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(54) **EXCAVATOR FOUR-BAR LINKAGE LENGTH AND ANGLE OFFSET DETERMINATION USING A LASER DISTANCE METER**

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G05D 1/02	(2006.01)
E02F 3/32	(2006.01)
E02F 9/26	(2006.01)
G01S 17/08	(2006.01)

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CPC *E02F 3/435* (2013.01); *E02F 3/32* (2013.01); *E02F 3/43* (2013.01); *E02F 9/265* (2013.01); *G01S 17/08* (2013.01); *G05D 1/024* (2013.01); *G05D 2201/0202* (2013.01)

(58) **Field of Classification Search**
CPC E02F 3/435; E02F 3/32
See application file for complete search history.

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(57) **ABSTRACT**

An excavator calibration framework comprises an excavator, a laser distance meter (LDM), and a laser reflector. The excavator comprises a chassis, linkage assembly (LA), sensor, implement, and control architecture. The LA comprises a boom, stick, and four-bar linkage (4BL) with the sensor on a 4BL dogbone linkage. The control architecture comprises a controller programmed to execute an iterative process at successive implement curl positions. The iterative process comprises generating a measured dogbone angle $\theta_{DF}^{Measured}$, determining a height $\hat{H}$ and a distance $\hat{D}$ between an implement node and the LDM, and determining an implement node position. The iterative process further comprises determining an estimated implement angle $\theta_{GH}^{Estimated}$ and generating a mapping equation comprising linkage angle inputs $(\theta_{DF}^{Measured}, \theta_{GH}^{Estimated})$ and n unsolved 4BL linkage length and angle offset parameters. The controller is programmed to generate and solve a set of m mapping equations comprising the n unsolved parameters.

20 Claims, 4 Drawing Sheets
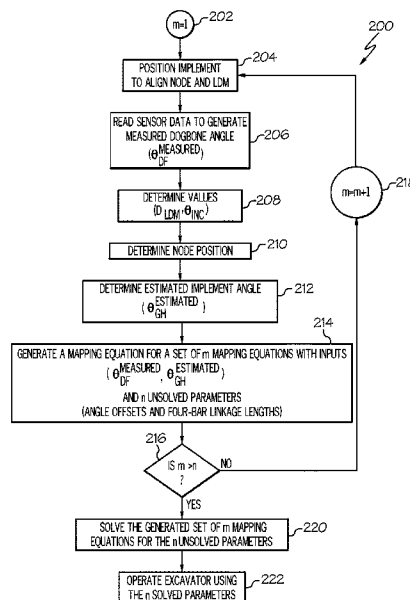
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FIG. 1

120

A_z

A_y

A_x

FIG. 2

104

θ_S

B
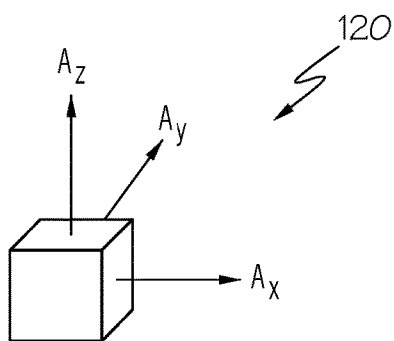
L_S

110

G

L_B

108

J

D_{LDM}

$\hat{H}$

θ_{INC}

θ_B

H_O

$\hat{D}$

A

124

D_O

FIG. 3

FIG. 4

FIG. 5

m=1 — 202

200

POSITION IMPLEMENT
TO ALIGN NODE AND LDM — 204

READ SENSOR DATA TO GENERATE
MEASURED DOGBONE ANGLE
$(\theta_{DF}^{MEASURED})$ — 206

DETERMINE VALUES
(D_{LDM}, θ_{INC}) — 208

DETERMINE NODE POSITION — 210

DETERMINE ESTIMATED IMPLEMENT ANGLE
$(\theta_{GH}^{ESTIMATED})$ — 212

m=m+1 — 218

214

GENERATE A MAPPING EQUATION FOR A SET OF m MAPPING EQUATIONS WITH INPUTS
$(\theta_{DF}^{MEASURED}, \theta_{GH}^{ESTIMATED})$
AND n UNSOLVED PARAMETERS
(ANGLE OFFSETS AND FOUR-BAR LINKAGE LENGTHS)

216

IS m >n
?

NO

YES

SOLVE THE GENERATED SET OF m MAPPING
EQUATIONS FOR THE n UNSOLVED PARAMETERS — 220

OPERATE EXCAVATOR USING
THE n SOLVED PARAMETERS — 222
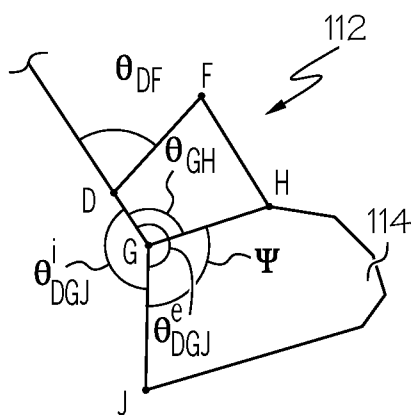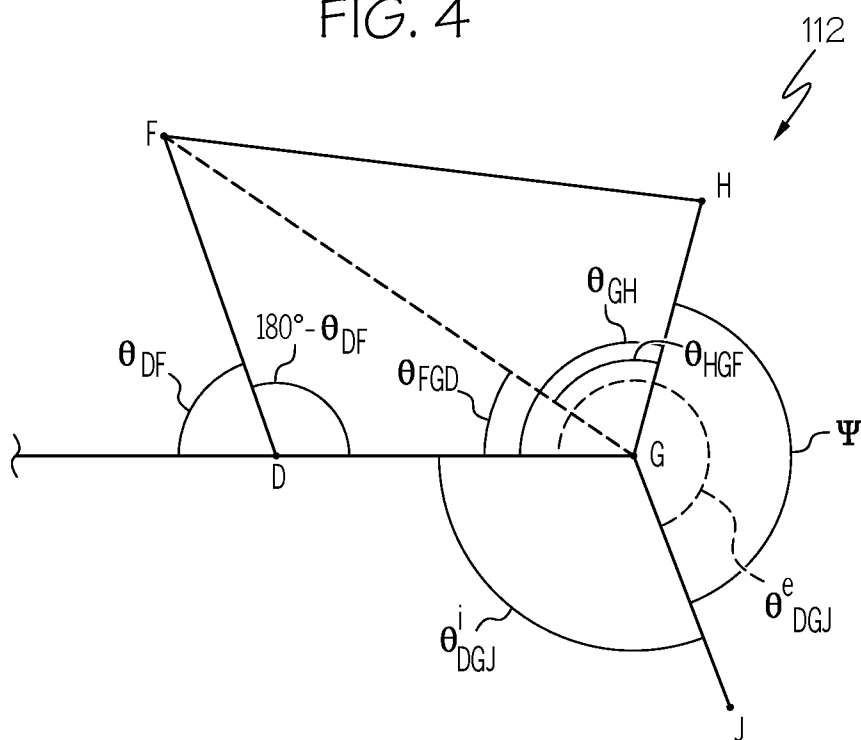
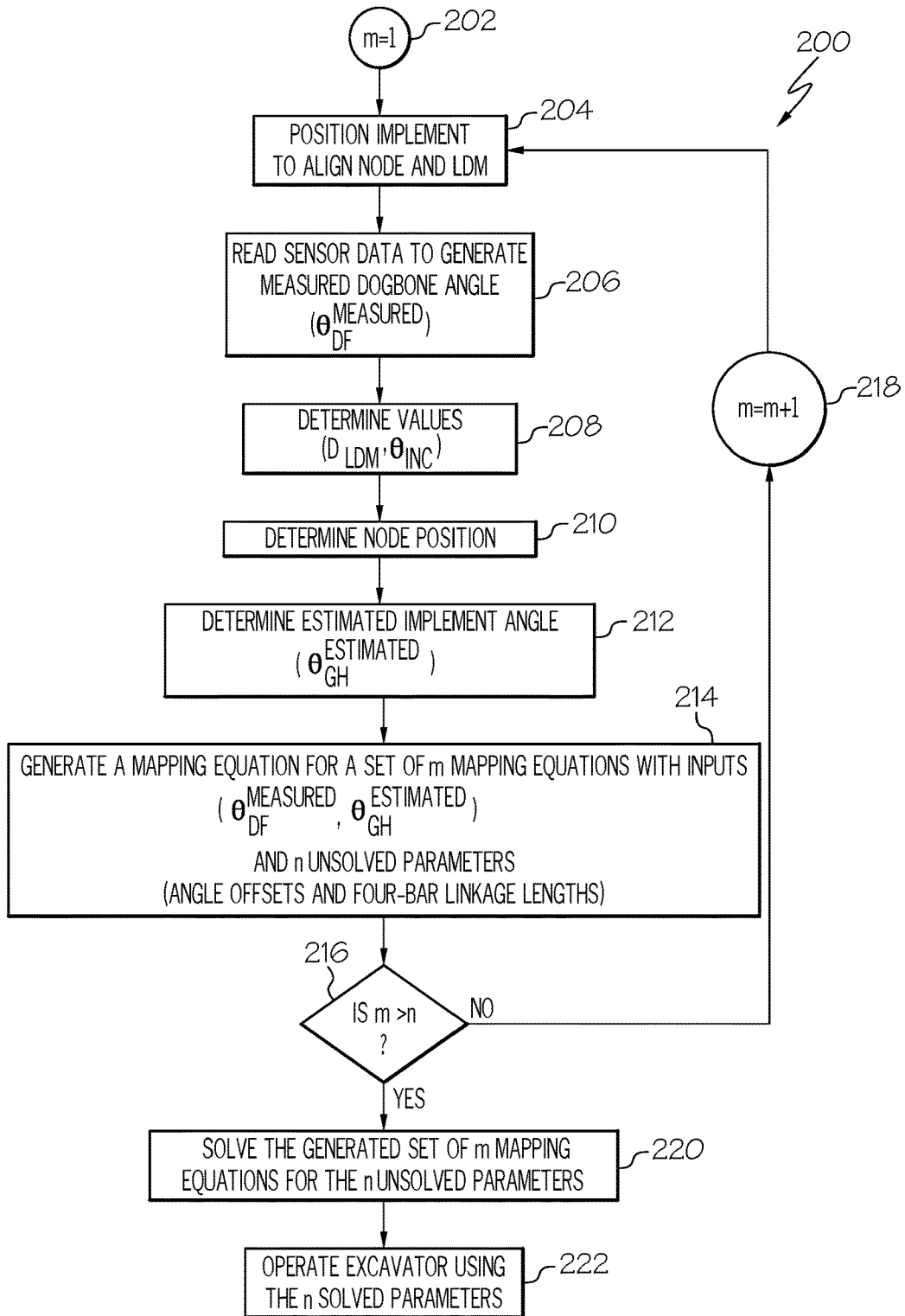FIG. 6

EXCAVATOR FOUR-BAR LINKAGE LENGTH AND ANGLE OFFSET DETERMINATION USING A LASER DISTANCE METER

BACKGROUND

The present disclosure relates to excavators which, for the purposes of defining and describing the scope of the present application, comprise an excavator boom and an excavator stick subject to swing and curl, and an excavating implement that is subject to swing and curl control with the aid of the excavator boom and excavator stick, or other similar components for executing swing and curl movement. For example, and not by way of limitation, many types of excavators comprise a hydraulically or pneumatically or electrically controlled excavating implement that can be manipulated by controlling the swing and curl functions of an excavating linkage assembly of the excavator. Excavator technology is, for example, well represented by the disclosures of U.S. Pat. No. 8,689,471, which is assigned to Caterpillar Trimble Control Technologies LLC and discloses methodology for sensor-based automatic control of an excavator, US 2008/0047170, which is assigned to Caterpillar Trimble Control Technologies LLC and discloses an excavator 3D laser system and radio positioning guidance system configured to guide a cutting edge of an excavator bucket with high vertical accuracy, and US 2008/0000111, which is assigned to Caterpillar Trimble Control Technologies LLC and discloses methodology for an excavator control system to determine an orientation of an excavator sitting on a sloped site.

BRIEF SUMMARY

According to the subject matter of the present disclosure, an excavator calibration framework comprises an excavator, a laser distance meter (LDM), and a laser reflector. The excavator comprises a machine chassis, an excavating linkage assembly, an implement dynamic sensor, an excavating implement, and control architecture. The excavating linkage assembly comprises an excavator boom, an excavator stick, and a four-bar linkage. The excavating implement and the excavator stick are mechanically coupled through the four-bar linkage comprising an implement linkage of length GH, a rear side linkage of length FH, a dogbone linkage of length DF, and a front side linkage of length DG. The implement dynamic sensor is positioned on the dogbone linkage of the four-bar linkage. The excavating implement is configured to curl relative to the excavator stick to define a plurality of implement curl positions. The LDM is configured to generate an LDM distance signal D_{LDM} indicative of a distance between the LDM and the laser reflector and an angle of inclination signal θ_{INC} indicative of an angle between the LDM and the laser reflector. The laser reflector is configured to be disposed at a position corresponding to a calibration node on the excavating implement. The control architecture comprises one or more linkage assembly actuators and an architecture controller programmed to execute an iterative process at successive implement curl positions. The iterative process comprises generating a measured dogbone angle $\theta_{DF}^{Measured}$ of the dogbone linkage from the implement dynamic sensor, determining a height $\hat{H}$ and a distance $\hat{D}$ between the calibration node on the excavating implement and the LDM based on the LDM distance signal D_{LDM} and the angle of inclination signal θ_{INC}, and determining a position of the calibration node at least partially based on the

height $\hat{H}$ and the distance $\hat{D}$. The iterative process further comprises determining an estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement at least partially based on the position of the calibration node, and generating a mapping equation comprising linkage angle inputs, unsolved linkage length parameters, and unsolved angle offset parameters. The linkage angle inputs comprise the measured dogbone angle $\theta_{DF}^{Measured}$ and the estimated implement angle $\theta_{GH}^{Estimated}$ the implement curl position. The unsolved linkage length parameters comprise the linkage lengths GH, FH, DF, and DG of the four-bar linkage. The unsolved angle offset parameters comprise an offset dogbone angle θ_{DF}^{Bias} of the dogbone linkage, and an offset implement angle θ_{GH}^{Bias} of the excavating implement. The architecture controller is further programmed to repeat the iterative process for successive implement curl positions to generate a set of m mapping equations, wherein the set of m mapping equations comprises n unsolved linkage length and unsolved angle offset parameters, and the iterative process is repeated until m>n. The architecture controller is further programmed to solve the generated set of m mapping equations comprising the n unsolved parameters to determine the linkage lengths GH, FH, DF, and DG of the four-bar linkage, the offset dogbone angle θ_{DF}^{Bias} of the dogbone linkage, and the offset implement angle θ_{GH}^{Bias} of the excavating implement, and operate the excavator using the linkage lengths GH, FH, DF, and DG, the offset dogbone angle θ_{DF}^{Bias}, and the offset implement angle θ_{GH}^{Bias}.

Although the concepts of the present disclosure are described herein with primary reference to the excavator illustrated in FIG. 1, it is contemplated that the concepts will enjoy applicability to any type of excavator, regardless of its particular mechanical configuration. For example, and not by way of limitation, the concepts may enjoy applicability to a backhoe loader including a backhoe linkage.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The following detailed description of specific embodiments of the present disclosure can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

FIG. 1 is a side view of an excavator incorporating aspects of the present disclosure;

FIG. 2 is a perspective view of a dynamic sensor disposed on a linkage of the excavator of FIG. 1 and according to various concepts of the present disclosure;

FIG. 3 is a side elevation view of a linkage assembly of an excavator calibration framework including a laser distance meter (LDM) and implement dimension points of an excavating implement of the excavator of FIG. 1;

FIG. 4 is a side elevation view of a four-bar linkage assembly of the excavator of FIG. 1, according to various concepts of the present disclosure;

FIG. 5 is another side elevation view of the four-bar linkage assembly of FIG. 4, according to various concepts of the present disclosure; and

FIG. 6 is a flow chart of a process used to determine four-bar linkage dimensions and angle offsets of the excavator of FIG. 1.

DETAILED DESCRIPTION

The present disclosure relates to earthmoving machines and, more particularly, to earthmoving machines such as

excavators including components subject to control. For example, and not by way of limitation, many types of excavators typically have a hydraulically controlled earth-moving implement that can be manipulated by a joystick or other means in an operator control station of the machine, and is also subject to partially or fully automated control. The user of the machine may control the lift, tilt, angle, and pitch of the implement. In addition, one or more of these variables may also be subject to partially or fully automated control based on information sensed or received by an adaptive environmental sensor of the machine. In the embodiments described herein, an excavator calibration framework utilizes a laser distance meter to determine four-bar linkage lengths of excavator limb components and related angle offsets, such as an angle offset of one or more sensors disposed on those respective linkages, as described in greater detail further below. Such determined values may be utilized by an excavator control to operate the excavator.

Referring initially to FIG. **1**, an excavator calibration framework comprises an excavator **100**, a laser distance meter (LDM) **124**, and a laser reflector **130**. The excavator **100** comprises a machine chassis **102**, an excavating linkage assembly **104**, an implement dynamic sensor **120**, an excavating implement **114**, and control architecture **106**. The excavating linkage assembly **104** comprises an excavator boom **108**, an excavator stick **110**, and a four-bar linkage **112**. The excavating implement **114** and the excavator stick **110** are mechanically coupled through the four-bar linkage **112**. In embodiments, the laser reflector **130** is on a pole or secured directly to the excavating implement **114**. The LDM **124** may be, for example, a Bosch GLM **100C** LDM as made commercially available by Robert Bosch GmbH of Germany. A laser signal from the LDM **124**, which is placed on ground **126**, may be transmitted in a direction of an arrow **132** to the calibration node and an aligned laser reflector, such as, for example, the laser reflector **130**, and the laser signal may be reflected back to the LDM **124** in the direction of an arrow **134**, as illustrated in FIG. **1**.

In embodiments, the implement dynamic sensor **120** comprises an inertial measurement unit (IMU), an inclinometer, an accelerometer, a gyroscope, an angular rate sensor, a rotary position sensor, a position sensing cylinder, or combinations thereof. The IMU may include a 3-axis accelerometer and a 3-axis gyroscope. As shown in FIG. **2**, the implement dynamic sensor **120** includes accelerations A_x, A_y, and A_z, respectively representing x-axis, y-axis-, and z-axis acceleration values.

The four-bar linkage **112** comprises an implement linkage of length GH, a rear side linkage of length FH, a dogbone linkage of length DF, and a front side linkage of length DG. The implement dynamic sensor **120** is positioned on the dogbone linkage of length DF of the four-bar linkage **112**. In embodiments, the four-bar linkage comprises a node D, a node F, a node G, a node H. As a non-limiting example, the implement linkage is disposed between respective positions corresponding to the node G and the node H. The rear side linkage is disposed between respective positions corresponding to the node F and the node H. The dogbone linkage is disposed between respective positions corresponding to the node D and the node F, and front side linkage is disposed between respective positions corresponding to the node D and the node G. Further, the node G of the four-bar linkage **112** may be disposed at a position corresponding to the terminal point of the excavator stick **110** through which the excavator stick **110** is coupled to the excavating implement **114**. Referring to FIG. **5**, the four-bar linkage **112** comprises a diagonal length FG between a front end node of the

implement linkage of length GH and a rear end node of the dogbone linkage of length DF.

The excavating implement **114** is configured to curl relative to the excavator stick **110** to define a plurality of implement curl positions. In embodiments, the excavating linkage assembly **104** may be configured to swing with, or relative to, the machine chassis **102**, and the excavator stick **110** may be configured to curl relative to the excavator boom **108**. Further, the machine chassis **102** may be mechanically coupled to a terminal pivot point A of the excavator boom **108**. The excavator stick **110** may comprise a stick terminal point corresponding to the position of the node G of the four-bar linkage **112** and may be mechanically coupled to a terminal pivot point B of the excavator boom **108**. Further, the excavator stick **110** may be mechanically coupled to the excavating implement **114** through the stick terminal point. A position of the terminal pivot point B and the node G may be identified prior to, for example, the iterative process being executed by the architecture controller.

Referring to FIG. **3**, a boom limb length L_B is a limb length of the excavator boom **108**, a boom angle θ_B is an angle of the excavator boom **108** between the terminal pivot points A and B relative to gravity, a stick limb length L_S is a limb length of the excavator stick **110**, and a stick angle θ_S is an angle of the excavator stick **110** between the terminal pivot point B and the node G relative to gravity. One or more dynamic sensors may be disposed on excavator components such as the limbs of the excavator boom **108** or the excavator stick **110** or on any of the linkages of the four-bar linkage **112**.

The LDM **124** is configured to generate an LDM distance signal D_{LDM} indicative of a distance between the LDM **124** and the laser reflector **139** and an angle of inclination signal θ_{INC} indicative of an angle between the LDM **124** and the laser reflector **130**. The laser reflector **130** is configured to be disposed at a position corresponding to a calibration node on the excavating implement **114**. In embodiments, the calibration node is positioned at a terminal point J at a bucket tooth tip of the excavating implement **114**. A height H_0 of the LDM **124** from the terminal pivot point A of the excavator boom **108** and a distance D_0 of the LDM from a terminal pivot point A of the excavator boom may be identified or determined prior to, for example, the iterative process being executed by the architecture controller.

The control architecture **106** comprises one or more linkage assembly actuators and an architecture controller programmed to execute an iterative process at successive implement curl positions. In embodiments, the control architecture comprises a non-transitory computer-readable storage medium comprising machine readable instructions that the architecture controller is programmed to execute. The one or more linkage assembly actuators may facilitate movement of the excavating linkage assembly **104**. Further, the one or more linkage assembly actuators may comprise a hydraulic cylinder actuator, a pneumatic cylinder actuator, an electrical actuator, a mechanical actuator, or combinations thereof.

The iterative process is illustrated in FIG. **6** through a control scheme **200** and steps **202-218**. In step **202**, the iterative process may start with a first iteration in which m=1. The calibration node may be aligned through the excavating linkage assembly **104** to align with the LDM **124** in step **204**. The iterative process comprises generating a measured dogbone angle $\theta_{DF}^{Measured}$ of the dogbone linkage from the implement dynamic sensor **120**, as illustrated in step **206**. The iterative process further comprises determining a height $\hat{H}$ and a distance $\hat{D}$ between the calibration node

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on the excavating implement **114** and the LDM **124** based on the LDM distance signal D_{LDM} and the angle of inclination signal θ_{INC}, as illustrated in step **208**. As shown in step **210**, the iterative process comprising determining a position of the calibration node at least partially based on the height $\hat{H}$ and the distance $\hat{D}$. Additionally, the iterative process comprises, as shown in step **212**, determining an estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement **114** at least partially based on the position of the calibration node.

In embodiments, the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement **114** may be determined at least partially based on the position of the node G and the position of the terminal pivot point B. Additionally or alternatively, the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement is determined at least partially based on a lookup table estimating the based on the measured dogbone angle $\theta_{DF}^{Measured}$. In another embodiment, a position of the node D of the four-bar linkage **112** is determined based on the measured dogbone angle $\theta_{DF}^{Measured}$, or may be otherwise identified, and the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement is determined at least partially based on the position of the node D and the position of the terminal pivot point B. As a non-limiting example, the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement is determined at least partially based on a determined internal angle θ_{DGJ}^{i} that based on the positions of nodes D and G and the terminal point J. Referring to FIGS. **4-5**, a determined external angle θ_{DGJ}^{e} may be determined based on the determined internal angle θ_{DGJ}^{i} per a following equation:

$$\theta_{DGJ}^{e}=360°-\theta_{DGJ}^{i} \qquad \text{(Equation 1)}$$

Further, the determined external angle θ_{DGJ}^{e} is a sum of the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement and a implement angle Ψ that is a constant angle formed between surfaces of the excavating implement **114** disposed between the terminal point J and the nodes G and H, such that:

$$\theta_{DGJ}^{e}=\theta_{GH}^{Estimated}+\Psi \qquad \text{(Equation 2)}$$

which is rearranged into a following equation:

$$\theta_{HG}^{Estimated}=\theta_{DGJ}^{e}-\Psi \qquad \text{(Equation 3)}$$

The iterative process further comprises, as shown in step **214** of FIG. **6**, generating a mapping equation comprising linkage angle inputs, unsolved linkage length parameters, and unsolved angle offset parameters. The linkage angle inputs comprise the measured dogbone angle $\theta_{DF}^{Measured}$ and the estimated implement angle $\theta_{GH}^{Estimated}$ at the implement curl position. The unsolved linkage length parameters comprise the linkage lengths GH, FH, DF, and DG of the four-bar linkage. The unsolved angle offset parameters comprise an offset dogbone angle θ_{DF}^{Bias} of the dogbone linkage, and an offset implement angle θ_{GH}^{Bias} of the excavating implement **114**.

In embodiments, the mapping equation comprises a following equation, which includes an actual dogbone angle θ_{DF}^{Actual} and an actual implement angle θ_{GH}^{Actual}:

$$\theta_{GH}^{Actual} = \frac{DG - DF*\cos(180° - \theta_{DF}^{Actual})}{FG} + \qquad \text{(Equation 4)}$$

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-continued
$$\frac{DF^2 + DG^2 + GH^2 - 2*DF*DG*\cos(180° - \theta_{DF}^{Actual}) - FH^2}{2*FG*GH}$$

The actual dogbone angle θ_{GH}^{Actual} is based on the measured dogbone angle $\theta_{GH}^{Estimated}$ and the offset dogbone angle θ_{GH}^{Bias} such that:

$$\theta_{DF}^{Actual}=\theta_{DF}^{Measured}-\theta_{DF}^{Bias} \qquad \text{(Equation 5)}$$

the actual implement angle θ_{GH}^{Actual} al is based on the estimated implement angle $\theta_{GH}^{Estimated}$ and the offset implement angle θ_{GH}^{Bias} such that:

$$\theta_{GH}^{Actual}=\theta_{GH}^{Estimated}-\theta_{GH}^{Bias} \qquad \text{(Equation 6)}$$

Further, the mapping equation is based on an implement angle equation, as follows:

$$\theta_{GH}^{Actual} = \frac{DG^2 + FG^2 - DF^2}{2*FG*DG} + \frac{FG^2 + GH^2 - FH^2}{2*FG*GH} \qquad \text{(Equation 7)}$$

The implement angle equation is based on an implement angle summation equation, as follows:

$$\theta_{GH}^{Actual}=\theta_{FGD}+\theta_{HGF} \qquad \text{(Equation 8)}$$

In Equation 8, θ_{HGF} is an angle between nodes H, G, and F, and θ_{FGD} is an angle between nodes F, G, and D. Further, θ_{HGF} and θ_{FGD} are based on a following pair of equations:

$$\theta_{FGD} = \frac{DG^2 + FG^2 - DF^2}{2*FG*DG} \text{ and} \qquad \text{(Equations 9-10)}$$

$$\theta_{HGF} = \frac{FG^2 + GH^2 - FH^2}{2*FG*GH}$$

The mapping equation is further based on a substitution of a FG^2 term in the implement angle equation with a diagonal length squared equation, which follows:

$$FG^2=DF^2+DG^2-2*DF*DG*\cos(180°-\theta_{DF}^{Actual}) \qquad \text{(Equation 11)}$$

Further, the diagonal length squared equation of Equation 11 is based on a diagonal length equation, as follows:

$$FG=\sqrt{DF^2+DG^2-2*DF*DG*\cos(180°-\theta_{DF}^{Actual})} \qquad \text{(Equation 12)}$$

In embodiments, the mapping equation maps a waveform as, for example, a graphical empirical chart or display, the waveform comprising linear and non-linear regions at least partially based on one or more linkage lengths.

The architecture controller is further programmed to repeat the iterative process for successive implement curl positions to generate a set of m mapping equations, wherein the set of m mapping equations comprises n unsolved linkage length and unsolved angle offset parameters, and the iterative process is repeated until m>n. For example, as shown in step **216** of FIG. **6**, if m>n is not true, then the iterative process continues to step **218** and the next iteration of m to repeat through steps **204-216**. If, in step **216**, m>n is true, the control scheme **200** continues on to step **220**. In embodiments, the iterative process is repeated until m passes a threshold greater than n. As a non-limiting example, n may be equal to 6 and the threshold may be 17 such that m is equal to 18 to generate a set of 18 mapping equations comprising 6 unsolved linkage length and unsolved angle offset parameters.

As shown in step **220** of FIG. **6**, the architecture controller is further programmed to solve the generated set of m mapping equations comprising the n unsolved parameters to determine the linkage lengths GH, FH, DF, and DG of the four-bar linkage, the offset dogbone angle θ_{DF}^{Bias} of the dogbone linkage, and the offset implement angle θ_{GH}^{Bias} of the excavating implement **114**. Further, as shown in step **222** of FIG. **6**, the architecture controller is programmed to operate the excavator **100** using the n solved parameters of linkage lengths GH, FH, DF, and DG, the offset dogbone angle θ_{DF}^{Bias}, and the offset implement angle θ_{GH}^{Bias}.

It is contemplated that the embodiments of the present disclosure may assist to permit a speedy and more cost efficient method of determining linkage lengths, sensor offsets of sensors on excavator linkages, and offsets of angular estimations of excavator linkages in a manner that minimizes a risk of human error with such value determinations. Further, the controller of the excavator or other control technologies are improved such that the processing systems are improved and optimized with respect to speed, efficiency, and output.

A signal may be "generated" by direct or indirect calculation or measurement, with or without the aid of a sensor.

For the purposes of describing and defining the present invention, it is noted that reference herein to a variable being a "function" of a parameter or another variable is not intended to denote that the variable is exclusively a function of the listed parameter or variable. Rather, reference herein to a variable that is a "function" of a listed parameter is intended to be open ended such that the variable may be a function of a single parameter or a plurality of parameters.

It is also noted that recitations herein of "at least one" component, element, etc., should not be used to create an inference that the alternative use of the articles "a" or "an" should be limited to a single component, element, etc.

It is noted that recitations herein of a component of the present disclosure being "configured" or "programmed" in a particular way, to embody a particular property, or to function in a particular manner, are structural recitations, as opposed to recitations of intended use. More specifically, the references herein to the manner in which a component is "configured" or "programmed" denotes an existing physical condition of the component and, as such, is to be taken as a definite recitation of the structural characteristics of the component.

It is noted that terms like "preferably," "commonly," and "typically," when utilized herein, are not utilized to limit the scope of the claimed invention or to imply that certain features are critical, essential, or even important to the structure or function of the claimed invention. Rather, these terms are merely intended to identify particular aspects of an embodiment of the present disclosure or to emphasize alternative or additional features that may or may not be utilized in a particular embodiment of the present disclosure.

For the purposes of describing and defining the present invention it is noted that the terms "substantially" and "approximately" are utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. The terms "substantially" and "approximately" are also utilized herein to represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue.

Having described the subject matter of the present disclosure in detail and by reference to specific embodiments thereof, it is noted that the various details disclosed herein

should not be taken to imply that these details relate to elements that are essential components of the various embodiments described herein, even in cases where a particular element is illustrated in each of the drawings that accompany the present description. Further, it will be apparent that modifications and variations are possible without departing from the scope of the present disclosure, including, but not limited to, embodiments defined in the appended claims. More specifically, although some aspects of the present disclosure are identified herein as preferred or particularly advantageous, it is contemplated that the present disclosure is not necessarily limited to these aspects.

It is noted that one or more of the following claims utilize the term "wherein" as a transitional phrase. For the purposes of defining the present invention, it is noted that this term is introduced in the claims as an open-ended transitional phrase that is used to introduce a recitation of a series of characteristics of the structure and should be interpreted in like manner as the more commonly used open-ended preamble term "comprising."

What is claimed is:

1. An excavator calibration framework comprising an excavator, a laser distance meter (LDM), and a laser reflector, wherein:

the excavator comprises a machine chassis, an excavating linkage assembly, an implement dynamic sensor, an excavating implement, and control architecture;

the excavating linkage assembly comprises an excavator boom, an excavator stick, and a four-bar linkage;

the excavating implement and the excavator stick are mechanically coupled through the four-bar linkage comprising an implement linkage of length GH, a rear side linkage of length FH, a dogbone linkage of length DF, and a front side linkage of length DG;

the implement dynamic sensor is positioned on the dogbone linkage of the four-bar linkage;

the excavating implement is configured to curl relative to the excavator stick to define a plurality of implement curl positions;

the LDM is configured to generate an LDM distance signal D_{LDM} indicative of a distance between the LDM and the laser reflector and an angle of inclination signal θ_{INC} indicative of an angle between the LDM and the laser reflector;

the laser reflector is configured to be disposed at a position corresponding to a calibration node on the excavating implement;

the control architecture comprises one or more linkage assembly actuators and an architecture controller programmed to execute an iterative process at successive implement curl positions, the iterative process comprising

generating a measured dogbone angle $\theta_{DF}^{Measured}$ of the dogbone linkage from the implement dynamic sensor,

determining a height $\hat{H}$ and a distance $\hat{D}$ between the calibration node on the excavating implement and the LDM based on the LDM distance signal D_{LDM} and the angle of inclination signal θ_{INC},

determining a position of the calibration node at least partially based on the height $\hat{H}$ and the distance $\hat{D}$,

determining an estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement at least partially based on the position of the calibration node, and

generating a mapping equation comprising linkage angle inputs, unsolved linkage length parameters, and unsolved angle offset parameters, wherein the

linkage angle inputs comprise the measured dogbone angle $\theta_{DF}^{Measured}$ and the estimated implement angle $\theta_{GH}^{Estimated}$ the implement curl position, the unsolved linkage length parameters comprise the linkage lengths GH, FH, DF, and DG of the four-bar linkage, and the unsolved angle offset parameters comprise an offset dogbone angle θ_{DF}^{Bias} of the dogbone linkage, and an offset implement angle θ_{GH}^{Bias} of the excavating implement; and

the architecture controller is further programmed to

repeat the iterative process for successive implement curl positions to generate a set of m mapping equations, wherein the set of m mapping equations comprises n unsolved linkage length and unsolved angle offset parameters, and the iterative process is repeated until m>n,

solve the generated set of m mapping equations comprising the n unsolved parameters to determine the linkage lengths GH, FH, DF, and DG of the four-bar linkage, the offset dogbone angle θ_{DF}^{Bias} of the dogbone linkage, and the offset implement angle θ_{GH}^{Bias} of the excavating implement, and

operate the excavator using the linkage lengths GH, FH, DF, and DG, the offset dogbone angle θ_{DF}^{Bias}, and the offset implement angle θ_{GH}^{Bias}.

2. An excavator calibration framework as claimed in claim **1**, wherein:

the four-bar linkage comprises a node D, a node F, a node G, a node H;

the implement linkage is disposed between respective positions corresponding to the node G and the node H;

the rear side linkage is disposed between respective positions corresponding to the node F and the node H;

the dogbone linkage is disposed between respective positions corresponding to the node D and the node F; and

the front side linkage is disposed between respective positions corresponding to the node D and the node G.

3. An excavator calibration framework as claimed in claim **2**, wherein the node G of the four-bar linkage is disposed at a position corresponding to a terminal point of the excavator stick through which the excavator stick is coupled to the excavating implement.

4. An excavator calibration framework as claimed in claim **1**, wherein the iterative process is repeated until m passes a threshold greater than n.

5. An excavator calibration framework as claimed in claim **4**, wherein n is equal to 6 and the threshold is 17 such that m is equal to 18 to generate a set of 18 mapping equations comprising 6 unsolved linkage length and unsolved angle offset parameters.

6. An excavator calibration framework as claimed in claim **1**, wherein the laser reflector is on a pole or secured directly to the excavating implement.

7. An excavator calibration framework as claimed in claim **1**, wherein the calibration node is positioned at a terminal point J at a bucket tooth tip of the excavating implement.

8. An excavator calibration framework as claimed in claim **1**, wherein the machine chassis is mechanically coupled to a terminal pivot point A of the excavator boom.

9. An excavator calibration framework as claimed in claim **1**, wherein the excavator stick comprises a stick terminal point corresponding to the position of a node G of the four-bar linkage and is mechanically coupled to a terminal pivot point B of the excavator boom; and

the excavator stick is mechanically coupled to the excavating implement through the stick terminal point.

10. An excavator calibration framework as claimed in claim **9**, wherein a position of the terminal pivot point B and the node G are identified.

11. An excavator calibration framework as claimed in claim **10**, wherein the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement is determined at least partially based on the position of the node G and the position of the terminal pivot point B.

12. An excavator calibration framework as claimed in claim **9**, wherein:

the four-bar linkage comprises a node D, a node F, a node G, a node H;

the calibration node is positioned at a terminal point J at a heading tooth tip of the excavating implement;

a position of the terminal pivot point B is identified;

a position of the node D of the four-bar linkage is determined based on the measured dogbone angle $\theta_{DF}^{Measured}$; and

the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement is determined at least partially based on the position of the node D and the position of the terminal pivot point B.

13. An excavator calibration framework as claimed in claim **12**, wherein the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement is determined at least partially based on:

a determined internal angle θ_{DGJ}^{i} based on the positions of nodes D and G and the terminal point J such that a determined external angle $\theta_{DGJ}^{e}=360°-\theta_{DGJ}^{i}$.

14. An excavator calibration framework as claimed in claim **13**, wherein the determined external angle θ_{DGJ}^{e} is a sum of the estimated implement angle $\theta_{GH}^{Estimated}$ of the excavating implement and a implement angle Ψ that is a constant angle formed between the surfaces of the excavating implement disposed between the terminal point J and the nodes G and H, such that:

$$\theta_{GH}^{Estimated}=\theta_{DGJ}^{e}-\Psi.$$

15. An excavator calibration framework as claimed in claim **1**, wherein:

the four-bar linkage comprises a diagonal length FG between a front end node of the implement linkage of length GH and a rear end node of the dogbone linkage of length DF; and

the mapping equation comprises a following equation, including an actual dogbone angle θ_{DF}^{Actual} and an actual implement angle θ_{GH}^{Actual}:

$$\theta_{GH}^{Actual} = \frac{DG - DF*\cos(180° - \theta_{DF}^{Actual})}{FG} + \frac{DF^2 + DG^2 + GH^2 - 2*DF*DG*\cos(180° - \theta_{DF}^{Actual}) - FH^2}{2*FG*GH}.$$

16. An excavator calibration framework as claimed in claim **15**, wherein the actual dogbone angle θ_{DF}^{Actual} based on the measured dogbone angle $\theta_{DF}^{Measured}$ and the offset dogbone angle θ_{DF}^{Bias} such that:

$$\theta_{DF}^{Actual}=\theta_{DF}^{Measured}-\theta_{DF}^{Bias}.$$

17. An excavator calibration framework as claimed in claim **15**, wherein the actual implement angle θ_{GH}^{Actual} is based on the estimated implement angle $\theta_{GH}^{Estimated}$ and the offset implement angle θ_{GH}^{Bias} such that:

$$\theta_{GH}^{Actual}=\theta_{GH}^{Estimated}-\theta_{GH}^{Bias}.$$

18. An excavator calibration framework as claimed in claim **15**, wherein the mapping equation is based on an implement angle equation, as follows:

$$\theta_{GH}^{Actual} = \frac{DG^2 + FG^2 - DF^2}{2*FG*DG} + \frac{FG^2 + GH^2 - FH^2}{2*FG*GH}$$

and a substitution of a FG^2 term in the implement angle equation with a diagonal length squared equation, as follows:

$$FG^2 = \sqrt{DF^2 + DG^2 - 2*DF*DG*\cos(180° - \theta_{DF}^{Actual})}.$$

19. An excavator calibration framework as claimed in claim **18**, wherein the diagonal length squared equation is based on a diagonal length equation, as follows:

$$FG = \sqrt{DF^2 + DG^2 - 2*DF*DG*\cos(180° - \theta_{DF}^{Actual})}.$$

20. An excavator calibration framework as claimed in claim **18**, wherein the implement angle equation is based on an implement angle summation equation, as follows:

$$\theta_{GH}^{Actual} = \theta_{FGD} + \theta_{HGF}.$$

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