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**Method and apparatus for determining a cross slope of a surface**

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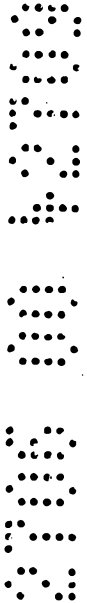
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# ABSTRACT

The present invention provides a method and apparatus for determining the cross slope created by a work implement (104) on an earth moving machine (108). The method includes  
5 the steps of determining a position of the work implement (104), determining a direction of travel of the machine (108), and responsively determining the cross slope.



translations from a first work implement position to a second work implement position.

18. A method, as set forth in claim 17,  
5 wherein said sequence of theoretical work implement translations includes the steps of:

translating said work implement angle of rotation to account for said work implement rotation;

translating said work implement to account  
10 for said work implement roll; and

translating said work implement to account for said work implement pitch.

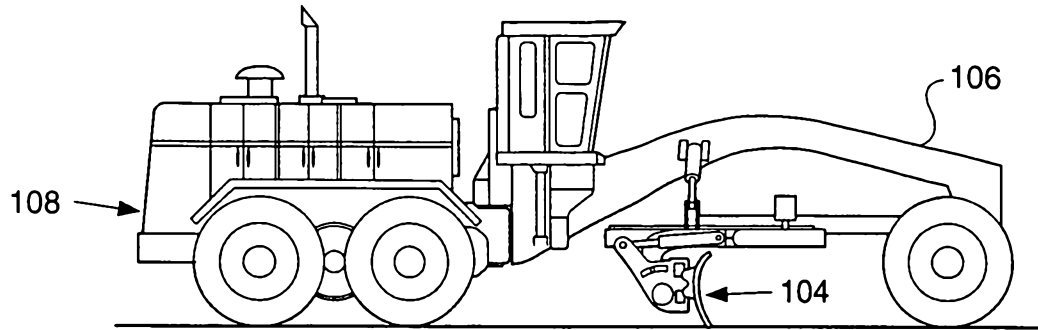
19. An apparatus adapted to determine a  
15 cross slope created by an earthmoving machine having a work implement, the work implement being movably connected to a frame of the earth moving machine, comprising:

a machine sensor system adapted to sense a  
20 plurality of machine parameters and responsively generate a plurality of machine parameter signals;

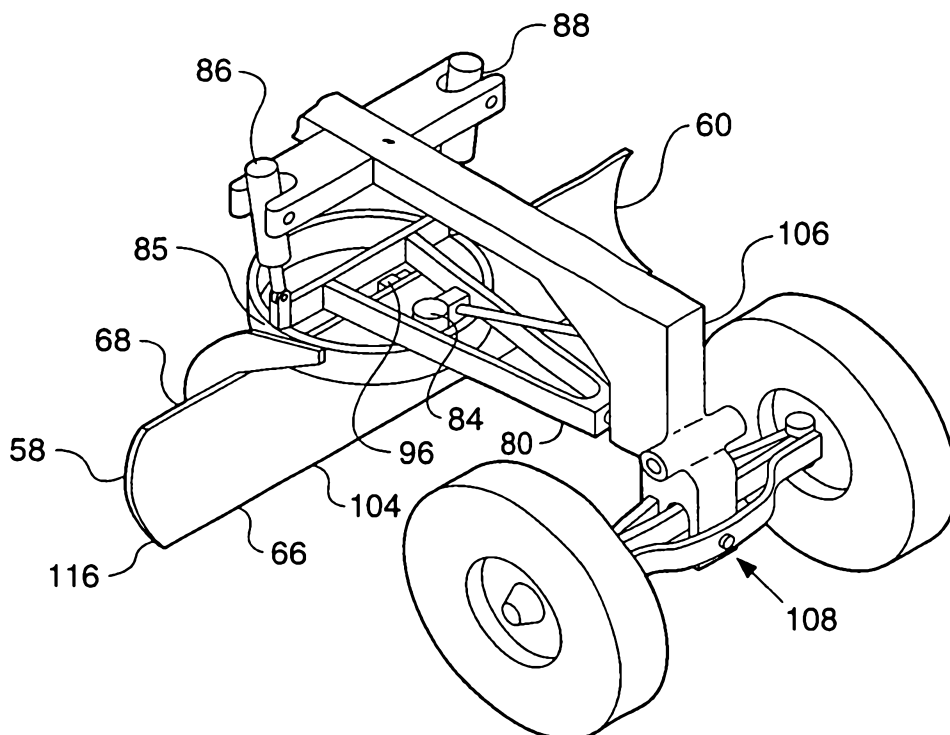
a work implement sensor system adapted to determine a plurality of work implement parameters and responsively generate a plurality of work implement  
25 parameter signals; and

a controller adapted to receive said machine parameter signals, and said work implement parameter signals, determine a direction of travel of the machine in response to said machine and said work  
30 implement parameters, determine a position of said work implement in response to said machine and said work implement parameters, and determine the cross slope in response to said machine direction of travel and said work implement position.

**FIG. 1.**



**FIG. 2.**



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**COMPLETE SPECIFICATION  
FOR A STANDARD PATENT**

**ORIGINAL**

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Invention Title:	<b>METHOD AND APPARATUS FOR DETERMINING A CROSS SLOPE OF A SURFACE</b>

The following statement is a full description of this invention, including the best method of performing it known to us

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Description

METHOD AND APPARATUS FOR DETERMINING A CROSS SLOPE OF  
A SURFACE

5

Technical Field

This invention relates generally to an  
implement control system for an earth moving machine  
and more particularly to a method and apparatus  
10 adapted to determine a cross slope created by an earth  
moving machine.

Background Art

In one embodiment, the cross slope created  
15 by an earth moving machine, such as a motor grader,  
may be described as the slope of a line lying on a  
surface path, such as a road, which is perpendicular  
to the direction of the path. Cutting an accurate  
cross slope into a land site is an important function  
20 for an earth moving machine such as a motor grader.  
Therefore, it would be advantageous to accurately  
determine the cross slope. The measured cross slope  
may be provided to an operator, or compared to a  
desired cross slope in order to determine if the  
25 machine is creating the appropriate slope, and make  
adjustments to the blade position if a position error  
is occurring.

Some previous implementations of systems  
determining cross slope created by the blade, utilize  
30 GPS and laser technology to determine position of the  
blade and the machine relative to the land site,  
thereby enabling an cross slope of cut of the blade to

be determined. However, these systems require GPS and laser detection systems that can be expensive, and are not easily implemented in remote sites, such as cutting a road in a remote location.

5           In addition, some previous implementations of systems that do not utilize GPS and laser technology, do use techniques which provide inaccurate information. For example, determining an angle of rotation of the blade may be used to ultimately  
10 determine the cross slope. Some implementations determine an angle of rotation of the blade relative to the direction of travel of the blade using measuring means which include velocity transducers, example radar guns, for measuring the ground velocity  
15 in the direction of travel of the blade. However these systems are expensive, and have associated inaccuracies, due in part, to the fact that the accuracy decreases as the measured velocity approaches zero.

20           In addition, some previous implementations did not account for the appropriate variables. Sensing too few parameters leads to inaccurate results.

          The present invention is directed to  
25 overcoming one or more of the problems as set forth above.

### Disclosure of the Invention

In one aspect of the present invention, a method for determining a cross slope created by a work implement on an earthmoving machine, is disclosed.

- 5 The method includes the steps of determining a position of the work implement, determining a direction of travel of the machine, and determining the cross slope created by the machine.

- 10 In another aspect of the present invention, a method for determining a cross slope created by a work implement on an earthmoving machine is disclosed. The method includes the steps of sensing a plurality of machine parameters, sensing a plurality of work implement parameters, and determining the cross slope  
15 created by the machine.

- In another aspect of the present invention, an apparatus adapted to determine a cross slope created by an earthmoving machine having a work implement, is disclosed. The apparatus includes a  
20 machine sensor system adapted to sense a plurality of machine parameters and responsively generate a plurality of machine parameter signals, a work implement sensor system adapted to determine a plurality of work implement parameters and  
25 responsively generate a plurality of work implement parameter signals, and a controller adapted to receive the machine parameter signals, and the work implement parameter signals, and determine the cross slope created by the machine.

30

### Brief Description of the Drawings

Fig. 1 is a high level diagram of one embodiment an implement control system;



Fig. 2 is a diagrammatic block diagram of a front portion of a motor grader;

Fig. 3 is a diagrammatic side view of the work implement;

5 Fig. 4 is a view of the apparatus for determining a cross slope created by the machine;

Fig. 5 is an example of blade roll angle and machine roll angle;

10 Fig. 6 is an example of angle of rotation of the blade;

Fig. 7A is an example of blade pitch angle;

Fig. 7B is an example of machine pitch angle;

15 Fig. 8 is an example of the direction of travel of the machine;

Fig. 9 is an example of the cross slope created by the machine;

20 Fig. 10 illustrates an alternative embodiment of the apparatus for determining a cross slope created by the machine;

Fig. 11 is an illustration of the method for determining a cross slope;

25 Fig. 12 is an illustration of the initial blade vector position;

Fig 13a - 13e illustrates five aspects of the blade translations; and

Fig. 14 illustrates the cross slope plane.

#### Best Mode for Carrying Out the Invention

30 The present invention includes a method and apparatus adapted to determine a cross slope created by a work implement on an earth moving machine. The work implement 104 is controllably movably mounted on

a frame 106 of an earth moving machine 108, as illustrated in Fig. 1. In one embodiment, the work implement is a blade 104, and the earthmoving machine 108 is a motor grader. The motor grader 108 may be  
5 either an articulated or non-articulated motor grader. It is to be noted that other machines such as dozers, scrapers, compactors, pavers, profilers, and the like, equipped with suitable surface altering equipment, are equivalents and considered within the scope of the  
10 invention. In addition, other work implements may be used without departing from the spirit of the invention.

The blade 104, as shown in Fig. 2 and 3, is movably connected to the frame 106 by a supporting  
15 mechanism 80, or drawbar. The supporting mechanism 80 includes a circle drive mechanism 82 having a selectively actuatable rotary drive motor 84 for rotating a circle 85, and the blade 104 connected thereto about an elevational axis located at the  
20 center of the circle 85 in a known manner.

As best seen in Fig. 2, the machine 108 may include a first and second selectively actuatable fluid operated lift jacks 86,88 which are connected to and between the frame 106 and the drawbar 80. The  
25 first and second lift jacks 86,88 are extensibly movable between first and second spaced apart positions and elevationally move the blade 104 relative to the frame 106. Simultaneous extension of the lift jacks 86,88 lowers the blade 104 and  
30 simultaneous retraction of lift jacks 86,88 raises the blade 104. Extension or retraction of either the first and second lift jacks 86,88, or extension of one of the first and second lift jacks 86,88 and retraction

of the other of the lift jacks 88,86 results in rolling of the blade 104 relative to the frame 106.

As shown in Fig. 3, a fluid operated tip jack 90 may be connected to and between the drawbar 80 and a bellcrank 92. The bellcrank 92 pivotally connects the blade 104 to the circle drive mechanism 82. The tip jack 90 is extensibly movable for tipping the bellcrank 92 about the pivotal connection. This results in tipping movement of the blade 104 in forward or rearward directions, as shown in phantom lines in Fig. 3, with the blade 104 oriented transversely of the vehicle frame 106. It should be noted that the terms blade tip and blade pitch are used interchangeably and have the same meaning.

In one embodiment, the machine 108 may include a machine sensor system 402, and a work implement sensor system 404 electrically connected to a controller 54, as illustrated in Fig. 4. The machine sensor system 402 is adapted to sense at least one machine parameter and responsively generate at least one machine parameter signal. The work implement sensor system 404 is adapted to sense at least one work implement parameter and responsively generate at least one work implement parameter signal.

As best seen in Fig. 3, the work implement system 404 may include a pitch sensor assembly 94 provided for sensing the pitch angle of the blade 104. The pitch sensor assembly 94 may include any appropriate transducer capable of sensing the pitch of the blade 104. In the preferred embodiment the sensor assembly 94 measures the pitch of the blade with respect to the earth's gravity. The sensor assembly 94 may include a potentiometer, an encoder, a resolver, and the like. In the preferred embodiment,

the sensor assembly 94 is connected to the circle 85, however, the sensor assembly 94 may be connected to the bellcrank 92. The pitch sensor assembly 94 generates a pitch angle signal, which may be either  
5 analog or digital. Alternatively, the pitch sensor assembly 94 may sense the pitch of the blade 104 relative to the machine.

The work implement assembly 404 may include a roll sensor assembly 110 for sensing a roll angle of  
10 the blade 104. The roll sensor assembly 110 may include any appropriate transducer capable of sensing the rolled position of the blade 104. In an alternative embodiment, the roll sensor assembly 110 and the pitch sensor assembly 94 may be located on the  
15 machine frame 106 and the appropriate translations performed to determine the pitch and roll of the blade 104. Alternatively, the roll sensor assembly 110 may determine a roll angle of the blade relative to the machine.

20 The angle of rotation of the blade 104 relative to the drawbar 80 may be determined by monitoring the commanded position of the circle drive mechanism 82. Alternatively, the work implement sensor system 404 may include a blade rotation sensor  
25 96 for determining the rotation of the blade 104 relative to the drawbar 80.

The machine sensor system may include a pitch sensor assembly 112 and a roll sensor assembly 114. The pitch sensor assembly 112 and a roll sensor  
30 assembly 114 may be analogous to the pitch and roll sensor assemblies 94, 110 respectively, and may be located on the machine frame 106 to sense the pitch and roll angles of the machine. In an alternative embodiment, the machine pitch and roll angles may be

derived from the sensed pitch and roll angles of the blade 104.

As illustrated in Fig. 5, using the roll sensors 110, 114, the roll angle  $\angle_{bs}$  of the blade 104, and the roll angle  $\angle_{ms}$  of the frame 106, may be sensed relative to horizontal 502. The angle of rotation  $\phi$  of the blade 104 relative to the frame 106 may be sensed, as illustrated in Fig. 6. As illustrated in Fig. 7A and 7B, using the pitch sensor assemblies 94, 112, the pitch angle  $\theta_{ms}$  of the frame 106, and the pitch  $\theta_b$  of the blade 104 may be sensed relative to horizontal. Fig. 7A illustrates an angle of rotation of the circle 85 to be zero degrees for exemplary purposes only. Other circle 85, or blade 104, rotations may be performed and measured accurately using the disclosed embodiment. The direction of travel of the machine, I, may be determined relative to the center axis of the frame 106, as illustrated in Fig. 8.

In one embodiment, the cross slope,  $\theta_{cs}$ , created by an earth moving machine, such as a motor grader, may be described as the slope of a line lying on a surface path, such as a road, which is perpendicular to the direction of the path, as illustrated in Fig. 9.

A controller 54 receives signals from the machine sensor system 402 and the work implement sensor system 404, as illustrated in Fig. 10. In one embodiment, as illustrated in Fig. 10, the controller 54 may receive sensed signals from the pitch sensor assemblies 94, 112, and the roll sensor assemblies 110, 114. The controller 54 may also receive signals

from at least one of a circle drive mechanism 82, a rotary drive motor 84 or a blade rotation sensor assembly 94, to determine the angle of rotation of the blade 104 relative to the drawbar 80. A  
5 microprocessor such as a Motorola 68HC11 may be used as the controller 54. However, other known microprocessors could be readily used without deviating from the scope of the present invention. The controller 54 determines a cross-slope in response  
10 to the sensed parameters. In one embodiment, the controller 54 receives an operator initiated desired cross slope signal 902. For example, the operator may enter a desired cross-slope using a keypad (not shown) which delivers the appropriate signal to the  
15 controller 54. The actual cross slope may then be compared to a desired cross slope, and a cross slope error responsively generated. The cross slope error may be used by the controller 54 to determine the necessary changes and commands that need to be  
20 delivered to either the blade 104, drawbar 80, or both to achieve the desired cross slope. The appropriate commands are then delivered by the controller 54 to adjust the cross slope created by the machine 108. The machine and work implement parameters are  
25 continuously sensed, enabling the cross slope to be continuously monitored and adjusted.

In one embodiment, the cross slope may be determined in response to the direction of travel of the machine 108 and the position of the blade 104. In  
30 the preferred embodiment of the present invention, the drawbar 80 is located symmetrically under the frame 106, the machine 108 is traveling in a straight line of motion, and there is no articulation of the machine 108.

The position of the blade 104 may be determined in response to sensing machine and work implement parameters. In one embodiment, work implement parameters, such as the angle of rotation of the blade 104 relative to the machine 102 ( $\psi$ ), the blade roll  $\lambda_{bs}$  and the blade pitch  $\theta_{bs}$  may be sensed. In addition, machine parameters, such as the machine roll  $\lambda_{ms}$  and the machine pitch  $\theta_{ms}$  may be sensed. In an alternative embodiment, the roll and pitch of the drawbar 80 may also be directly sensed by placing the appropriate sensors on the drawbars.

In one embodiment, the method for determining the cross slope created by a work implement on an earth moving machine includes the steps of determining a position of the work implement 104, determining a direction of travel of the machine 108, and determining the cross slope in response to the direction of travel and the work implement position.

Fig. 11 illustrates a flow diagram of one method for determining the current position of the blade. The current position of the blade 104 may be determined by: determining an initial blade position vector in a first control block 1002, translating the initial blade vector to achieve a theoretical current blade position in a second control block 1004, and determining the current blade position by correlating the sensed parameters to the theoretical current blade position in a third control block 1006.

The initial blade vector ( $\bar{P}_{Bo}$ ) represents a theoretical initial position of the blade 104. A local, or machine based, coordinate system may be defined as a three dimensional coordinate system

established relative to the frame 106. In one embodiment, the local coordinates may be based on earth based coordinates. The initial blade vector may be represented as:

5

$$\bar{P}_{B_0} \equiv \text{Initial blade vector} = [1 \ 0 \ 0]^T$$

Where the right hand tip 116 of the blade 104 is at  $\bar{P}_{B_0}$  and the center of the blade 104 is at the origin (0,0,0), as illustrated in Fig. 12. The current blade vector may be stated as:

$$\bar{P}_B = \text{Final blade vector} = [P_{B_x} \ P_{B_y} \ P_{B_z}]^T$$

15 A theoretical blade position vector may be determined by theoretically translating, or rotating, the machine 108, drawbar 80, and/or blade 104 through a sequence of maneuvers. That is, a sequence of theoretical work implement translations may be used to translate the  
20 implement from a first position, e.g., an initial position, to a second position, e.g., a current blade position. One example of the theoretical sequence of maneuvers is:

1. Rotate the blade relative to the machine  
25  $(\psi_{bs})$ .
2. Roll the drawbar  $(\alpha_d)$ ,
3. Pitch the drawbar  $(\theta_d)$ .
4. Roll the mainframe  $(\alpha_m)$ , and;
5. Pitch the mainframe  $(\theta_m)$ .

30



The theoretical translation sequence is illustrated in Figs. 13a-13e. The rotational sequence defined yields a theoretical blade position:

$$\begin{aligned} \bar{P}_B &= \begin{bmatrix} P_{B_x} \\ P_{B_y} \\ P_{B_z} \end{bmatrix} = [Rot\_x(\theta_m)] [Rot\_y(\phi_m)] [Rot\_x(\theta_d)] [Rot\_y(\phi_d)] \times \\ & [Rot\_z(\psi_b)] \bullet \bar{P}_{B_0} \end{aligned}$$

Where  $Rot\_x(\theta_m)$ ,  $Rot\_y(\phi_m)$ ,  $Rot\_x(\theta_d)$ ,  $Rot\_y(\phi_d)$ ,  $Rot\_z(\psi_b)$ , are homogeneous transforms. For example,  $Rot\_x(\theta_m)$  may be determined to be:

$$Rot\_x(\theta_m) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_m) & -\sin(\theta_m) \\ 0 & \sin(\theta_m) & \cos(\theta_m) \end{bmatrix}$$

Homogenous transforms are well known in the art and each transform will not be elaborated on at this point.

The theoretical blade vector  $\bar{P}_B$  may be simplified by defining the overall transformation matrix as:

$$H_{b_0}^b = Rot\_x(\theta_m) Rot\_y(\phi_m) Rot\_x(\theta_d) Rot\_y(\phi_d) Rot\_z(\psi_b)$$

The equation for the theoretical blade position simplifies to:

$$\bar{P}_B = H_{b_0}^b \bullet \bar{P}_{B_0}$$

Where:

$$H_{b_0}^b = \begin{bmatrix} h(1,1) & h(1,2) & h(1,3) \\ h(2,1) & h(2,2) & h(2,3) \\ h(3,1) & h(3,2) & h(3,3) \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} & h_{1,3} \\ h_{2,1} & h_{2,2} & h_{2,3} \\ h_{3,1} & h_{3,2} & h_{3,3} \end{bmatrix}$$

The matrix elements may be determined by matrix  
5 algebra. For example:

$$h_{1,1} = [\cos(\phi_m) \cos(\psi_b)] \cos(\phi_d) - [\sin(\phi_m) \cos(\psi_b)] \cos(\theta_d) \sin(\phi_d) + [\sin(\phi_m) \sin(\psi_b)] \sin(\theta_d)$$

Therefore, the theoretical current blade position  
10 vector may be represented as:

$$\bar{P}_b = \langle h_{1,1}, h_{2,1}, h_{3,1} \rangle$$

The actual current blade position may be determined by  
correlating the sensed parameters to the theoretical  
15 current blade position, and determining the actual  
machine roll and pitch and the actual blade roll and  
pitch, and the blade rotation.

The variables  $\alpha_m$ ,  $\alpha_d$ ,  $\hat{h}_m$ ,  $\hat{h}_d$ ,  $b$  are  
theoretical translation variables. The sensed  
20 variables may be correlated to the translation  
variables.

In the preferred embodiment, the actual  
machine roll may be determined by initializing a unit  
vector  $\hat{i}_{xm}$  which is representative of the roll and  
25 pitch of the machine starting in the direction  $i_x$ ,  
where  $i_x$  is the unit vector in the x direction. The  
unit vector  $\hat{i}_{xm}$  may be rolled with respect to the Y-  
axis. Therefore, the actual machine roll may be  
determined by the following equation:

$$\hat{i}_{x_m} = Rot\_Pitch(Rot\_Roll \cdot \hat{i}_x) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_m) & -\sin(\theta_m) \\ 0 & \sin(\theta_m) & \cos(\theta_m) \end{bmatrix} \times \begin{bmatrix} \cos(\phi_m) & 0 & \sin(\phi_m) \\ 0 & 1 & 0 \\ -\sin(\phi_m) & 0 & \cos(\phi_m) \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

Therefore, the dot product of the unit vector  $\hat{i}_{x_m}$  in the vertical direction may be determined to isolate the roll component. The resulting actual machine roll equation is:

$$\sin(\phi_m) - \cos(\theta_m)\sin(\phi_m) = 0$$

The actual machine pitch may be determined by initializing a unit vector,  $\hat{i}_{x_m}$ , which is representative of the roll and pitch of the machine in the direction  $i_y$ . The vector  $\hat{i}_{x_m}$  is then rolled the amount indicated by the roll sensor, and pitched by the amount indicated by the pitch sensor. Resulting in:

$$\hat{i}_{x_m} = Rot\_Pitch(Rot\_Roll(i_y))$$

The dot product of the unit vector in the vertical direction may be taken to determine the pitch component of the vector  $i_y$ . The resulting actual machine pitch is:

$$\sin(\theta_m) = \sin(\theta_m)$$

25

Therefore:

$$\theta_m = \theta_{m_i}$$

$$\phi_m = \sin^{-1} \left[ \frac{\sin(\phi_{m_i})}{\cos(\theta_{m_i})} \right]$$

The actual blade roll,  $\phi_m$ , can be computed by

- 5 determining the angle between the position of the blade 104 and the horizon. The blade roll with regard to the horizon (x-y plane) is given by:

$$\sin(-\phi_b) = -[H_{b_0}^b \cdot \bar{P}_{B_0}] \cdot \hat{i}_z$$

10

Measurement of the actual blade pitch can be computed by determining the angle between a normal blade vector ( $N_b$ ) and the horizon.

15

$$\bar{N}_B = H_{b_0}^b \cdot \bar{N}_{B_0}$$

Where:

$$\bar{N}_{B_0} = [0 \quad 1 \quad 0]$$

20

The actual blade pitch, with regard to the horizon (x-y plane), may be given by:

$$\sin(\theta_b) = -[H_{b_0}^b \cdot \bar{N}_{B_0}] \cdot \hat{i}_z$$

25

The actual drawbar pitch and roll may be determined. The following analysis is based on the assumption that there is no direct sensing of the drawbar 80 pitch and roll. If there is a direct sensing means, such as a roll or pitch sensor attached to the drawbar 80, then analysis analogous to the

30

above determinations of machine roll and machine pitch may be used to determine drawbar roll and drawbar pitch. A numerical analysis approach for solving systems of non-linear equations, such as the Newton-Raphson Method, may be used to solve for the actual drawbar roll  $\alpha_d$  and pitch  $\beta_d$ .

$$\sin(\phi_b) = -[H_{b0}^b \cdot \bar{P}_{B_0}] \cdot \hat{i}_z \Rightarrow f_1(\psi_b, \theta_b, \phi_b, \theta_m, \phi_m, \theta_d, \phi_d) = 0$$

$$10 \quad \sin(-\theta_b) = -[H_{b0}^b \cdot \bar{N}_{B_0}] \cdot \hat{i}_z \Rightarrow f_2(\psi_b, \theta_b, \phi_b, \theta_m, \phi_m, \theta_d, \phi_d) = 0$$

$$f_1(\theta_d, \phi_d) = 0$$

$$f_2(\theta_d, \phi_d) = 0$$

Utilizing a numerical approach:

15

$$\mathbf{F}(\mathbf{x}_k) = \begin{bmatrix} f_1(x_1, x_2) \\ f_2(x_1, x_2) \end{bmatrix}$$

$$\mathbf{x}_k = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \theta_d \\ \phi_d \end{bmatrix}$$

20

$$x_{k+1} = x_k - J_k^{-1} \cdot F(x_k)$$

Where  $J_k$  represents a Jacobian matrix.

$$J^{-1} = \begin{bmatrix} \frac{\partial f_2}{\partial \phi_d} & -\frac{\partial f_1}{\partial \phi_d} \\ -\frac{\partial f_2}{\partial \theta_d} & \frac{\partial f_1}{\partial \theta_d} \end{bmatrix}$$

25

$$\Delta J$$

Where:

$$\Delta J = \left( \frac{\partial f_1}{\partial \theta_d} \right) \left( \frac{\partial f_2}{\partial \phi_d} \right) - \left( \frac{\partial f_1}{\partial \phi_d} \right) \left( \frac{\partial f_2}{\partial \theta_d} \right)$$

$$\mathbf{x} = \begin{bmatrix} \theta_d \\ \phi_d \end{bmatrix}$$

$$\mathbf{x}_0 = \begin{bmatrix} \theta_b \\ \phi_b \end{bmatrix}$$

10

For an initial estimate of blade position, the initial drawbar pitch and roll may be assumed to be equal to the initial blade pitch and roll. This assumption provides an initial estimate that may be modified.

15

Alternatively the last drawbar pitch and roll calculated may be used.

Therefore, the actual current blade position may be determined using:

20

$$\bar{P}_{B_x} = h_{1,i} = g_1(\psi_b, \theta_m, \phi_m, \theta_d, \phi_d)$$

$$\bar{P}_{B_y} = h_{2,i} = g_2(\psi_b, \theta_m, \phi_m, \theta_d, \phi_d), \text{ and}$$

$$\bar{P}_{B_z} = h_{3,i} = g_3(\psi_b, \theta_m, \phi_m, \theta_d, \phi_d)$$

Where  $g(\psi_b, \theta_m, \phi_m, \theta_d, \phi_d)$  represents the functional analysis illustrated above.

25

The current blade position may be used in conjunction with the direction of the machine to determine the cross slope. The direction of travel of the machine may be represented by a direction path vector ( $\bar{D}_i$ ). In the preferred embodiment, the machine

102 is operating in a non-articulated manner.

Therefore, the direction path vector ( $\bar{D}_t$ ) is aligned with the mainframe 106, and is affected by the pitch of the machine 102. Therefore, in one embodiment, the direction path vector may be given by the following equation:

$$\bar{D}_t = \langle 0, \cos(\theta_m), \sin(\theta_m) \rangle^T$$

10 The cross slope is a function of the blade position vector and the direction of travel vector:

$$\text{Cross Slope} = f(\bar{D}_t, \bar{P}_b)$$

15 The cross slope,  $\theta_{cs}$ , may be represented as a vertical measurement that is perpendicular to the direction of travel and is measured with respect to the horizon, as illustrated in Fig. 9. The blade's path as it passed through the cross section of the cut plane may be determined.

20 In one embodiment, the cross slope plane may be illustrated as the  $x_m$  -  $z$  plane, as shown in Fig. 14. A normal vector that crosses through the cross slope cut plane 1402 may be determined. The normal vector may be determined by taking the cross product of two  
25 known vectors that lie within the plane, such as  $\hat{i}_{x_m}$ , containing the point  $\bar{P}_{Bo}$ , and  $\hat{i}_z$ , which contains the point (0,0,0) and is part of the earth coordinate system. Therefore:

$$\bar{N}_{x_z} = \hat{i}_{x_m} \times \hat{i}_z$$

Where:

$$\hat{i}_{x_m} = Rot\_Pitch(Rot\_Roll(\hat{i}_x))$$

Resulting in

5

$$\therefore \bar{N}_{x_i} = \begin{bmatrix} \sin(\theta_m) \sin(\phi_m) \\ -\cos(\theta_m) \\ 0 \end{bmatrix}$$

Therefore, the plane equation containing the point  $x_0, y_0, z_0 = (0, 0, 0)$ : is

10

$$\boxed{\sin(\theta_m) \sin(\phi_m) \cdot x + [-\cos(\theta_m)] y = 0}$$

In the preferred embodiment, the machine follows straight line motion, where no angular variables are changing. Therefore, the right blade tip follows a line l:

15

$$l_r : x = P_{b_x}, \frac{y - P_{b_y}}{\cos(\theta_m)} = \frac{z - P_{b_z}}{\sin(\theta_m)}$$

20 The cross slope may then be determined by projecting  $\bar{P}_B$  back or forward in time, along the line l 1406, until it intersects the cross slope plane, as illustrated in Fig. 14. The point of intersection  $(x^*, y^*, z^*)$  1404 is:

25

$$x^* = P_{b_x}, y^* = \frac{\sin(\theta_m) \cdot \sin(\phi_m) \cdot x^*}{\cos(\phi_m)}, z^* = -\tan(\theta_m) \cdot P_{b_y} + P_{b_z}$$



The x,y component is the measure of this point along the  $\hat{i}_{x_m}$  direction. Therefore, to get the measurement of the x,y component.

5

$$r = \sqrt{x^2 + y^2}$$

The cross slope created by the work implement 104 of a machine 108 may then be defined as:

10

$$\text{Cross Slope} = \frac{-z'}{\sqrt{x^2 + y^2}} = \frac{\Delta z}{\Delta r}$$

#### Industrial Applicability

The present invention provides a method and apparatus for determining the cross slope created by a work implement on an earth moving machine. In one embodiment, the method includes the steps of determining a position of the work implement, determining a direction of travel of the machine, and determining a cross slope in response to the direction of travel and the work implement position.

In one embodiment, a plurality of machine parameters, such as the roll of the machine, and work implement parameters, such as the angle of rotation of the work implement relative to the machine, are used to determine the position of the work implement.

In one embodiment, the actual cross slope is determined and then compared to a desired cross slope. The desired cross slope may be determined in response to either an operator input, or a program that is providing automated control of some or all of the

grading functions of the motor grader. The machine 108 and/or the blade 104 may be controlled in response to the desired and actual cross slope. For example, if an error exists between the actual and desired  
5 cross slope, the implement commands may be determined which will bring the actual cross slope to within a threshold of the desired cross slope. The threshold may be determined base on the desired accuracy of the system.

10 Other aspects, objects, and advantages of the present invention can be obtained from a study of the drawings, the disclosure, and the claims.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method for determining a cross slope created by a work implement on an earthmoving machine,  
5 the work implement being movably connected to a frame of the earth moving machine comprising the steps of:  
determining a position of said work implement;  
determining a direction of travel of said  
10 machine; and  
determining a cross slope in response to said direction of travel and said work implement position.
- 15 2. A method, as set forth in claim 1, including the steps of:  
sensing a plurality of machine parameters, said machine parameters including a roll of said machine;  
20 sensing a plurality of work implement parameters, said work implement parameters including an angle of rotation of the work implement relative to the machine; and  
wherein, the step of determining said work  
25 implement position, includes the step of determining said work implement position in response to said machine parameters and said work implement parameters.
3. A method, as set forth in claim 2,  
30 wherein the step of determining said work implement parameters includes the step of determining a pitch of said work implement relative to said machine.

4. A method, as set forth in claim 3,  
wherein the step of determining said work implement  
parameters includes the step of determining a roll of  
the work implement relative to said machine.

5

5. A method, as set forth in claim 2,  
wherein the step of determining said work implement  
parameters includes the steps of:

determining a pitch of the work implement  
10 relative to the earth's gravitational field; and  
determining a roll of the work implement  
relative to the earth's gravitational field.

6. A method, as set forth in claim 5,  
15 wherein the step of determining said machine  
parameters include the step of determining a pitch of  
said machine.

7. A method, as set forth in claim 6,  
20 including the steps of:  
comparing said cross slope with a desired  
cross slope; and  
determining a cross slope error in response  
to said comparison.

25

8. A method, as set forth in claim 7,  
including the step of controlling said work implement  
in response to said cross slope error.

9. A method, as set forth in claim 8,  
30 wherein the step of determining said work implement  
position includes the steps of:  
determining said work implement position in  
response to a sequence of theoretical work implement

translations from a first work implement position to a second work implement position.

10. A method, as set forth in claim 9,  
5 wherein said sequence of theoretical work implement translations includes the steps of:

translating said work implement angle of rotation to account for said work implement rotation;  
translating said work implement to account  
10 for said work implement roll; and  
translating said work implement to account for said work implement pitch.

11. A method, as set forth in claim 9,  
15 including the step of correlating said sensed machine parameters and said sensed work implement parameters to an associated theoretically translated variables.

12. A method for determining a cross slope  
20 created by a work implement on an earthmoving machine, the work implement being movably connected to a frame of the earth moving machine comprising the steps of:

sensing a plurality of machine parameters,  
said machine parameters including a roll of said  
25 machine;  
sensing a plurality of work implement parameters, said work implement parameters including an angle of rotation of the work implement relative to the machine; and

30 determining said cross slope in response to said machine parameters, said work implement parameters, and said angle of rotation of said work implement.

13. A method, as set forth in claim 12,  
wherein the step of sensing a plurality of machine  
parameters includes the steps of:

5                   determining a roll of said machine; and  
                  determining a pitch of said machine.

14. A method, as set forth in claim 13,  
wherein the step of sensing a plurality of work  
implement parameters includes the steps of:

10                   determining a pitch of the work implement  
relative to the earth's gravitational field; and  
                  determining a roll of the work implement  
relative to the earth's gravitational field.

15                   15. A method, as set forth in claim 13,  
wherein the step of sensing a plurality of work  
implement parameters includes the steps of:

                  determining a pitch of the work implement  
relative to the machine; and  
20                   determining a roll of the work implement  
relative to the machine.

16. A method, as set forth in claim 14,  
including the step of determining a direction of said  
25 machine, wherein said cross slope is determined in  
response to said direction of said machine, said  
machine parameters, said work implement parameters,  
and said angle of rotation of said work implement.

30                   17. A method, as set forth in claim 16,  
wherein the step of determining said work implement  
position includes the steps of:

                  determining said work implement position in  
response to a sequence of theoretical work implement

translations from a first work implement position to a second work implement position.

18. A method, as set forth in claim 17,  
5 wherein said sequence of theoretical work implement translations includes the steps of:  
translating said work implement angle of rotation to account for said work implement rotation;  
translating said work implement to account  
10 for said work implement roll; and  
translating said work implement to account for said work implement pitch.

19. An apparatus adapted to determine a  
15 cross slope created by an earthmoving machine having a work implement, the work implement being movably connected to a frame of the earth moving machine, comprising:

a machine sensor system adapted to sense a  
20 plurality of machine parameters and responsively generate a plurality of machine parameter signals;

a work implement sensor system adapted to determine a plurality of work implement parameters and responsively generate a plurality of work implement  
25 parameter signals; and

a controller adapted to receive said machine parameter signals, and said work implement parameter signals, determine a direction of travel of the machine in response to said machine and said work  
30 implement parameters, determine a position of said work implement in response to said machine and said work implement parameters, and determine the cross slope in response to said machine direction of travel and said work implement position.

20. An apparatus, as set forth in claim 19, wherein said machine sensor system includes:

5 a roll sensor adapted to determine a roll of the machine; and

a pitch sensor adapted to determine a pitch of the machine.

10 21. An apparatus, as set forth in claim 20, wherein said work implement sensor system includes:

a roll sensor adapted to determine a roll of the work implement relative to the machine; and

15 a pitch sensor adapted to determine a pitch of the work implement relative to the machine.

22. An apparatus, as set forth in claim 20, wherein said work implement sensor system includes:

20 a roll sensor adapted to determine a roll of the work implement relative to the earth's gravitational field; and

a pitch sensor adapted to determine a pitch of the work implement relative to the earth's gravitational field.

25 23. An apparatus, as set forth in claim 22, wherein said controller determines an angle of rotation of said work implement relative to the machine, and cross slope is determined in response to said machine parameters, said work implement  
30 parameters and said angle of rotation.

24. An apparatus, as set forth in claim 22, wherein said work implement sensor system includes a rotation sensor adapted to sense an angle of rotation



of the work implement relative to the machine, and responsively generate an angle of rotation signal, said work implement parameter signals including said angle of rotation signal

5

25. A method for determining a cross slope created by a work implement on an earthmoving machines substantially as hereinbefore described with reference to the accompanying drawings.

10

26. An apparatus adapted to determine a cross slope created by an earthmoving machine having a work implement substantially as hereinbefore described with reference to the accompanying drawings.

15

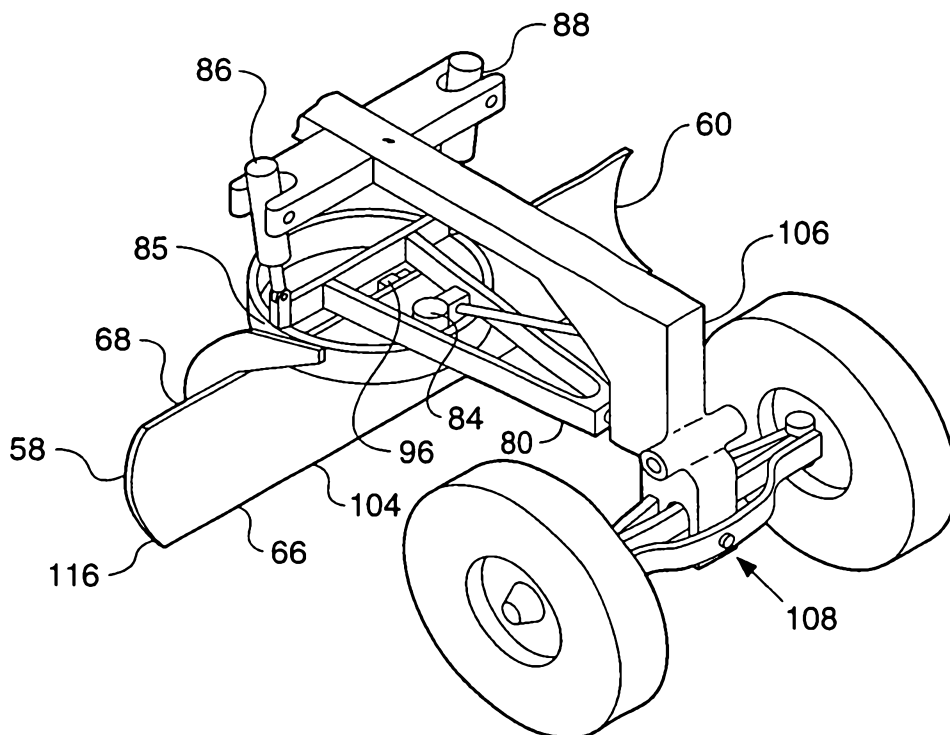
DATED: 27 June 2000

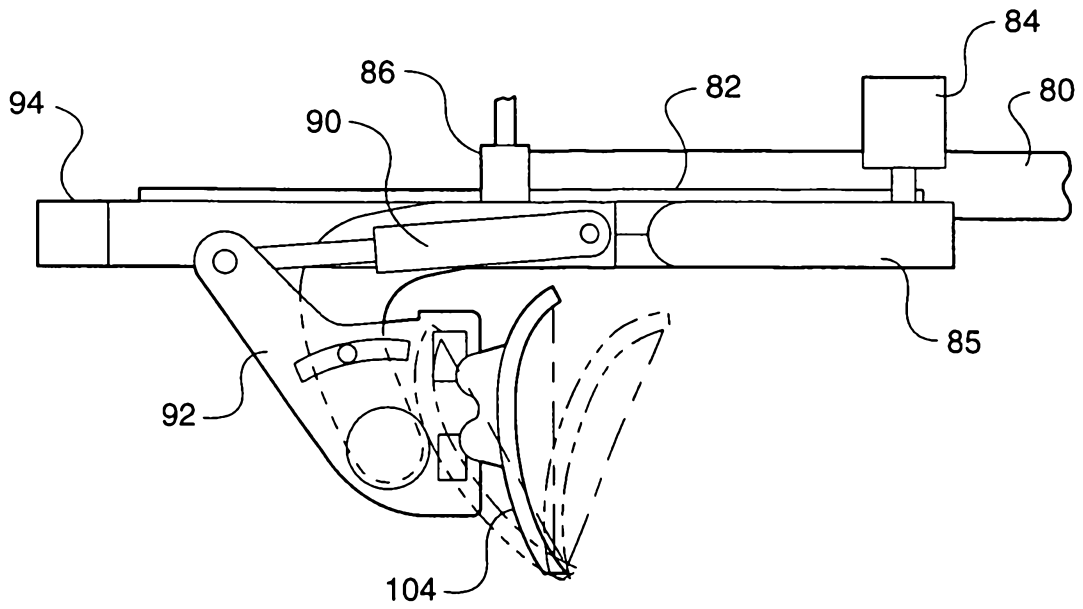
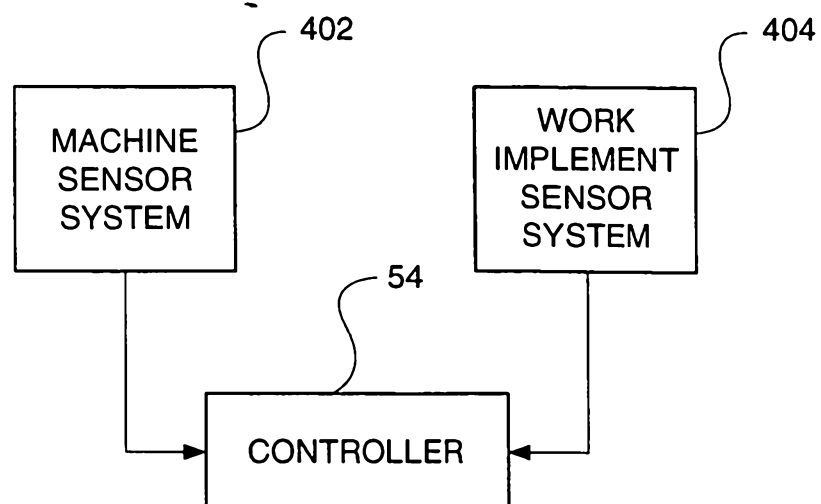
**FREEHILLS CARTER SMITH & BEADLE**  
Patent Attorneys for the Applicant:

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**CATERPILLAR INC.**

Fig. 2.



**FIG. 3.****FIG. 4.**

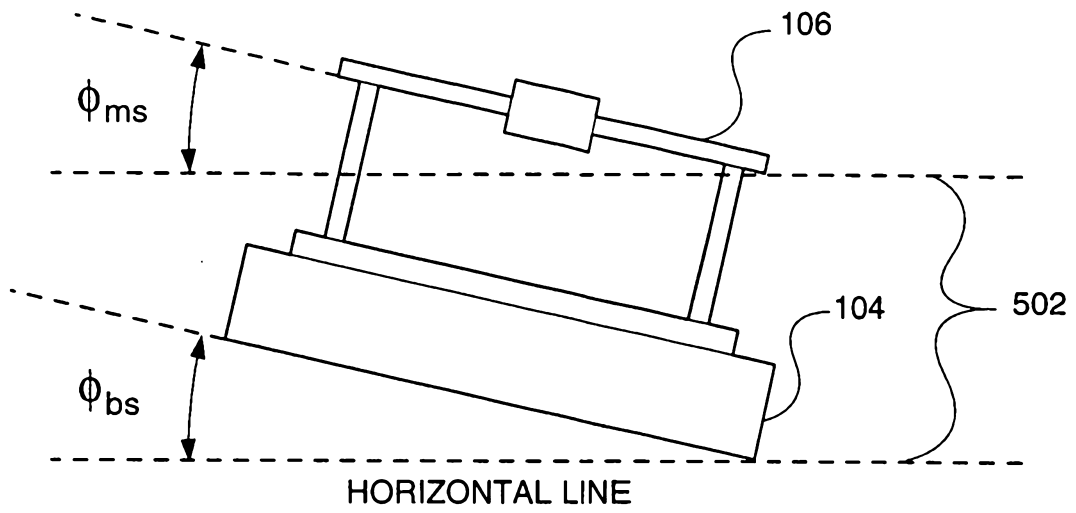
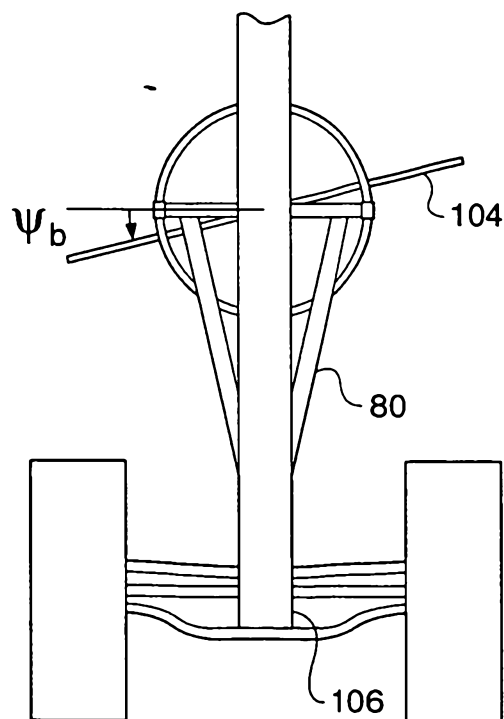
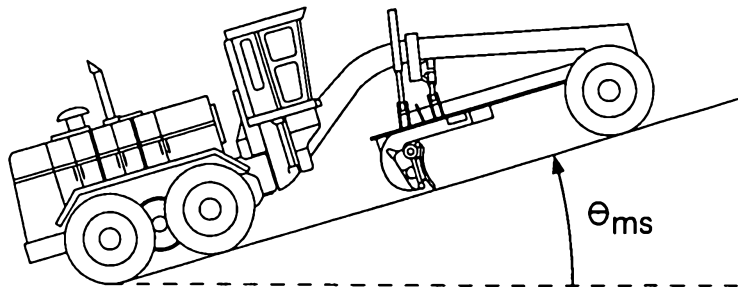
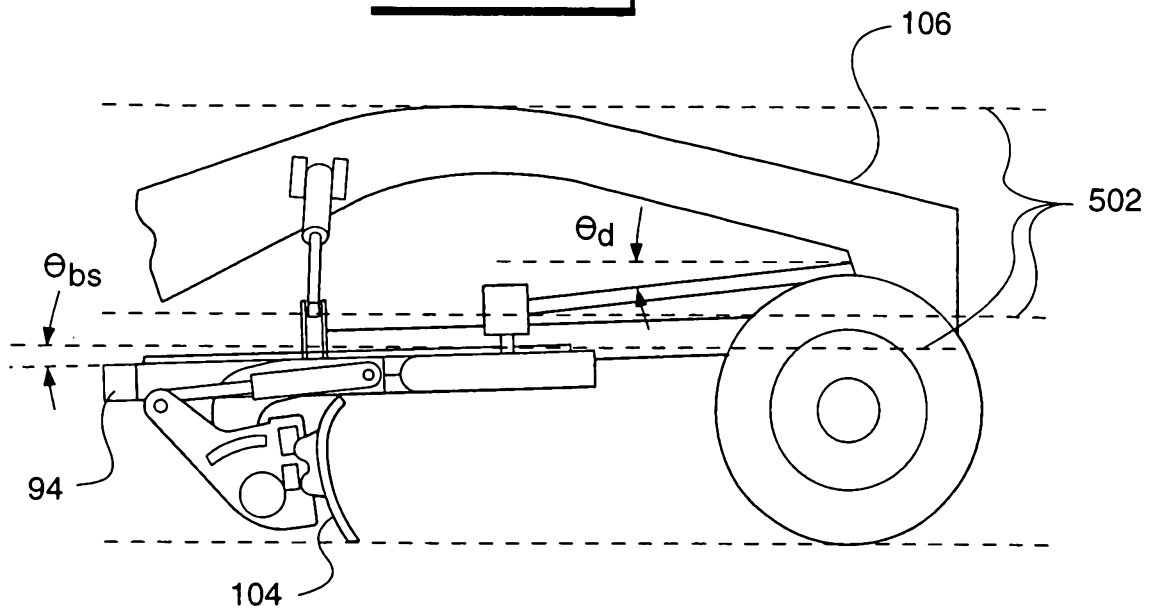
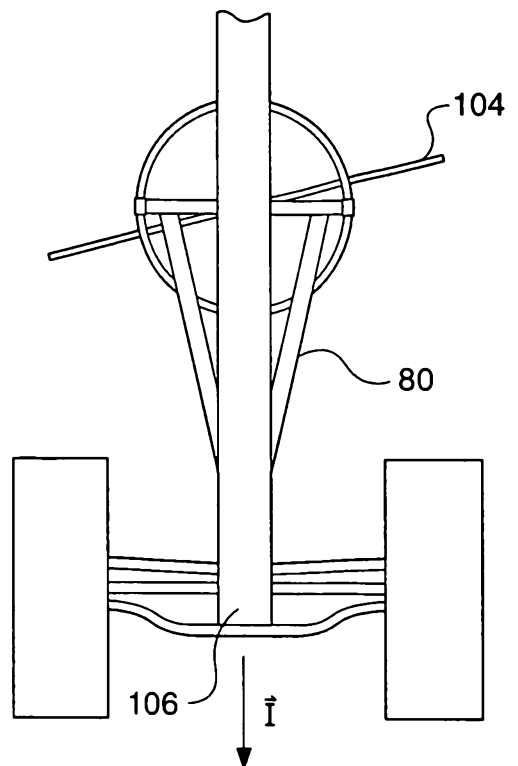
**FIG. 5.****FIG. 6.**

Fig. 7a.Fig. 7b.Fig. 8.

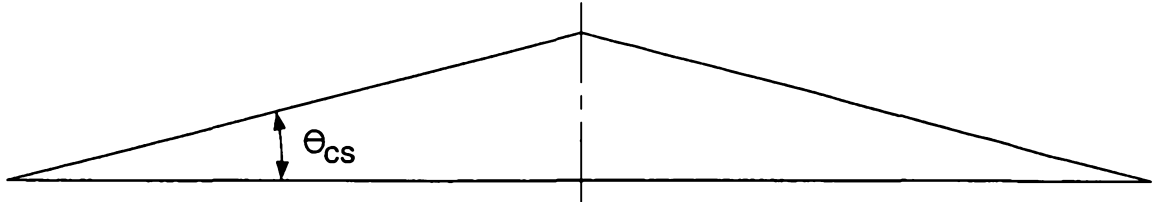
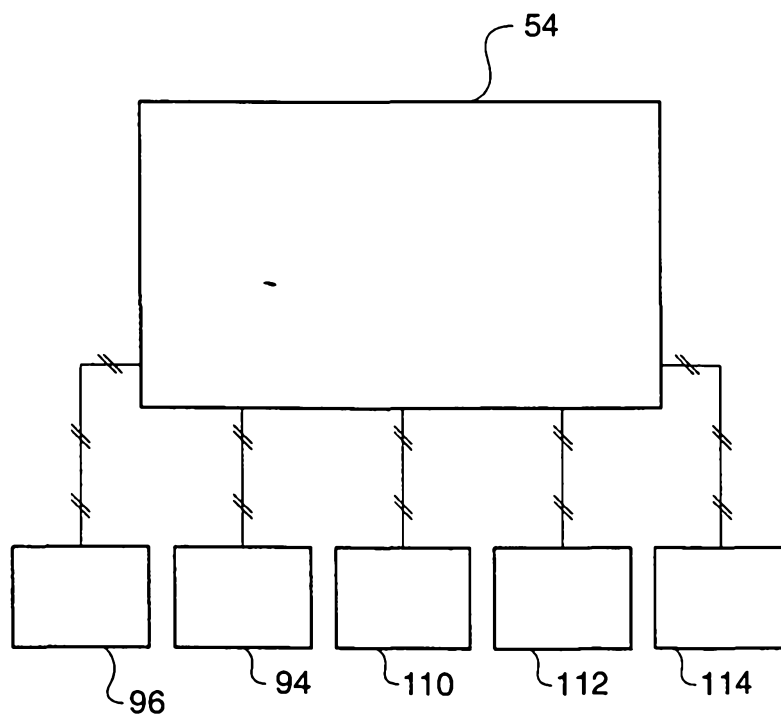
**Fig. 9.****Fig. 10.**

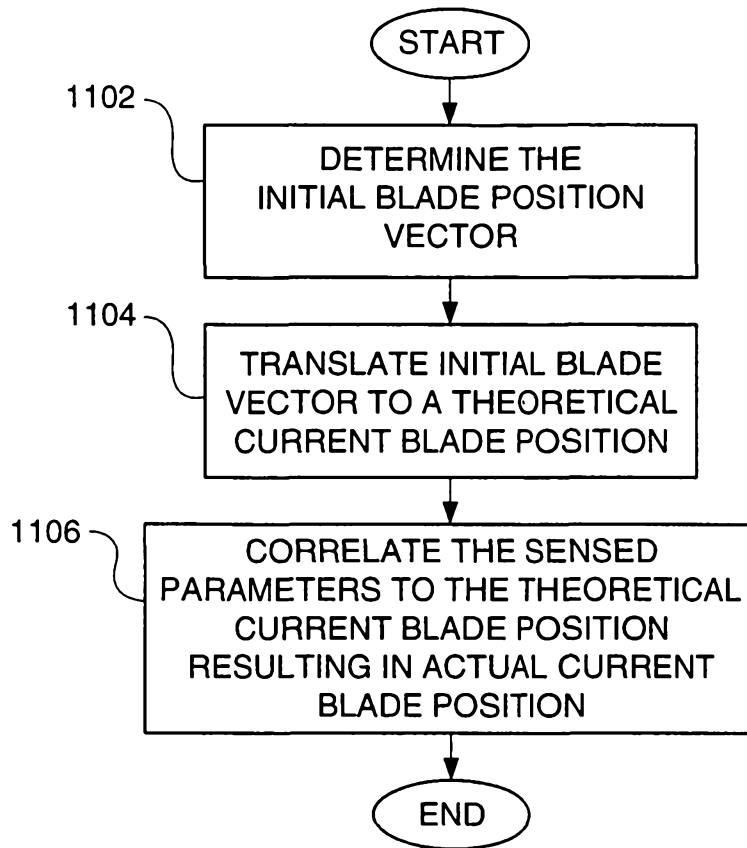
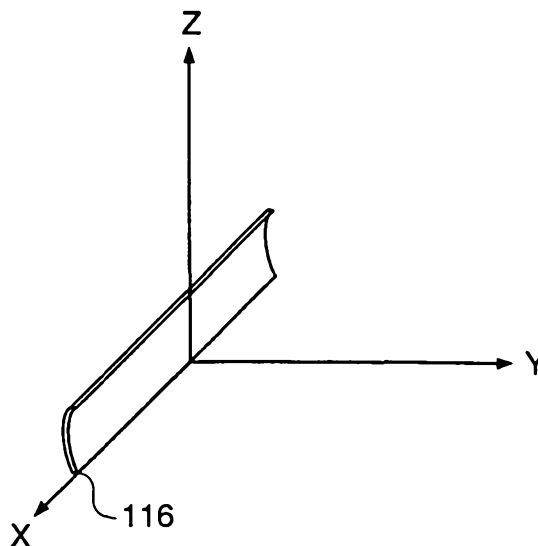
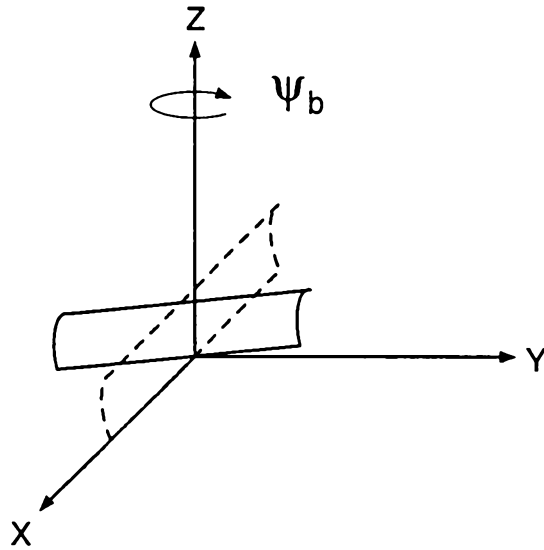
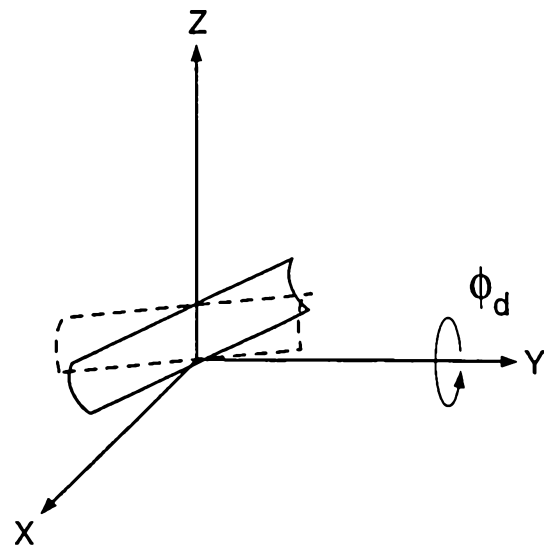
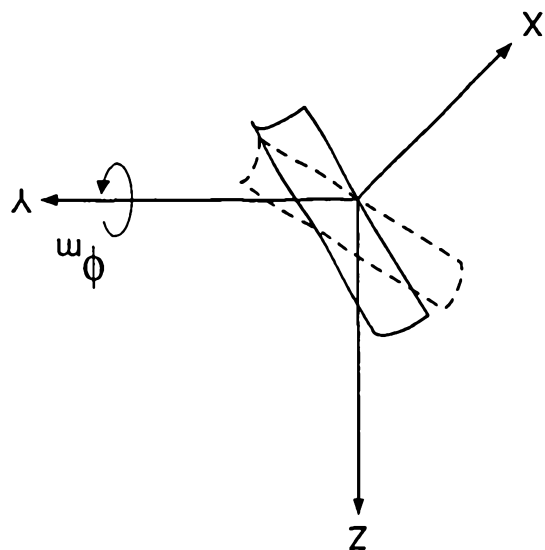

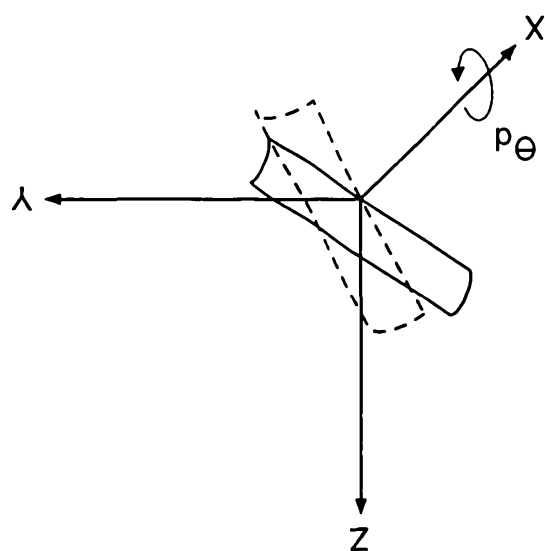
FIG. 11.FIG. 12.

FIG-13a.FIG-13b.






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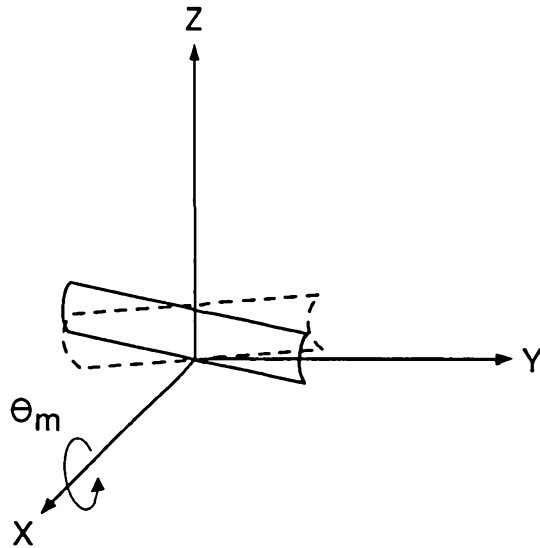

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FIG-13e.FIG-14.