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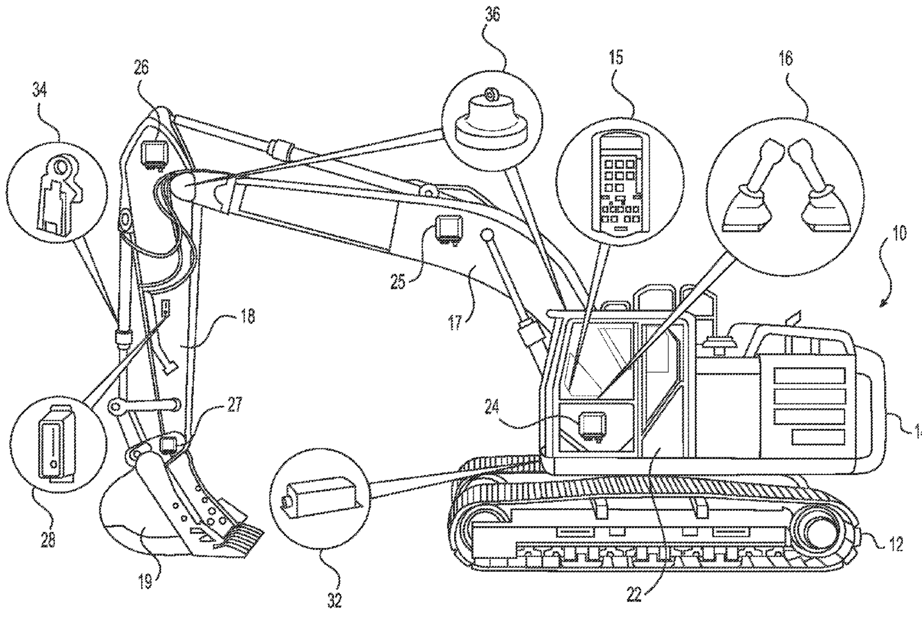

FIG. 1

(57) Abstract: A mechanical swing brake variable control system for an earth-moving machine including an upper revolving car body (14) with swing components (17, 18, 19) mounted on the upper revolving car body (14), a lower traveling car body (12) with traction components mounted on the lower traveling car body, and a mechanical service brake interconnected with the upper and lower car bodies, controls relative rotation between the upper and lower car bodies. A pressure control device (602) controls a variable pressure applied to the mechanical service brake to vary an amount of swing drive holding torque. An electronic controller (241) monitors and processes signals received from sensors (210, 230) associated with the swing components and machine operator commands, and variably controls the amount of holding torque exerted on the upper revolving car body (14) using the mechanical service brake as a function of one or more of machine roll angle, operational configuration of the swing components, inertial mass of the swing components, and

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machine operator commands.

Description

SWING MOTION VARIABLE CONTROL SYSTEM

Technical Field

The present disclosure relates generally to a swing motion control system for variably controlling a swing mechanism of a machine operating on a cross slope and, more particularly, to a swing motion variable control system of a machine that applies a variable pressure command to a mechanical swing brake device.

Background

Machines such as, for example, dozers, motor graders, wheel loaders, wheel tractor scrapers, and other types of heavy equipment are used to perform a variety of tasks. Effective control of the machines requires accurate and responsive sensor reading to perform calculations providing information in near real time to the machine control or operator. Autonomously and semi-autonomously controlled machines are capable of operating with little or no human input by relying on information received from various machine systems. For example, based on machine movement input, terrain input, and/or machine operational input, a machine can be controlled to remotely and/or automatically complete a programmed task. By receiving appropriate feedback from each of the different machine systems and sensors during performance of the task, continuous adjustments to machine operation can be made that help to ensure precision and safety in completion of the task. In order to do so, however, the information provided by the different machine systems and sensors should be accurate and reliable, and real time data should be processed and acted upon in a manner that avoids creating any risks or unwarranted stresses on the machine. The position, velocity, and distance traveled by the machine, and positions, movements, and orientations of different parts or components of the machine are parameters whose accuracy may be important for control of the machine and its operations. In machines such as excavators including swing components such as a boom, stick, and implement or work tool, a swing control system may be provided to control the swinging movement of the components from a digging or loading position to a dumping position, or from the dumping position back to the digging or loading position. When the machine is located on a slope, for example, the components such as the boom, stick, and implement mounted on an upper revolving car body of the machine may drift from a position commanded by an operator as a result of the effects of gravity on the components. A conventional solution to this drift problem may include the use of low leakage hydraulic control valves (e.g., spool valves) in a closed loop hydraulic swing circuit to attempt to hydraulically lock the swing components and prevent them from drifting when the machine is on a slope. However, if inputs from one or more sensors are inaccurate or nonexistent due to a sensor failure, the upper revolving car body with the swing components may be prevented from moving relative to a lower traveling car body on the machine as a result of the hydraulic swing system controls, or in some cases, the hydraulic swing controls in conjunction with mechanical braking of swing motion by application of a holding torque using mechanical friction elements interconnected with the upper and lower car bodies of the machine. When the swing components are prevented from swinging during a digging operation, the result can be excessive torsional loading on swing drive components, resulting in failure of one or more components of the swing drive.

Conventional machines may use a navigation or positioning system to determine various operating parameters such as position, velocity, pitch rate, yaw rate, and roll rate for the machine. The position and orientation of the machine is referred to as the “pose” of the machine. The machine “state” includes the pose of the machine as well as various additional operating parameters that can be used to model the real time kinematics and dynamics of the machine, such as parameters characterizing the various linkages, joints, tools, hydraulics, and power systems of the machine. Some conventional machines utilize a combination of one or more of Global Navigation Satellite System (GNSS) data, a Distance Measurement Indicator (DMI) or odometer measurement data, Inertial Measurement Unit (IMU) data, etc. to determine these parameters. Some machines utilize RADAR sensors, SONAR sensors, LIDAR sensors, IR and non-IR cameras, and other similar sensors to help guide the machines safely and efficiently along different kinds of terrain. Conventional machines have attempted to fuse these different types of data to determine the position of a land-based vehicle. Nonetheless, when so many different sensors are involved in the modeling of the kinematics and dynamics of the machine, there may be failures of one or more sensors providing data that should be indicative of the positions and operations of various components of the machine, which may lead to a failure to control the resistance to swinging motion during operation of the machine by an amount that will not exert excessive forces on swing components, for example, when the machine is digging.

An exemplary system that may be utilized to determine the position of a machine is disclosed in U.S. Patent Application Publication No. 2008/0033645 (“the ’645 publication”) to Levinson et al. that published on February 7, 2008. The system of the ’645 publication utilizes location data from sensors such as Global Positioning System (GPS), as well as scene data from a LIDAR (light detection and ranging) device to determine a location or position of the machine. Specifically, the data is used to create a high-resolution map of the terrain and the position of the machine is localized with respect to the map.

Although the system of the ’645 publication may be useful in determining the overall position of the machine, the system may not provide accurate estimates for the position of the machine or components of the machine while dead-reckoning (i.e., during periods of time when GPS signals are unavailable). Moreover, the system of the ’645 publication may not provide accurate position information when GPS signals are unreliable or erroneous due to multipath errors, position jumps, etc. because the system of the ’645 publication does not check for the accuracy of the GPS signal. Finally, the system of the ’645 publication does not provide a means to monitor and controllably maintain the position of swing components of the machine with a variable amount of holding torque when the machine is operating on a slope, while avoiding too much resistance to swinging motion during operation of the machine, resulting in the potential for excessive forces on swing components, for example, when the machine is digging.

The system and method of the present disclosure provides for accurate determination of the position of a machine and components of the machine, as well as including new control logic that may provide variable control of the amount of mechanical service brake holding torque between the upper revolving car body and the lower traveling car body on an excavator. This new variable control of the amount of mechanical holding torque (e.g., implemented by a clutch pack or other mechanical braking elements) may be based on one or more of the results of a sensor detecting the cross slope on which the excavator is operating, machine linkage configurations, operator input commands, and even the inertial mass of the swing components mounted on the upper revolving car body. The variable control may be implemented by retrieving data from a map and/or by performing various calculations to determine the amount of holding torque for resisting relative rotation between the upper revolving car body and the lower traveling car body of a machine that is appropriate for the machine operating on terrain with a detected amount of cross slope. The amount of holding torque generated by a mechanical service brake as controlled by this new control logic may be reduced when the excavator is grounded (e.g., a bucket of the excavator is in contact with the ground) in order to avoid putting excessive torsional load on the swing drive components during digging, but may be increased on a particular cross slope to prevent relative movement between the upper car body and the lower car body when the excavator is not grounded.

<u>Summary</u>

In one aspect, the present disclosure is directed to a mechanical swing brake variable control system for an earth-moving machine including an upper revolving car body and a lower traveling car body. The mechanical swing brake variable control system may include a pressure control device configured to control a variable pressure applied to a mechanical service brake on the machine

in order to vary an amount of swing drive holding torque. The mechanical swing brake variable control system may include a controller configured to monitor and process signals received from sensors and operator inputs. The signals received from sensors may be indicative of one or more of machine roll angle, operational position and configuration of swing component linkages, and inertial mass of one or more of the swing components. The controller may also be configured to variably control the amount of the swing drive holding torque exerted on the upper revolving car body relative to the lower traveling car body of the machine through friction components of the mechanical service brake interconnected with the upper and lower car bodies, with the variable control of the amount of swing drive holding torque being a function of one or more of the roll angle of the machine, the operational position and configuration of the swing component linkages, the inertial mass of one or more swing components, and the operator inputs.

In another aspect, the present disclosure is directed to an earth moving machine including a mechanical swing brake variable control system. The mechanical swing brake variable control system may include a pressure control device configured to control a variable pressure applied to a mechanical service brake on the machine in order to vary an amount of swing drive holding torque. The mechanical swing brake variable control system may include a controller configured to monitor and process signals received from sensors and operator inputs. The signals received from sensors may be indicative of one or more of machine roll angle, operational position and configuration of swing component linkages, and inertial mass of one or more of the swing components, with or without a payload. The controller may also be configured to variably control the amount of the swing drive holding torque exerted on the upper revolving car body relative to the lower traveling car body of the machine through friction components of the mechanical service brake interconnected with the upper and lower car bodies, with the variable control of the amount of swing drive holding torque being a function of one or more of the roll angle of the machine, the operational position and configuration of the swing component linkages, the inertial mass of one or more swing components, and the operator inputs.

In yet another aspect, the present disclosure is directed to a method of controlling the amount of holding torque exerted on an upper revolving car body of an earth-moving machine relative to a lower traveling car body of the machine during operation of swing components of the machine mounted on the upper revolving car body. The machine may include a plurality of sensors configured to generate signals indicative of machine roll angle, operational position and configuration of the swing components, inertial mass of one or more of the swing components, and operator control commands. The method may include using an electronic controller to receive and process the operator control commands and the signals from the sensors. The method may further include controlling a variable pressure applied to a mechanical service brake on the machine in order to vary the amount of holding torque exerted on the upper revolving car body relative to the lower traveling car body as a function of one or more of the machine roll angle, the operational position and configuration of the swing components mounted on the upper revolving car body of the machine, the inertial mass of one or more of the swing components, and the operator control commands.

Brief Description of the Drawings

Fig. 1 is a pictorial illustration of an exemplary disclosed earth-moving machine, which may be operated using a system and method for controlling the amount of holding torque exerted on an upper revolving car body of the machine relative to a lower traveling car body of the machine during operation of swing components of the machine mounted on the upper revolving car body, according to exemplary embodiments of this disclosure;

Fig. 2 is a diagrammatic illustration of an exemplary disclosed sensor fusion system for determining the state of the machine of Fig. 1;

Fig. 3 is a diagrammatic illustration of an exemplary application of the outputs from the sensor fusion system of Fig. 2 for providing real time information used in controlling operations and pose of the exemplary disclosed machine of Fig. 1;

Fig. 4 is a diagrammatic illustration of an exemplary application of the outputs from the sensor fusion system of Fig. 2 for providing boosted hydraulic pressure outputs during selected operations of the exemplary disclosed machine of Fig. 1;

Fig. 5 is a diagrammatic illustration of an exemplary implementation of a mechanical swing brake variable control system according to an embodiment of this disclosure; and

Fig. 6 is a diagrammatic illustration of an exemplary mechanical service brake hydraulic circuit operated by a mechanical swing brake variable control system according to an embodiment of this disclosure.

Detailed Description

Fig. 1 illustrates a machine 10 including a plurality of Inertial Measurement Units (IMU's) 24, 25, 26, and 27 applied at different positions on components or portions of the machine 10, such as on the upper revolving car body 14, the lower traveling car body 12, the boom 17, the stick 18, and the bucket (or other tool) 19. In a machine state control system according to various exemplary embodiments of this disclosure, the IMU's mounted on different components and/or portions of the machine 10 may replace or supplement conventional sensors such as pitch and roll sensors 32, cylinder position sensors 34, and rotary position sensors 36. Each IMU may include one or more accelerometers, one or more gyroscopes, and in some cases a magnetometer for providing signals indicative of direction relative to earth's magnetic poles. The accelerometers and gyroscopes of each IMU provide signals that can be used to discern the position and orientation of the IMU relative to a body frame of reference, and hence of the machine component to which the IMU is attached. The IMU's may provide a lower cost and more reliable alternative to traditional sensors such as position sensing cylinders and rotary position sensors, and may also be more easily retrofittable to existing machines by simply welding the

IMU's on different external portions of the machine without requiring disassembly of the machine or of components of the machine. A machine electronic control module (ECM) configured to send control signals to the various systems and subsystems of the machine may be reprogrammed and configured to receive signals from the retrofitted IMU's, with the signals being processed and converted to real time inputs used by the ECM to modify control signals based on the inputs.

Various non-IMU sensors 230 (see Fig. 2) may be added or removed depending on the particular machine application and configuration. The non-IMU sensors may include various perception sensors included as part of a vision system, position and/or velocity sensors, such as an upper structure position/velocity sensor 22, a laser catcher sensor 28 configured to provide a signal indicative of position as measured by a laser, a cylinder position sensor 34, hydraulic system sensors, electrical system sensors, braking system sensors, fuel system sensors, and other sensors providing real time inputs to the ECM for use in monitoring the status of and controlling the operation of the systems and subsystems of the machine.

In various exemplary embodiments according to this disclosure, a mechanical swing brake variable control system may monitor and responsively and controllably maintain the position of a swing mechanism including swing components such as boom 17, stick 18, and work tool 19 mounted on upper revolving car body 14 relative to lower traveling car body 12 of machine 10 such as the excavator illustrated in Fig. 1. When a machine with swing components, such as machine (excavator) 10 of Fig. 1, is operating on a cross slope or uneven terrain, the upper revolving car body with swing components such as boom 17, stick 18, and tool 19 may drift away from a speed and/or position they have been commanded to by a machine operator.

In some exemplary embodiments, a mechanical swing brake variable control system, such as shown in Fig. 5, may operate in parallel with a closed, hydrostatic loop fluidly connecting an independent, dedicated hydrostatic swing pump with one or more hydraulic motors operatively connected to upper revolving car body 14 of machine 10 in order to control the swing motion of boom 17, stick 18, and tool 19 mounted on the upper revolving car body relative to the undercarriage or lower traveling car body 12 of machine 10. A closed, hydrostatic loop may include a pressure control device in the form of a closed-loop control which adjusts pump displacement based on an overall system pressure. Hydrostatic loop pressure sensors may be configured to produce signals indicative of the resulting hydraulic fluid pressures on opposite sides of the hydrostatic swing pump.

In other exemplary embodiments, the mechanical swing brake variable control system may be configured to provide variable holding torque control of rotating movement of upper revolving car body 14 with swing components such as boom 17, stick 18, and work tool 19, relative to lower traveling car body 12. The variable holding torque of the mechanical swing brake variable control system may be implemented by variably controlling the pressure of hydraulic fluid applied to a brake piston in a mechanical service brake used to control relative rotational movement between upper revolving car body 14 and lower traveling car body 12. An electronic pressure relief valve or electronic pressure reducing valve (EPRV) with variable solenoid control may provide the desired pressure regulation. In various exemplary embodiments the variable solenoid control may include an initial determination of whether the particular machine includes an EPRV, and then when such a device is present on the machine, current command sequencing for the variable solenoid and control of a rate of change of pressure may be implemented.

The mechanical swing brake variable control system may provide variable control of the amount of mechanical service brake holding torque between upper revolving car body 14 and the lower traveling car body on an excavator. The variable control of the amount of mechanical holding torque (e.g., implemented by application of variable hydraulic fluid pressure directed through a spool valve actuated by the variable solenoid control to a piston that presses against a stack of friction plates and separator plates in a clutch pack) may be based on one or more of a linkage configuration for swing components on the machine, operator input commands, roll angle of the machine operating on a cross slope as detected by one or more sensors, and an inertial mass of one or more swing components with or without a payload, in conjunction with a mapping or calculation of the amount of holding torque needed for the machine operating on terrain with the detected amount of cross slope. The amount of holding torque generated by the mechanical service brake as controlled by this new control logic may be reduced or even turned completely off when the excavator is grounded and actually digging, or when a tool of the machine is in contact with a work surface, in order to avoid putting excessive torsional load on the swing drive components as a result of restrictions to relative rotational movement between the upper and lower car bodies.

The holding torque may be variably increased as necessary when the machine is operating on a cross slope in order to prevent undesired relative movement between the upper car body and the lower car body when the machine tool is not grounded and the swing components are in the air and not constrained by contact with a work surface. In an exemplary embodiment, the variable amount of holding torque may be determined based only on information indicative of the cross slope on which the machine is operating, as received, for example, from a chassis IMU mounted on upper revolving car body 14. In this exemplary embodiment, limiting the input information used in determining the amount of holding torque may also avoid potential errors in the determination of holding torque that could arise if there are multiple sensors involved with the resulting increase in the possibility of erroneous inputs. For example, while receiving input information from a variety of sensors, and then using a Kalman filter to fuse the data received from the sensors, as shown in Fig. 2, may enable a more accurate determination of the machine state in some situations, the multiple sensors may also introduce more instances of failed or inaccurate sensors, thus potentially leading to a more conservative determination of when the holding torque should be reduced to avoid potential damage to swing drive components.

An ECM configured to send control signals to the various systems and subsystems of the machine, or a completely separate and dedicated swing controller may be configured to receive and process, via control logic, signals from the IMU's and various non-IMU sensors positioned on machine 10 to determine the roll, angle, slope, and other information indicative of the position and orientation of machine 10, and the position and orientation of the swing components relative to upper revolving car body 14 and lower traveling car body 12 of machine 10. In some exemplary embodiments, an electronic controller may also be configured to receive and process signals indicative of anticipated inertia of swing component linkages such as boom 17, stick 18, and tool 19, with and without a payload. These signals indicative of anticipated inertia may include, for example, sensor-generated signals indicative of boom head-end pressures, in concert with, based upon, and/or as a function of the roll angle, slope, and positional orientation of machine 10.

When rotation or movement of upper revolving car body 14 and swing components such as boom 17, stick 18, and tool 19 on excavator 10, is commanded by a machine operator, a mechanical swing brake variable control system such as shown in Fig. 5 may be configured to engage and actuate variable holding torque control through a service brake configured to control the relative rotational movement between upper revolving car body 14 and lower traveling car body 12. Control of the swing mechanism in conjunction with control of a swing braking system may be based upon the foregoing positional and inertial information to prevent unintended and/or un-commanded acceleration, swinging, or movement, particularly when machine 10 is operating on a sloped or uneven surface. Alternatively, control of the swing mechanism by actuation of the mechanical swing brake variable control system may be based entirely on a measurement of the cross slope on which the machine is operating (and hence the roll angle of the machine).

In various alternative configurations, machine 10 may be configured to perform some type of operation associated with an industry such as mining, construction, farming, transportation, power generation, or any other industry known in the art. For example, machine 10 may be an earth moving machine such as a haul truck, a dozer, a loader, a backhoe, an excavator, a motor grader, a wheel tractor scraper or any other earth moving machine. Machine 10 may generally include track assemblies or other traction devices (i.e., ground engagement devices) that are mounted on lower traveling car body 12, which supports a rotating frame on which the upper revolving car body 14 forming an upper structure is mounted. The rotating frame and upper revolving car body 14 may support an operator station or cab, an integrated display 15 mounted within the cab, operator controls 16 (such as integrated joysticks mounted within the cab), and one or more engines and drive trains that drive the traction devices on lower traveling car body 12 to propel the machine 10. The boom 17 may be pivotally mounted at a proximal end to the upper revolving car body 14, and articulated relative to the upper revolving car body by one or more fluid actuation cylinders (e.g., hydraulic or pneumatic cylinders), electric motors, or other electro-mechanical components. The stick 18 may be pivotally mounted at a distal end of the boom 17 and articulated relative to the boom by one or more fluid actuation cylinders, electric motors, or other electro-mechanical components. The tool 19, such as a bucket, may be mounted at a distal end of the stick 18, optionally articulated relative to the stick 18 by one or more fluid actuation cylinders, electric motors, or other electro-mechanical components, and provided with ground engagement tools or other attachments for performing various tasks.

Fig. 2 is a block diagram of an exemplary embodiment of a mechanical swing brake variable control system. The sensor fusion system may be configured to provide accurate, real time outputs to a machine state control system 50 configured for controlling various operational aspects of the machine 10. Machine state control system 50 may be associated with or configured as an integral part of the machine electronic control module (ECM). Machine state control system 50 may also include a mechanical swing brake variable control system, illustrated in Fig. 5, to be used for controlling swing motion of the swing mechanism of machine 10. Alternative configurations may include the mechanical swing brake variable control system as an entirely separate and distinct control system including its own independent electronic controller. The sensor fusion system may be configured to receive signals from a plurality of IMU's 210 and additional non-IMU sensors 230, as well as signals indicative of various operator commands, such as signals generated by an operator's movement of a joystick, lever, or other input device or operator control 16. "Sensor fusion" is the combining of the sensory data or data derived from disparate sources such that the resulting information has less uncertainty than would be possible when the sources were used individually. The sensor fusion system may also be configured to receive information on the dimensional design of the particular machine with which the sensor fusion system is associated from a dimensional design information database 250 (see also 522 in Fig. 5). The particular dimensional design information received from the design information database 250, 522 for a particular machine may be used by a processor 241 associated with the sensor fusion system and configured for deriving the kinematics and dynamics of the machine 10 in conjunction with a kinematics library module 260 (see also 524 in Fig. 5) and/or through the empirical derivation of the kinematics and dynamics using physics-based equations and algorithms. The various sensors and processors may be connected to each other via any suitable architecture, including any combination of wired and/or wireless networks. Additionally, such networks may be integrated into any local area network (LAN), wide area network (WAN), and/or the Internet.

The IMU's 210 may be applied to the machine in multiple different positions and orientations, including on different portions of the upper revolving car body 14, the boom 17, the stick 18, and the work tool (e.g., the bucket) 19. The IMU's may be retrofitted at multiple positions and orientations along each of the portions of the machine, and may be added and removed depending on a particular machine application and configuration. Raw data received from each IMU may be processed through a Kalman filter. In some implementations the Kalman filter for each IMU sensor may be included as part of the IMU, and in other implementations the Kalman filter may be part of a separate sensor fusion module provided as part of a separate sensor fusion system.

Gyroscopes of each IMU sense orientation through angular velocity changes, while accelerometers of each IMU sense changes in direction with respect to gravity. The gyroscope measurements have a tendency to drift over time because they only sense changes and have no fixed frame of reference. The addition of accelerometer data allows bias in the gyroscope data to be minimized and better estimated to reduce propagating error and improve orientation readings. The accelerometers may provide data that is more accurate in static calculations, when the system is closer to a fixed reference point, while the gyroscopes are better at detecting orientation when the system is already in motion. Signals indicative of linear acceleration and angular rate of motion received from the accelerometers and gyroscopes of the IMU's associated with each of the different portions and/or components of the machine may be combined by the Kalman filter(s) to more accurately predict the output angle, velocity, and acceleration of each of the separate components of the machine.

The Kalman filter associated with each IMU mounted on a separate machine component takes measured values and finds estimates of future values by varying an averaging factor to optimize the weight assigned to estimated or predicted values as compared to the weight assigned to actual measured values, thereby converging on the best estimates of the true values for output joint angles, velocity, and acceleration for each component of the machine. The averaging factor is weighed by a measure of predicted uncertainty, sometimes called the covariance, to pick a value somewhere between the predicted and measured values. The Kalman filter estimates a machine state by using a form of feedback control in a recursive and iterative process, with each iteration including a time update or "predict" phase, and a measurement or "correct phase". During each iteration performed by the Kalman filter, a "gain" or weighting is determined by comparing an error in the estimate for a measured value and an error in the actual measurement of the value. The Kalman gain is equal to the ratio between the error in the estimate and the sum of the error in the estimate and the error in the actual measurement. A current estimate for the value is then calculated from the previous estimate and a new measured value. A new error in the estimate of the value is then determined and fed back for use in determining the gain to be applied in the next iteration. The combined or fused information provided by the Kalman filter may provide accurate, real time information on the angle of the cross slope on which the machine is operating, pitch rate, yaw rate, roll rate, boom angle, stick angle, and other angles depending on linkage configuration and the number of IMU’s installed on different portions or components of the machine.

As shown in the exemplary embodiment of Fig. 2, a Kalman filter of a sensor fusion system according to this disclosure may be configured to estimate bias of gyroscope information provided by the IMU’s, such as the pitch rate, the yaw rate, and the roll rate of each of the components. Because the linear positions and angular positions of points on each of the components are calculated by twice integrating linear accelerations and angular rates of motion from the IMU’s, the calculated information can drift over time, deviating more and more from the actual positions as small errors in the measurements are magnified by the integrations. Therefore, the gyroscope biasing aspect of the Kalman filter increases the accuracy of the joint angles calculated from the information provided by the IMU’s. The output joint angles for each of the individual portions or components of the machine may be fused with each other at a machine level in order to account for movement of two or more components relative to the machine while the two or more components remain in a substantially fixed orientation relative to each other. For example, both the IMU sensor 25 on the boom 17 of the machine 10 illustrated in Fig. 1, and the IMU sensor 26 on the stick 18 may indicate a change in output joint angles relative to a global reference frame when the boom 17 moves upwardly, however the actual angle between the boom 17 and the stick 18 may not have changed. Fusing the output joint angles for each of the boom 17 and the stick 18 at a machine level will provide this information so that actual positions of different points on the separate machine components relative to a machine reference frame and a global reference frame can be determined in real time. The accurate determination of actual, real time positions of different points on the separate machine components relative to a machine reference frame and a global reference frame also enables the input of accurate and timely information to the mechanical swing brake variable control system shown in Fig. 5, thus enabling very precise control and mitigation of any drift of swing components that may result from the effects of gravity on the swing components when machine 10 is operating on a slope or uneven surfaces.

As further illustrated in the exemplary embodiment of Fig. 2, the output joint angles that have been fused at the machine level by the Kalman filter 240 may be received by a kinematic library module 260. The kinematics library module 260 may be configured to receive the output joint angles from the Kalman filter(s) 240 and dimensional design information specific to the machine 10 from a dimensional design information database 250, and solve for a frame rotation and position at each component or point of interest on the machine. The frame can have offsets applied to the information derived from the IMU's in order to solve for any particular point on the machine, and all of the updated position information can be provided to machine state control system 50 and swing motion actuation and control system, which may be associated with or programmed as part of the machine ECM.

In the case of an excavator or other machine where IMU's may be mounted on portions of the machine that are rotated or swung through an arc during operation, the 3 dimensional position information associated with each of the IMU's mounted on those portions of the machine may also be fed back to a swing compensation module 220. The swing compensation module 220 may be configured to correct the acceleration information provided by the IMU's mounted on the rotating or swinging portions of the machine by compensating for centripetal acceleration. This correction of the acceleration information received from the IMU's 210 may be performed before the information is provided to the Kalman filter 240.

The additional non-IMU sensors 230 may include any devices capable of generating signals indicative of parametric values or machine parameters associated with performance of the machine 10. For example, the non-IMU sensors 230 may include sensors configured to produce signals indicative of boom and/or stick swing velocity, boom and/or stick position in global and machine reference frames, and work tool angle. A payload sensor may also be included and configured to provide a signal indicative of a payload of the machine 10. A slip detector may be included and configured to provide a signal indicative of a slip of the machine 100. Additional non-IMU sensors may include devices capable of providing signals indicative of a slope of the ground on which the machine 10 is operating, an outside temperature, tire pressure if the traction devices on lower traveling car body 12 are pneumatic wheels, hydraulic or pneumatic pressures in various fluid actuation control devices, electrical voltages, currents, and/or power being supplied to electrical control devices, etc.

The non-IMU sensors 230 may include one or more locating devices capable of providing signals indicative of the machine's location and/or the position of various components of the machine relative to a global or local frame of reference. For example, a locating device could embody a global satellite system device (e.g., a GPS or GNSS device) that receives or determines positional information associated with machine 10, and may provide an independent measurement of the machine's position. The locating device and any other non-IMU sensor 230 may be configured to convey signals indicative of the received or determined positional information, or other information relating to various machine operational parameters to one or more interface devices such as the integrated display 15 in the operator cab for display of real time machine operating characteristics. The signals from the IMU's 210 and non-IMU sensors 230 may be directed to a controller configured to include the Kalman filter 240, and the Kalman filter 240 may be configured for implementation by one or more processors 241 associated with storage 243 and memory 245. The one or more processors 241 of the controller may be configured to implement a Kalman filtering process including sensor fusion performed in a sensor fusion module 242. The Kalman filter 240 may also be configured to perform gyroscope bias estimation in a gyroscope bias estimation module 244 in order to compensate for any drift over time in the readings provided by one or more gyroscopes associated with the IMU's. In some exemplary embodiments, a locating device may receive a GPS signal as the location signal indicative of the location of the machine 10 and provide the received location signal to the processor 241 for further processing. Additionally, the locating device may also provide an uncertainty measure associated with the location signal. However, it will be understood by one of ordinary skill in the art that the disclosed exemplary embodiments could be modified to utilize other indicators of the location of the machine 10, if desired.

The non-IMU sensors 230 may also include one or more perception sensors, which may include any device that is capable of providing scene data describing an environment in the vicinity of the machine 10. A perception sensor may embody a device that detects and ranges objects located 360 degrees around the machine 10. For example, a perception sensor may be embodied by a LIDAR device, a RADAR (radio detection and ranging) device, a SONAR (sound navigation and ranging) device, a camera device, or another device known in the art. In one example, a perception sensor may include an emitter that emits a detection beam, and an associated receiver that receives a reflection of that detection beam. Based on characteristics of the reflected beam, a distance and a direction from an actual sensing location of the perception sensor on the machine 10 to a portion of a sensed physical object may be determined. By utilizing beams in a plurality of directions, the perception sensor may generate a picture of the surroundings of the machine 10. For example, if the perception sensor is embodied by a LIDAR device or another device using multiple laser beams, the perception sensor, such as the laser catcher sensor 28 mounted on the stick 18 of the machine, may generate a cloud of points as the scene data describing an environment in the vicinity of the machine 10. It will be noted that the scene data may be limited to the front side (180 degrees or less) of the machine 10 in some embodiments. In other embodiments, the perception sensor may generate scene data for objects located 360 degrees around the machine 10.

The IMU's 210 may include devices that provide angular rates and acceleration of the machine 10 or, more particularly, of components or portions of the machine on which the IMU's are mounted, such as the upper revolving car body 14, the boom 17, the stick 18, and the bucket or other tool 19. For example, the IMU's 210 may include a 6-degree of freedom (6 DOF) IMU. A 6 DOF IMU sensor consists of a 3-axis accelerometer, 3-axis angular rate gyroscopes, and sometimes a 2-axis inclinometer. Each of the IMU's 210 may be retrofitted to an existing machine by welding the IMU to a portion or component of the machine where precise information on the real time position, orientation, and motion of that particular portion or component of the machine is desired. The machine's electronic control module (ECM) or other machine controller(s) may be programmed to receive signals from the IMU's and implement various machine controls based at least in part on the inputs received from the IMU's. In some exemplary implementations of this disclosure, the controls implemented by an ECM in response to the signals received from the IMU's may include actuation of one or more electrical or electro-hydraulic solenoids that are configured to control the opening and closing of one or more valves regulating the supply of pressurized hydraulic or pneumatic fluid to one or more fluid actuation cylinders. In addition, or alternatively, as shown in Fig. 6, the controls may include actuation of a solenoid 602 that controls a spool valve 604 to regulate the flow of hydraulic fluid through a port 606 and pilot pressure manifold 603, through passages 605 and 607, and through a line 608 to a swing drive port 613 in a swing drive housing 609. The swing drive housing 609 may include a brake cylinder barrel 614 and a brake piston 615 in a piston chamber 612 of a service brake used to engage or disengage friction plates 610 and separator plates 611 in a clutch pack that controls relative motion between upper revolving car body 14 and lower traveling car body 12 of machine 10. The hydraulic fluid supplied to piston chamber 612 actuates brake piston 615 in one direction and a brake spring 616 actuates brake piston 615 in the opposite direction.

The Kalman filter module 240 may be associated with one or more of the processor 241, storage 243, and memory 245, included together in a single device and/or provided separately. The processor 241 may include one or more known processing devices, such as a microprocessor from the Pentium™ or

Xeon™ family manufactured by Intel™, the Turion™ family manufactured by AMD™, any of various processors manufactured by Sun Microsystems, or any other type of processor. The memory 245 may include one or more storage devices configured to store information used by the Kalman filter 240 to perform certain functions related to disclosed embodiments. The storage 243 may include a volatile or non-volatile, magnetic, semiconductor, tape, optical, removable, nonremovable, or other type of storage device or computer-readable medium or device. The storage 243 may store programs and/or other information, such as information related to processing data received from one or more sensors.

In one embodiment, the memory 245 may include one or more position estimation programs or subprograms loaded from the storage 243 or elsewhere that, when executed by the processor 241, perform various procedures, operations, or processes consistent with the disclosed embodiments. For example, the memory 245 may include one or more programs that enable the Kalman filter 240 to, among other things, collect data from an odometer, a locating device, a perception sensor, any one or more of the IMU's 210, and any one or more of the non-IMU sensors 230, and process the data according to disclosed embodiments, and estimate the position(s) of the machine 10 and various portions and components of the machine in real time based on the processed data.

In certain exemplary embodiments, position estimation programs may enable the Kalman filter 240 of the processor 241 to process the received signals to estimate the real time positions and orientations of different portions or components of the machine 10. A Kalman filter implements a method that may be used to determine accurate values of measurements observed over time, such as measurements taken in a time series. The Kalman filter's general operation involves two phases, a propagation or "predict" phase and a measurement or "update" phase. In the predict phase, the value estimate from the previous timestep in the time series is used to generate an *a priori* value estimate. In the update phase, the *a priori* estimate calculated in the predict phase is combined with an estimate of the accuracy of the *a priori* estimate (e.g., the variance or the uncertainty), and a current measurement value to produce a refined *a posteriori* estimate. The Kalman filter is a multiple-input, multiple output digital filter that can optimally estimate, in real time, the states of a system based on its noisy outputs. These states are all the variables needed to completely describe the system behavior as a function of time (such as position, velocity, voltage levels, and so forth). The multiple noisy outputs can be thought of as a multidimensional signal plus noise, with the system states being the desired unknown signals indicative of the true values for each of the variables. The Kalman filter 240 can be configured to filter the noisy measurements, such as the measurements received as signals from the plurality of IMU's 210 mounted on different portions and components of the machine 10, to estimate desired signals. The estimates derived by the Kalman filter from the signals provided by the IMU's and non-IMU sensors are statistically optimal in the sense that they minimize the mean-square estimation error of the signals. The state uncertainty estimate for the noisy measurements may be determined as a covariance matrix, where each diagonal term of the covariance matrix is the variance or uncertainty of a scalar random variable. A gain schedule module 222 may be configured to calculate weights (or gains) to be used when combining each successive predicted state estimate with a successive actual measurement value to obtain an updated "best" estimate. As the Kalman filter 240 receives multiple measurements over time from the IMU's 210 and the non-IMU sensors 230, a recursive algorithm of the Kalman filter processes each of the multiple measurements sequentially in time, iteratively repeating itself for each new measurement, and using only values stored from the previous cycle (thereby saving memory and reducing computational time).

In one exemplary embodiment, the memory 245 may include one or more pose estimation programs or subprograms loaded from storage 243 or elsewhere that, when executed by the processor 241, perform various procedures, operations, or processes consistent with disclosed embodiments. For example, the memory 245 may include one or more programs that enable the Kalman filter 240 to, among other things, collect data from the above-mentioned units and process the data according to disclosed embodiments such as those embodiments discussed with regard to Fig. 5, and determine a state of the machine 10 based on the processed data.

The Kalman filter is very useful for combining data from several different indirect and noisy measurements to try to estimate variables that are not directly measurable. For example, the gyroscopes of the IMU's measure orientation by integrating angular rates, and therefore the output signals from the gyroscopes may drift over time. The inclinometer and direction heading features (compass) of the IMU's may provide a different noisy, but drift-free measurement of orientation. In the exemplary embodiment of Fig. 2, the Kalman filter may be configured to weight the two sources of information appropriately using weights retrieved from a gain schedule module 222 to make the best use of all the data from each of the sources of information.

In determining the state of the machine 10 using the Kalman filter 240, the filter may also be configured to consider other operational parameters of the machine 10. For example, if the machine 10 is an excavator, the Kalman filter may be configured to consider whether the machine 10 is digging, dumping, swinging in between digging and dumping positions, driving to a new location, etc. When the machine 10 is in one or more of the above operational states, certain parameters of the Kalman filter may be changed to reflect the accuracy or confidence in certain input parameters. For example, when the machine 10 is driving from one location to another, the Kalman filter may be configured to apply a lower weighting (gain) from the gain schedule module 222 to the input from the IMU inclinometers. To lower the weighting applied to the inclinometer input from the IMU's, the Kalman filter may be configured to increase the value of variance 'R' associated with the inclinometer input in equation (3). Similarly, when the machine 10 is digging, the Kalman filter may be configured to increase the weighting applied to the inclinometer input to reflect a higher confidence in the accuracy of the inclinometer input. For example, to indicate a higher confidence in the accuracy, the Kalman filter may be configured to apply a higher weighting (gain) from the gain schedule module 222 to the input from the IMU inclinometers and decrease the value of ‘R’ associated with the inclinometer input.

With reference to the diagram of Fig. 5, in one exemplary implementation of a mechanical swing brake variable control system according to this disclosure, the control system may be configured to determine swing speed at one or more swing component swivel joints 502, acceleration of one or more swing components using signals provided by one or more IMU’s 504 mounted on the one or more swing components, with the measured values for swing speed and other values from the IMU’s or other sensors being optionally processed using sensor fusion 508 to accurately determine joint angles and swing speed, interpret inputs from one or more operator joysticks 506 through lever processing 510, and process dimensional design information 522, positional information, and kinematics data 524 specific to the machine or machine type on which the control system is operating. A swing brake torque electronic pressure reducing valve (EPRV) may produce a calibration current 528 and input that calibration current to one or more processors 542 configured to receive and process the calibration current along with information on the machine’s specific linkage configuration, determined machine roll angle, lever command signals from lever processing 510, and in some cases, the determined inertial mass of upper revolving carbody 14 or of the swing components mounted on the upper carbody. The one or more processors 542 may be configured to determine a variable swing brake holding torque from the above-described input information and target torque mapping or calculations based on physics-based equations and the lever commands, machine roll angle, linkage configuration, and upper carbody inertial mass, and output a target swing brake torque command. The mechanical swing brake variable control system according to embodiments of this disclosure may be further configured to determine the installation status 532 of an EPRV, which enables the variable control of hydraulic fluid pressures, determine on/off swing brake control state arbitration 534, and send this information to another processor 544 configured to determine current command control, including command sequencing and rate of change limiting, for a swing brake solenoid, which then generates a swing brake torque EPRV command in order to regulate the amount of holding torque that the mechanical swing brake will exert between upper revolving car body 14 and lower traveling car body 12.

Industrial Applicability

The disclosed machine state control system 50 and mechanical swing brake variable control system may be applicable to any machine or machine system benefiting from accurate, real time detection of the variables needed to completely describe the system behavior as a function of time (such as position, velocity, linear acceleration, and angular rate of motion of each machine component) and from accurate compensation and control of a swing mechanism to mitigate the effects of gravity on drifting of the swing components away from commanded positions. The disclosed sensor fusion system in conjunction with multiple IMU's and non-IMU sensors retrofittably attached to different portions or components of the machine may provide for improved estimation of the positions and orientations of all of the different machine components by utilizing a Kalman filter associated with each IMU mounted on each of a plurality of machine components.

In some exemplary implementations of the disclosed sensor fusion system, the Kalman filter 240 may utilize machine parameters, odometer signals, and IMU inputs received from IMU's mounted on various portions and components of the machine to propagate or "predict" the machine states. For example, the Kalman filter 240 may predict the following states: position, forward velocity, angular velocities, joint angles, and angular orientation (attitude) of each of the machine components relative to global and machine reference frames, and of the machine itself relative to a global reference frame. In addition to the signals indicative of acceleration and angular rate of motion received from each IMU, each of the Kalman filters associated with each IMU mounted on a different machine component may receive, from a variety of different non-IMU sensors, such as an odometer, proximity sensors, and other perception sensors, signals indicative of the distance moved by the component of the machine during operation, or the distance between the component of the machine and a potential obstacle. The Kalman filter may also calculate the distance traveled by the machine 10 itself by multiplying a received scale factor by the number of rotations of a traction device. The Kalman filter may also calculate velocity of the machine 10 or velocity of a portion or component of the machine by integrating a signal indicative of linear acceleration from an IMU sensor mounted on a particular portion or component of the machine. The Kalman filter may calculate the velocity of the machine or the portion or component of the machine on which one or more IMU's are mounted using signals from the IMU's and weighting the resulting velocities to generate a predicted velocity. In some implementations, the distance traveled by the machine itself may be adjusted to account for slipping of the machine. Each Kalman filter may also receive signals indicative of the angular rates of motion (roll rate, yaw rate, and pitch rate) of the machine or portion of the machine from one or more IMU's. By integrating the angular rates of motion, the Kalman filter 240 may determine the attitude or angular orientation (roll, heading, and pitch) of each machine component or of the machine itself.

The Kalman filter may utilize one or more of the propagated states to propagate or "predict" the position of the machine 10 or the position of a portion or component of the machine relative to a machine reference frame and relative to a global reference frame. For example, by utilizing the angular rates of motion and predicted velocities, the Kalman filter may predict a position of the machine or component of the machine. The Kalman filter may also calculate an uncertainty for the predicted position that may be set equal to the uncertainty as designated by an error covariance matrix of the Kalman filter. Various positions on the machine may also be determined independently from the IMU's. Having determined the independent position measurements, the Kalman filter may be configured to fuse the predicted position information and the independent position measurement to determine updated position estimates for each location. Kalman filter measurement update equations may be utilized to determine the updated position estimate. Having determined an updated position estimate for the machine 10, the Kalman filter 240 may also determine the biases for each of the IMU's. As discussed above, an example of a bias parameter estimation that may be performed by the Kalman filter is an estimation of the bias of gyroscope determined angular positions after integration of measured angular rates.

In one exemplary application of the machine state control system according to an implementation of this disclosure, accurate, updated, real time information on the positions and orientations (pose) of the machine and portions or components of the machine may provide feedback to an information exchange interface 350 in order to effect machine controls that achieve optimal positioning and operation of the machine and components of the machine for improved productivity and reliability. In some implementations, the feedback may assist an operator by coaching the operator on how to effect controls that result in improved machine footing and stability, and hence improved productivity. In other implementations the information received at the information exchange interface 350 may result in the generation of autonomous or semi-autonomous control command signals that are provided to various machine systems and subsystems for effecting changes in machine pose and changes in the relative positions and orientations of machine components. In one exemplary implementation, as shown in Fig. 3, sensor feedback from machine sensors regarding machine linkage positions and velocity, machine pitch rate and roll rate, and swing angle for a boom and stick of an excavator may be fused with signals provided by a vision system and perception sensors 320 indicative of the locations of obstacles or other features at a job site, and signals received from various operator controls 324. The fused data may be provided to the information exchange interface 350 in order to effect the generation of control command signals that change the operation of various solenoid actuators, throttle controls, fluid cylinder actuation devices, electrical controls, and motion control devices to result in the optimal positioning of the machine during a digging operation. The information exchange interface 350 may provide accurate and real time updated information to a human operator in some implementations, as well as acting as an information interface with autonomous or semi-autonomous control systems that use the information to process control command signals for operating various machine systems and machine subsystems automatically or semi-automatically.

In digging with an excavator, the machine state control system 50 may determine from historical and/or empirical data regarding the kinematics and dynamics for the excavator that the car body of the machine should be parallel to the digging linkages with the idler wheels for the tracks of the excavator pointed toward the front linkages for the best stability during digging. Feedback can also be provided to the information exchange interface 350 regarding the machine pitch and roll so that if the footing is poor underneath the idler wheels when the tracks of the excavator are pointed forward, the information exchange interface can result in the generation of control command signals that cause a change in the pose of the machine to improve the footing and prevent the machine from pitching and rolling, as well as maneuvering the machine to make full contact with the ground to counteract digging forces. The angle of the bucket or other tool and the leverage being achieved by the particular orientation of the stick and boom at any particular point in time during a digging operation can also impact the digging efficiency of the excavator.

The mechanical swing brake variable control system according to this disclosure may provide continually updated feedback information to the information exchange interface regarding the real time efficiency of a linkage position during digging. The feedback information may result in a change to the angle of the bucket or the position of the stick during excavation in order to improve the efficiency of the machine by achieving better loading of the bucket, quicker loading of the bucket, and/or improved kinematics of the linkages that will result in a better use of the machine power and improve the longevity of the machine. The information provided to the information exchange interface from the machine state control system may also result in a change in control command signals that cause a change in the pose of the machine to avoid digging with the car body oriented at 90 degrees to the linkage, which is not optimal for stability or digging. When machine controls respond to the information provided at the information exchange interface 350 to implement controls such that the car body of the machine is parallel to the digging linkages with the idler wheels for the tracks of the excavator pointed toward the front linkages, the result is that energy is not wasted lifting the machine off the ground, productivity rates are increased with the resulting reduced cycle times, and loads on the final drive components are reduced for improved longevity of the machine and reduced down time.

Various exemplary implementations of this disclosure may include a method of controlling the amount of holding torque exerted on an upper revolving car body of an earth-moving machine relative to a lower traveling car body of the machine during operation of swing components of the machine mounted on the upper revolving car body. The machine may include a plurality of sensors configured to generate signals indicative of machine roll angle, operational position and configuration of the swing components, inertial mass of one or more of the swing components, and operator control commands. The method may include using an electronic controller to receive and process the operator control commands and the signals from the sensors. The method may further include controlling a variable pressure applied to a mechanical service brake on the machine in order to vary the amount of holding torque exerted on the upper revolving car body relative to the lower traveling car body as a function of one or more of the machine roll angle, the operational position and configuration of the swing components mounted on the upper revolving car body of the machine, the inertial mass of one or more of the swing components, and the operator control commands.

In another exemplary application of the machine state control system according to this disclosure, as shown in Fig. 4, the sensor fusion system may receive, combine, and process operator command inputs received from operator controls 324 with inputs from IMU's and non-IMU machine sensors that measure linkage position, fluid pressures, engine speed, machine and machine component positions and orientations (including pitch rate, yaw rate, and roll rate), inputs from a vision system 320 that includes perception sensors providing signals indicative of the presence and location of objects, and inputs from hydraulic system sensors 430. In some implementations, the signal inputs from the hydraulic system sensors may be indicative of conditions under which higher pressures for fluid actuation cylinders are needed to avoid stalling. In order to avoid unnecessary stresses on the machine, components, and structures, the machine state control system 50 may be configured to automatically adjust boost pressures of hydraulic pumps 450 and command a controlled ramp up in relief pressure set points for one or more relief valves 425 if possible without causing damage to the machine or creating instabilities. The fused sensor outputs from the sensor fusion system according to various embodiments of this disclosure allow the machine state control system to determine when the machine may be stalling or about to stall during a lifting or digging operation. The machine state control system may then determine when and how much to boost relief pressure settings for the relief valve(s) 425 based on the fused sensor feedback information in combination with operator commands.

In one exemplary implementation, an excavator may be lifting a heavy load or performing a digging operation, and the boom actuation cylinder(s) may be at their maximum pressure, with the pump output pressure equal to the pressure in the boom actuation cylinders and the boom stalled while the bucket and stick are still moving. The machine state control system can determine from the accurate, real time fused sensor data being received from the sensor fusion system, including data indicative of the pitch rate, and roll rate for the machine, whether the machine is in an unstable and/or overstressed state. The machine state control system may determine that the relief pressure for the boom actuation cylinder(s) can be increased in a controlled ramp up to get the boom moving again without exceeding acceptable stress levels, and while maintaining the stability of the machine. Additionally, stress levels on the various swing drive components during digging operations may be controlled through implementation of a mechanical swing brake variable control system according to embodiments of this disclosure. The mechanical swing brake variable control system may use a pressure control device to control a variable pressure applied to a mechanical service brake on the machine in order to vary an amount of swing drive holding torque. The control system may monitor and process signals received from sensors and operator inputs. The signals received from sensors may be indicative of one or more of machine roll angle, operational position and configuration of swing component linkages, and inertial mass of one or more of the swing components. The control system may also variably control the amount of the swing drive holding torque exerted on the upper revolving car body relative to the lower traveling car body of the machine through friction components of the mechanical service brake interconnected with the upper and lower car bodies, with the variable control of the amount of swing drive holding torque being a function of one or more of the roll angle of the machine, the operational position and configuration of the swing component linkages, the inertial mass of one or more swing components, and the operator inputs.

In additional exemplary implementations of the machine state control system according to this disclosure, the machine state control system may output commands to adjust the maximum output pressure of a pump providing pressurized fluid to various fluid actuation cylinders on the machine. As shown in Fig. 4, the machine state control system 50 receives the fused sensor data from the sensor fusion system, including operator inputs, measured linkage positions, fluid pressures, engine speeds, machine pitch rates and roll rates, and scene data such as the presence and location of objects. The machine state control system may determine what operations are being conducted, and adjust the maximum pressures allowed in the system electronically through high pressure cut offs that are established for different operations. The system can thereby prevent excessive stresses on various components and structures of the machine, and also prevent over-torqueing of the components or slamming of the components into objects at high rates of speed by slowing down pump flow, varying swing motor displacement, variably controlling the amount of holding torque exerted by the mechanical service brake, or overriding valve commands received from operator inputs. For components of a machine such as the boom and stick of an excavator, which may include an associated dedicated hydraulic swing circuit for moving the boom and stick between digging and dumping positions, the hydraulic pressure in the swing circuit or swing motor displacement can be electronically limited in accordance with real time output commands received from the machine state control system. In some implementations, one or more pumps provided in the swing circuit or other hydraulic circuits on the machine may be adaptable to a zero displacement or near-zero displacement operational configuration. The machine state control system 50 may determine what operations are being conducted, and adjust the displacement of the one or more pumps to a zero or near-zero displacement in certain situations. The displacement of the one or more pumps may be adjusted to a low enough value that only leakage of the system is compensated for, and movement of a linkage by a fluid actuation cylinder supplied by the pump or pumps in a very low displacement mode will not result in overstressing of the linkage or other machine components. In addition to or as an alternative to overriding valve commands or other control commands received from operator inputs in a semi-autonomous mode, the machine state control system 50 may provide feedback directly to an operator through one or more displays associated with the information exchange interface 350, or through haptic feedback in joysticks, the operator seat, heads-up displays (HUD) projected onto a windshield of the operator cab, or through sounds and other stimuli implemented to coach the operator and improve future operational control commands.

It will be apparent to those skilled in the art that various modifications and variations can be made to the disclosed mechanical swing brake variable control system. Other embodiments and implementations will be apparent to those skilled in the art from consideration of the specification and practice of the disclosed machine state control system. It is intended that the specification and examples be considered as exemplary only, with a true scope being indicated by the following claims and their equivalents.

Claims

1. A mechanical swing brake variable control system for an earth-moving machine including an upper revolving car body (14) with swing components (17, 18, 19) mounted on the upper revolving car body (14), a lower traveling car body (12) with traction components mounted on the lower traveling car body (12), and a mechanical service brake interconnected with the upper and lower car bodies to control relative rotation between the upper and lower car bodies, the control system comprising:

a pressure control device (602) configured to control a variable pressure applied to the mechanical service brake on the machine in order to vary an amount of swing drive holding torque; and

an electronic controller (241, 542) configured to:

monitor and process signals received from sensors (210, 230) associated with the swing components and machine operator commands, wherein the signals received from the sensors are indicative of one or more of a machine roll angle, an operational configuration of linkages of the swing components, and inertial mass of the swing components, and

variably control the amount of holding torque exerted on the upper revolving car body (14) relative to the lower traveling car body (12) of the machine through friction components of the mechanical service brake interconnected with the upper and lower car bodies, wherein the variable control of the amount of holding torque is a function of one or more of the machine roll angle, the operational configuration of the linkages of the swing components, the inertial mass of the swing components, and the machine operator commands.

2. The mechanical swing brake variable control system of claim 1, wherein the controller (241, 542) is configured to determine the value of the variable holding torque from a map of target holding torques for a plurality of different machines operating on a plurality of different cross slopes.

3. The mechanical swing brake variable control system of claim 1, wherein the controller (241, 542) is configured to determine the value of the variable holding torque from a calculation of target holding torques using physics-based equations.

4. The mechanical swing brake variable control system of claim 1, wherein the controller (241, 542) is configured to variably control the amount of holding torque exerted on the upper revolving car body (14) relative to the lower traveling car body (12) of the machine by controlling a flow of hydraulic fluid using a swing brake solenoid (544, 602) to a cylinder (614) and a piston chamber (612) housed within a swing drive housing (609) to actuate a brake piston (615) within the piston chamber (612) configured to apply and release a variable braking force to the friction components (610) of the mechanical service brake, generating a variable holding torque between the upper car body (14) and the lower car body (12).

5. The mechanical swing brake variable control system of claim 4, wherein the controller (241, 542) is further configured to variably control the amount of holding torque exerted on the upper revolving car body (14) relative to the lower traveling car body (12) based at least in part on the signals indicative of the operational configuration of the linkages of the swing components on the machine.

6. The mechanical swing brake variable control system of claim 4, wherein the controller (241, 542) is further configured to variably control the amount of holding torque exerted on the upper revolving car body (14) relative to the lower traveling car body (12) based at least in part on the machine operator commands.

7. The mechanical swing brake variable control system of claim 6, wherein the machine operator commands include one or more of a travel

right lever command, a travel left lever command, a boom lever command, a stick lever command, or a bucket lever command.

8. The mechanical swing brake variable control system of claim 1, wherein the controller (241, 542) is further configured to monitor and process signals indicative of one or more of swing speed or acceleration of the upper revolving car body (14) or the swing components mounted on the upper revolving car body, dimensional design information and kinematics of the swing components, payload carried by one or more of the swing components, and the inertial mass of one or more of the swing components.

9. The mechanical swing brake variable control system of claim 4, wherein the controller (241, 542) is further configured to generate a target swing brake torque command and send the torque command to the swing brake solenoid (544, 602) in the form of a current command controlled at a particular sequence and with a predetermined rate of change calculated to control the flow of hydraulic fluid to the cylinder and the piston chamber to generate the target swing brake torque.

10. An earth moving machine comprising:

an upper revolving car body (14) with swing components mounted on the upper revolving car body;

a lower traveling car body (12) with traction components mounted on the lower traveling car body;

a mechanical service brake interconnected with the upper and lower car bodies to control relative rotation between the upper and lower car bodies; and

an electronic control system (241, 542) comprising:

a pressure control device configured to control a variable pressure applied to the mechanical service brake on the machine in order to vary an amount of swing drive holding torque between the upper revolving car body and the lower traveling car body; and

an electronic controller configured to:

monitor and process signals received from sensors associated with the swing components and machine operator commands, wherein the signals received from the sensors are indicative of one or more of a machine roll angle, an operational configuration of linkages of the swing components, and inertial mass of the swing components, and

variably control the amount of holding torque exerted on the upper revolving car body relative to the lower traveling car body of the machine through friction components (610) of the mechanical service brake interconnected with the upper and lower car bodies, wherein the variable control of the amount of holding torque is a function of one or more of the machine roll angle, the operational configuration of the linkages of the swing components, the inertial mass of the swing components, and the machine operator commands.

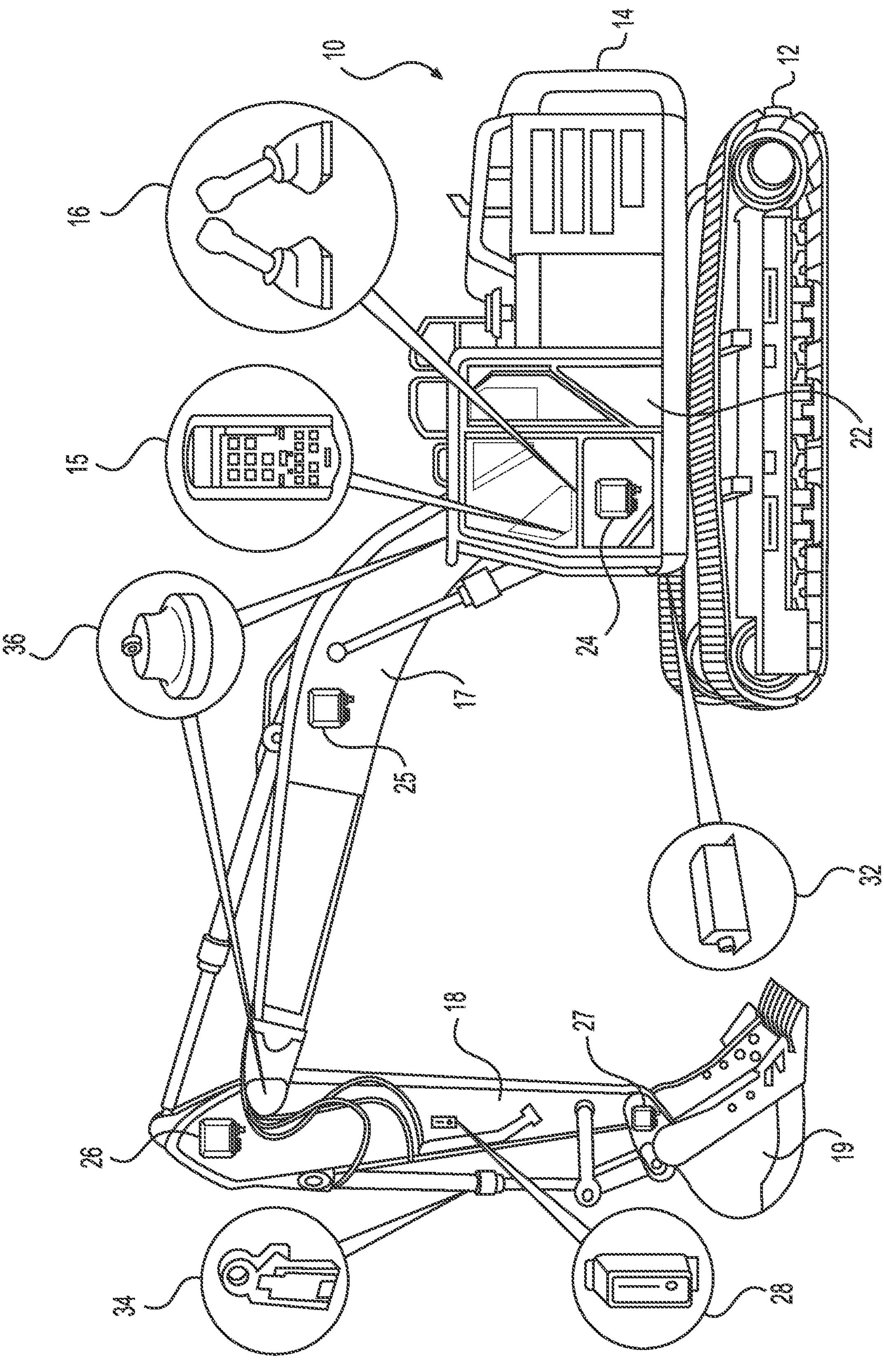


FIG. 1

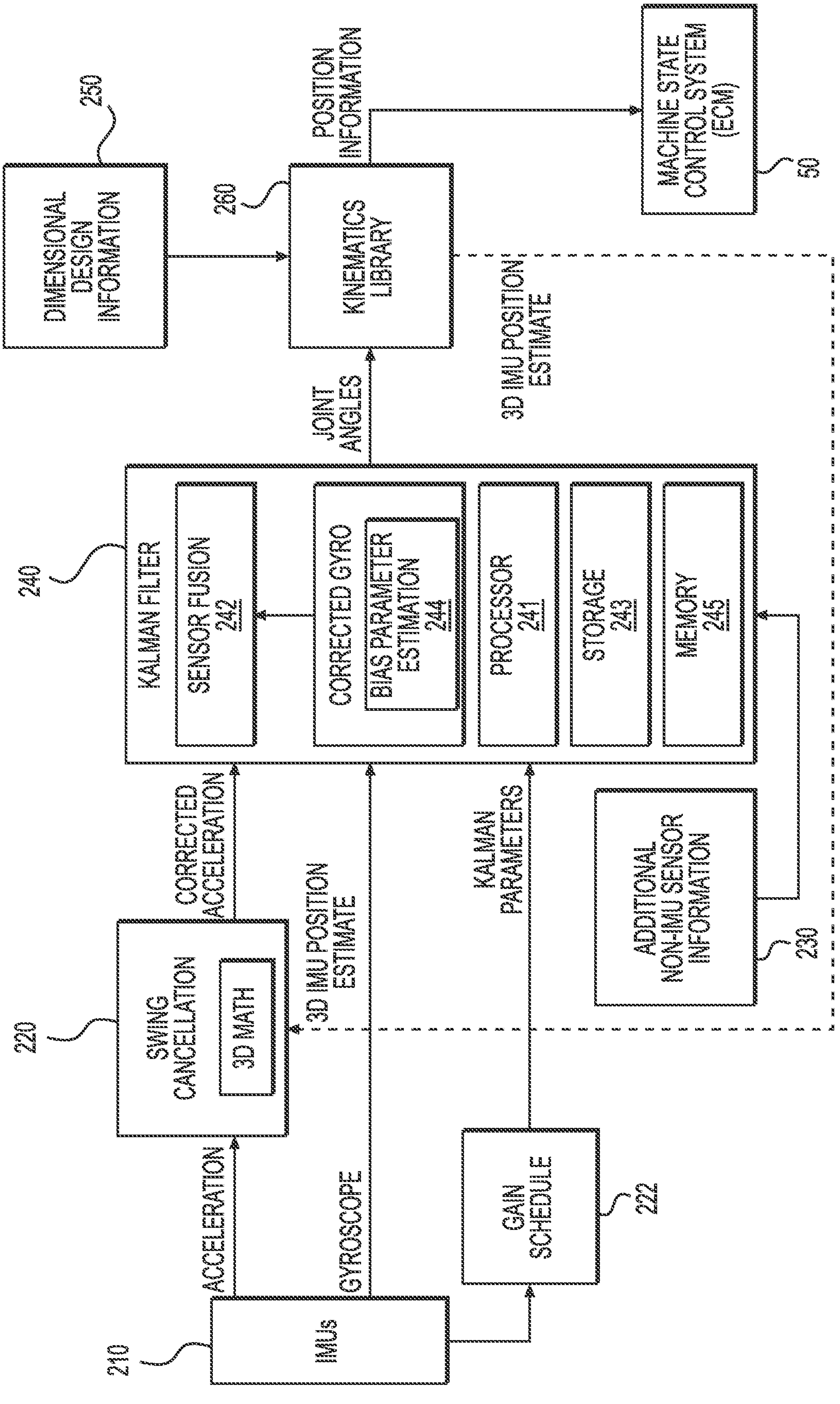
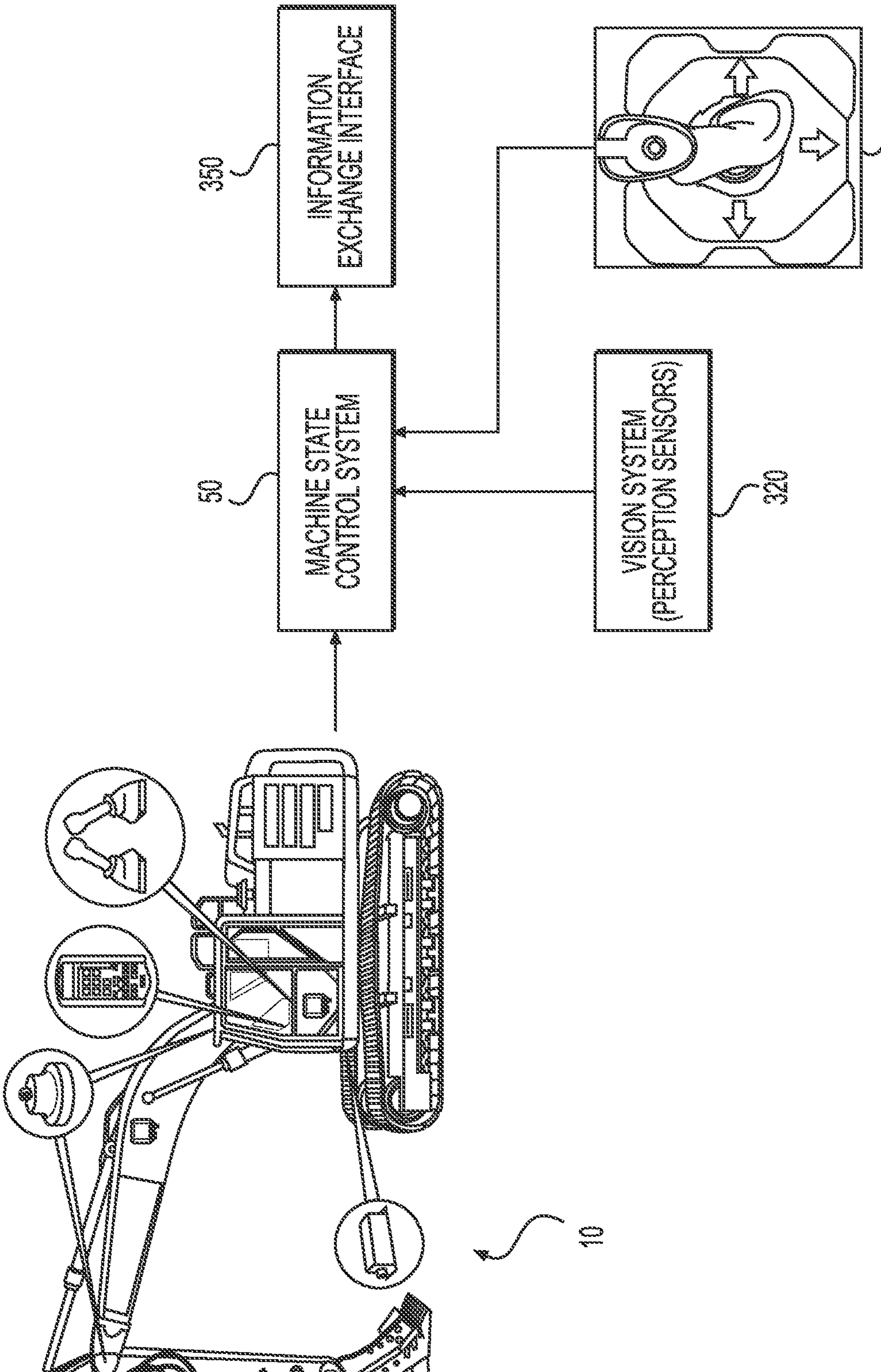

IMUs
210
ACCELERATION
GYROSCOPE
SWING CANCELLATION
3D MATH
220
GAIN SCHEDULE
222
CORRECTED ACCELERATION
3D IMU POSITION ESTIMATE
KALMAN PARAMETERS
ADDITIONAL NON-IMU SENSOR INFORMATION
230
KALMAN FILTER
240
SENSOR FUSION 242
CORRECTED GYRO
BIAS PARAMETER ESTIMATION 244
PROCESSOR 241
STORAGE 243
MEMORY 245
JOINT ANGLES
3D IMU POSITION ESTIMATE
DIMENSIONAL DESIGN INFORMATION
250
KINEMATICS LIBRARY
260
POSITION INFORMATION
MACHINE STATE CONTROL SYSTEM (ECM)
50

FIG. 2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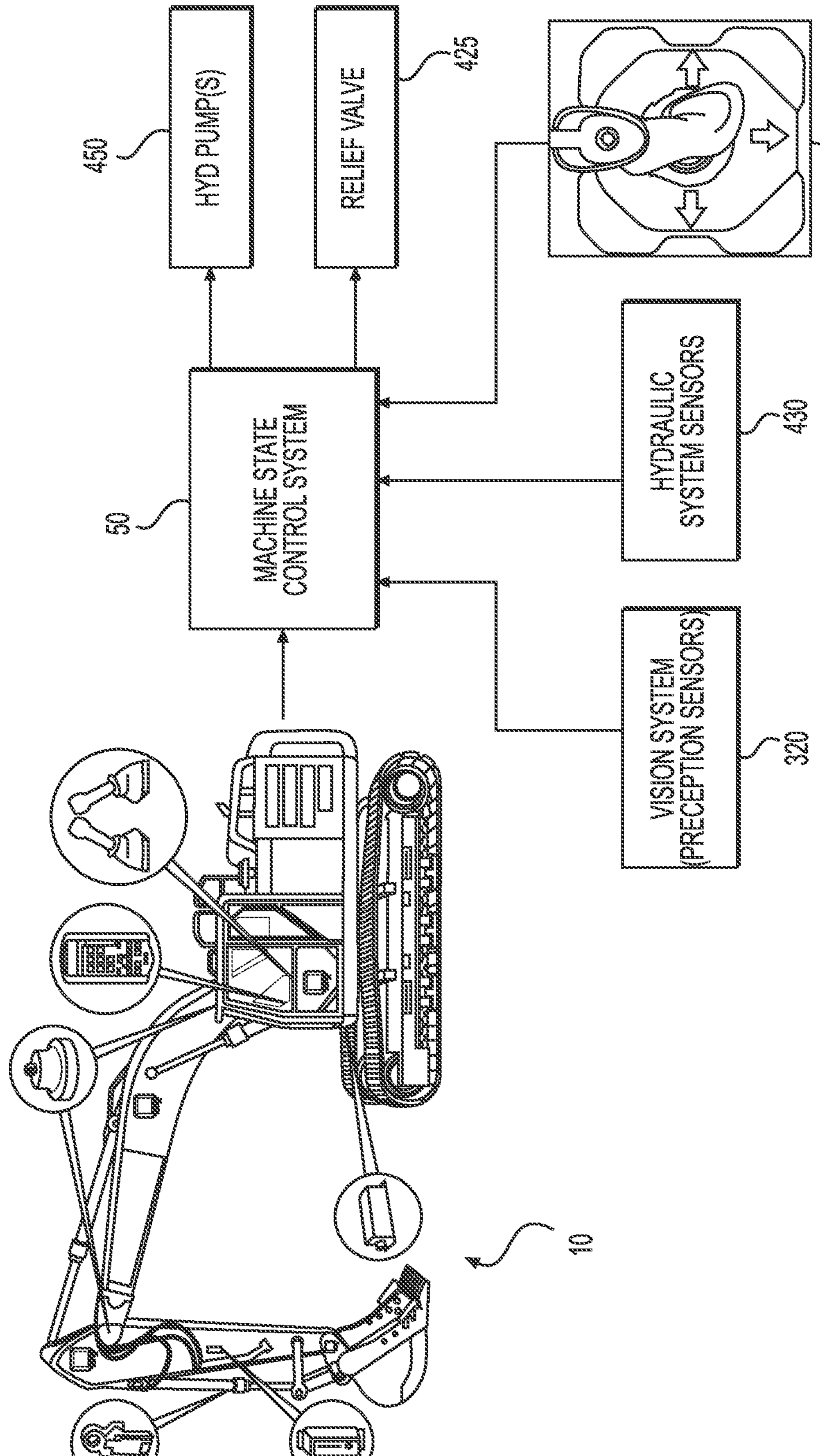
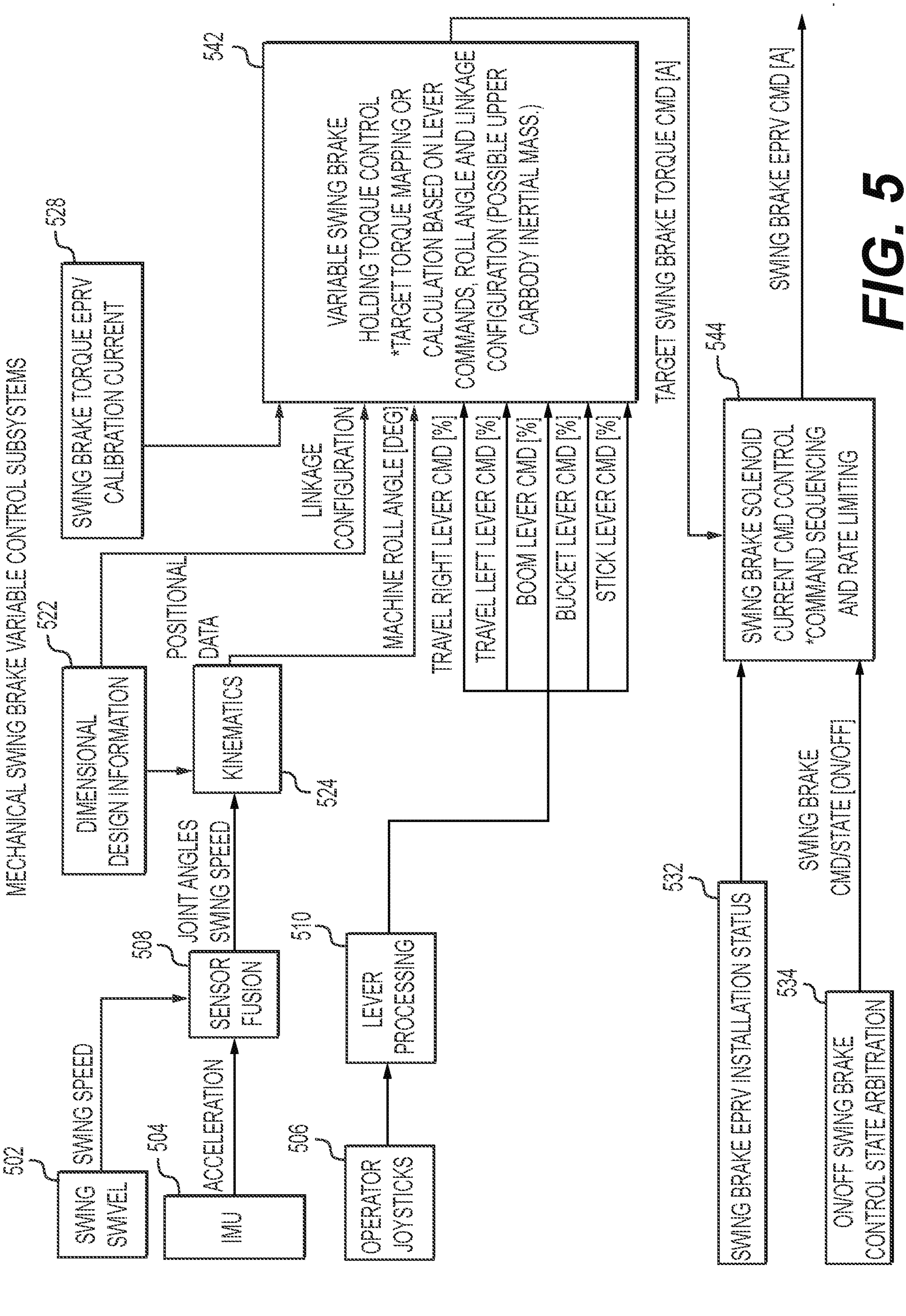
INFORMATION EXCHANGE INTERFACE
50
MACHINE STATE CONTROL SYSTEM
VISION SYSTEM (PERCEPTION SENSORS)
320
324
10

FIG. 3



HYD PUMP(S)
450
RELIEF VALVE
425
324
MACHINE STATE CONTROL SYSTEM
50
HYDRAULIC SYSTEM SENSORS
430
VISION SYSTEM (PRECEPTION SENSORS)
320
10

FIG. 4


MECHANICAL SWING BRAKE VARIABLE CONTROL SUBSYSTEMS
502
SWING SWIVEL
SWING SPEED
504
IMU
ACCELERATION
506
OPERATOR JOYSTICKS
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SENSOR FUSION
JOINT ANGLES SWING SPEED
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DIMENSIONAL DESIGN INFORMATION
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KINEMATICS
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528
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TRAVEL LEFT LEVER CMD [%]
BOOM LEVER CMD [%]
BUCKET LEVER CMD [%]
STICK LEVER CMD [%]
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ON/OFF SWING BRAKE CONTROL STATE ARBITRATION
SWING BRAKE CMD/STATE [ON/OFF]
544
SWING BRAKE SOLENOID CURRENT CMD CONTROL *COMMAND SEQUENCING AND RATE LIMITING
SWING BRAKE EPRV CMD [A]

FIG. 5

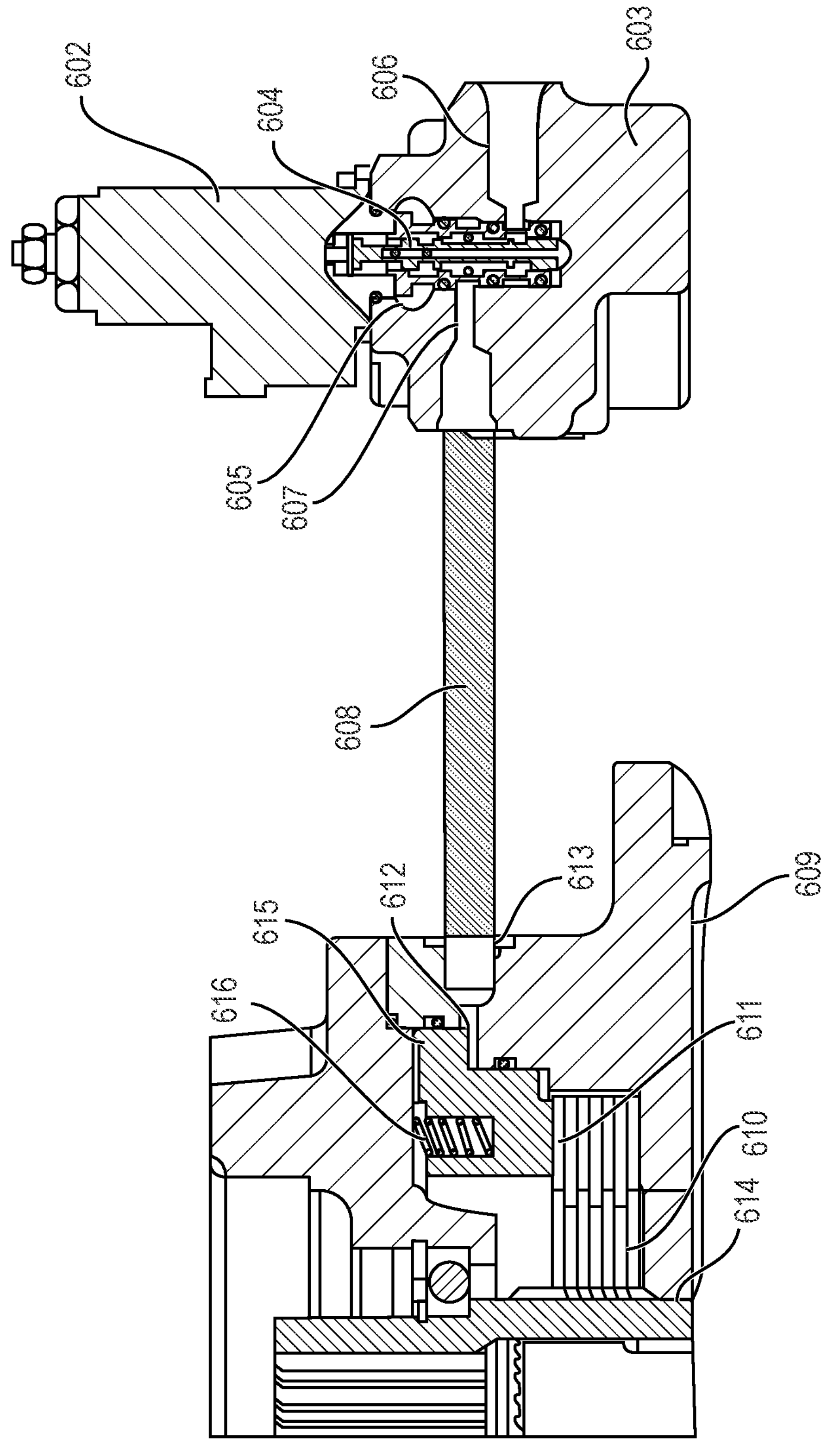

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/029034

A. CLASSIFICATION OF SUBJECT MATTER
INV. E02F9/12
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 104 912 150 A (SUMITOMO HEAVY INDUSTRIES) 16 September 2015 (2015-09-16) abstract; figures 1-8 -----	1-10
A	CN 111 247 296 A (KOBELCO CONSTR MACH CO LTD) 5 June 2020 (2020-06-05) abstract; figures 1-4 -----	1-10
A	WO 2009/051247 A1 (SUMITOMO HEAVY INDUSTRIES [JP] ET AL.) 23 April 2009 (2009-04-23) abstract; figures 1-6 -----	1-10
A	WO 2015/046901 A1 (DOOSAN INFRACORE CO LTD [KR]) 2 April 2015 (2015-04-02) abstract; figures 1-4 -----	1-10
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
28 August 2024	09/09/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Faymann, L

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Form PCT/ISA/210 (second sheet) (April 2005)

International application No
PCT/US2024/029034

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 366 805 A1 (KOMATSU MFG CO LTD [JP]) 9 May 1990 (1990-05-09) abstract; figures 1-5 -----	1-10
A	CN 102 762 798 A (DOOSAN INFRACORE CO LTD) 31 October 2012 (2012-10-31) abstract; figures 1-6 -----	1-10

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2024/029034

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
CN 104912150	A	16-09-2015	CN 104912150	A	16-09-2015
			JP 6628958	B2	15-01-2020
			JP 2015175092	A	05-10-2015
			US 2015259879	A1	17-09-2015
CN 111247296	A	05-06-2020	CN 111247296	A	05-06-2020
			EP 3690149	A1	05-08-2020
			JP 6981186	B2	15-12-2021
			JP 2019085791	A	06-06-2019
			US 2020340211	A1	29-10-2020
			WO 2019093070	A1	16-05-2019
WO 2009051247	A1	23-04-2009	CN 102124166	A	13-07-2011
			EP 2208829	A1	21-07-2010
			JP 5653041	B2	14-01-2015
			JP WO2009051247	A1	03-03-2011
			KR 20100072259	A	30-06-2010
			US 2010222970	A1	02-09-2010
			WO 2009051247	A1	23-04-2009
WO 2015046901	A1	02-04-2015	KR 20160045743	A	27-04-2016
			WO 2015046901	A1	02-04-2015
EP 0366805	A1	09-05-1990	EP 0366805	A1	09-05-1990
			KR 900700701	A	16-08-1990
			WO 8909310	A1	05-10-1989
CN 102762798	A	31-10-2012	CN 102762798	A	31-10-2012
			KR 20110074311	A	30-06-2011
			US 2013008155	A1	10-01-2013
			WO 2011078587	A2	30-06-2011