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(54) **EXCAVATOR IMPLEMENT ANGLE DETERMINATION USING A LASER DISTANCE METER**

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G01S 17/88	(2006.01)
E02F 3/32	(2006.01)

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CPC *E02F 3/435* (2013.01); *E02F 9/264* (2013.01); *E02F 9/265* (2013.01); *G01S 17/08* (2013.01); *G01S 17/88* (2013.01); *G05D 1/024* (2013.01); *E02F 3/32* (2013.01); *G05D 2201/0202* (2013.01)

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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 plurality of laser reflectors. The excavator comprises a chassis, linkage assembly (LA), implement, and control architecture. The LA comprises a boom, stick, the implement, and a four-bar linkage including nodes, with a laser reflector at each node. The control architecture comprises a controller programmed to execute an iterative process at n linkage assembly positions to determine a position of an nth calibration node of the plurality of nodes of the four-bar linkage to determine triangular angles and side lengths of an external triangle formed between the nth calibration node and two other nodes having identified positions. The iterative process is repeated n times until triangular angles and side lengths of three external triangles are determined that form an internal triangle. Angles of the internal triangle are determined to generate an implement angle.
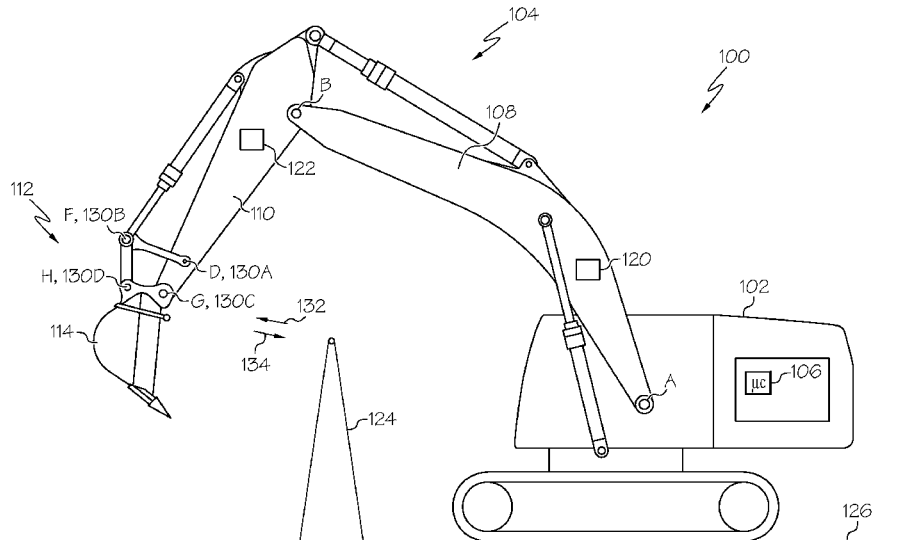
20 Claims, 4 Drawing Sheets

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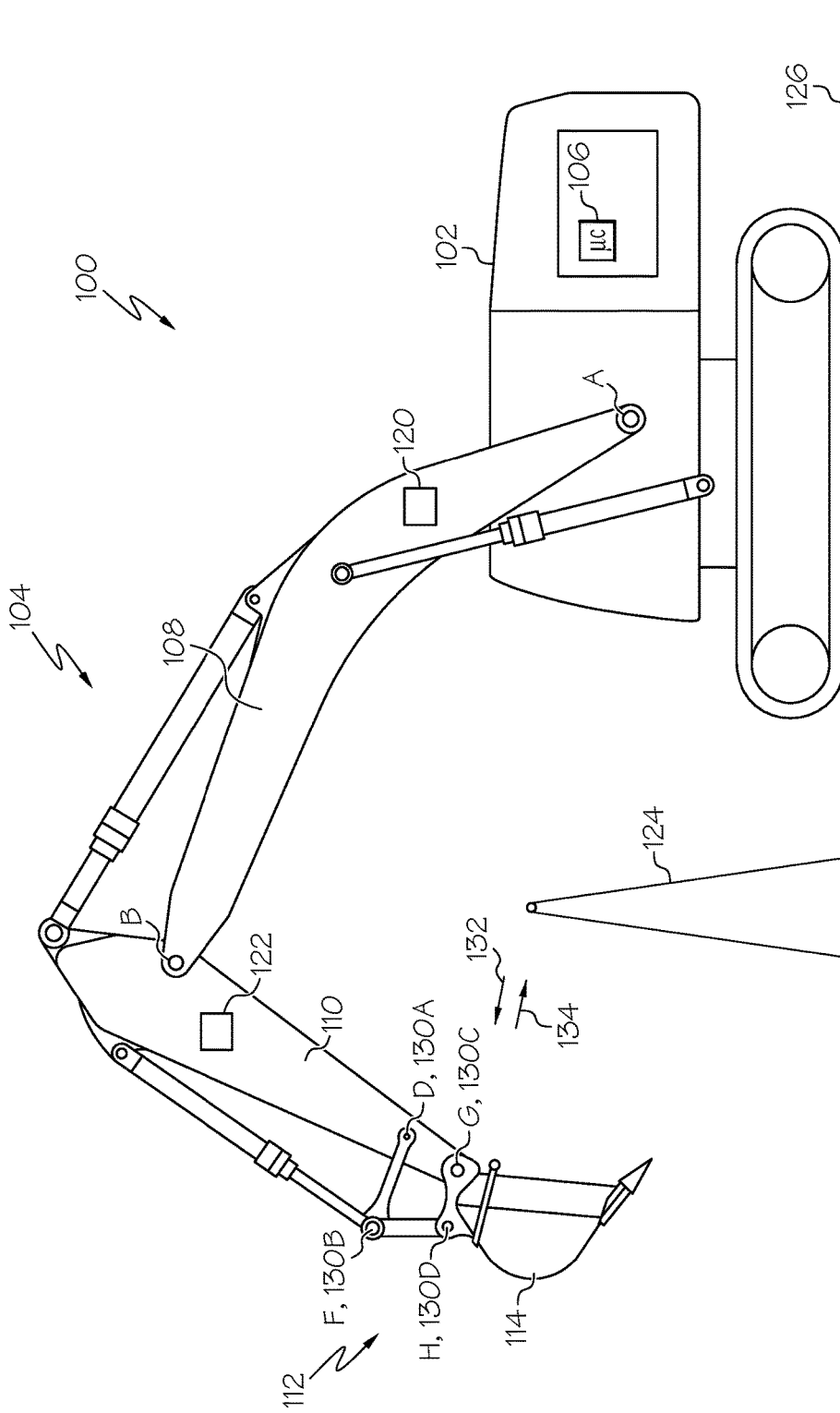| 6,253,160 | B1 | 6/2001 | Hanseder |
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FIG. 1

FIG. 2

FIG. 3

FIG. 4

200

202

n=1

204
POSITION STICK AND
BOOM AT NODE n

206
READ LDM VALUES
(D_{LDM}, θ_{INC})

208
DETERMINE MEASUREMENTS
(H, D)

210
DETERMINE POSITION OF NODE N

212
DETERMINE DISTANCES OF A TRIANGLE FORMED
FROM NODE N AND TWO OTHER NODES

214
DETERMINE ANGLES OF THE TRIANGLE

216
ARE SUFFICIENT
DISTANCES AND ANGLES OF THREE
TRIANGLES FORMING AN INTERNAL TRIANGLE
DETERMINED?

NO

218
n=n+1

YES

220
DETERMINE ANGLES OF THE
INTERNAL TRIANGLE

222
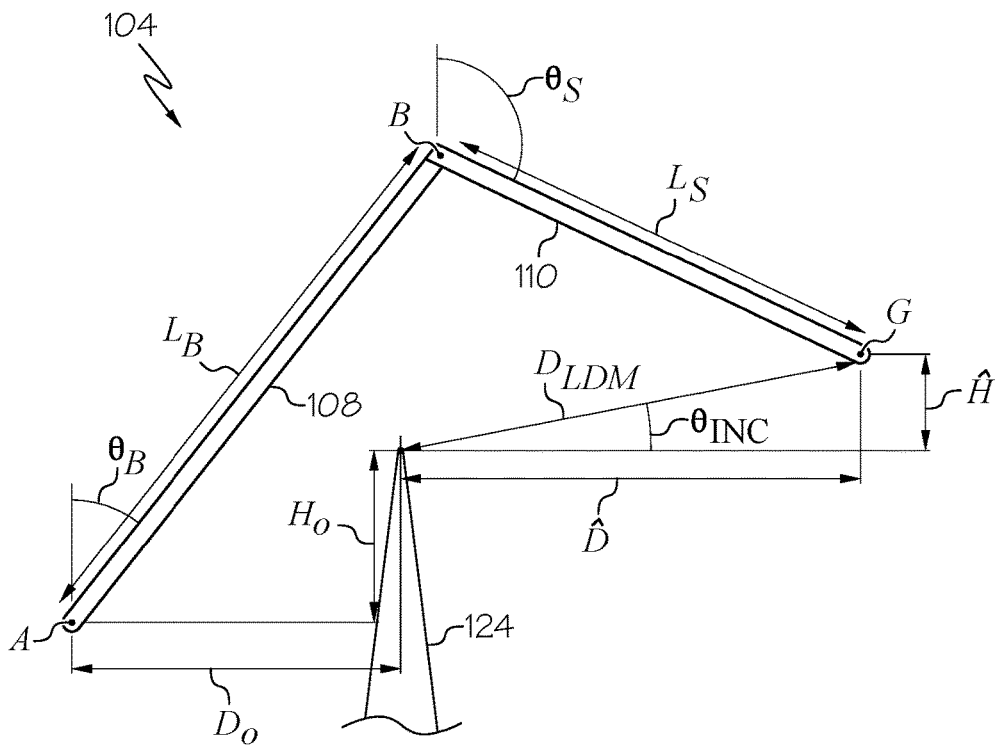DETERMINE IMPLEMENT ANGLE
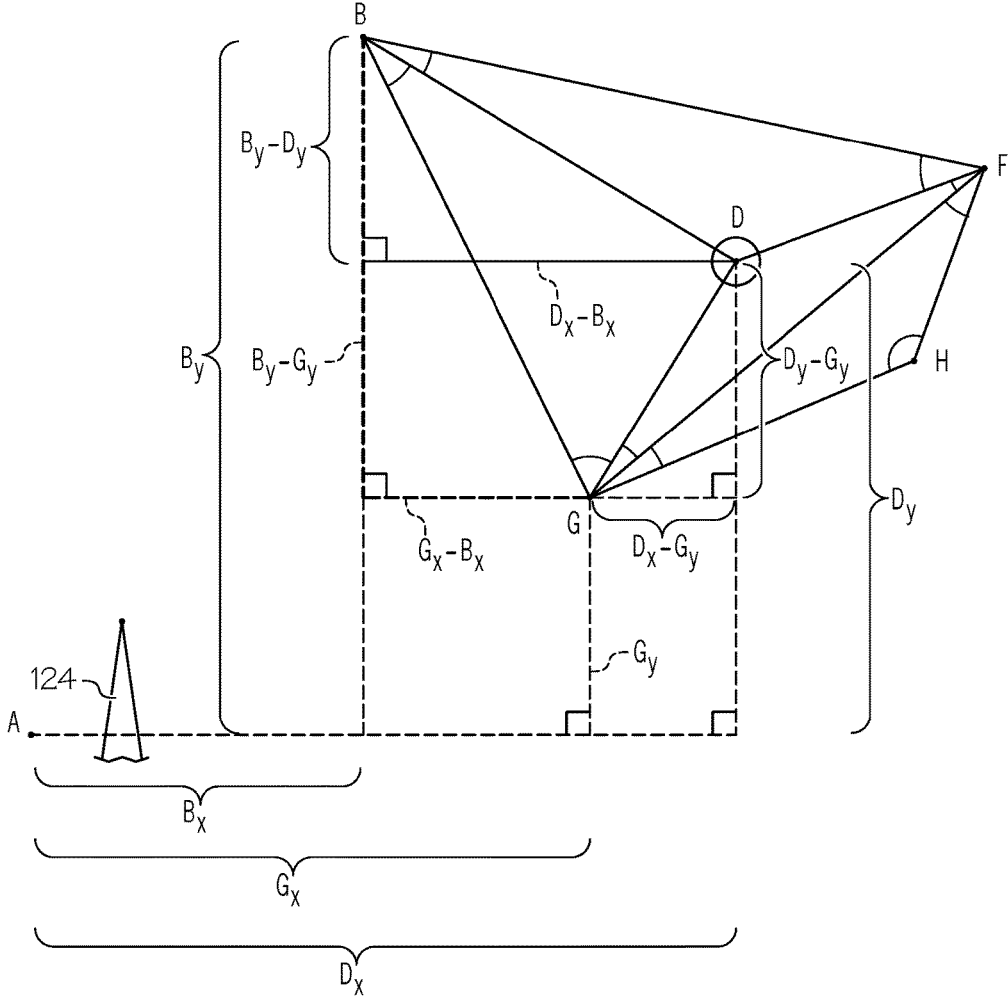
224
OPERATE EXCAVATOR
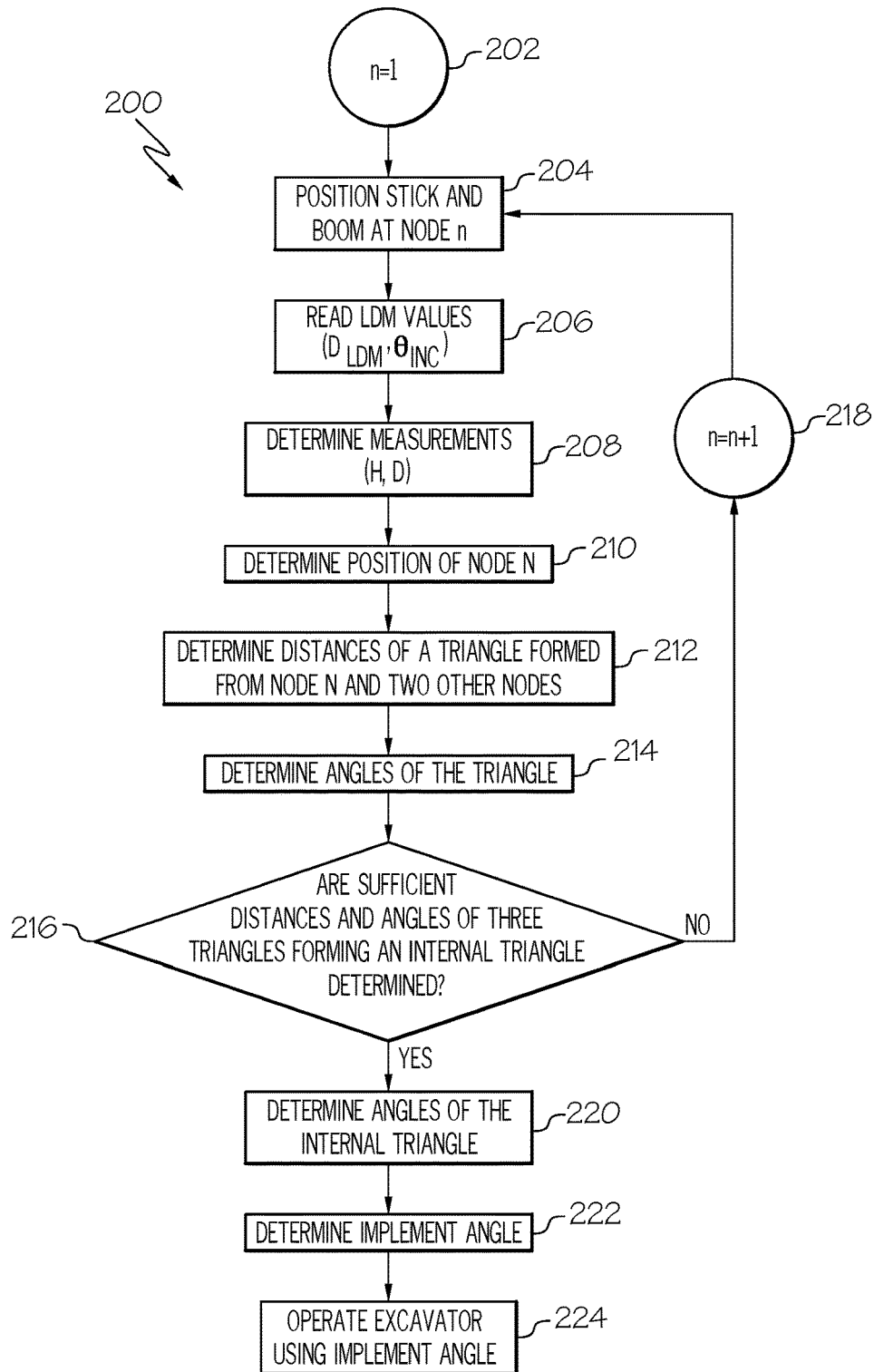USING IMPLEMENT ANGLE

FIG. 5

EXCAVATOR IMPLEMENT ANGLE 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 plurality of laser reflectors. The excavator comprises a machine chassis, an excavating linkage assembly, an excavating implement, and control architecture. The excavating linkage assembly comprises an excavator boom, an excavator stick, the excavating implement, and a four-bar linkage that collectively define a plurality of linkage assembly positions. The excavator stick comprises a terminal point and is mechanically coupled to a terminal pivot point B of the excavator boom. The four-bar linkage comprises a node D, a node F, a node G, a node H, and linkages disposed therebetween. The node G of the four-bar linkage is disposed at a position corresponding to the terminal point of the excavator stick through which the excavator stick is coupled to the excavating implement. 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 plurality of laser reflectors are disposed at respective positions corresponding to the nodes D, F, G, and H of the four-bar linkage. The control architecture comprises one or more linkage assembly actuators and an architecture controller programmed to execute an iterative process at n linkage assembly positions. The iterative process comprises positioning the excavating linkage assembly at a linkage assembly position n, setting one of the nodes D, F, G, and H as the nth calibration node with the excavating linkage assembly at the linkage assembly position n, and determining a height $\hat{H}$ and a distance $\hat{D}$ between the nth calibration node and the LDM based on the LDM distance signal D_{LDM} and angle of inclination signal θ_{INC}. The iterative process

further comprises determining a position of the nth calibration node at least partially based on the height $\hat{H}$ and the distance $\hat{D}$, and identifying respective positions of two other nodes that, together with the nth calibration node, form an external triangle. The two other nodes comprise one of nodes D, F, G, H, and a node corresponding to a position of the terminal pivot point B of the excavator boom. The iterative process further comprises determining side lengths for each of the legs of the external triangle formed between the nth calibration node and two other nodes, and determining triangular angles of the external triangle based on the side lengths of the external triangle. The architecture controller is further programmed to repeat the iterative process n times until triangular angles and side lengths of at least three external triangles are determined. The external triangles form an internal triangle therebetween, the internal triangle shares two nodes and one side with each of the three external triangles and comprises a set of three internal triangle side lengths. The architecture controller is further programmed to determine the angles of the internal triangle at least partially based on the set of three internal triangle side length, generate an implement angle of the excavating implement at least partially based on a summation of a set of adjacent determined triangular angles, and operate the excavator using the implement angle. The set of adjacent determined triangular angles comprise an angle from the internal triangle and angles from at least two of the external triangles.

In accordance with one embodiment of the present disclosure, an excavator calibration framework comprises an excavator, a laser distance meter (LDM), and a plurality of laser reflectors. The excavator comprises a machine chassis, an excavating linkage assembly, an excavating implement, and control architecture. The excavating linkage assembly comprises an excavator boom, an excavator stick, the excavating implement, and a four-bar linkage that collectively define a plurality of linkage assembly 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 plurality of laser reflectors are disposed at respective positions corresponding to a plurality of nodes of the four-bar linkage. The control architecture comprises one or more linkage assembly actuators and an architecture controller programmed to execute an iterative process at n linkage assembly positions to determine a position of an nth calibration node of the plurality of nodes of the four-bar linkage to determine triangular angles and side lengths of an external triangle formed between the nth calibration node and two other nodes having identified positions. The architecture controller is further programmed to repeat the iterative process n times until triangular angles and side lengths of at least three external triangles are determined. The external triangles form an internal triangle therebetween, the internal triangle shares two nodes and one side with each of the three external triangles and comprises a set of three internal triangle side lengths. The architecture controller is further programmed to determine the angles of the internal triangle at least partially based on the set of three internal triangle side lengths, generate an implement angle of the excavating implement at least partially based on a summation of a set of adjacent determined triangular angles, and operate the excavator using the implement angle. The set of adjacent determined triangular angles comprise an angle from the internal triangle and angles from at least two of the external triangles.

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) 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; and

FIG. 5 is a flow chart of a process used to determine an implement angle of an excavating implement 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 earthmoving 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 an implement angle of an excavating implement of an excavator, 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, excavator calibration framework comprises an excavator 100, a laser distance meter (LDM) 124, and a plurality of laser reflectors 130A, 130B, 130C, and 130D. The excavator comprises a machine chassis 102, an excavating linkage assembly 104, an excavating implement 114, and control architecture 106. The excavating linkage assembly 104 comprises an excavator boom 108, an excavator stick 110, the excavating implement 114, and a four-bar linkage 112 that collectively define a plurality of linkage assembly positions. The excavator stick 110 comprises a terminal point and is mechanically coupled to a terminal pivot point B of the excavator boom 108. The machine chassis 102 is mechanically coupled to a terminal pivot point A of the excavator boom 108. In embodiments, the excavating linkage assembly 104 is configured to swing

with, or relative to, the machine chassis 102, and the excavator stick 110 is configured to curl relative to the excavator boom 108. Further, the excavating implement 114 and the excavator stick 110 are mechanically coupled to each other through the four-bar linkage 112.

The four-bar linkage 112 comprises a node D, a node F, a node G, a node H, and linkages disposed therebetween. In embodiments, the linkages comprise an implement linkage GH, a rear side linkage FH, a dogbone linkage DF, and a front side linkage GD. The implement linkage GH is disposed between respective positions corresponding to the node G and the node H. The rear side linkage FH is disposed between respective positions corresponding to the node F and the node H. The dogbone linkage DF is disposed between respective positions corresponding to the node D and the node F. The front side linkage GD is disposed between respective positions corresponding to the node D and the node G.

The node G of the four-bar linkage 112 is 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. The LDM 124 is configured to generate an LDM distance signal D_{LDM} indicative of a distance between the LDM and the laser reflector (for example, one of 130A-130D) and an angle of inclination signal θ_{INC} indicative of an angle between the LDM and the laser reflector (for example, one of 130A-130D). The plurality of laser reflectors 130A, 130B, 130C, and 130D are disposed at respective positions corresponding to the nodes D, F, G, and H of the four-bar linkage 112. In embodiments, the laser reflector (for example, one of 130A-130D) is on a pole or secured directly to the corresponding nodes. 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, and the laser signal may be reflected back to the LDM 124 in the direction of an arrow 134, as illustrated in FIG. 1.

The control architecture 106 comprises one or more linkage assembly actuators and an architecture controller programmed to execute an iterative process at n linkage assembly positions. In embodiments, the control architecture 106 comprises a non-transitory computer-readable storage medium comprising machine readable instructions. The one or more linkage assembly actuators may facilitate movement of the excavating linkage assembly 104. 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.

Steps 202-218 of a control scheme 200 of FIG. 5 illustrate the iterative process. In step 202, the iterative process starts with n=1 at a first linkage assembly position. In embodiments, for n=1, the 1st calibration node is positioned at the node D, for n=2, the 2nd calibration node is positioned at the node F, and for n=3, the 3rd calibration node is positioned at the node H.

In step 204, the iterative process comprises positioning the excavating linkage assembly 104 at a linkage assembly position n, setting one of the nodes D, F, G, and H as the nth calibration node with the excavating linkage assembly 104 at the linkage assembly position n. In steps 206-208, the iterative process comprises determining a height $\hat{H}$ and a distance D between the nth calibration node and the LDM based on the LDM distance signal D_{LDM} and angle of inclination signal θ_{INC}. In step 210, the iterative process

comprises determining a position of the nth calibration node at least partially based on the height $\hat{H}$ and the distance $\hat{D}$. In embodiments of the iterative process, determining a position of the nth calibration node at least partially based on the height $\hat{H}$ and the distance $\hat{D}$ comprises calculating a total height $\check{H}$ and a total distance $\check{D}$ between the nth calibration node and the terminal pivot point A of the excavator boom **108**. Referring to FIG. **3**, the calculation is based on a summation of the height $\hat{H}$ and the distance $\hat{D}$ between the nth calibration node and the LDM **124** and the height H_0 and the distance D_0 between the LDM **124** and the terminal pivot point A. The height $\hat{H}$ and the distance $\hat{D}$ between the nth calibration node and the LDM **124** is determined per a following set of equations:

$$\hat{D}=D_{LDM}\cos(\theta_{INC}), \text{ and}$$

$$\hat{H}=D_{LDM}\sin(\theta_{INC}). \hspace{1cm} \text{(Equations 1-2)}$$

Further, referring to FIG. **4** and in an embodiment when n=1 and the 1st calibration node is positioned at the node D, calculating a total height $\check{H}$ and a total distance $\check{D}$ between the 1st calibration node and the terminal pivot point A of the excavator boom, respectively comprising D_y and D_x, based on a summation of the height $\hat{H}$ and the distance $\hat{D}$ between the 1st calibration node and the LDM and the height H_0 and the distance D_0 between the LDM and the terminal pivot point A comprises use of a following set of questions:

$$D_y=H_0+\hat{H}_D, \text{ and}$$

$$D_x=D_0+\hat{D}_D. \hspace{1cm} \text{(Equations 3-4)}$$

In an embodiment when n=2, the 2nd calibration node is positioned at pin F, such that calculating a total height $\check{H}$ and a total distance $\check{D}$ between the 2nd calibration node and the terminal pivot point A of the excavator boom, respectively comprising F_y and F_x, based on a summation of the height $\hat{H}$ and the distance $\hat{D}$ between the 3rd calibration node and the LDM and the height H_0 and the distance D_0 between the LDM and the terminal pivot point A comprises use of a following set of equations:

$$F_y=H_0+\hat{H}_F, \text{ and}$$

$$F_x=D_0+\hat{D}_F. \hspace{1cm} \text{(Equations 5-6)}$$

In an embodiment when n=3, the 3rd calibration node is positioned at pin H, such that calculating a total height $\check{H}$ and a total distance $\check{D}$ between the 3rd calibration node and the terminal pivot point A of the excavator boom, respectively comprising H_y and H_x, based on a summation of the height $\hat{H}$ and the distance $\hat{D}$ between the 3rd calibration node and the LDM and the height H_0 and the distance D_0 between the LDM and the terminal pivot point A comprises use of a following set of equations:

$$H_y=H_0+\hat{H}_H, \text{ and}$$

$$H_x=D_0+\hat{D}_H. \hspace{1cm} \text{(Equations 7-8)}$$

In embodiments, the architecture controller is further programmed to execute machine readable instructions to determine a total height $\check{H}$ and a total distance $\check{D}$ between the terminal point G and the terminal pivot point A based on a boom limb length L_B, a stick limb length L_S, a boom angle θ_B, and a stick angle θ_S. For example, and referring to FIG. **3**, L_S is a stick limb length of the excavator stick **110**, θ_S is a stick angle of the excavator stick **110** relative to gravity, L_B is a boom limb length of the excavator boom **108**, and θ_B is a boom angle of the excavator boom **108** relative to gravity. Further, the architecture controller is programmed to deter-

mine a total height $\check{H}$ and a total distance $\check{D}$ between the terminal pivot point B and the terminal pivot point A based on a boom limb length L_B, and a boom angle θ_B. The architecture controller is programmed to identify a height H_0 and a distance D_0 between the LDM and the terminal pivot point A.

The iterative process further comprises identifying respective positions of two other nodes that, together with the nth calibration node, form an external triangle. The two other nodes comprise one of nodes D, F, G, H, and a node corresponding to a position of the terminal pivot point B of the excavator boom **108**. Further, in step **212**, the iterative process comprises determining side lengths for each of the legs of the external triangle formed between the nth calibration node and two other nodes. In step **214**, the iterative process comprises determining triangular angles of the external triangle based on the side lengths of the external triangle. In embodiments and referring to FIG. **4**, the external triangles may comprise triangles BGD, BDF, and GFH.

For example, when n=1 and the 1st calibration node is positioned at the node D, the two other nodes comprise the terminal pivot point B and the node G, the legs of the external triangle comprise GD, BD, BG, and the triangular angles of the external triangle comprise angles BGD, GDB, DBG and are determined based on the side lengths determined for the legs GD, BD, and BG and the law of cosines.

Further, determining the side lengths for the legs BG, GD, and BD comprises calculating the side length for the leg BG based on the total height $\check{H}$ and the total distance $\check{D}$ between the node G and the terminal pivot point A, respectively comprising G_y and G_x and the total height $\check{H}$ and the total distance $\check{D}$ between the terminal pivot point B and the terminal pivot point A, respectively comprising B_y and B_x. With respect to G_y and G_x, a following set of equations may be used:

$$G_y=L_S\cos(\theta_S)+L_B\cos(\theta_B), \text{ and}$$

$$G_x=L_S\sin(\theta_S)+L_B\sin(\theta_B). \hspace{1cm} \text{(Equations 9-10)}$$

With respect to B_y and B_x, a following set of equations may be used:

$$B_y=L_B\cos(\theta_B), \text{ and}$$

$$B_x=L_B\sin(\theta_B). \hspace{1cm} \text{(Equations 11-12)}$$

Thus, determining the side lengths for the legs BG, GD, and BD may include a following set of equations:

$$BG=\sqrt{(G_y-B_y)^2+(G_x-B_x)^2},$$

$$GD=\sqrt{(G_y-D_y)^2+(G_x-D_x)^2}, \text{ and}$$

$$BD=\sqrt{(D_y-B_y)^2+(D_x-B_x)^2} \hspace{1cm} \text{(Equations 13-15)}$$

The side length BG should be a length of the excavator stick and should be equivalent to L_S. In further embodiments, the excavator boom further comprises a variable-angle (VA) excavator boom, and for which L_V is a limb length of the VA excavator boom, and θ_V is a VA boom angle of the VA excavator boom relative to gravity:

$$G_y=L_V\cos(\theta_V)+L_S\cos(\theta_S)+L_B\cos(\theta_B), \text{ and}$$

$$G_x=L_V\sin(\theta_V)+L_S\sin(\theta_S)+L_B\sin(\theta_B). \hspace{1cm} \text{(Equations 16-17)}$$

In such embodiments, with a VA excavator boom, the total height $\check{H}$ and the total distance $\check{D}$ between the terminal pivot point B and the terminal pivot point A, respectively comprising By and Bx, such that:

$$B_y = L_V \cos(\theta_V) + L_B \cos(\theta_B), \text{ and}$$

$$B_x = L_V \sin(\theta_V) + L_B \sin(\theta_B). \quad \text{(Equations 18-19)}$$

In embodiments, when n=2 and the 2nd calibration node is positioned at the node F, the two other nodes comprise the terminal pivot point B and the node D. Further, the legs of the external triangle comprise DF, BF, and BD, where

$$DF = \sqrt{(D_y - F_y)^2 + (D_x - F_x)^2}, \text{ and}$$

$$BF = \sqrt{(B_y - F_y)^2 + (B_x - F_x)^2}. \quad \text{(Equations 20-21)}$$

Additionally, the triangular angles of the external triangle comprise angles BDF, DFB, FBD and are determined based on the side lengths determined for the legs DF, BF, and BD and the law of cosines. The angle BDF is representative of an actual dogbone angle BDF.

In an embodiment, the excavator further comprises an implement dynamic sensor disposed on a dogbone linkage DF of the four-bar linkage **112**. The architecture controller is further programmed to execute machine readable instructions to generate a dogbone measured angle θ_{DF} from the implement dynamic sensor. Further, the machine readable instructions may comprise instructions to compare the dogbone measured angle θ_{DF} to an actual dogbone angle BDF to determine a bias therebetween, and calibrate the implement dynamic sensor based on the bias. One or more dynamic sensors may include the implement sensor and dynamic sensors **120**, **122** positioned on other excavator limbs such as the excavator boom **108** and the excavator stick **110**, which are similar to the implement dynamic sensor. The one or more dynamic sensors may comprise 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 comprise a 3-axis accelerometer and a 3-axis gyroscope. As shown in FIG. **2**, the dynamic sensors **120**, **122** include accelerations A_x, A_y, and A_z, respectively representing x-axis, y-axis-, and z-axis acceleration values.

In embodiments when n=3 and the 3rd calibration node is positioned at the node H, the two other nodes comprise the node F and the node G. Further, the legs of the external triangle comprise GH, FH, and FG, where

$$GH = \sqrt{(G_y - H_y)^2 + (G_x - H_x)^2},$$

$$FH = \sqrt{(F_y - H_y)^2 + (F_x - H_x)^2}, \text{ and}$$

$$FG = \sqrt{(F_y - G_y)^2 + (F_x - G_x)^2}. \quad \text{(Equations 22-23)}$$

Additionally, the triangular angles of the external triangle comprise angles FGH, GHF, HFG and are determined based on the side lengths determined for the legs GH, FH, and FG and the law of cosines.

The architecture controller is further programmed to repeat the iterative process n times until triangular angles and side lengths of at least three external triangles are determined. The external triangles form an internal triangle therebetween. Further, the internal triangle shares two nodes and one side with each of the three external triangles and comprises a set of three internal triangle side lengths. In an embodiment and referring to FIG. **4**, the internal triangle comprises internal triangle GDF disposed between and internally of external triangles BGD, BDF, and GFH. The internal triangle GDF shares nodes G and D with the external triangle BGD, nodes DF with the external triangle BDF, and nodes F and G with the external triangle GFH.

As a non-limiting example, in step **216**, the iterative process determines if sufficient distances and angles of three external triangles forming an internal triangle have been determined. If the answer is no, the iterative process proceeds to step **218** and repeat step **204** to position the excavating linkage assembly **104** at a next linkage assembly position n. If the answer is yes, the iterative process proceeds to step **220**.

The architecture controller is further programmed to, as shown in step **220**, determine the angles of the internal triangle at least partially based on the set of three internal triangle side lengths. As a non-limiting example, when, as described above, the 1st, 2nd, and 3rd calibration nodes have been respectively positioned at the nodes D, F, and H through the iterative process, in step **220**, the set of internal triangle side lengths are length are legs DF, FG, and GD that form the internal triangle. Further, the angles of the internal triangle comprise angles DGF, GDF, and DFG and are determined based on the determined side lengths of the legs DF, FG, and GD and the law of cosines.

The architecture controller is further programmed to, as shown in step **222**, generate an implement angle of the excavating implement at least partially based on a summation of a set of adjacent determined triangular angles. The set of adjacent determined triangular angles comprises an angle from the internal triangle and angles from at least two of the external triangles. In the example above, generating the implement angle comprises generate an angle BGH based on a summation of the determined angles DGF, BGD, and FGH. The architecture controller is further programmed to, as shown in step **224**, operate the excavator using the implement angle.

It is contemplated that the embodiments of the present disclosure may assist to permit a speedy and more cost efficient method of determining implement dimensions such as an implement angle, and methods to determine and calibrate sensor offsets of sensors on 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 plurality of laser reflectors, wherein:

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

the excavating linkage assembly comprises an excavator boom, an excavator stick, the excavating implement, and a four-bar linkage that collectively define a plurality of linkage assembly positions;

the excavator stick comprises a terminal point and is mechanically coupled to a terminal pivot point B of the excavator boom;

the four-bar linkage comprises a node D, a node F, a node G, a node H, and linkages disposed therebetween;

the node G of the four-bar linkage is disposed at a position corresponding to the terminal point of the excavator stick through which the excavator stick is coupled to the excavating implement;

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

the plurality of laser reflectors are disposed at respective positions corresponding to the nodes D, F, G, and H of the four-bar linkage;

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

positioning the excavating linkage assembly at a linkage assembly position n;

setting one of the nodes D, F, G, and H as the nth calibration node with the excavating linkage assembly at the linkage assembly position n,

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

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

identifying respective positions of two other nodes that, together with the nth calibration node, form an external triangle, the two other nodes comprising one of nodes D, F, G, H, and a node corresponding to a position of the terminal pivot point B of the excavator boom;

determining side lengths for each of the legs of the external triangle formed between the nth calibration node and two other nodes; and

determining triangular angles of the external triangle based on the side lengths of the external triangle; and

the architecture controller is further programmed to:

repeat the iterative process n times until triangular angles and side lengths of at least three external triangles are determined, wherein the external triangles form an internal triangle therebetween, the internal triangle shares two nodes and one side with each of the three external triangles and comprises a set of three internal triangle side lengths;

determine the angles of the internal triangle at least partially based on the set of three internal triangle side lengths;

generate an implement angle of the excavating implement at least partially based on a summation of a set of adjacent determined triangular angles, the set of adjacent determined triangular angles comprising an angle from the internal triangle and angles from at least two of the external triangles; and

operate the excavator using the implement angle.

2. An excavator calibration framework as claimed in claim 1, wherein the linkages comprise an implement linkage GH, a rear side linkage FH, a dogbone linkage DF, and a front side linkage GD.

3. 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; and

in the iterative process, determining a position of the nth calibration node at least partially based on the height $\hat{H}$ and the distance $\hat{D}$ comprises:

calculating a total height $\check{H}$ and a total distance $\check{D}$ between the nth calibration node and the terminal pivot point A of the excavator boom based on a summation of the height $\hat{H}$ and the distance $\hat{D}$ between the nth calibration node and the LDM and a height H_0 and a distance D_0 between the LDM and the terminal pivot point A.

4. An excavator calibration framework as claimed in claim **1**, wherein the architecture controller is further programmed to execute machine readable instructions to

    determine a first total height $\check{H}$ and a first total distance $\check{D}$ between the terminal point G and a terminal pivot point A based on a boom limb length L_B, a stick limb length L_S, a boom angle θ_B, and a stick angle θ_S,

    determine a second total height $\check{H}$ and a second total distance $\check{D}$ between the terminal pivot point B and the terminal pivot point A based on a boom limb length L_B, and a boom angle θ_B, and

    identify a height H_0 and a distance D_0 between the LDM and the terminal pivot point A.

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

    for n=1, the 1st calibration node is positioned at the node D;

    for n=2, the 2nd calibration node is positioned at the node F; and

    for n=3, the 3rd calibration node is positioned at the node H.

6. 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; and

    when n=1:

        the 1st calibration node is positioned at the node D, such that calculating a total height $\check{H}$ and a total distance $\check{D}$ between the 1st calibration node and the terminal pivot point A of the excavator boom, respectively comprising D_y and D_x, is based on a summation of the height $\hat{H}$ and the distance $\hat{D}$ between the 1st calibration node and the LDM and a height H_0 and a distance D_0 between the LDM and the terminal pivot point A;

        the two other nodes comprise the terminal pivot point B and the node G;

        the legs of the external triangle comprise GD, BD, BG; and

        the triangular angles of the external triangle comprise angles BGD, GDB, DBG and are determined based on the side lengths determined for the legs GD, BD, and BG and the law of cosines.

7. An excavator calibration framework as claimed in claim **6**, wherein determining the side lengths for the legs BG, GD, and BD comprises calculating the side length for the leg BG based on:

    the total height $\check{H}$ and the total distance $\check{D}$ between the node G and the terminal pivot point A, respectively comprising G_y and G_x; and

    the total height $\check{H}$ and the total distance $\check{D}$ between the terminal pivot point B and the terminal pivot point A, respectively comprising B_y and B_x.

8. An excavator calibration framework as claimed in claim **7**, wherein when n=2:

    the 2nd calibration node is positioned at pin F, such that calculating a total height $\check{H}$ and a total distance between the 2nd calibration node and the terminal pivot point A of the excavator boom, respectively comprising F_y and F_x, is based on a summation of the height $\hat{H}$ and the distance $\hat{D}$ between the 2nd calibration node and the LDM and the height H_0 and the distance D_0 between the LDM and the terminal pivot point A;

    the two other nodes comprise the terminal pivot point B and the node D;

    the legs of the external triangle comprise DF, BF, and BD;

    the triangular angles of the external triangle comprise angles BDF, DFB, FBD and are determined based on the side lengths determined for the legs DF, BF, and BD and the law of cosines; and

    the angle BDF is representative of an actual dogbone angle BDF.

9. An excavator calibration framework as claimed in claim **8**, wherein when n=3:

    the 3rd calibration node is positioned at pin H, such that calculating a total height $\check{H}$ and a total distance $\check{D}$ between the 3rd calibration node and the terminal pivot point A of the excavator boom, respectively comprising H_y and H_x, based on a summation of the height $\hat{H}$ and the distance $\hat{D}$ between the 3rd calibration node and the LDM and the height H_0 and the distance D_0 between the LDM and the terminal pivot point A;

    the two other nodes comprise the node F and the node G;

    the legs of the external triangle comprise GH, FH, and FG; and

    the triangular angles of the external triangle comprise angles FGH, GHF, HFG and are determined based on the side lengths determined for the legs GH, FH, and FG and the law of cosines.

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

    the set of internal triangle side lengths are length are legs DF, FG, and GD that form the internal triangle;

    the angles of the internal triangle comprise angles DGF, GDF, and DFG and are determined based on the determined side lengths of the legs DF, FG, and GD and the law of cosines; and

    generating the implement angle comprises generate an angle BGH based on a summation of the determined angles DGF, BGD, and FGH.

11. An excavator calibration framework comprising an excavator, a laser distance meter (LDM), and a plurality of laser reflectors, wherein:

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

    the excavating linkage assembly comprises an excavator boom, an excavator stick, the excavating implement, and a four-bar linkage that collectively define a plurality of linkage assembly positions;

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

    the plurality of laser reflectors are disposed at respective positions corresponding to a plurality of nodes of the four-bar linkage;

    the control architecture comprises one or more linkage assembly actuators and an architecture controller programmed to

        execute an iterative process at n linkage assembly positions to determine a position of an nth calibration node of the plurality of nodes of the four-bar linkage to determine triangular angles and side lengths of an external triangle formed between the nth calibration node and two other nodes having identified positions;

        repeat the iterative process n times until triangular angles and side lengths of at least three external triangles are determined, wherein the external triangles form an internal triangle therebetween, the internal triangle shares two nodes and one side with

each of the three external triangles and comprises a set of three internal triangle side lengths;

determine the angles of the internal triangle at least partially based on the set of three internal triangle side lengths;

generate an implement angle of the excavating implement at least partially based on a summation of a set of adjacent determined triangular angles, the set of adjacent determined triangular angles comprising an angle from the internal triangle and angles from at least two of the external triangles; and

operate the excavator using the implement angle.

12. An excavator calibration framework as claimed in claim **11**, wherein the excavating implement and the excavator stick are mechanically coupled to each other through the four-bar linkage.

13. An excavator calibration framework as claimed in claim **11**, wherein the excavator stick comprises a terminal point and is mechanically coupled to a terminal pivot point B of the excavator boom.

14. An excavator calibration framework as claimed in claim **11**, wherein the plurality of nodes of the four-bar linkage comprise a node D, a node F, a node G, a node H, and linkages disposed therebetween.

15. An excavator calibration framework as claimed in claim **14**, wherein the node G of the four-bar linkage is disposed at a position corresponding to the terminal point of the excavator stick through which the excavator stick is coupled to the excavating implement.

16. An excavator calibration framework as claimed in claim **11**, wherein the iterative process comprises:

positioning the excavating linkage assembly at a linkage assembly position n;

setting one of a node D, F, G, and H as the nth calibration node with the excavating linkage assembly at the linkage assembly position n,

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

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

identifying respective positions of two other nodes that, together with the nth calibration node, form the external triangle, the two other nodes comprising one of nodes D, F, G, H, and a node corresponding to a position of a terminal pivot point B of the excavator boom;

determining side lengths for each of three legs of the external triangle formed between the nth calibration node and two other nodes; and

determining triangular angles of the external triangle based on the side lengths of the external triangle.

17. An excavator calibration framework as claimed in claim **16**, wherein:

for n=1, the 1st calibration node is positioned at the node D;

for n=2, the 2nd calibration node is positioned at the node F; and

for n=3, the 3rd calibration node is positioned at the node H.

18. An excavator calibration framework as claimed in claim **11**, wherein the control architecture comprises a non-transitory computer-readable storage medium comprising machine readable instructions.

19. An excavator calibration framework as claimed in claim **11**, wherein the one or more linkage assembly actuators facilitate movement of the excavating linkage assembly.

20. An excavator calibration framework as claimed in claim **19**, wherein the one or more linkage assembly actuators comprise a hydraulic cylinder actuator, a pneumatic cylinder actuator, an electrical actuator, a mechanical actuator, or combinations thereof.

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