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(54) **SYSTEM FOR ESTIMATING A SENSOR OUTPUT**

(71) Applicant: **Caterpillar Inc.**, Peoria, IL (US)

(72) Inventors: **Santosh Ancha**, Peoria, IL (US);
Aleksandar Egelja, Peoria, IL (US);
Hongliu Du, Peoria, IL (US); **Takayuki Sasaki**, Peoria, IL (US)

(73) Assignee: **Caterpillar Inc.**, Peoria, IL (US)

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CPC *F15B 19/005* (2013.01); *E02F 9/2278* (2013.01); *F15B 19/007* (2013.01); *F15B 2211/20523* (2013.01); *F15B 2211/20546* (2013.01); *F15B 2211/20576* (2013.01); *F15B 2211/633* (2013.01); *F15B 2211/6309* (2013.01); *F15B 2211/6333* (2013.01); *F15B 2211/6652* (2013.01); *F15B 2211/855* (2013.01); *F15B 2211/862* (2013.01); *F15B 2211/87* (2013.01); *F15B 2211/8752* (2013.01)

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USPC 73/168, 798
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,267,441 A		12/1993	Devier et al.	
5,307,631 A	*	5/1994	Tatsumi	E02F 9/2228 60/452
5,337,629 A	*	8/1994	Kita	B60W 10/06 475/72
5,944,492 A		8/1999	Konishi et al.	

(Continued)

OTHER PUBLICATIONS

U.S. Appl. No. 14/599,238, filed Jan. 16, 2015, Du; Hongliu et al.

Primary Examiner — Max Noori
(74) *Attorney, Agent, or Firm* — Caterpillar Inc.; James Bennin

(57) **ABSTRACT**

A system for determining an estimated output from a variable displacement hydraulic pump includes a prime mover, a torque sensor, a pressure sensor, and a displacement sensor. A controller is configured to determine the output torque from the prime mover, determine an input torque to the variable displacement hydraulic pump based upon the output torque, determine an output from one of the pressure sensor and the displacement sensor based upon the signals. The controller is further configured to determine a failure of another of the pressure sensor and the displacement sensor and determine an estimated output from the another of the pressure sensor and the displacement sensor based upon the input torque to the variable displacement hydraulic pump and the output from the one of the pressure sensor and the displacement sensor.

20 Claims, 6 Drawing Sheets
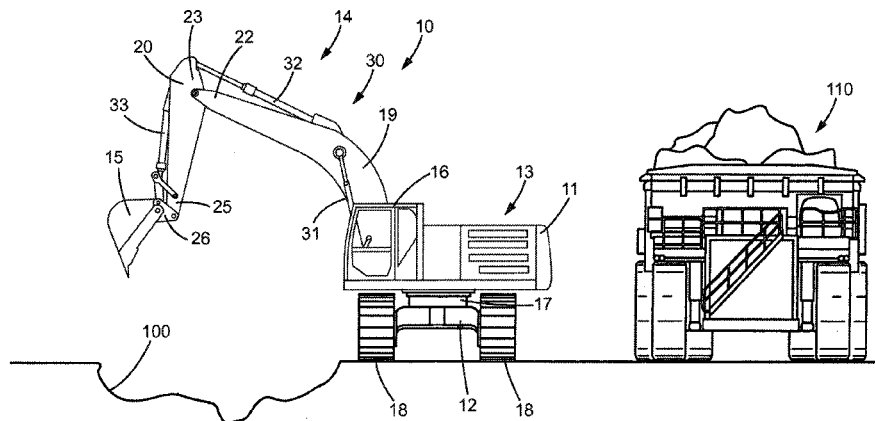
(56) **References Cited**

U.S. PATENT DOCUMENTS

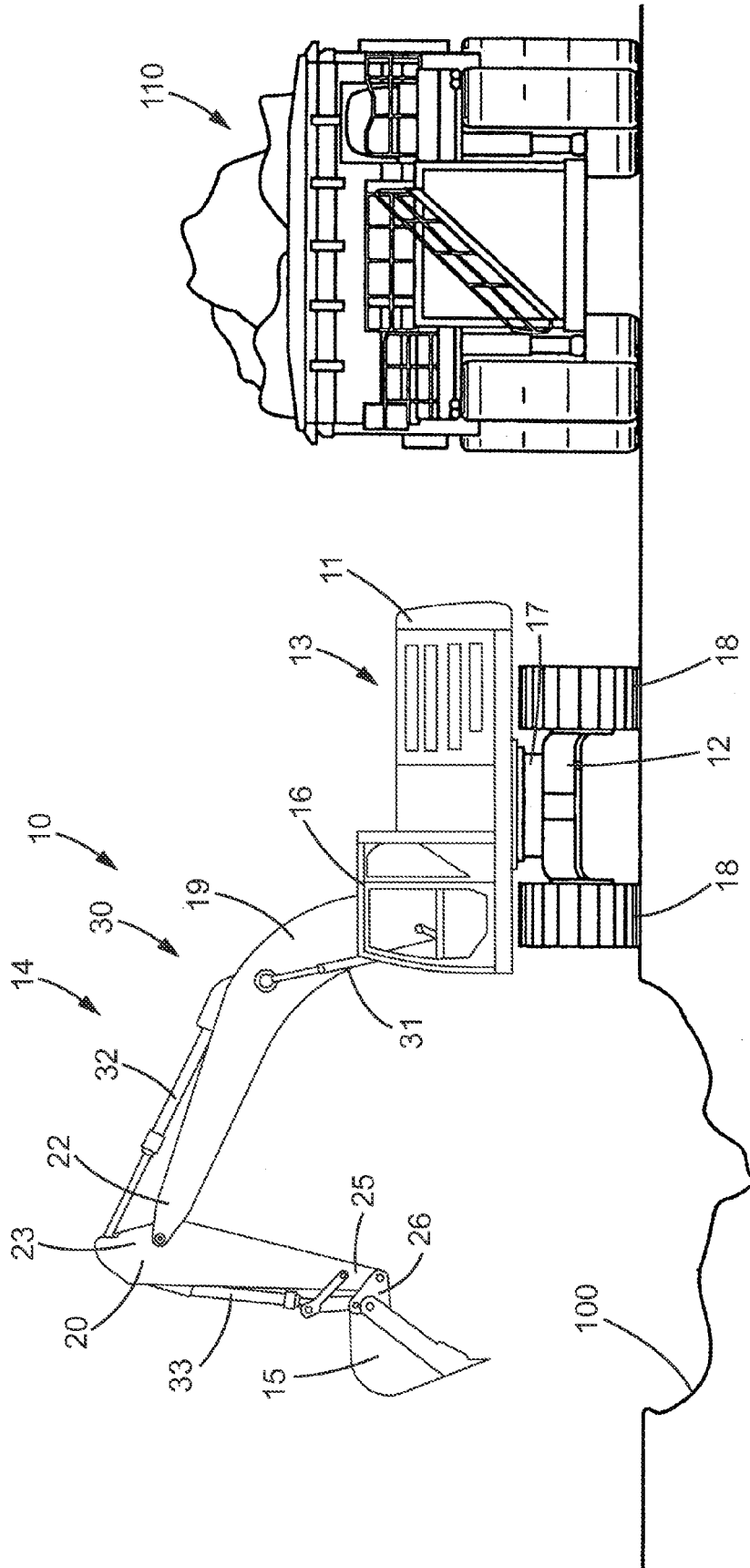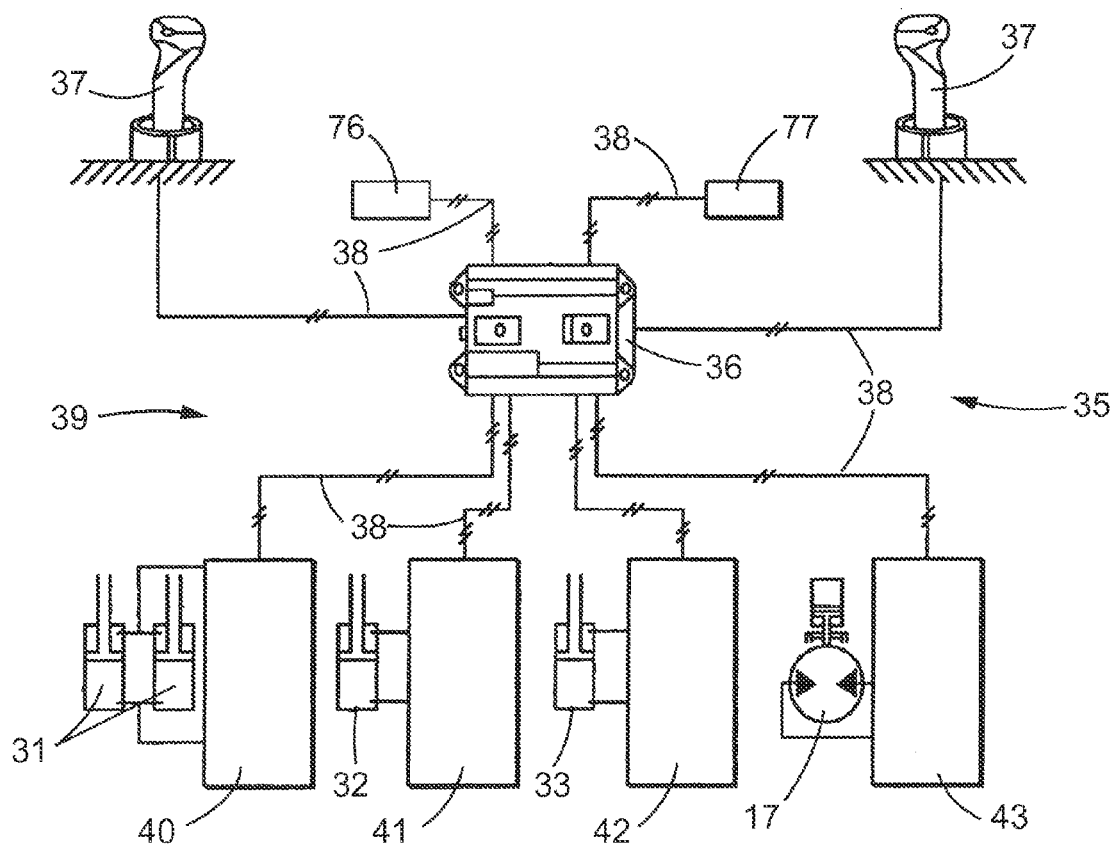|			
8,162,618 B2	4/2012	Nakamura et al.	
8,548,661 B2	10/2013	Wu	
8,838,314 B2	9/2014	Bissontz	
2010/0218493 A1*	9/2010	Nakamura	E02F 9/2235
			60/426
2012/0263604 A1	10/2012	Jung	
2013/0230413 A1	9/2013	Yamaji	
2014/0023523 A1	1/2014	Berg	
2015/0267697 A1*	9/2015	Gorman	F04B 49/065
			701/50

* cited by examiner

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

Start

Set operational estimates — 80

Receive sensor data — 81

Are pump sensors operating properly? — 82

Yes

Has more than one pump sensor failed? — 83

Yes → Generate alert command — 84

No

Determine prime mover output torque — 85

Estimate input torque to pumps — 86

Determine output of operating sensors — 87

Determine output torque of pump with operating sensors — 88

Determine estimate of output torque from pump with non-operating sensor — 89

Determine estimate of output at non-operating sensor — 90
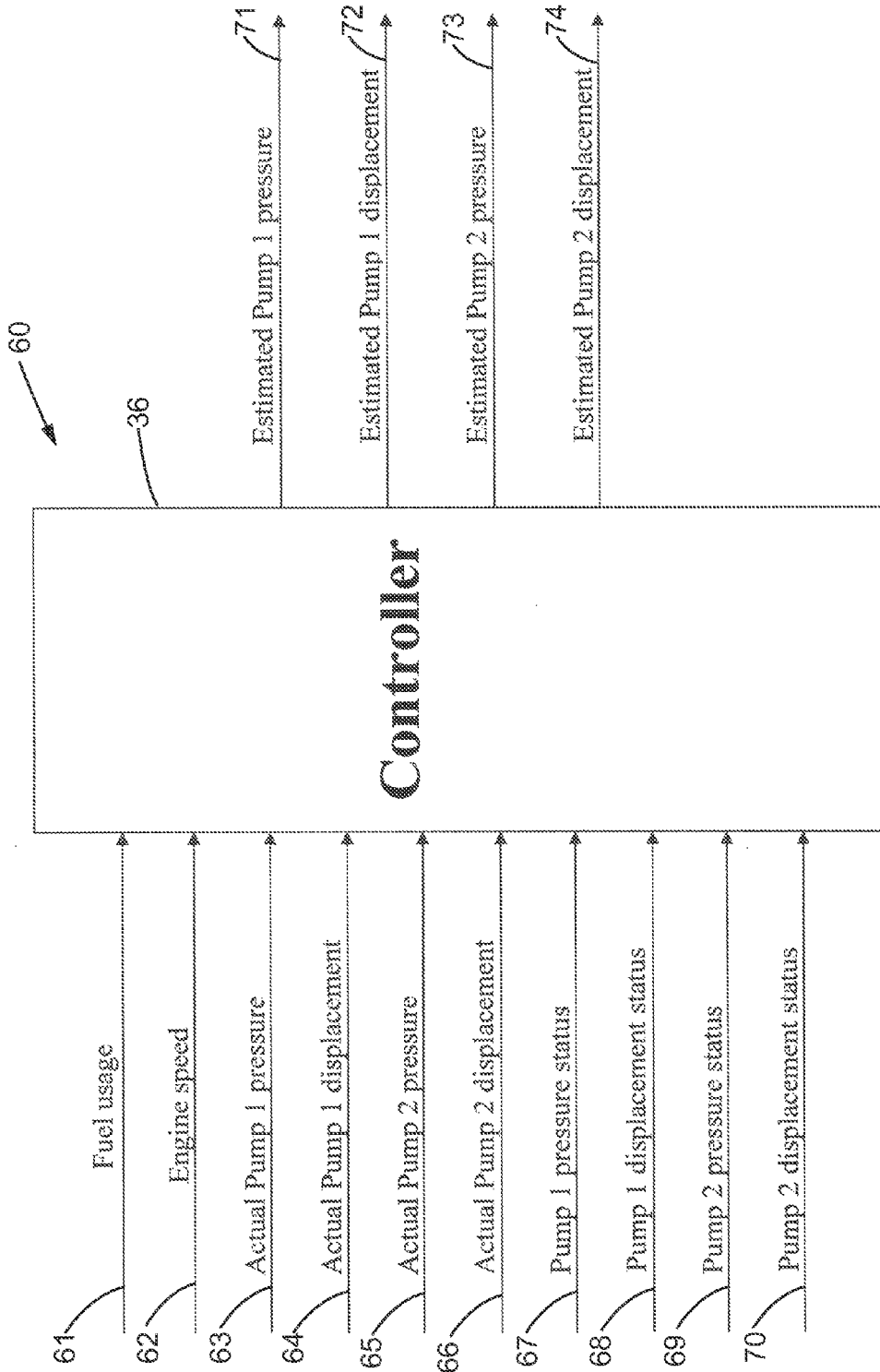
Multiply estimate by pump efficiency factor — 91

End
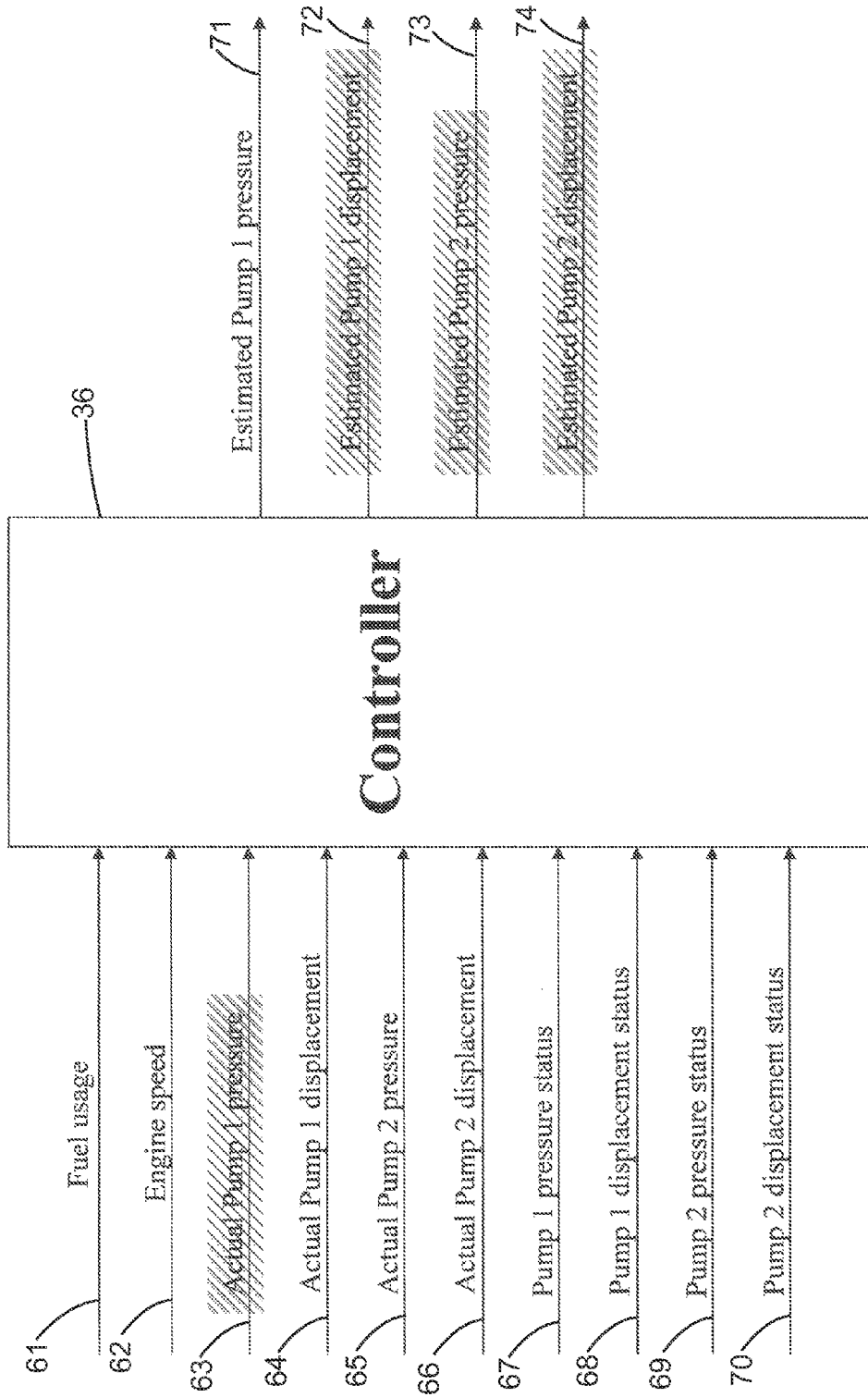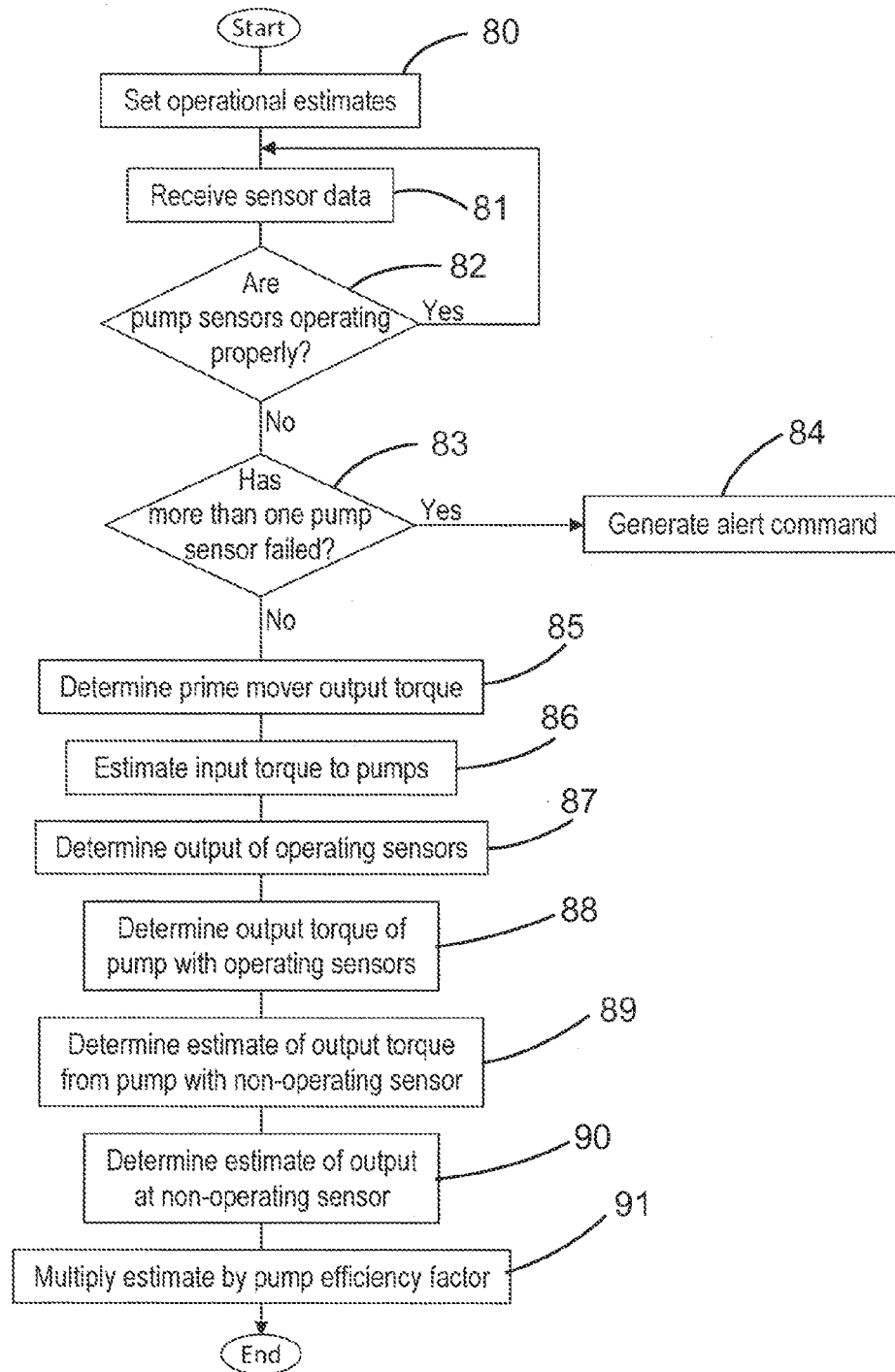
FIG. 6

SYSTEM FOR ESTIMATING A SENSOR OUTPUT

TECHNICAL FIELD

This disclosure relates generally to a system for estimating a sensor output and, more particularly, to a system for determining an estimation of an output of a sensor associated with a variable displacement hydraulic pump.

BACKGROUND

Many different types of machines utilize hydraulic systems to operate work implements and hydrostatic drives. Examples of these machines include excavators, backhoes, loaders, haul trucks, and various other machines. The machines typically include a plurality of sensors and use closed-loop feedback systems to monitor the operation of the various systems within the machine.

Due to the complexity and size of the machines and to prevent undesired or uncontrolled operation, the systems are often configured to shut down or substantially reduce the performance of the machine upon the failure of a pressure or displacement sensor. In such case, productivity is lost while waiting for replacement of the inoperative sensor.

U.S. Pat. No. 8,548,661 discloses a hybrid hydraulic excavator having an engine with both a variable displacement hydraulic pump and a motor generator connected to the engine. A controller is operative to determine a calculation value of the hydraulic pump based upon a pump current supplied to the pump and a discharge pressure of the pump using an algorithm, and corrects a hydraulic pump characteristic parameter used in the algorithm based upon an assumed pressure error. The controller further calculates an assumed hydraulic pressure correction output using the corrected hydraulic pump characteristic parameter, and controls the operation of the motor generator based upon the assumed hydraulic pressure correction output.

The foregoing background discussion is intended solely to aid the reader. It is not intended to limit the innovations described herein, nor to limit or expand the prior art discussed. Thus, the foregoing discussion should not be taken to indicate that any particular element of a prior system is unsuitable for use with the innovations described herein, nor is it intended to indicate that any element is essential in implementing the innovations described herein. The implementations and application of the innovations described herein are defined by the appended claims.

SUMMARY

In one aspect, a system for determining an estimated output from a variable displacement hydraulic pump includes a prime mover operatively connected to drive the variable displacement hydraulic pump, a torque sensor for generating torque signals indicative of an output torque from the prime mover, a pressure sensor for generating pressure signals indicative of an output pressure from the variable displacement hydraulic pump, and a displacement sensor for generating displacement signals indicative of a displacement of the variable displacement hydraulic pump. A controller is configured to receive torque signals from the torque sensor, determine the output torque from the prime mover, determine an input torque to the variable displacement hydraulic pump based upon the output torque, and receive signals from one of the pressure sensor and the displacement sensor. The controller is further configured to determine an output from

the one of the pressure sensor and the displacement sensor based upon the signals, determine a failure of another of the pressure sensor and the displacement sensor, and determine an estimated output from the another of the pressure sensor and the displacement sensor based upon the input torque to the variable displacement hydraulic pump and the output from the one of the pressure sensor and the displacement sensor.

In another aspect, a controller-implemented method of determining an estimated output from a variable displacement hydraulic pump includes providing a variable displacement hydraulic pump, providing a pressure sensor for generating pressure signals indicative of an output pressure from the variable displacement hydraulic pump, and providing a displacement sensor for generating displacement signals indicative of a displacement of the variable displacement hydraulic pump. The method further includes receiving torque signals from a torque sensor indicative of an output torque from a prime mover, determining the output torque from the prime mover based upon the torque signals, determining an input torque to the variable displacement hydraulic pump based upon the output torque, and receiving signals from one of the pressure sensor and the displacement sensor. The method also includes determining an output from the one of the pressure sensor and the displacement sensor based upon the signals, determining a failure of another of the pressure sensor and the displacement sensor, and determining an estimated output from the another of the pressure sensor and the displacement sensor based upon the input torque to the variable displacement hydraulic pump and the output from the one of the pressure sensor and the displacement sensor.

In still another aspect, a machine includes a variable displacement hydraulic pump, a prime mover operatively connected to drive the variable displacement hydraulic pump, a torque sensor for generating torque signals indicative of an output torque from the prime mover, a pressure sensor for generating pressure signals indicative of an output pressure from the variable displacement hydraulic pump, and a displacement sensor for generating displacement signals indicative of a displacement of the variable displacement hydraulic pump. A controller is configured to receive torque signals from the torque sensor, determine the output torque from the prime mover, determine an input torque to the variable displacement hydraulic pump based upon the output torque, and receive signals from one of the pressure sensor and the displacement sensor. The controller is further configured to determine an output from the one of the pressure sensor and the displacement sensor based upon the signals, determine a failure of another of the pressure sensor and the displacement sensor, and determine an estimated output from the another of the pressure sensor and the displacement sensor based upon the input torque to the variable displacement hydraulic pump and the output from the one of the pressure sensor and the displacement sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a side view of a hydraulic excavator including a sensor output estimation system in accordance with the disclosure and with an adjacent target vehicle;

FIG. 2 illustrates a simplified schematic view of a control system of the hydraulic excavator of FIG. 1;

FIG. 3 illustrates a simplified schematic view of a hydraulic power system of the hydraulic excavator of FIG. 1;

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FIG. 4 illustrates a block diagram of a sensor output estimation system of the hydraulic excavator of FIG. 1 depicting all possible inputs and outputs;

FIG. 5 illustrates the block diagram of FIG. 4 with one pump input sensor inoperable; and

FIG. 6 illustrates a flowchart of the sensor output estimation process in accordance with the disclosure.

DETAILED DESCRIPTION

FIG. 1 illustrates an exemplary machine 10 such as an excavator having multiple systems and components that cooperate to perform an operation such as excavating earthen material from a dig site 100 and loading it onto a nearby target such as haul machine 110. Machine 10 may include a swing member or platform 11, an undercarriage 12, a prime mover 13, and an implement system 14 including a work implement or tool 15 such as a bucket. Other types of work implements may also be used.

Platform 11 may be rotatably disposed on undercarriage 12 and includes an operator station 16 from which an operator may control the operation of machine 10. Rotation of platform 11 relative to undercarriage 12 may be effected by a swing motor 17 (FIG. 3).

Undercarriage 12 may be a structural support for one or more ground-engaging traction devices. The ground engaging traction devices may include one or more tracks 18 configured to allow translational motion of machine 10 across a work surface. Alternatively, the ground engaging fraction devices may include wheels, belts, or other traction devices known in the art.

A prime mover 13 may provide power for the operation of machine 10. Prime mover 13 may embody a combustion engine, such as a diesel engine, a gasoline engine, a gaseous fuel powered engine (e.g., a natural gas engine), or any other type of combustion engine known in the art. Prime mover 13 may alternatively embody a non-combustion source of power, such as a fuel cell or a power storage device such as a battery coupled to a motor. Further, if desired, both a combustion engine and a non-combustion source of power may be provided as a hybrid source of power that operates to increase the efficiency of the machine operation. Prime mover 13 may provide a rotational output to tracks 18, thereby propelling machine 10. Prime mover 13 may also provide power to other systems and components of machine 10.

Implement system 14 may include one or more linkage members configured to move a load. In one example, the implement system may include a boom member 19, a stick member 20, and a work implement or tool 15 such as a bucket. A first end (not shown) of boom member 19 may be pivotally connected to platform 11 to permit the boom member to pivot or rotate relative to the platform. A second end 22 of boom member 19 may be pivotally connected to a first end 23 of stick member 20 to permit the stick member to pivot or relative to the boom member. A first end 26 of the work implement or tool 15 may be pivotally connected to a second end 25 of stick member 20 to permit the tool to pivot or rotate relative to the stick member. The linkage members may translate or rotate in a plane that is generally orthogonal to the platform 11.

The linkage members may be operatively connected to an actuator system 30 that includes one or more actuators such as hydraulic cylinders. Boom member 19 may be propelled or moved along a path by a pair of boom hydraulic cylinders 31 (only one being shown in FIG. 1). Stick member 20 may be propelled by a stick hydraulic cylinder 32.

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Rotation of the tool 15 relative to the stick member 20 may be effected by actuation of the tool hydraulic cylinder 33.

Each of the boom hydraulic cylinders 31, the stick hydraulic cylinder 32, and the tool hydraulic cylinder 33 may embody a linear actuator as depicted in FIG. 2 having a tubular or cylindrical body and a piston and rod assembly therein arranged to form two distinct pressure chambers. The pressure chambers may be selectively supplied with pressurized fluid and drained of the pressurized fluid to cause the piston and rod assembly to displace within the cylindrical body. The flow rate of fluid into and out of the pressure chambers may relate to the speed of extension or retraction of the hydraulic cylinders while a pressure differential between the two pressure chambers may relate to the force imparted by the hydraulic cylinders to their associated linkage members. The extension and retraction of the hydraulic cylinders results in the movement of the linkage members including tool 15. It is also contemplated that the actuators may alternatively embody electric motors, pneumatic motors, or any other actuation devices.

Swing motor 17 may also be driven by differential fluid pressure. Specifically, swing motor 17 may be a rotary actuator including first and second chambers (not shown) located on opposite sides of an impeller (not shown). Upon filling the first chamber with pressurized fluid and draining the second chamber of fluid, the impeller is urged to rotate in a first direction. Conversely, when the first chamber is drained of fluid and the second chamber is filled with pressurized fluid, the impeller is urged to rotate in an opposite direction. The flow rate of fluid into and out of the first and second chambers affects the rotational speed of swing motor 17, while a pressure differential across the impeller affects the output torque thereof.

Machine 10 may be equipped with a plurality of sensors that provide data, directly or indirectly, of the performance or conditions of various aspects of the machine. The term "sensor" is meant to be used in its broadest sense to include one or more sensors and related components that may be associated with the machine 10 and that may cooperate to sense various functions, operations, and operating characteristics of the machine. For example, fuel usage sensor 76 (FIG. 2) may be provided to sense and indicate the amount of fuel being used by the engine. Further, an engine speed sensor 77 may be provided to sense and indicate the speed of the engine.

Referring to FIG. 2, a control system 35 may be provided to control the operation of the machine 10. The control system 35 may include an electronic control module such as controller 36. The controller 36 may receive operator input commands or signals and control the operation of the various systems of the machine 10. The control system 35 may include one or more operator input devices 37 such as a joystick to control the machine 10 and one or more sensors. The controller 36 may communicate with the sensors, the operator input devices 37, and other components via communication lines 38 or wirelessly.

The controller 36 may be an electronic controller that operates in a logical fashion to perform operations, execute control algorithms, store and retrieve data and other desired operations. The controller 36 may include or access memory, secondary storage devices, processors, and any other components for running an application. The memory and secondary storage devices may be in the form of read-only memory (ROM) or random access memory (RAM) or integrated circuitry that is accessible by the controller. Various other circuits may be associated with the

controller such as power supply circuitry, signal conditioning circuitry, driver circuitry, and other types of circuitry.

The controller 36 may be a single controller or may include more than one controller disposed to control various functions and/or features of the machine 10. The term "controller" is meant to be used in its broadest sense to include one or more controllers and/or microprocessors that may be associated with the machine 10 and that may cooperate in controlling various functions and operations of the machine. The functionality of the controller 36 may be implemented in hardware and/or software without regard to the functionality. The controller 36 may rely on one or more data maps relating to the operating conditions of the machine 10 that may be stored in the memory of controller. Each of these maps may include a collection of data in the form of tables, graphs, and/or equations. The controller 36 may use the data maps to maximize the performance and efficiency of the machine 10.

The boom hydraulic cylinders 31, the stick hydraulic cylinder 32, the tool hydraulic cylinder 33, and the swing motor 17 may function together with other cooperating fluid components to move tool 15 in response to input received from the operator input device 37. In particular, control system 35 may include one or more fluid circuits (not shown) configured to produce and distribute streams of pressurized fluid. One or more boom control valves 40, one or more stick control valves 41, one or more tool control valves 42, and one or more swing control valves 43 may be configured or positioned to receive the streams of pressurized fluid and selectively meter the fluid to and from the boom hydraulic cylinders 31, the stick hydraulic cylinder 32, the tool hydraulic cylinder 33, and the swing motor 17, respectively, to regulate the motions thereof.

Controller 36 may be configured to receive input from the operator input device 37 and to command operation of the boom control valves 40, the stick control valves 41, the tool control valves 42, and the swing control valves 43 in response to the input and based on the data maps described above. More specifically, controller 36 may receive an input device position signal indicative of a desired speed and/or type of movement in a particular direction and refer to the data maps stored in the memory of controller 36 to determine flow rate values and/or associated positions for each of the supply and drain elements within the boom control valves 40, the stick control valves 41, the tool control valves 42, and the swing control valves 43. The flow rates or positions may then be commanded of the appropriate supply and drain elements to cause filling and/or draining of the chambers of the actuators at rates that result in the desired movement of tool 15.

FIG. 3 depicts a hydraulic power system 39 for providing pressurized hydraulic fluid to operate the various systems within the machine 10. Prime mover 13 such as a combustion engine and/or a non-combustion source of power may be operatively connected to a gear set 45 that is operatively connected to drive one or more pumps such as a first variable displacement hydraulic pump 46, a second variable displacement hydraulic pump 47, and a fan pump 48. A charge pump 49 may be operatively connected to one of the variable displacement hydraulic pumps or may be directly connected to the gear set 45. As depicted in FIG. 3, the charge pump 49 is operatively connected to the first variable displacement hydraulic pump 46.

Each of the variable displacement hydraulic pumps may be configured to discharge high pressure hydraulic fluid with the first variable displacement hydraulic pump 46 being connected to a first output line 50 and the second variable

displacement hydraulic pump 47 being connected to a second output line 51. High pressure hydraulic fluid from the first output line 50 and the second output line 51 may be used for any desired purpose such as operating the hydraulic cylinders of the actuator system 30 and the swing motor 17 to move the work implement as well as operating a hydraulic propulsion system to move the machine 10 about the dig site 100.

A first pressure sensor 55 may be operatively associated with the first variable displacement hydraulic pump 46 to monitor the output pressure of the hydraulic fluid exiting from the first hydraulic pump. A first displacement sensor 56 may be operatively associated with the first variable displacement hydraulic pump 46 to monitor the displacement of the first hydraulic pump. A second pressure sensor 57 may be operatively associated with the second variable displacement hydraulic pump 47 to monitor the output pressure of the hydraulic fluid exiting from the second hydraulic pump. A second displacement sensor 58 may be operatively associated with the second variable displacement hydraulic pump 47 to monitor the displacement of the second hydraulic pump. Each of the first pressure sensor 55, the first displacement sensor 56, the second pressure sensor 57, and the second displacement sensor 58 may also include a status sensor 59 associated therewith that function to determine whether the pressure and displacement sensors are operating properly.

The status sensors 59 may operate by monitoring the operating status of each of the pressure sensors and the displacement sensors. The status sensors 59 may take any form and thus may be implemented in hardware and/or software. For example, each of the pressure and displacement sensors may include discrete status sensors or the status sensors may be integrally formed as part of the pressure and displacement sensors as depicted in FIG. 3. In another example, the status sensors 59 may be a part of the control system 35 or controller 36 and operate by monitoring the types, frequency or intervals, and range or amplitude of signals from the pressure and displacement sensors. In still another example, the status sensors 59 may form a portion of a calibration and/or diagnostics system of each pressure and displacement sensor. If the signals from the pressure and displacement sensors are outside of desired or expected ranges, the controller 36 may determine that the respective pressure or displacement sensor is not operating properly.

If the status sensors 59 are discrete elements, they may generate status signals that transmitted to and received by controller 36. For example, a first pressure status sensor associated with the first pressure sensor 55 may be configured to generate first pressure sensor status signals indicative of the status of the first pressure sensor. A first displacement status sensor associated with the first displacement sensor 56 may be configured to generate first displacement sensor status signals indicative of the status of the first displacement sensor. A second pressure status sensor associated with the second pressure sensor 57 may be configured to generate second pressure sensor status signals indicative of the status of the second pressure sensor. A second displacement status sensor associated with the second displacement sensor 58 may be configured to generate second displacement sensor status signals indicative of the status of the second displacement sensor.

If the status sensors 59 are not discrete elements, the controller 36 may not receive specific signals but may generate within the controller 36 signals indicative of the status of the sensors. The systems described herein are

equally applicable regardless of the manner in which the status signals are generated and/or received by the controller **36**.

Fan pump **48** may be a variable displacement pump configured to discharge pressurized hydraulic fluid to a fixed displacement fan pump that is operatively connected to a fan **52**. Charge pump **49** may be a fixed displacement pump configured to discharge relatively low pressure hydraulic fluid to a charge pump line **53**. The relatively low pressure hydraulic fluid passing through the charge pump line **53** may be used for any desired purpose such as operating control valves (e.g., boom control valves **40**, stick control valves **41**, tool control valves **42**, and swing control valves **43**) used to control the position of the actuator system **30**.

Control system **35** and hydraulic power system **39** may be configured as a closed-loop system in which feedback and proper operation of all of the sensors may be required for full operation of all systems associated with machine **10**. Absent all of the necessary inputs, the control system **35** may "de-stroke" or reduce the displacement of the pump associated with the failed sensor and the hydraulic power system **39** will operate in a limited or minimum flow condition. In such case, the machine **10** may be substantially inoperative.

In case of a failure of one of the output sensors associated with the first variable displacement hydraulic pump **46** or the second variable displacement hydraulic pump **47** (i.e., first pressure sensor **55**, first displacement sensor **56**, second pressure sensor **57**, or second displacement sensor **58**), the control system **35** may include a sensor output estimation system **60** to estimate the output from the variable displacement hydraulic pump associated with the failure. The sensor output estimation system **60** may operate generally by determining an input into the pumps, determining the known outputs from the pumps, and estimating the missing output based upon the input into the pumps and the known outputs.

As depicted in FIG. **4**, the sensor output estimation system **60** may be configured so that the controller **36** receives information from various sensors and systems of the machine **10** and processes the information to generate the necessary or desired estimate from the inoperative sensor. As such, all possible inputs and outputs are depicted in FIG. **4**. At node **61**, the controller **36** may receive fuel usage signals or data from fuel usage sensor **76** (FIG. **2**) indicative of the amount of fuel being used by the prime mover **13**. At node **62**, the controller **36** may receive engine speed signals or data from engine speed sensor **77** (FIG. **2**) indicative of the speed of the engine. The controller **36** may use the amount of fuel being used by the prime mover **13** together with the engine speed to determine the output torque from the prime mover. Such determination may be made through the use of look-up tables, data maps, equations, or other aspects of the controller **36**.

The combination of the fuel usage sensor **76** and the engine speed sensor **77** may act as an equivalent of a torque sensor for generating torque signals indicative of an output torque from the prime mover **13**. Other manners of determining the output torque from the prime mover **13** are contemplated. For example, other sensors may be used when using a non-combustion power source.

At node **63**, the controller **36** may receive pressure signals or data from the first pressure sensor **55** indicative of the pressure of the hydraulic fluid exiting from the first variable displacement hydraulic pump **46** through first output line **50**. At node **64**, the controller **36** may receive displacement signals or data from the first displacement sensor **56** indicative of the displacement of the first variable displacement hydraulic pump **46**.

At node **65**, the controller **36** may receive pressure signals or data from the second pressure sensor **57** indicative of the pressure of the hydraulic fluid exiting from the second variable displacement hydraulic pump **47** through second output line **51**. At node **66**, the controller **36** may receive displacement signals or data from the second displacement sensor **58** indicative of the displacement of the second variable displacement hydraulic pump **47**.

At node **67**, controller **36** may receive status signals from the status sensor **59** associated with the first pressure sensor **55** indicative of whether the first pressure sensor is operating properly. At node **68**, controller **36** may receive status signals from the status sensor **59** associated with the first displacement sensor **56** indicative of whether the first displacement sensor is operating properly. At node **69**, controller **36** may receive status signals from the status sensor **59** associated with the second pressure sensor **57** indicative of whether the second pressure sensor is operating properly. At node **70**, controller **36** may receive status signals from the status sensor **59** associated with the second displacement sensor **58** indicative of whether the second displacement sensors operating properly.

Controller **36** may generate an estimate of the output from the sensor that is inoperative. Accordingly, at node **71**, in case of a failure of the first pressure sensor **55**, the controller **36** may generate signals that are an estimate of the pressure of the hydraulic fluid exiting from the first variable displacement hydraulic pump **46** through first output line **50**. At node **72**, in case of a failure of the first displacement sensor **56**, the controller **36** may generate signals that are an estimate of the displacement of the first variable displacement hydraulic pump **46**. At node **73**, in case of a failure of the second pressure sensor **57**, the controller **36** may generate signals that are an estimate of the pressure of the hydraulic fluid exiting from the second variable displacement hydraulic pump **47** through second output line **51**. At node **74**, in case of a failure of the second displacement sensor **58**, the controller **36** may generate signals that are an estimate of the displacement of the second variable displacement hydraulic pump **47**.

Although FIG. **4** depicts an input from each of first pressure sensor **55** (node **63**), first displacement sensor **56** (node **64**), second pressure sensor **57** (node **65**), and second displacement sensor **58** (node **66**) and an estimated output from each of those sensors (nodes **71**-**74**), it should be noted that the sensor output estimation system **60** is configured to operate when only one of the sensors is inoperative. The controller **36** thus determines which data is missing and generates an estimate of the missing output. In other words, if all of the pressure sensors and displacement sensors are operating properly, the sensor output estimation system **60** is not necessary and the machine **10** may be operated in its desired manner. However, when only one of the pressure or displacement sensors is not operating properly, the sensor output estimation system **60** is operative to determine an estimate of the missing output signal. Estimates of the output from the sensors that are operating properly will not be generated. The estimated output of the failed sensor may then be used by the control system **35** so that the hydraulic power system **39** is fully operational.

Referring to FIG. **5**, a second block diagram of the sensor output estimation system **60** is depicted. The block diagram of FIG. **5** is identical to that of FIG. **4** except that it depicts an example in which the first pressure sensor **55** is not operating properly and thus the controller **36** is not receiving input signals or data from the first pressure sensor **55** at node **63**. The absence of such input is depicted by striking out the

text at node **63**. Since the inoperative sensor is the first pressure sensor **55**, only an estimate of the output pressure from the first variable displacement hydraulic pump **46** will be generated at node **71**. Estimates of the output from the first displacement sensor **56**, the second pressure sensor **57**, and the second displacement sensor **58** will not be generated. The absence of estimates of the outputs from those sensors is depicted by striking out the text at nodes **72-74**.

If the first displacement sensor **56** were inoperative rather than the first pressure sensor **55**, the input at node **64** would be omitted and the output at nodes **71** and **73-74** would be omitted. Similarly, an inoperative second pressure sensor **57** would result in an omitted input at node **65** and omitted output at nodes **71-72** and **74** while an inoperative second displacement sensor **58** would result in an omitted input at node **66** and omitted output at nodes **71-73**.

A flowchart of the operation of the sensor output estimation system **60** is depicted in FIG. **6**. At stage **80**, operational estimates and other desired factors utilized to improve the accuracy of the sensor output estimation system **60** may be set or entered within controller **36**. For example, an estimate of the amount of energy or torque lost or used to drive the fan pump **48** (and thus fan **52**) as well as the charge pump **49** may be set within controller **36**. In addition, a pump efficiency factor may also be set or entered within controller **36**. The values may be entered by a machine operator, management personnel, technicians, other personnel, or preset at a default value.

At stage **81**, the controller **36** may receive data or signals from the various sensors of the machine **10**. At decision stage **82**, the controller **36** may determine whether the pump sensors are operating properly. To do so, the controller **36** may analyze the signals from the pressure and displacement sensors or from the status sensor **59** associated with each of first pressure sensor **55**, first displacement sensor **56**, second pressure sensor **57**, and second displacement sensor **58**. If all of the pump sensors are operating properly at decision stage **82**, the controller **36** may continue to receive sensor data at stage **81**.

If any of the pump sensors are not operating properly at decision stage **82**, the controller **36** may determine at decision stage **83** whether more than one pump sensor has failed. If more than one pump sensor has failed, the controller **36** may generate an alert command at stage **84**. The alert command may be operative to notify the machine operator, management personnel, and/or any other desired person or system of the pump sensor failures.

If only one pump sensor has failed, the controller **36** may determine the prime mover output torque at stage **85**. In one example, the controller may determine the prime mover output torque based upon the fuel usage and engine speed of the prime mover. In other instances, other manners of determining the prime mover output torque may be utilized. When using a non-combustion source of power, other sensors may be used to determine the prime mover output torque. The controller **36** may determine at stage **86** an estimate of the input torque or input pump torque based upon the prime mover output torque and estimates of fan pump loss and charge pump loss as set at stage **80**. In doing so, the controller **36** may subtract estimates of the fan pump loss and charge pump loss from the prime mover output torque.

At stage **87**, the controller **36** may determine the output at each of the operating sensors. More specifically, the controller **36** may determine the output pressures from the first variable displacement hydraulic pump **46** and the second variable displacement hydraulic pump **47** based upon data from the first pressure sensor **55** and the second pressure

sensor **57**, respectively, to the extent that they are operative. Further, the controller **36** may determine the displacements of the first variable displacement hydraulic pump **46** and the second variable displacement hydraulic pump **47** based upon data from the first displacement sensor **56** and the second displacement sensor **58**, respectively, to the extent that they are operative.

The controller **36** may determine at stage **88** the output torque of the pump in which both the pressure sensor and the displacement sensor are operative. For example, if one of the second sensors (i.e., second pressure sensor **57** or second displacement sensor **58**) is inoperative, the controller **36** may determine at stage **88** the output torque of the first variable displacement hydraulic pump **46**. If one of the first sensors (i.e., first pressure sensor **55** or first displacement sensor **56**) is inoperative, the controller **36** may determine at stage **88** the output torque of the second variable displacement hydraulic pump **47**. To determine the output torque of one of the pumps, the controller **36** may multiply the pressure of the output as determined by the operative pressure sensor by the displacement as determined by the operative displacement sensor.

At stage **89**, the controller **36** may determine an estimate of the output torque of the pump having the non-operating sensor. To do so, the controller **36** may subtract the output torque of the pump having the operating sensors calculated at stage **88** from the estimate of the input pump torque determined at stage **86**. The remaining torque is approximately equal to the output torque of the pump having the non-operating or inoperative sensor.

At stage **90**, the controller **36** may determine an estimate of the output at the non-operating sensor. To do so, the controller **36** may divide the output torque of the pump having the non-operating sensor (as determined at stage **89**) by the output of the operating sensor associated with that same pump. In other words, if the pressure sensor of a pump is inoperative, the controller **36** may divide the output torque of that pump by the displacement as determined by the displacement sensor associated with that pump to determine an estimate of the output pressure from the pump. Similarly, if the displacement sensor of a pump is inoperative, the controller **36** may divide the output torque of that pump by the pressure as determined by the pressure sensor associated with that pump to determine an estimate of the displacement of the pump.

If desired, the estimate of the pressure or displacement as determined at stage **90** may be multiplied at stage **91** by the pump efficiency factor set at stage **80**. The estimated output from the inoperative sensor may then be used by the controller **36** as input to the control system **35** and hydraulic power system **39** so that the systems and machine **10** remain operative.

If desired, the pump efficiency factor set at stage **80** may be adjusted during operation of the machine **10** prior to a pump sensor failure. To do so, upon determining that the pump sensors are operating properly at decision stage **82**, the controller **36** may calculate estimated outputs from each of the pressure sensors and displacement sensors and compare them to the actual outputs from the sensors. To the extent that the estimated outputs are different, the pump efficiency factor may be adjusted so that the estimated outputs more closely match the actual outputs.

INDUSTRIAL APPLICABILITY

The industrial applicability of the sensor output estimation system **60** described herein will be readily appreciated

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from the foregoing discussion. The present disclosure is applicable to machines **10** having one or more variable displacement hydraulic pumps. One exemplary machine for which the sensor output estimation system **60** is suited is an excavator or hydraulic shovel. However, the sensor output estimation system **60** may be applicable to other machines in which an approximation of an output value from a variable displacement hydraulic pump is desirable when an exact value is not available such as due to a sensor failure.

The disclosed sensor output estimation system **60** provides many advantages while operating a machine. In case of a failure of one of the output sensors associated with a variable displacement hydraulic pump, the controller **36** may be configured to determine an approximate value of the output associated with the inoperative sensor and thus permit the control system **35** and the hydraulic power system **39** to remain fully or close to fully operational. This permits an operator to continue to operate machine **10** in a productive manner even while waiting for replacement of the inoperative sensor.

It will be appreciated that the foregoing description provides examples of the disclosed system and technique. However, it is contemplated that other implementations of the disclosure may differ in detail from the foregoing examples. All references to the disclosure or examples thereof are intended to reference the particular example being discussed at that point and are not intended to imply any limitation as to the scope of the disclosure more generally. All language of distinction and disparagement with respect to certain features is intended to indicate a lack of preference for those features, but not to exclude such from the scope of the disclosure entirely unless otherwise indicated.

Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context.

Accordingly, this disclosure includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the disclosure unless otherwise indicated herein or otherwise clearly contradicted by context.

The invention claimed is:

1. A system for determining an estimated output from a variable displacement hydraulic pump, the system comprising:
   a variable displacement hydraulic pump;
   a prime mover operatively connected to drive the variable displacement hydraulic pump;
   a torque sensor for generating torque signals indicative of an output torque from the prime mover;
   a pressure sensor for generating pressure signals indicative of an output pressure from the variable displacement hydraulic pump;
   a displacement sensor for generating displacement signals indicative of a displacement of the variable displacement hydraulic pump; and
   a controller configured to:
      receive torque signals from the torque sensor;
      determine the output torque from the prime mover;
      determine an input torque to the variable displacement hydraulic pump based upon the output torque;
      receive signals from one of the pressure sensor and the displacement sensor;
      determine an output from the one of the pressure sensor and the displacement sensor based upon the signals;
      determine a failure of another one of the pressure sensor and the displacement sensor;
      determine an estimated output from the other one of the pressure sensor and the displacement sensor based upon the input torque to the variable displacement hydraulic pump and the output from the one of the pressure sensor and the displacement sensor; and
      generate an alert command when the pressure sensor and the displacement sensor are inoperative.

2. The system of claim **1**, further including a pressure status sensor for generating pressure status signals indicative of an operating status of the pressure sensor and a displacement status sensor for generating displacement status signals indicative of an operating status of the displacement sensor, and
   wherein the controller is configured to determine the failure of the other one of the pressure sensor and the displacement sensor based upon status signals from one of the pressure status sensor and the displacement status sensor.

3. The system of claim **2**, wherein the controller is further configured to determine the estimated output only upon determining a failure of only one of the pressure sensor and the displacement sensor.

4. The system of claim **1**, wherein the controller is further configured to determine the input torque to the variable displacement hydraulic pump based upon the output torque from the prime mover together with an estimate of a fan pump loss and an estimate of a charge pump loss.

5. The system of claim **1**, wherein the controller is further configured to determine the estimated output from the other one of the pressure sensor and the displacement sensor based upon an estimate of a pump efficiency factor of the variable displacement hydraulic pump.

6. The system of claim **1**, further including a second variable displacement hydraulic pump;
   a second sensor for generating second signals indicative of an output torque from the second variable displacement hydraulic pump; and
   the controller is further configured to:
   receive second signals from the second sensor;
   determine the output torque of the second variable displacement hydraulic pump based upon the second signals;
   determine the estimated output further based upon the output torque from the second variable displacement hydraulic pump.

7. The system of claim **6**, wherein the controller is further configured to determine the estimated output based upon an estimate of a second pump efficiency factor of the second variable displacement hydraulic pump.

8. The system of claim **1**, further including a second variable displacement hydraulic pump driven by the prime mover;
   a second pressure sensor for generating second pressure signals indicative of a second output pressure from the second variable displacement hydraulic pump;
   a second displacement sensor for generating second displacement signals indicative of a second displacement of the second variable displacement hydraulic pump; and

wherein the controller is further configured to:

receive the second pressure signals from the second pressure sensor;

determine a second output pressure from the second variable displacement hydraulic pump based upon the second pressure signals from the second pressure sensor;

receive the second displacement signals from the second displacement sensor;

determine a second displacement of the second variable displacement hydraulic pump based upon the second displacement signals from the second displacement sensor; and

determine the estimated output further based upon the output from the second pressure sensor and the output from the second displacement sensor.

9. The system of claim 8, wherein the controller is further configured to determine the estimated output based upon an estimate of a second pump efficiency factor of the second variable displacement hydraulic pump.

10. The system of claim 8, further including a second pressure status sensor for generating second pressure status signals indicative of an operating status of the second pressure sensor and a second displacement status sensor for generating second displacement status signals indicative of an operating status of the second displacement sensor.

11. The system of claim 10, wherein the controller is further configured to determine the estimated output only upon determining a failure of only one of the pressure sensor, the displacement sensor, the second pressure sensor, and the second displacement sensor.

12. The system of claim 10, further including a gear set operatively connected to the prime mover to drive the variable displacement hydraulic pump and the second variable displacement hydraulic pump.

13. A controller-implemented method of determining an estimated output from a variable displacement hydraulic pump, the controller-implemented method comprising:

providing a variable displacement hydraulic pump;

providing a pressure sensor for generating pressure signals indicative of an output pressure from the variable displacement hydraulic pump;

providing a displacement sensor for generating displacement signals indicative of a displacement of the variable displacement hydraulic pump;

receiving torque signals from a torque sensor indicative of an output torque from a prime mover;

determining the output torque from the prime mover based upon the torque signals;

determining an input torque to the variable displacement hydraulic pump based upon the output torque;

receiving signals from one of the pressure sensor and the displacement sensor;

determining an output from the one of the pressure sensor and the displacement sensor based upon the signals;

determining a failure of another one of the pressure sensor and the displacement sensor;

determining an estimated output from the other one of the pressure sensor and the displacement sensor based upon the input torque to the variable displacement hydraulic pump and the output from the one of the pressure sensor and the displacement sensor; and

generating an alert command when the pressure sensor and the displacement sensor are inoperative.

14. The method of claim 13, further including providing a pressure status sensor for generating pressure status signals indicative of an operating status of the pressure sensor and

a displacement status sensor for generating displacement status signals indicative of an operating status of the displacement sensor, and determining the failure of the other one of the pressure sensor and the displacement sensor based upon status signals from one of the pressure status sensor and the displacement status sensor.

15. The method of claim 14, further including determining the estimated output only upon determining a failure of only one of the pressure sensor and the displacement sensor.

16. The method of claim 13, further including providing a second variable displacement hydraulic pump;

providing a second sensor for generating second signals indicative of an output torque from the second variable displacement hydraulic pump;

receiving second signals from the second sensor;

determining the output torque of the second variable displacement hydraulic pump based upon the second signals; and

determining the estimated output further based upon the output torque from the second variable displacement hydraulic pump.

17. The method of claim 13, further including providing a second variable displacement hydraulic pump driven by the prime mover;

providing a second pressure sensor for generating second pressure signals indicative of a second output pressure from the second variable displacement hydraulic pump;

providing a second displacement sensor for generating second displacement signals indicative of a second displacement of the second variable displacement hydraulic pump;

receiving the second pressure signals from the second pressure sensor;

determining a second output pressure from the second variable displacement hydraulic pump based upon the second pressure signals from the second pressure sensor;

receiving the second displacement signals from the second displacement sensor;

determining a second displacement of the second variable displacement hydraulic pump based upon the second displacement signals from the second displacement sensor; and

determining the estimated output further based upon the output from the second pressure sensor and the output from the second displacement sensor.

18. The method of claim 17, further including providing a second pressure status sensor for generating second pressure status signals indicative of an operating status of the second pressure sensor and a second displacement status sensor for generating second displacement status signals indicative of an operating status of the second displacement sensor, and determining the estimated output only determining a failure of only one of the pressure sensor, the displacement sensor, the second pressure sensor, and the second displacement sensor.

19. A machine comprising:

a variable displacement hydraulic pump;

a prime mover operatively connected to drive the variable displacement hydraulic pump;

a torque sensor for generating signals indicative of an output torque from the prime mover;

a pressure sensor for generating pressure signals indicative of an output pressure from the variable displacement hydraulic pump;

a displacement sensor for generating displacement signals indicative of a displacement of the variable displacement hydraulic pump; and

a controller configured to:

receive torque signals from the torque sensor;

determine the output torque from the prime mover;

determine an input torque to the variable displacement hydraulic pump based upon the output torque;

receive signals from one of the pressure sensor and the displacement sensor;

determine an output from the one of the pressure sensor and the displacement sensor based upon the signals;

determine a failure of another one of the pressure sensor and the displacement sensor; and

determine an estimated output from the one of the pressure sensor and the displacement sensor based upon the input torque to the variable displacement hydraulic pump and the output from the one of the pressure sensor and the displacement sensor; and

generate an alert command when the pressure sensor and the displacement sensor are inoperative.

20. The machine of claim 19, wherein the controller is further configured to determine the input torque to the variable displacement hydraulic pump based upon the output torque from the prime mover and an estimate of a fan pump loss and an estimate of a charge pump loss.

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