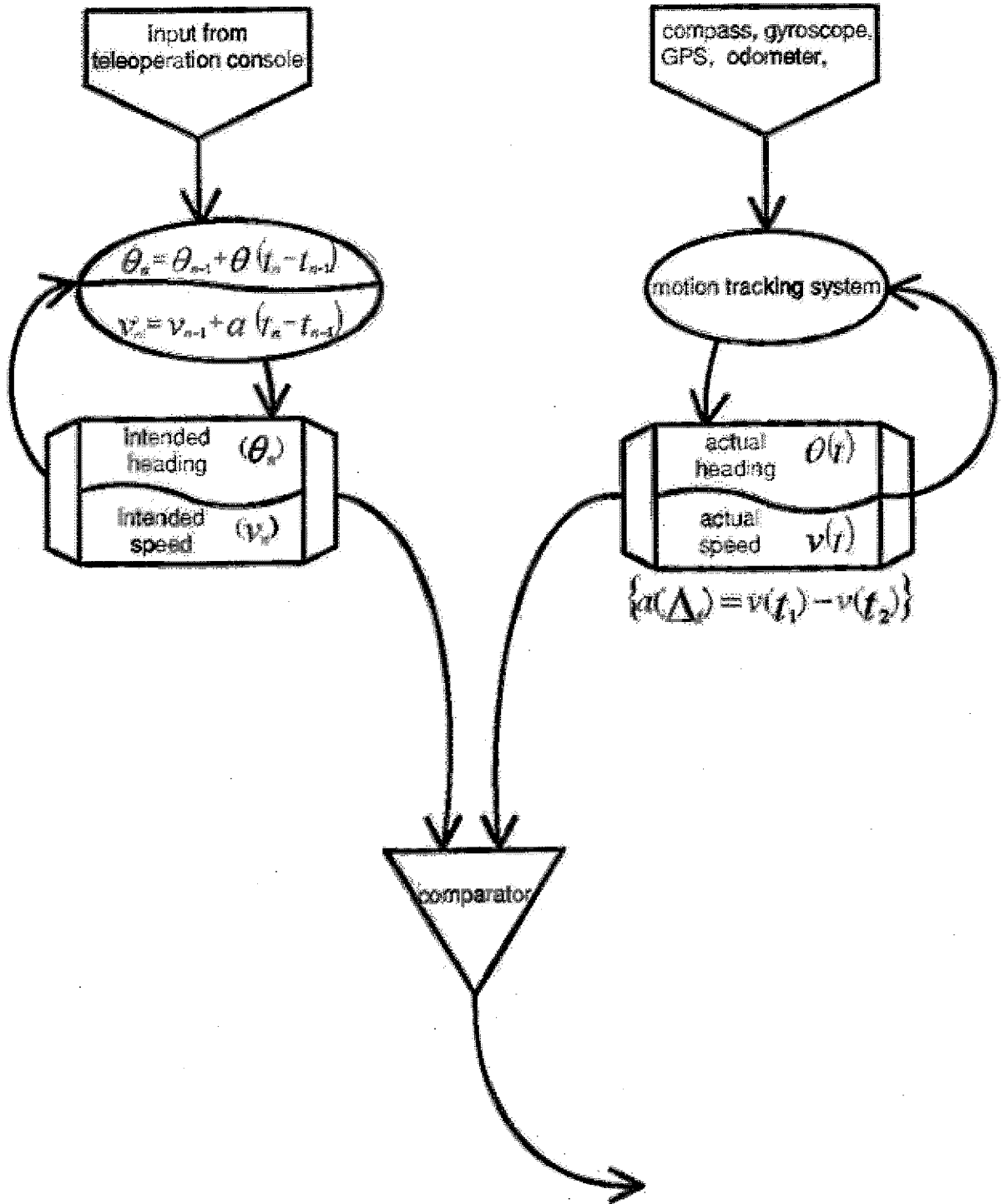


FIG. 52

FIG. 53

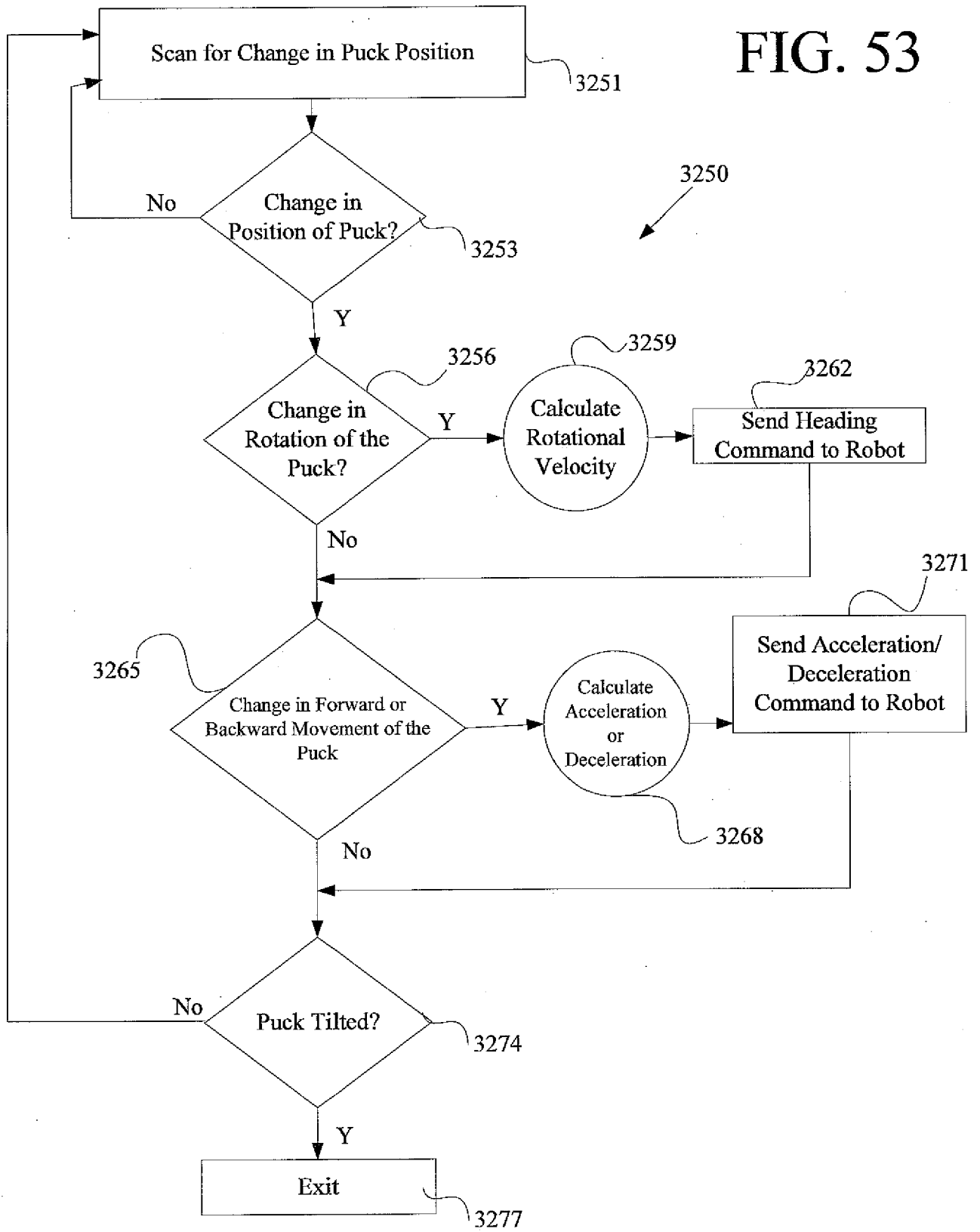
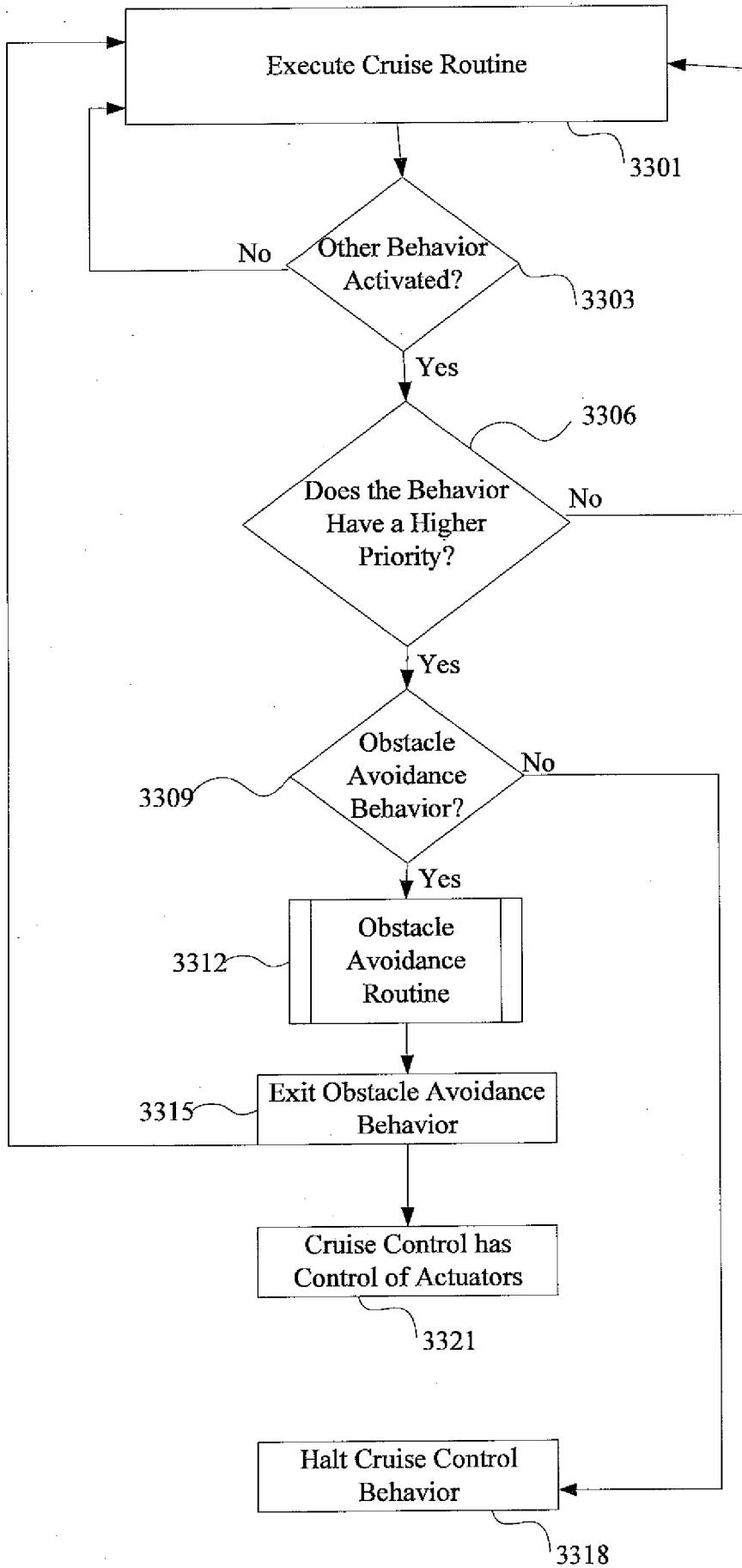


FIG. 54



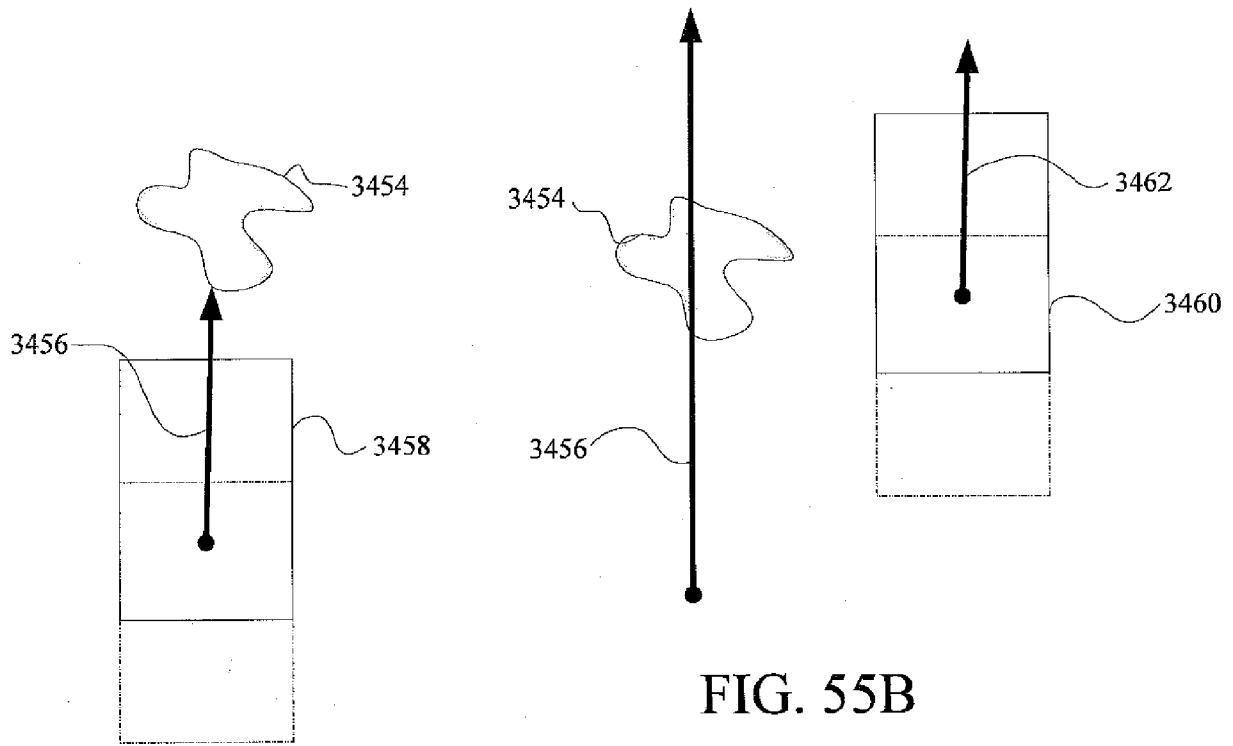


FIG. 55B

FIG. 55A

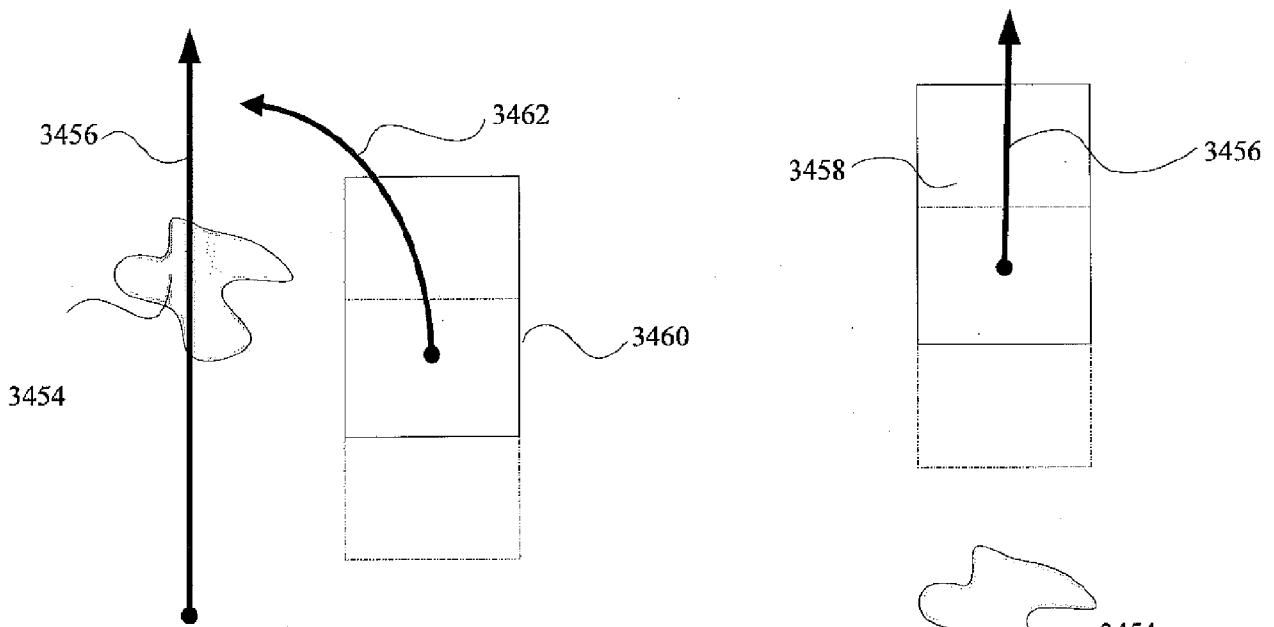


FIG. 55C

FIG. 55D

FIG. 56

