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(71) Applicant *(for all designated States except US):* BALCO, INCORPORATED [US/US]; 3550 Snell Avenue, San Jose, CA 95136 (US).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)* : JACKSON, Bernie, Fergus [US/US]; 23485 Summit Road, Los Gatos, CA 95030 (US).

(74) Agent: HAMRICK, Claude, A., S.; Rosenblum, Parish & Isaacs, 160 West Santa Clara Street, 15th Floor, San Jose, CA 95113 (US).

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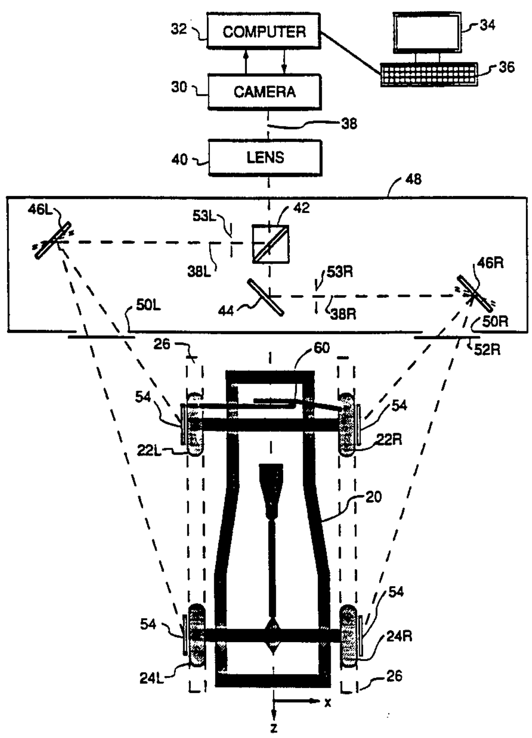
(54) Title: METHOD AND APPARATUS FOR DETERMINING THE ALIGNMENT OF MOTOR VEHICLE WHEELS

(57) Abstract

An apparatus for determining the alignment of a motor vehicle's wheels and including targets (22L, 22R, 24L, 24R) which either form part of the wheels or are attached thereto, an optical sensing means such as a television camera (30) for viewing the targets, an electronic processing means (32) connected to the optical sensing means for processing the target images to determine wheel alignment, and a display means (34, 36) for displaying the alignment information. The optical sensing means (30) views a target located on each wheel and forms an image of each target. Electronic signals corresponding to each of the images are transferred to the electronic processing means (32) which correlates the perspective image of each of the targets with the true shape of each target and calculates the alignment of the wheels of the vehicle.



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SPECIFICATION

Method and Apparatus for Determining the Alignment of Motor Vehicle Wheels

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to a method and apparatus for determining the alignment of motor vehicle wheels. More particularly, this invention relates to a method and apparatus including an opto-electronic image detector for detecting wheel orientation and producing electronic image data representing the wheels, or a reference mounted thereon, computational means for determining the alignment of the wheels, and means for comparing the electronic images, or data corresponding thereto, to previously stored alignment data and generating information which can be used to perform necessary adjustment to the vehicle.

Terms and Definitions

In the vehicle wheel alignment industry the following terms, with corresponding definitions, are commonly used:

Camber is the angle representing the inward or outward tilt from true vertical of the wheel and is positive if the top of the wheel tilts outward.

Caster is the angle representing the forward or rearward tilt from true vertical of the steering axis. When a wheel is viewed from the side, the angle is positive when the upper ball joint (or top of king pin, or upper mount of a McPherson strut) is rearward of the lower ball joint (or bottom of the king pin, or lower mount of a McPherson strut).

Thrust Line (T/L) is a line that bisects the angle formed by the rear toe lines. Lines and angles measured clockwise from the 12:00 axis are positive.

Geometric Center Line, is the line that runs from a point on the rear axle midway between the rear wheels to a point on the front axle midway between the front wheels.

Individual Toe is the angle formed by a front-to-back line through the wheel compared to the **geometric center line.** Angles pertaining to the left side are positive when clockwise of the **thrust line** and angles pertaining to the right side are positive when counterclockwise of the **thrust line.**

Offset is the amount that a front wheel and its corresponding rear wheel are out of line with each other. If there is no offset, the rear wheel is directly behind the front wheel.

Setback is the amount that one wheel on one side of the vehicle is displaced back from its corresponding wheel on the other side of the vehicle.

Steering Axis is a line projected from the upper pivot point of the upper ball joint or top of kingpin, or McPherson strut, through the lower ball joint.

Steering Axis Inclination (SAI) is the angle between the **steering axis** and true vertical. If the **steering axis** appears to tilt inward at the bottom of the wheel (as viewed from the driver position), the SAI is positive. SAI also is also known as kingpin inclination (KPI).

Thrust Angle (T/A) is the angle between the **thrust line** and the **geometric center line.** Angles measured clockwise from the **geometric center line** are positive.

Total Toe is the sum of individual, side-by-side toe measurements. If lines projected parallel to the primary planes of the wheels intersect at a point ahead of the side-by-side wheels, the angle is positive (toe in). If the lines would intersect behind the side to side wheels, the angle is negative (toe out). If the projected lines are parallel, the toe is zero.

Traditionally, the Camber and Toe measurements for each wheel of the vehicle are relative measurements i.e. relative to a vertical plane or to another wheel and these measurements are therefore made when the wheels are stationary. On the other hand, the calculation of Caster and SAI is a dynamic procedure and entails determining how the Camber of the front wheels changes with respect to a change in steering angle. This is usually done by swinging the front wheels from left to right through an angle of between 10° and 30°, or vice versa, while determining the resultant changes in Camber of the wheel with steering angle changes. From these determinations the Caster and SAI are determined by methods well known in the wheel alignment industry.

Similarly, once Camber, Toe, Caster and SAI have been measured, all other relevant wheel alignment parameters can be calculated by methods and formulations well known in the industry.

__Brief Description of the Prior Art__

The wheels of a motor vehicle need to be periodically checked to determine whether or not they are in alignment with each other because, if any of the wheels are out of alignment, this can result in excessive or uneven wear of the tires of the vehicle and/or adversely affect the handling and stability of the vehicle.

The typical steps of determining and correcting the alignment of a vehicle's wheels are as follows:

1. The vehicle is driven onto a test bed or rack which has previously been levelled to ensure a level base for the vehicle.

2. Some components of the alignment determination apparatus are mounted onto the wheels of the vehicle. These components are not necessarily accurately placed with respect to the wheel axis. The extent of the inaccuracy by which these components are mounted is called the "mounting error".

3. A "runout" calculation is done by jacking the vehicle up and rotating each wheel and taking measurements of the orientation of that wheel at different positions. These measurements are then used to calculate a correction factor to compensate for the "mounting error" and actual rim run-out.

4. A determination of the alignment of each of the wheels is done. The results of these determinations are compared to the specifications of alignment parameters for the vehicle being tested.

5. The operator then adjusts the various linkages of each wheel to correct for the misalignment, if any, of the wheels.

6. Steps 4 and 5 are repeated until the alignment is up to standard and/or is within manufacturer's specifications.

A large variety of devices for measuring the alignment of a motor vehicle's wheels exist. Many of these use optical instrumentation and/or light beams to determine the alignment of the wheels. Examples can be found in United States Patent Nos. 3,951,551 (Macpherson); 4,150,897 (Roberts); 4,154,531 (Roberts); 4,249,824 (Weiderrich); 4,302,104 (Hunter) ; 4,311,386 (Coetsier); 4,338,027 (Eck); 4,349,965 (Alsina); 4,803,785 (Reilly) and 5,048,954 (Madey).

All these devices operate with an apparatus which is mounted onto the wheel of a vehicle and which emits or reflects a light beam to illuminate an area on some form of reference such as a reference grid. As the position of the area illuminated by the beam on the reference is a function of the deflection of the beam, which in turn is a function of the orientation of the wheel, the alignment of the wheel can be calculated from the positioning of the illuminated area on the reference.

Other devices utilize a measuring head mounted onto each wheel of the vehicle. These heads typically include gravity gauges that are either connected to adjacent heads by means of cords or wires under tension or, alternatively, configured with beams of light shining between adjacent heads. The measuring heads, which must be maintained level, are then able to measure the relative angles between adjacent cords/beams of light as well as the angles between each wheel and its adjacent cord/beam of light and, from these measurements, calculate the alignment of the wheels.

Another type of alignment device is illustrated in United States Patents 4,899,218 (Waldecker) and 4,745,469 (Waldecker et al). This device operates by projecting structured light onto a wheel of the motor vehicle so that at least two contour lines on the surface of the wheel are illuminated. These contour lines are then read by video cameras which are positioned offset from the optical plane of the structured light and which are connected to a processor which calculates the spatial position of the contour lines (and therefore that of the wheel) by means of triangulation.

Generally, the heads used in the above described wheel alignment devices are delicate and expensive, complicated to use and must be carefully set up. Furthermore, certain of these devices rely on the accurate placing of optical or other measuring devices either on or in a set position relative to the wheels of the vehicle. This can be time consuming and complicated for the technicians operating the alignment determination apparatus. Such equipment also has the disadvantage that components which are carelessly left secured to the wheels when the vehicle is moved from the test area can very easily be damaged. Such damage, particularly in the case of sophisticated equipment, can be costly.

German patent application DE 29 48 573 in the name of Siemens Aktiengesellschaft discloses an apparatus which can be used to determine both the orientation and the spatial position of the plane of the wheel of a motor vehicle as well as the three-dimensional position of the steering axis of this wheel. The application discloses a method whereby a television camera takes an image of the rim on the wheel from two different known height positions. These images are fed into a processor which relates them to the known coordinates and viewing angles of the camera at its two height positions and determines the three-dimensional position of the rim.

In a similar way, a number of images of each wheel, in different steering positions, are taken to determine a three-dimensional solid of revolution for the wheel. From the axis of this solid of revolution the steering axis of the wheel under investigation can be determined. As a result, the three-dimensional position of both the steering axis and the center point of the plane defined by the rim of the wheel is determined.

In addition to the fact that little indication is given as to how the above values are determined, the method and apparatus of the described application has the disadvantage that, because a triangulation technique is used, at least two images (from different cameras or from a single camera viewing along different axes) of the wheel must be taken. Furthermore, both the coordinated three-dimensional position for each point from where an image of the wheel is taken as well as the orientation of each of the view paths must be accurately known.

This is a major disadvantage of this invention because the accurate determination of the three dimensional positions and the orientation of the view paths, requires sophisticated equipment which can easily go out of calibration due to temperature changes, vibration, ground movement, etc.

A further disadvantage is that the method in this application does not indicate how it makes allowances for the perspective distortion of the image of the rim of the wheel. This perspective distortion causes the image of the rim to be in the form of a distorted ellipse with the edge of the ellipse closest to the television camera appearing larger and the image of the edge farthest from the camera appearing smaller. If allowance for this distortion is not made, inaccuracies can result.

The need therefore still exists for a wheel alignment apparatus which is simple and easy to use, which has its sophisticated alignment detection components remote from the wheels of the motor vehicle, and which can provide reliably accurate alignment measurements over a large range of rim diameters, track widths and wheel bases.

SUMMARY OF THE INVENTION

Objects of the Invention

It is therefore an object of this invention to provide a wheel alignment apparatus which is simple, easy and quick to use.

It is a further object of this invention to provide a wheel alignment apparatus which can operate with its precision components removed from the motor vehicle.

Yet another object of this invention is to provide a wheel alignment apparatus which uses an opto-electronic image detection device to determine the alignment of the wheel.

Still a further object of this invention is to provide a wheel alignment apparatus which uses a perspective image, of a known target attached to a wheel, to determine the orientation of the target and thereby the alignment of the wheel.

Summary

Briefly a presently preferred embodiment of this invention includes an apparatus for determining the alignment of a motor vehicle's wheels and comprises an optical sensing means such as a television camera, an electronic processing means connected to the optical sensing means, at least one predetermined target which either forms part of the wheel or is attached thereto, and a display for indicating the detected alignment. The optical sensing means views a target attached to each wheel and forms a perspective image of each target. Electronic signals corresponding to each of the images are transferred to the electronic processing means which correlates the perspective image of each of the targets with the true shape of each target. In so doing, the processor relates the dimensions of certain known geometric elements of the target with the dimensions of corresponding elements in the perspective image and by performing certain trigonometric calculations (or by any other suitable mathematical or numerical methods), calculates the alignment of the wheels of the vehicle. This invention can also be used to calculate the three-dimensional position and orientation of the axis of rotation of the wheel (wheel axis). The detected alignment is then displayed for use in performing alignment adjustments to the vehicle.

Preferably, the optical sensor means forms images of a target attached to each of at least two wheels mounted on the same axle of the vehicle and the electronic processing means calculates the relative angles between the two wheels. Even more preferably, the optical sensor means forms images of all the targets on the wheels and relative alignment calculations are computed by the electronic processor means for all these images.

DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

FIGS. 1(a)-(c) illustrate three different images of a circle resulting from various degrees of rotation about different axes;

FIG. 2 is a schematic representation illustrating the apparatus and method of the invention;

FIG. 2a is an illustration of a quasi three-dimensional representation of a type that may be generated on a system display screen to report detected alignment and to guide the technician in making appropriate vehicle adjustments;

FIG. 2b is a cross-section through a pan-and-tilt mirror used in one embodiment of this invention;

FIG. 3 is a representation of an exemplary target that can be used with the apparatus in FIG. 2;

FIG. 4 is a schematic representation of a preferred embodiment of the apparatus of this invention;

FIG. 5 is a perspective view of an alternative target mounted on a vehicle's wheel;

FIG. 6 is a schematic representation of an image of the target illustrated in FIG. 5 formed by using the optical system in FIG. 4;

FIG. 7 illustrates one method of how the apparatus calculates the run-out factor of the wheel; and

FIGS. 8a-8c illustrate certain aspects of the mathematics performed in the method and apparatus of this invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

Basic Theory of the Invention

This invention is based on the fact that the image of a body varies according to the perspective from which such body is viewed and that the variation in the image is directly related to and determinable from the perspective angle of the view path along which the body is viewed.

Furthermore it is known that it is possible to determine the perspective angles at which an object is viewed merely by relating the perspective image of that object with a true non-perspective image thereof. Conversely put, it is possible to determine the angles at which an object is orientated to a view path (or a plane perpendicular thereto) by comparing a perspective image of an object with a non-perspective image thereof.

This is illustrated in FIGS. 1(a)-(c) with reference to a circle 10, shown as it would appear if viewed from three different perspectives. In FIG. 1 (a) the circle 10 is illustrated as it would appear if it were viewed along an axis perpendicular to its primary plane which, in this case, is in the plane of the paper. If this circle is rotated through an angle θ, being less than 90°, about the y-axis 12 and viewed along the same view path, the image of the circle 10 will be that of an ellipse as shown in FIG. 1(b). Similarly, if the circle is rotated about both the x and the y-axes, 12 and 14 respectively, through angles θ and ϕ respectively, the image of the circle (the ellipse) will be as shown in FIG. 1(c), in which the major axis 16 of the ellipse is shown to be angled relative to both the x and y-axes.

It will, however, be realized that the ellipses here are idealized in that they make no allowance for the distortion which results in an image when it is viewed from a perspective angle. This distortion is illustrated by the broken lines 11 in FIGS. 1(b) and (c). As can be seen from these Figures, the edge of the ellipse 11, which is closer to the viewer, appears larger while the edge 11, which is farther from the viewer, appears smaller. The resulting image 11 is thus a distorted ellipse.

Returning to the idealized conditions shown in these figures, and assuming the angles θ and φ are not known, it is possible to determine the orientation of the primary plane of the ellipse illustrated in FIG. 1(c) by relating the image of the ellipse to the circle 10 in FIG. 1(a). This is usually done by relating the geometric characteristics (e.g. dimension) of at least one element of the ellipse (e.g. the major and minor axes 16, 18 thereof) to characteristics of corresponding elements (the diameters) of the circle in FIG. 1(a).

Under idealized conditions, these orientation calculations are done by applying trigonometric functions or any other mathematical/numerical methods to the ratios between the minor and/or major axis and the diameter. In addition, the angles of the minor and major axes to the horizontal (x-) axis or vertical (y-) axis can be calculated. Once all these angles have been determined, the orientation in space of the primary plane of the ellipse will be determined.

Although not illustrated, it is also possible to determine the position in space of the circle 10. This will, however, be demonstrated below with reference to FIG. 8.

The performance of the above illustrated calculations is complicated by the real-life perspective distortion of the image, as illustrated by the broken lines 11. How this foreshortening is allowed for will, once again, be discussed with reference to the mathematics illustrated in FIG. 8.

Brief Description of One Embodiment of the Alignment Apparatus of the Invention

The apparatus with which this theory is applied in this invention is illustrated in the schematic representation in FIG. 2. In this figure a motor vehicle 20, on which a wheel alignment is to be performed, is represented by a schematic illustration of its chassis and is shown to include two front wheels 22L and 22R and two rear wheels 24L and 24R. The vehicle 20 is shown positioned on a conventional wheel alignment test bed 26, indicated in dotted lines, which does not form part of this invention.

The alignment apparatus of this invention is shown to be constituted by a video camera 30 which is in electrical communication with an electronic processing means such as a computer 32 which, in operation, displays results and calculations on a visual display unit 34. In addition, the apparatus includes a keyboard 36 (or some other suitable means) for inputting data and relevant information into the computer 32. It will, of course, be appreciated that display and keyboard entry could be provided by a remote unit which communicates with the computer through a cable, lightwave or radio link.

In accordance with a preferred embodiment and as illustrated in FIG. 2a, a computer-generated quasi three-dimensional representation of the wheels being aligned may be depicted on the display unit 34 along with suitable indicia evidencing the detected alignment. In addition, alphanumeric and/or pictorial hints or suggestions may be depicted to guide the technician in adjusting the various vehicle parameters as required to bring the alignment into conformance with predetermined specifications.

The video camera 30 sights onto the wheels 22L, 22R, 24L and 24R along a view path 38 which passes through a lens 40 and onto a beam splitter 42. The beam splitter 42 splits the view path 38 into two components 38L and 38R, respectively. As is apparent from this figure, the left hand component 38L of the view path 38 is reflected perpendicularly to the initial view path by the beam splitter 42 while the right hand component 38R is reflected perpendicularly to the initial view path by a mirror or prism 44 mounted adjacent to the beam splitter. The apparatus also includes a housing 48 into which the beam splitter 42, mirror 44 and at least two pan-and-tilt mirrors, 46L and 46R, are mounted. From this point onwards the respective components of the apparatus and the view path are identical for both the left and right side of the motor vehicle and therefore a description of only one side will suffice.

The left hand component of the view path 38L is reflected onto the wheels 22L and 24L by the left side pan-and-tilt mirror 46L which is movable to allow the video camera 30 to consecutively view the front wheel 22L and the rear wheel 24L of the vehicle 20. In some embodiments of this invention the pan-and-tilt mirror 46L can be configured so that both the front and rear wheels of the motor vehicle can be viewed simultaneously.

In this embodiment, the view path 38L passes from the pan-and-tilt mirror 46L through an aperture 50L in the wall of the housing 48 and onto the respective wheels 22L and 24L. A shutter 52L is positioned so that it can be operated to close the aperture 50L thereby effectively blocking the view path 38L and allowing the video camera 30 to sight onto the right hand side of the vehicle 20 only. Alternatively, shutters could be placed at the locations 53L and 53R and/or an electronic shutter within the camera 30 could be synchronized with one or more strobed light sources to permit capture of an image only when a particular target or targets are illuminated.

<u>Operation of the Alignment Apparatus</u>

In a typical operation, the apparatus of this embodiment of the invention works as follows: The vehicle 20 is driven onto the test bed 26 which basically consists of two parallel metal strips on which the wheels of the vehicle rest. Under the test bed, a lift mechanism is located (but not shown) which acts to lift the metal strips and the vehicle to allow the wheel alignment technician to access the wheel mountings to correct misalignment of the wheels. In addition, a rotationally mounted circular plate commonly called a turnplate (not shown), is located under each front wheel of the vehicle. The turnplates allow the front wheels to be pivoted about their steering axes relatively easily. This facilitates the procedure involved during the calculation of caster and other angles determined dynamically. The rear wheels are positioned on elongate, rectangular, smooth metal plates mounted on the metal strips. These plates are usually termed skid plates and allow the rear wheels to be adjusted by a technician once the rear wheel mountings have been loosened. Such plates also prevent preload to wheels tending to affect their angular position.

In addition, as in some sophisticated alignment machines, the vehicle make and model year can be entered into the apparatus at some time early on in the procedure, and this information is used by the apparatus to determine the alignment parameters, for the vehicle concerned, from previously programmed lookup tables within the computer 32. Furthermore, from the vehicle's make and model year, the track width and wheelbase dimensions can be determined by retrieving the data from memory. These can be used to drive the mirrors of the alignment apparatus to "home" in on the wheels of the vehicle more accurately. Alternatively, previous operational history information can be used to select likely wheel location. Still another possibility is to cause the mirrors to sweep a particular pattern.

Once the vehicle 20 has been driven onto the test bed 26, a target 54 is mounted onto each wheel. The shape and configuration of the target will be described later with reference to FIG. 3. The apparatus first makes a "run-out" factor calculation according to the method that will more fully be described with reference to FIG. 7.

Once the "run-out" factor has been calculated, the alignment apparatus forms an image (a detected image) of each of the targets 54 on the wheels of the motor vehicle 20. These detected images are processed in the electronic processing means/computer 32 which calculates, using the method of the invention as will be more fully described, the orientation of each of the targets to the respective view paths 38L, 38R. The computer 32 then takes into account the "run-out" factors mentioned above to calculate the true orientation of the wheels relative to the respective view paths. Thereafter the apparatus makes allowance for the orientation of the pan-and-tilt mirrors

46L, 46R to calculate the actual orientation of the primary planes of each of the wheels. Upon this being done, the results of the computation are displayed on the display 34 which gives the operator the required instructions as to which corrections need to be made to, for example, adjustments to the steerage linkages 60 of the front wheels 22L and 22R to correct the detected misalignment of the wheels of the vehicle.

Orientation Calculations

The computer 32 does all the required calculations using a computer program such as IMAGE ANALYST, which is capable of analyzing images and values associated therewith. Typically, IMAGE ANALYST produces values for the center points of these images in coordinates relating to the pixels on the screen of the video camera. These values are then processed by software which incorporates the later-to-be-described mathematics illustrated with respect to FIG. 8. Although software such as IMAGE ANALYST may have many features, in this application it is apparent that the main features utilized in this application is that of being able to provide screen coordinates for the images detected by the video camera. It is, therefore, possible for software other than IMAGE ANALYST to be used with this method and apparatus. IMAGE ANALYST is supplied by AUTOMATIX, INC. of 755 Middlesex Turnpike, Billerca, MA 01821.

Orientation of the Pan-and-Tilt Mirrors

In the above-described method it is evident that knowledge of the orientation of the pan-and-tilt mirrors 46L, 46R is required for the effective calculation of the relative alignment of the wheels of the vehicle 20 to each other. The orientation of these mirrors 46L, 46R can be determined in one of two ways. One way of determining the orientation is by linking the mirrors 46L, 46R to a sensitive tracking and orientation determination device which outputs data to the computer 32 which, in turn, calculates the orientation of the mirrors in three-dimensional space. Alternatively, and preferably, the face of each mirror includes a clearly defined pattern, usually in the form of a number of small, spaced-apart dots, which define an identifiable pattern that can be detected by the video camera 30 as it sights onto the wheels of the motor vehicle 20. Once the video camera 30 has detected the pattern on the mirrors 46L, 46R it can form an image thereof; an image which, because of the orientation of the mirrors, will be a perspective image, and which can then be electronically fed into the computer which, in turn, can calculate the minor orientation in three-dimensional space along the same lines as the orientation of the wheels of the vehicle 20 are calculated. This second alternative is preferable because it does not require sophisticated and expensive electronic tracking and orientation determination equipment.

One way of implementing this second, preferable alternative, is to incorporate a lens 40 into the apparatus. The lens has a focal length such that it projects an adequately clear image of both the targets and the mirrors onto the camera 30.

In FIG. 2b, one way of enhancing the images of the dots on the pan-and-tilt mirrors is illustrated. This figure illustrates a cross-section through a pan-and-tilt mirror 46L with two dots 41 shown formed on its upper surface. A plano-convex lens 43 is located on top of each dot. The focal length of each of these lenses is such that, together with the lens 40, they form a clear image of the dots in the video camera 30. Although this figure illustrates two individual plano-convex lenses 43, it will be evident that a single lens spanning two or more dots could be used. Similarly, other optical methods can be used to accomplish this.

Orientation of the Targets

An example of a typical target 54 that can be used on the wheels of the vehicle 20 is illustrated in FIG. 3. As can be seen from this figure, the target consists of a flat plate with a pattern of two differently sized circles

62, 63 marked in a pre-determined format thereon. Although a specific pattern is shown in this figure, it will be evident that a large number of different patterns can be used on the target 54. For example, the target need not be circular, a larger or smaller number of dots may be included. Moreover, other sizes and shapes can be used for the dots. In addition, multifaceted plates or objects can also be used for the targets.

In practice, a mathematical representation, or data corresponding to a true image (i.e. an image taken by viewing the target perpendicularly to its primary plane) and the dimensions of the target are preprogrammed into the memory of the computer 32 so that, during the alignment process, the computer has a reference image to which the viewed perspective images of the targets can be compared.

The way that the computer calculates the orientation of the target 54 is to identify certain geometric characteristics on the target 54, take perspective measurements of these and compare these measurements with the true image previously pre-programmed into the memory of the computer.

The apparatus could, for example, calculate the center of each of the circles 62a, 62b by means of, say, a method called centroiding. This is a method commonly used by image analysis computers to determine the positioning of the center point or center line of an object. Once the center points of the two circles 62a, 62b have been determined, the distance between the two can be measured. This process is then repeated for other circles in the pattern on the target 54. These distances can then be compared to the true distances (i.e. non-perspective distances) between the respective centers. Similarly, the angle to the horizontal (or vertical) of the line joining the two centers can be determined. Once allowance has been made for the effect of the focal length of the lens 40 and other optical characteristics of the components, such as beam splitter 42, mirror 44 and mirrors 46L, 46R, are considered, a calculation can be made as to what the orientation of the target 54 is. This calculation can be done by using trigonometric functions or other suitable mathematical or numerical methods. As explained above, this will also yield the orientation of the primary plane of the wheel of the vehicle.

Although the above describes one method of calculating the orientation of the target 54, it will be evident that other methods are also available. For example, the apparatus could sight onto only one of the circles, say the circle 63, and by using the perspective image thereof (the distorted ellipse) calculate, in very much the same way as described with reference to FIG. 1, the orientation of that circle and, therefore, the orientation of the target 54. Another example is to take two images rotated about 60° relative to each other and use such information to calculate the orientation of the target with respect to its axis of rotation. Note that only two images are required so long as wheel axle does not change its axial orientation. In addition, it is envisaged that in sophisticated alignment systems more than one calculation will be completed for each target and that the different results of these calculations will be compared to each other to ensure the required accuracy.

Furthermore, as the true dimensions of the target are preprogrammed into the memory of the computer 32, the method and apparatus of this invention can be used to determine the exact position of the wheels in three-dimensional space. This can be done by firstly determining the perspective image of certain of the elements of the pattern on the target (for example, the distances between circles) and comparing the dimensions of this image to the true dimensions of those elements. This will yield the distance that the element and, accordingly, the target 54 is from the video camera.

As the processes described above have already yielded the orientation of target 54 with respect to the view path and/or some other reference plane, this result can be combined with the calculated distance and the geometric coordinates of the alignment apparatus to yield a position of the target 54 relative to the alignment apparatus. During this comparison process, the effect of the focal length of the lens 40, as well as the optical characteristics of the beam splitter 42, mirror 44 and the pan-and-tilt mirrors 46L and 46R must also be taken into consideration. Typically, these characteristics would be input into the computer by direct entry or, preferably, by calibration techniques. In this way the exact positioning of each of the wheels of the vehicle 20 can be calculated.

A Brief Description of an Alternative Embodiment of the Apparatus of the Invention

It will be evident to one skilled in the art that a number of different configurations of lens, beam splitter and mirrors (i.e. the optical system) are possible to achieve the required result with the method and apparatus of this invention. One such configuration is illustrated in FIG. 4 of the accompanying drawings.

In this figure the equipment is shown to be suspended over the motor vehicle 20 and includes a video camera 30, computer 32 with associated display 34 and data entry keyboard 36 as well as lens 40 similar to those illustrated in FIG. 2. As with the configuration in FIG. 2, the view path or optical center line of the video camera 30 is deflected into two directions 38L and 38R by a combination of beam splitter 42 and plane mirror 44.

This configuration also includes two pan-and-tilt mirrors 70L, 72L, located on the left side of the apparatus and two pan-and-tilt mirrors 70R and 72R located on the right side of the apparatus. The mirrors 70L, 72L are arranged to view the left front and left rear wheels 22L, 24L, respectively and the mirrors 70R, 72R are arranged to view the right wheels 22R, 24R respectively. As the mirrors 70L, 72L, 70R, 72R are pan-and-tilt mirrors, they can be moved to view the wheels on the vehicle 20 even though the vehicle is not accurately centered below the apparatus. These mirrors are also useful in making allowance for vehicles of different lengths of wheelbase and track width.

A further modification of this apparatus would include the replacement of the beam splitter 42 and the plane mirror 44 with a single reflecting prism. The prism has the advantage over the beam splitter combination in that more light is reflected from the prism into the camera 30. This results in a brighter image of the target 54 being formed by the camera 30.

Target and Target Image Details

With the apparatus as illustrated in this figure, as with the other illustrated apparatus, a modification of the target, as indicated in FIG. 5, can be used. In this figure the target, generally indicated as 80, is shown to include a flat, rectangular plate 82 which is clamped to the rim 84 of a wheel 86 by means of a clamping mechanism 88. It will be evident from this figure that the plate 82 is angled relative to the primary plane of the wheel 86 as well as to its axis of rotation 89.

The precise orientation of this plate 82 is, however, not known and will, as is described later, be computed by the determination of a run-out factor for this wheel 86. The general orientation of the plate 82 is, however, chosen so that it can be adequately viewed by the video camera 30 as it sights onto it.

Finally, plate 82 includes a plurality of dots 90 which, as shown, constitute a pattern not unlike that on the target illustrated in FIG. 3.

With targets of this nature, the image formed by the video camera 30, when used together with the apparatus illustrated in FIG. 4, will be something like that illustrated in FIG. 6. In this figure, it is apparent that four discrete images 92, 94, 96, 98 are formed to make up the complete image, generally indicated as 99, formed by the video camera 30. Each of the four images that make up the complete image 99 is an image of one of the rectangular plates 82, respectively disposed on the four wheels of the motor vehicle. For example, the image 92 at the top of the picture 100 could correspond to the plate 82 on the right rear wheel 24R of the vehicle 20.

Similarly, image 94 could correspond to the right front wheel 22R, image 96 to the left front wheel 22L and image 98 to the left rear wheel 24L.

The advantage of the target 80 when used with the apparatus illustrated in FIG. 4 is that a single image can be taken simultaneously of all four wheels. This single image can then be processed, in very much the same way as described above, to yield the orientation and location of all the wheels to each other. More particularly, the relative orientation of the right front wheel to the left front wheel and the right rear wheel to the left rear wheel can be calculated.

On either end of the images 92, 94, 96, 98 a pair of dots 100 can be seen. These dots 100 are in fact images of the dots on the respective pan-and-tilt mirrors referred to in the discussion of FIG. 2. As was pointed out in that discussion, these dots are used to calculate the orientation of the pan-and-tilt mirrors to the view path of the camera; a calculation which is essential to determine both the orientation and the location of the primary plane of each of the wheels of the vehicle.

In addition, this figure illustrates that the images of the marks 100 can be separated from the images of the patterns on the plate by means of a vertical line 101. This line 101 serves as a demarkation line between the pattern (from which the orientation of the target is calculated) and the image of the dots 100 (from which the orientation of the pan-and-tilt mirrors is calculated).

Runout Factor Calculations

In FIG. 7 of the drawings, a method of calculating the run-out factor for a target 104 mounted in a slightly different way on a wheel 103 is illustrated. In this method, the wheel 103 is slowly rotated while a number of different images of the target 104 are taken. This target is, for the sake of clarity, off-set fairly substantially from the center of the wheel. In practice, however, the target may be mounted closer to the center, much like the target illustrated in FIG. 5. For each image, the inclination of the plane of the target, as well as its location in space is calculated. Once these have been determined for each image, they are integrated to define a surface of revolution 106. This surface of revolution 106 will represent the path which the target 104 tracks as the wheel is rotated about its axis, and the axis of rotation 108 thereof is the same as the axis of rotation of the wheel. This means that a plane perpendicular to the axis of rotation 108 of the surface of revolution 106 will be parallel to the primary plane of the wheel 106. As the surface of revolution 106 is determined, its axis of rotation 108 is determined and, therefore, the orientation and position in space of the primary plane of the wheel of the vehicle can be determined.

From these results, the run-out factor can be determined by calculating the angle between the plane of the target and the primary plane of the wheel. This run-out factor is then stored in the computer 32 and used when the alignment of the wheel is calculated from a single image of the target.

The calculation of the run-out factor can also be used to determine whether or not the suspension of the vehicle is badly worn. Using the method of the invention an apparent run-out factor (i.e., the orientation of the target with respect to the wheel) can be determined for each image which is taken of the target. From this group of individual run-out factors a mean value can be calculated (which will represent the true "run-out" factor) as well as the extent of the deviation from the mean of the individual factors. If this deviation is above a certain tolerance, this indicates that the suspension of the motor vehicle is worn so badly that it needs to be attended to.

Accuracy Determination

Turning once again to the targets, it should be realized that an important feature of the target illustrated either in FIG. 3 or 5 (or any other target for that matter) is that it should have sufficient data points to allow redundant calculations to be made using different sets of data points. This will yield multiple wheel alignment angles which can be averaged out to improve the accuracy of the final measurement. In addition, a statistical distribution of the different alignment angles calculated for each wheel can be used as a measurement of accuracy of the operation of the apparatus. If a suitable check is built into the computer 32, a statistical distribution such as this can enable the computer 32 to determine whether or not sufficient accuracies exist and, if not, to produce a signal which can alert an operator to this fact.

Similarly, if the above checking indicates that one or more of the targets used yield(s) unacceptably poor results while the remaining target(s) yield acceptable results, it can be assumed that some of the targets being used are unacceptable. The computer can give an indication to this effect and the operator can, for example, be instructed to remove, clean or repair the offending target(s).

A further benefit derived from forming suitable multiple images and computing a statistical analysis, is that the computer 32 can determine whether or not enough images have been taken to suitably ensure the required accuracy of the alignment measuring process. If insufficient readings exist, the computer can direct the apparatus to take further readings which, although sacrificing speed, would result in improved accuracy of the measurement.

Furthermore, the target could include a machine-readable, e.g. a bar code or the like, which can be used for identification, target tracking, intensity threshold measurement, evaluation of illumination quality, and encoding of defects to allow the use of cheap targets. For example, if the target was twisted and the amount of twist was encoded in the bar code, then the computer could compensate for the twist.

Another important feature of the target is that the pattern thereon should allow very quick and accurate location of the pattern to an accuracy approaching substantially less than a camera pixel. To achieve this the pattern should exhibit a high contrast and be of a configuration which allows the specific apparatus used to achieve the required speed and accuracy. In one embodiment, retro-reflective materials are used for the dots, and a color that is absorptive of the particular light used is chosen for the background.

This apparatus also allows for calibration, which is important as all optical systems have some geometric distortion. The total image area of the apparatus could, for example, be calculated using a perfect target and the result used to determine correction values that can be stored for use when operating the system in alignment procedures.

The absolute accuracy of the apparatus can be checked or calibrated by using a simple 2-sided flat plate target which is placed so that the apparatus views both sides simultaneously. As the plate is flat, the net angle (relative alignment) between the two planes of the target should be zero. If not, a suitable correction factor can be stored in the computer. Alternatively, two views of the same side of the target taken from different angles could be used for this purpose.

Mathematical Algorithms Used

This section provides the mathematics necessary to reduce measurements made by the video camera to wheel positions in space using instantaneous measurement.

Assumptions

The camera system can be defined to include two planes positioned arbitrarily (within reasonable constraints of visibility) with respect to one another. One is the image plane, which maps what is "seen" by the camera and the other is the object plane, which contains three-dimensional, essentially point targets.

Based on this, the assumptions made are:

(i) the camera principal axis is normal to the image plane (most cameras are built this way);

(ii) there exists, at a known distance of f (i.e. the imaging system's focal length when set at infinity) from the image plane, along the camera principal axis, a point called the center of perspectivity (CP) such that the behavior of the camera is that the image of a viewed point anywhere in the camera's field of view is to project it onto the image plane by moving it along a line passing both through the viewed point in space and the CP;

(iii) the origin of the coordinate system fixed in the image plane is located at the center of perspectivity, with z unit vector directed toward camera along its principal axis; and

(iv) the units of the image plane measurements are the same as those of the object plane measurements.

These assumptions are commonplace in the visual sciences.

<u>**Overview**</u>

For this configuration, mathematics can be provided to determine the relative orientations and positions of the object and image planes.

This mathematics can be used in 2 ways:

(i) during calibration, to find the position of the image plane with respect to the location of an object plane of known position of a calibration target; and

(ii) during the alignment process, to find the position and orientation of the primary plane of the target mounted on the wheels of the vehicle. It is essential in this step that the known coordinate system is fixed in space, and that it remains the same for all four wheels of the car.

As has been described above, once the location of the target planes on the wheels is known, by rotating the wheels, the axis of rotation of the wheels can be determined, and from there, the alignment of the wheels.

Main Algorithm

It should be noted that this main algorithm presents no treatment of the various pan-and-tilt mirrors; this is done later.

The main algorithm requires the following inputs:

(i) A list of points expressed in object plane coordinates.

$$^{o}q_j = (x_j, y_j), \; j = 1, n \; / \; n \geq 4$$

These are actually three-dimensional points, but the object plane coordinate system can always be chosen so that the third coordinate $z_i = 0$.

(ii) A corresponding list of image plane point coordinates $^{i}q_j = (u_j, v_j)$, $j = 1, n$.

For these inputs, the algorithm produces an output which is a homogeneous coordinate transform matrix expressing the center of perspectivity and unit vectors fixed with respect to the principal axes of the image plane. This matrix will normally be inverted, and then applied to transform the viewed points into image system coordinates.

Step 1: Determine a Collineation

Convert all the two-dimensional input coordinates to affine form and find a 3x3 transformation matrix T such that:

$$\begin{bmatrix} k_i u_i \\ k_i v_i \\ k_i \end{bmatrix} = \begin{bmatrix} & & \\ & T & \\ & & \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} \tag{1}$$

for $i = 1, n$ and where the k_i are arbitrary scalar constants.

One way in which the transformation matrix T can be determined is given below.

Step 2: Determine transforms of key points and invariants.

The transform matrix T will transform points in the object plane to points in the image plane under the projectivity whose center is the center of perspectivity (CP). When inverted, it will also perform the reverse transformation, viz:

(2)

$$\begin{bmatrix} m_i x_i \\ m_i y_i \\ m_i \end{bmatrix} = \begin{bmatrix} T^{-1} \end{bmatrix} \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix}$$

It will be noted that the whole equation may be multiplied by an arbitrary scalar and still remain true. The value m_i is such a scalar, and is required to permit normalization of $(u_i\ v_i\ 1)^T$ so that its third coordinate is a unit. The matrix T is also useful for transforming lines, which are dual to points on the projective plane. The equation of a line in the projective plane is:

(3)

$$\begin{bmatrix} c_1 & c_2 & c_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = 0 \qquad c^T X = 0$$

Where c is the coordinate vector of the line and X is the specimen vector. Any homogeneous representation of a point which satisfies equation 3 lies on the line. Suppose that an object co-ordinate ${}^0c$ lies on a line, then:

(4)

$$[\,{}^{\circ}c\,] \begin{bmatrix} {}^{\circ}x \end{bmatrix} = 0$$

is the equation of a line in the object plane, expressed in object plane coordinates. Using equation 2 we can transform to image plane co-ordinates:

$$[\,{}^{\circ}c\,] \begin{bmatrix} T^{-1} \end{bmatrix} \begin{bmatrix} {}^{i}x \end{bmatrix} = 0$$

or

$$\left[\ {}^{i}c\ \right]\left[\ {}^{i}x\ \right] = 0 \tag{5}$$

Therefore

$$\left[\ {}^{i}c\ \right] = \left[\ T^{-T}\ \right]\left[\ {}^{o}c\ \right] \tag{6}$$

is the way to transform line coordinates from the object plane to the image plane and

$$\left[\ {}^{o}c\ \right] = \left[\ T^{T}\ \right]\left[\ {}^{i}c\ \right] \tag{7}$$

is the way to perform the inverse transformation.

Note that the projective plane differs from the non-projective plane in that it includes points at infinity whose projective coordinate is 0. These points together constitute a <u>line at infinity</u>, whose coordinates are [0,0,1] viz.

$$[\,0\ 0\ 1\,]\begin{bmatrix} x \\ y \\ w \end{bmatrix} = 0 \tag{8}$$

$$\Rightarrow W = 0$$

This is illustrated in FIG. 8a which represents a side view of an object plane OP and image plane IP positioned non-parallel to each other at some angle θ.

The object plane OP intersects a plane parallel to the image plane IP but passing through the center of perspectivity CP. This plane is called the view image plane VIP and intersects the object plane OP at the "vanishing line" mapped to the object plane, shown as point VLO. Similarly, the figure shows a plane parallel to the object plane called the viewed object plane VOP which intersects the image plane IP at a "vanishing line" mapped to the image plane, shown as point VLI.

As VIP is parallel to IP they intersect at infinity. The collineation matrix T can therefore be used to map the line at infinity of the image to its transformed position in the object plane as follows:

$$VLO \equiv \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} T^T \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{9}$$

and likewise:

$$VLI \equiv \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} T^{-T} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{10}$$

By the assumptions stated above with respect to the camera system, the coordinates of the principal point of the image PPI are:

$$PPI = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{11}$$

The coordinates of the principal point of the object PPO are:

$$PPO \equiv \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} = \begin{bmatrix} T^{-1} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{12}$$

Step 3: <u>Complete Remaining Inclination Values</u>

The minimum distance between a line in a projective plane with line coordinates $[z_1 \; z_2 \; z_3]^T$ and a point with coordinates $[p_1 \; p_2 \; p_3]^T$ is given by

$$d = \left| \frac{z_1 p_1 + z_2 p_2 + z_3 p_3}{p_3 \sqrt{z_1^2 + z_2^2}} \right| \tag{13}$$

This makes it possible to solve for DI, θ and DO:

(14)

$$DI = \left| \frac{a3}{\sqrt{a_1^2 + a_2^2}} \right|$$

(15)

$$\theta = \arctan \left(\frac{f}{DI}\right)$$

(16)

$$DO = \left| \frac{b_1 c_1 + b_2 c_2 + b_3 c_3}{c_3 \sqrt{b_1^2 + b_2^2}} \right|$$

Step 4: Compute Pan Values

FIG. 8b illustrates a plan view of the object plane, looking down from the center of perspectivity.

We have

(17)

$$\phi = \arctan \left(\frac{-b_2}{b_1}\right)$$

(18)

$$\text{Let} \quad x_+ = sgn(S_x - PPO) \cdot {}^\circ\hat{x}$$

$$= -sgn\left(\frac{b_1 c_1 + b_2 c_2 + b_3 c_3}{b_1 c_3}\right)$$

(19)

$$y_+ = sgn(S_y - PPO) \cdot {}^\circ\hat{y}$$

$$= -sgn\left(\frac{b_1 c_1 + b_2 c_2 + b_3 c_3}{b_2 c_3}\right)$$

Step 5: Solve for Remaining Unknowns

Referring to FIGS. 8a and 8b together:

(20)

$$DCP = | DO \cdot \sin\theta |$$

(21)

$$^{\circ}z_i = \begin{bmatrix} x_+ & \cdot & \sin\theta\cos\phi \\ y_+ & \cdot & \sin\theta\sin\phi \\ & & \cos\theta \end{bmatrix}$$

(22)

$$^{\circ}0_i = {}^{\circ}PPI = {}^{\circ}PPO + DCP.{}^{\circ}\hat{z}_i$$

$$= \begin{bmatrix} \frac{C_1}{C_3} \\ \frac{C_2}{C_3} \\ 0 \end{bmatrix} + DCP\,{}^{\circ}\hat{z}_i$$

This is the origin of the image plane coordinate system expressed in object plane coordinates. It is located at CP.

$^{\circ}\tilde{x}_i$ and $^{\circ}\tilde{y}_1$ the remaining unit vectors can be computed by transformation of the corresponding unit vectors in the image plane, and subsequent orthogonalization with respect to z_1.

(23)

Let

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} = \begin{bmatrix} T^{-1} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

(24)

Then

$$^{\circ}\tilde{x}_i \equiv \begin{bmatrix} \frac{X_1}{X_3} - \frac{C_1}{C_3} \\ \frac{X_2}{X_3} - \frac{C_2}{C_3} \\ 0 \end{bmatrix}$$

can be <u>orthogonalized</u> with respect to $^{\circ}\hat{z}_i$

$$ {}^{\circ}\tilde{x}_i' = {}^{\circ}\tilde{x}_i - ({}^{\circ}\tilde{x}_i \cdot {}^{\circ}\hat{z}_1)\ {}^{\circ}\hat{z}_f \tag{25} $$

and renormalized

$$ {}^{\circ}\hat{x}_i = \frac{{}^{\circ}\tilde{x}_i'}{{}^{\circ}\tilde{x}_4'} \tag{26} $$

Similarly, let

$$ \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} T^{-1} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{27} $$

$$ \text{Then } {}^{\circ}\tilde{y}_1 = \begin{bmatrix} \frac{y_1}{y_3} - \frac{c_1}{c_3} \\ \frac{y_2}{y_3} - \frac{c_2}{c_3} \\ 0 \end{bmatrix} \tag{28} $$

$$ {}^{\circ}\tilde{y}_i' = {}^{\circ}\tilde{y}_i - ({}^{\circ}\tilde{y}_i \cdot {}^{\circ}\hat{z}_1)\ {}^{\circ}\hat{z}_i \tag{29} $$

and

$$ {}^{\circ}\hat{y}_i = \frac{{}^{\circ}\tilde{y}_i'}{{}^{\circ}\tilde{y}_i'} \tag{30} $$

Finally

$$ {}^{\circ}F_i = \left[\begin{array}{c|c|c|c} {}^{\circ}\hat{x}_i & {}^{\circ}\hat{y}_i & {}^{\circ}\hat{z}_i & {}^{\circ}o_i \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \tag{31} $$

Frames transform from image space to object space is the frame to return, and to express points given in the object plane coordinates in terms of the coordinate system fixed with respect to the image plane, we note

$$ {}^{i}F_{0} = {}^{0}F_{i}^{-1} \tag{32} $$

and

$$ {}^{i}q_{k} = {}^{i}F_{0} \begin{pmatrix} x_k \\ y_k \\ 0 \\ 1 \end{pmatrix} \tag{33} $$

That is the general case, but there is also the special case when the object and image planes are parallel. This is detectable when VLO or VLI (equations 9 or 10) turn out to lie at infinity themselves (meaning their first two coordinates lie sufficiently close to 0).

In this case,

$$ {}^{o}z_{1} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \tag{34} $$

and the distance DCP can be determined by taking any point in the object plane $(x_k\ ,\ y_k)$ whose corresponding $(u_k\ ,\ v_k)$ is not zero and calculating according to the diagram in FIG. 8(c):

Let

$$ r_{o} = \sqrt{x_k^2 + y_k^2} \tag{35} $$

$$ r_{i} = \sqrt{u_k^2 + v_k^2} \tag{36} $$

$$ DCP = \frac{r_o}{r_i} f \tag{37} $$

and then proceeding as from equation (22).

This concludes the description of the main algorithm to determine plane displacements.

9.4 Determination of Transform Matrix

This section illustrates how to calculate the transform matrix T used in equation (1).

The method presented here is an analytic method which maps between only 4 coplanar points and is based on the fundamental theorem of projective geometry which tells us that given four points in the projective plane:

$$\begin{aligned} p_1 &= (x_1 \;\; y_1 \;\; w_1) \\ p_2 &= (x_2 \;\; y_2 \;\; w_2) \\ p_3 &= (x_3 \;\; y_3 \;\; w_3) \\ p_4 &= (x_4 \;\; y_4 \;\; w_4) \end{aligned} \tag{38}$$

constants c_1, c_2 and c_3 can be found such that

$$p_4 = c_1 p_1, + c_2 p_2 + c_3 p_3 \tag{39}$$

When this is represented in matrix form:

$$(\, x_4 \;\; y_4 \;\; w_4 \,) = (\, c_1 \;\; c_2 \;\; c_3 \,) \begin{pmatrix} x_1 & y_1 & w_1 \\ x_2 & y_2 & w_2 \\ x_3 & y_3 & w_3 \end{pmatrix} \tag{40}$$

then the matrix M consisting of

$$M = \begin{pmatrix} c_1 & 0 & 0 \\ 0 & c_2 & 0 \\ 0 & 0 & c_3 \end{pmatrix} \begin{pmatrix} x_1 & y_1 & w_1 \\ x_2 & y_2 & w_2 \\ x_3 & y_3 & w_3 \end{pmatrix} \tag{41}$$

will transform the ideal points origin and unit points as follows:

$$\begin{aligned} p_1 &= (1 \;\; 0 \;\; 0)M = i_x M && \text{(unit x vector)} \\ p_2 &= (0 \;\; 1 \;\; 0)M = i_y M && \text{(unit y vector)} \\ p_3 &= (0 \;\; 0 \;\; 1)M = oM && \text{(origin)} \\ p_4 &= (1 \;\; 1 \;\; 1)M = uM && \text{(unit point)} \end{aligned} \tag{42}$$

Therefore, to construct a transform which maps four arbitrary points p_1, p_2, p_3, p_4 to four arbitrary other points q_1, q_2, q_3, q_4, two transforms must be constructed:

(43)

M_i	M_2
$i_x \rightarrow p_1$	$i_x \rightarrow q_i$
$i_y \rightarrow p_2$	$i_y \rightarrow q_2$
$0 \rightarrow p_3$	$0 \rightarrow q_3$
$u \rightarrow p_4$	$u \rightarrow q_4$

and then M, such that

$$q_i = p_i \, M \tag{44}$$

is given by

$$M = M_1^{-1} \, M_2 \tag{45}$$

Note that in this section, the p's and q's are now vectors. In the main section, column vectors are used, so

$$T = M^T \tag{46}$$

Finally, another method (not illustrated here) accepts more than four points and does a least-squares approximation using pseudo-inverses. This second method can be used in the case where the number of points measured has been increased to compensate for expected errors.

Allowance for Pan-and-Tilt Mirrors

After the imaged data points have been converted back to three-dimensional points given in image plane coordinates, it remains to make allowance for reflections by the beam splitter assembly and the pan-and-tilt mirrors.

If ${}^i x$ is a point to be reflected, and ${}^i n$ is a unit-length normal to the plane of reflection, ${}^i x_0$ is a point in the plane of reflection (all expressed in image-plane coordinates) then ${}^i x_r$, its reflection is given by

(47)

$$\left[\begin{array}{c} {}^i x_r \\ \hline 1 \end{array}\right] = \left[\begin{array}{c|c} I - 2\,{}^i n\,{}^i n^T & 2\,{}^i n\,{}^i n^{T\,i} x_0 \\ \hline 0 & 1 \end{array}\right] \left[\begin{array}{c} {}^i x \\ \hline 1 \end{array}\right]$$

The matrix above is a standard displacement style transform which may be inverted using standard methods though there is no need to do so in the present application. These matrices may also be cascaded as usual from right to left, to deal first with the beam-splitter and then with the pan-and-tilt mirror, <u>but</u> the reflection plane point $^{i}x_0$ and normal ^{i}n for the pan-and-tilt mirror must first be transformed by the beam-splitter reflection matrix before the pan-and-tilt mirror reflection matrix is formed from them.

Finally, it should be noted that when the main algorithm is used to find the position of the pan-and-tilt mirror, once these have been reflected through the beam splitter. $^{i}\tilde{z}_0$ and $^{i}0_0$ are directly usable as normal and point in the reflection plane directly.

A subsequent use of an iterative fitting procedure may result in improved accuracies.

Other mathematical processes can also be used to process the images detected using the apparatus of the present invention.

<u>Additional Features of the Invention</u>

This invention can also be used to determine the condition of the shock absorbers of the vehicle. This is done by firstly "jouncing" the vehicle. Jouncing a vehicle is a normal step in alignment procedures, or, for that matter, checking the shock absorbers, and entails applying a single vertical force to the vehicle by, eg. pushing down onto the hood of the vehicle and releasing the vehicle, to cause it to oscillate up and down. Secondly, as the vehicle oscillates up and down, the apparatus of the invention takes readings of the targets on each of the wheels. In so doing, the movement of the targets, which will define a dampened waveform, can be monitored to determine the extent of the dampening. If the dampening is not sufficient (i.e. the up and down movement or rocking of the vehicle does not stop soon enough) this indicates that the shock absorbers are faulty.

This method is particularly advantageous in that a determination can be made as to the soundness of a specific shock absorber; a result which can be indicated to the operator of the alignment apparatus by means of the computer 32.

It will be evident that in the determination of the condition of the shock absorbers of the vehicle, any suitable portion of the body of the motor vehicle can be selected to monitor the oscillation of the vehicle. So, for example, the apparatus can focus on the edge of the wheel housing or, alternatively, a small target placed on a convenient position on the body work of the motor vehicle.

In addition, this apparatus can be used to calculate the ride height of the motor vehicle. This parameter is particularly important in the determination of the alignment of the wheels of vehicles such as pick-ups which, in operation, may carry a load. This load would have the effect of lowering the vehicle and it is, therefore, preferable to make allowance for this during alignment procedures. Traditionally, the ride height, or height of the chassis of the vehicle from the floor, is determined by physically measuring it with an instrument such as a tape measure. This measurement is then compared to standard tables which yield a compensation factor for the vehicle concerned.

The method and apparatus of this invention can, however, make this measurement directly by viewing an appropriate portion of the body and determining its height from the test bed on which the vehicle rests. Once this height has been determined it can be compared to standard look-up tables stored within the computer which can, in turn, produce the compensation factor.

Advantages of the Invention

A general advantage of the apparatus of this invention is that it is relatively simple to use as no delicate mechanical or electronic equipment need be attached to the wheels of the motor vehicle concerned. As the sensitive and delicate equipment is mounted within a housing which stands independent and distant from the motor vehicle being tested, no damage can be caused to it if the motor vehicle were, for example, to be driven off the wheel guides. Whereas prior art heads can be knocked out of calibration by simple jarring or dropping, it takes major damage to the wheel-mounted components to affect the calculated results.

Another advantage is that the equipment requires very few operator commands and could readily be made hands free with simple auditory outputs and equally simple voice recognition means to receive and/or record operator responses and/or commands.

The present invention has the further advantage that alignment determinations can be done relatively quickly. This allows a higher turn around rate within the business conducting the alignment determinations.

Still further advantages of this apparatus is that it can be placed, as is illustrated in FIG. 4, above and out of the way of the motor vehicle being tested. This has the distinct advantage that the chances of damaging the sensitive alignment determining apparatus is substantially reduced as the apparatus is out of the way of the motor vehicle. Another advantage of this configuration is that the measuring apparatus uses minimal floor space and has no equipment blocking access to the front of the motor vehicle.

Furthermore, as the vehicle can be backed up and driven forward, this apparatus has the advantage that it is unnecessary to jack the vehicle up to make the required calculations for "run-out". In addition, this apparatus can be used to determine information other than the relative alignment of the wheels. For example, the alignment apparatus, if equipped with a suitable character recognition capability, could be used to read the license plate of the motor vehicle which could, in turn, yield information such as the make and model of the vehicle and its service history (if available) and, therefore, the required alignment parameters of such vehicle. This would save the operator from entering the motor vehicle's details into the apparatus. As more manufacturers are adding bar codes to the VIN number plates, similar information can also be obtained by optically viewing and processing the bar-coded plate. In addition, it would also be possible to optically identify the vehicle type by comparing certain features of the body or trim thereof to database information.

Yet another advantage of the invention is that no wires, cords or beams of light pass in front of the vehicle being tested. As most alignment correction is made by accessing the wheels of the car from the front, wires, cords or beams passing in front of the vehicle tend to get in the way of the technician. Often these wires, cords or beams are sensitive to being interfered with and so their absence makes alignment correction work much easier.

Related to this advantage is the fact that there are no cords or wires passing between the targets on the wheels, nor are there any wires supplying power to the targets from a remote power source. This absence of wires or cords once again makes work on the vehicle easier.

In addition, as the targets are not interlinked or interdependent, after initial capture of target images, it is possible to block off one of the targets from the camera's view without interfering with the orientation calculations for the other wheels. In the prior art devices described earlier, all the test heads are interdependent and cannot function if one of the heads is "blocked" out.

It will be evident to those skilled in the art that the concept of this invention can be applied in many different ways to determine the alignment of the wheels of a motor vehicle. So, for example, the apparatus could define a reference point for each wheel with the referent point being located at, say, the intersection of the axis of rotation of the wheel, with that wheel. These points can then be processed to define an approximately horizontal reference plane, relative to which the alignment of the wheels can be calculated.

This method has the particular advantage that the rack on which the vehicle is being supported does not have to be levelled, a process which requires expensive apparatus and which is necessary to define a horizontal reference plane and which is used in prior art alignment devices.

While the invention has been particularly shown and described with reference to certain preferred embodiments, it will be understood by those skilled in the art that various alterations and modifications in form and in detail may be made therein. Accordingly, it is intended that the following claims be interpreted as covering all such alterations and modifications as may fall within the true spirit and scope of the invention.

What is claimed is:

CLAIMS

1. An apparatus for determining the alignment of motor vehicle wheels comprising:

target means including at least one visually perceptible target object for attachment to a wheel of a vehicle under inspection and including at least one geometrically configured target object having known geometric characteristics;

optical inspection means establishing a spatial reference system including at least a first viewing path intersecting a first target object attached to a first wheel of a vehicle under inspection, said optical inspection means being operable to inspect an image of said first target object as viewed along said first viewing path and to generate first image information describing the geometric characteristics of the first target object;

processing means for relating said first image information to predetermined reference information describing the known geometric characteristics of said first target object to determine the angular orientation of said target object relative to said spatial reference system and for generating first orientation information commensurate therewith; and

means for using said orientation information to indicate the alignment of said first wheel.

2. An apparatus as recited in claim 1 wherein said spatial reference system further includes

a second viewing path intersecting a second target object attached to a second wheel of the vehicle under inspection, and

wherein said optical inspection means is further operable to inspect an image of said second target object components as viewed along said second viewing path and to generate second image information describing the geometric characteristics of the second target objects, and

wherein said processing means is further operative to relate said second image information to predetermined information describing the known geometric characteristics of said second target object to determine the angular orientation of said second target object relative to said spatial reference system and for generating second orientation information commensurate therewith, and

wherein said means for using further uses said second orientation information to indicate the alignment of said second wheel.

3. An apparatus as recited in claim 2 wherein said means for using is a display means which uses said first orientation information and said second orientation information to indicate the relative alignment of said first wheel to said second wheel.

4. An apparatus as recited in claim 3 wherein said first and second target objects are respectively attached to the

front wheels of a vehicle under inspection and said display means simultaneously indicates the detected alignment angle status of said first and second wheels.

5. An apparatus as recited in claim 1 wherein said first image is viewed with said first wheel in a first position, and wherein said optical image inspection means is further operable to inspect another image of said first target object after said first wheel has been rotated about its axis to a second position, and to generate additional image information describing the geometric characteristics of the first target object as they appear in said another image, and wherein said processing means is further operable to relate said additional image information to said first image information to determine the relationship of said first target object to the axis of rotation of said first wheel.

6. A method for determining the alignment of a motor vehicle wheel comprising the steps of:

defining a spatial reference system;

providing a target having a plurality of geometrically configured components defining a pattern on the target, said components having known geometric characteristics and relationships to each other;

locating the target on the wheel such that it has a determinable relationship to the wheel;

viewing the target along a viewing path to form a detected image of the components of the target, said viewing path having a known relationship to said spatial reference system;

determining geometric characteristics of at least two of the components of the detected image and the relationship therebetween;

relating the determined characteristics and relationship of the detected image components to the known geometric characteristics and relationship of corresponding components on the target to determine the angular orientation of the target relative to the spatial reference system; and

using said angular orientation to determine the alignment of the wheel relative to the spatial reference system.

7. A method for determining the alignment of a motor vehicle wheel as recited in claim 6 wherein the target is viewed using an electronic imaging device which develops the detected image.

8. A method for determining the alignment of a motor vehicle wheel as recited in claim 7 and further comprising the step of establishing a reference plane with respect to which the alignment of the wheel is determined.

9. A method for determining the alignment of a motor vehicle wheel as recited in claim 7 wherein the established reference plane is the primary plane of another wheel of the vehicle.

10. A method for determining the alignment of a motor vehicle wheel as recited in claim 8 wherein the step of relating determined characteristics and relationships of components includes relating particular dimensions of the components to corresponding dimensions of the detected image of the components, and using such dimensional relationships to determine the orientations of the detected components.

11. A method for determining the alignment of a motor vehicle wheel as recited in claim 10, and further comprising the step of establishing a reference image by viewing the target along a viewing path normal to a component containing surface of said target.

12. A method for determining the alignment of a motor vehicle wheel as recited in claim 10 and further comprising establishing a reference image of the target by accessing previously stored electronic data corresponding thereto.

13. A method for determining the alignment of a motor vehicle wheel as recited in claim 6 and for further determining the integrity of the suspension of said vehicle, comprising the steps of:

imparting a force to said vehicle to cause it to oscillate vertically up and down;

allowing the suspension of said vehicle to dampen the oscillations;

causing the target to produce time-related data evidencing the manner in which the oscillations are dampened; and

comparing said time-related data to corresponding data representing idealized dampening to obtain information indicative of the integrity of the suspension.

14. A method for determining the alignment of a motor vehicle wheel as recited in claim 7 and further comprising the step of determining the relationship of the target to the wheel by

rotating the wheel to cause the target to move through a plurality of different rotational positions;

viewing the target to form a plurality of discrete detected images of at least two components of the target at each rotational position of the target;

determining geometric characteristics and relationships of the components in each detected image;

relating each of said determined geometric characteristics and relationships to the known geometric characteristics and relationships of corresponding components of the target to determine the spatial position of said target at each of the rotational positions;

forming a surface of revolution by integrating the detected images;

determining the axis of rotation of said surface of revolution;

comparing the orientation of said axis of rotation to the orientation of the axis of rotation of the wheel to determine the orientation of the target to the axis of rotation of the wheel; and

defining the principal plane of the wheel to be perpendicular to the axis of rotation thereof, thereby determining the orientation of the wheel.

15. A method for determining the alignment of a motor vehicle wheel as recited in claim 14 and further comprising the steps of:

determining a reference point for each wheel located on the axis of rotation of the wheel;

defining a generally horizontal reference plane including said reference points; and

determining the alignment of the wheels of the motor vehicle relative to said reference plane.

16. An apparatus for determining the alignment of at least one motor vehicle wheel relative to at least one viewing path comprising:

means defining a target on the wheel and having a determinable relationship to the wheel, said target including at least one element of known geometric characteristics;

imaging means for viewing said target along said one viewing path and for developing element information defining geometric characteristics of an element of the viewed image corresponding to said one element;

computational means for relating said element information to the known geometric characteristics of said one element to first determine the orientation of said target relative to the viewing axis and to then develop alignment information evidencing the alignment of the wheel; and

means responsive to said alignment information and operative to provide an indication of the alignment useful in performing alignment adjustments to the wheel.

17. An apparatus as recited in claim 16 wherein said imaging means includes an electronic imaging device and associated optical components for directing light from said target to said device.

18. An apparatus as recited in claim 17 wherein said optical component includes lens means for focusing said light onto said imaging device.

19. An apparatus as recited in claim 18 wherein said means defining a target includes reflective means forming a target surface having one element disposed thereon and means for attaching said reflective means to the wheel.

20. An apparatus as recited in claim 16 and further comprising means defining another target on another wheel and having a determinable relationship thereto and further having at least one other element of known geometric characteristics and wherein said imaging means is further operative to view said another target along another viewing path and for developing additional element

information defining the geometric characteristics of an element of the viewed image corresponding to said another element, and wherein said computational means is further operative to relate said additional element information to the known characteristics of said another element to first determine the orientation of said another target relative to the second viewing axis and then develop additional alignment information evidencing the alignment of the other wheel, and wherein said means responsive to said alignment information is additionally responsive to said additional alignment information and operative to provide an indication of the alignment useful in performing alignment adjustments to the other wheel.

21. Apparatus for determining the alignment of a motor vehicle wheel as recited in claim 20 wherein said imaging means includes means to split the viewing path into first and second component paths, the first component path being used for viewing a target on the left side of the vehicle and the second component path being used for viewing a target on the right side of the vehicle.

22. Apparatus for determining the alignment of a motor vehicle wheel as recited in claim 21 wherein said imaging means further includes pan-and-tilt mirrors for respectively directing the first and second component paths onto targets affixed to the wheels on the left and right side of the vehicle.

23. Apparatus for determining the alignment of a motor vehicle wheel as recited in claim 22 wherein the elements of said targets include at least one circular shape.

24. Apparatus for determining the alignment of a motor vehicle wheel as recited in claim 23 wherein said targets are planar and each includes a plate and means for affixing the plate to a wheel of the motor vehicle, said plates each including a plurality of circular elements formed on its surface.

25. A method for determining the orientation of an object relative to a viewing path comprising the steps of:

establishing a target on the object such that the target has a determinable relationship to the object and wherein the target includes at least one element of known geometric characteristics;

viewing the target along the viewing path to form at least one detected image thereof;

determining the geometric characteristics of at least one element on the detected image;

relating said determined characteristics to the known geometric characteristics of a corresponding element on the target to determine the angular orientation of the target relative to the viewing path; and

using said angular orientation and said determinable relationship to determine the orientation of said object.

26. A method for determining the orientation of an object relative to a known reference comprising the steps of:

establishing a target on the object wherein said target includes at least one target element of known geometric characteristics;

rotating the object to cause the target to rotate through a number of different rotational positions;

viewing the target as it is rotated to form a plurality of discrete detected images of the target element, each of the detected images being formed at a different rotational position of the target;

determining the geometric characteristics of the target element for each of the detected images;

relating each of said determined geometric characteristics to the known geometric characteristics of the target element to determine the spatial position of said target element at each of the different rotational positions at which the target was viewed to form a detected image;

forming a surface of revolution by integrating the different spatial positions of the target element;

determining the axis of rotation of said surface of revolution; and

relating the orientation of said axis of rotation of said surface of revolution to the orientation of the axis of rotation of the object to determine the orientation of the object.

27. An apparatus for determining the orientation of an object relative to a viewing path comprising:

means for defining a target on the object wherein said target has a determinable relationship to the object and wherein said target includes at least one element of known geometric characteristics;

imaging means for viewing the target along the viewing path and for determining at least one detected image of the target;

computational means for determining the geometric characteristics of at least one element on the detected image and for relating said determined characteristics to the known geometric characteristics of a corresponding element on the target to determine the orientation of the target relative to the viewing axis; and

means for using said determined orientation of the target to determine the orientation of the object.

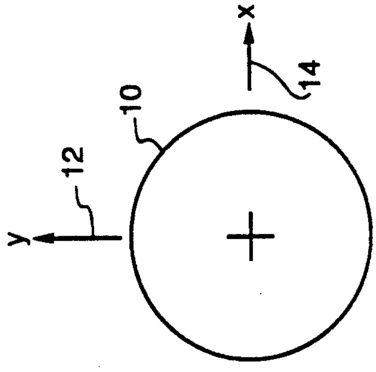

Fig. 1a

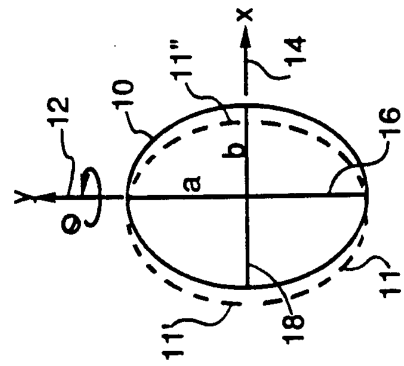

Fig. 1b

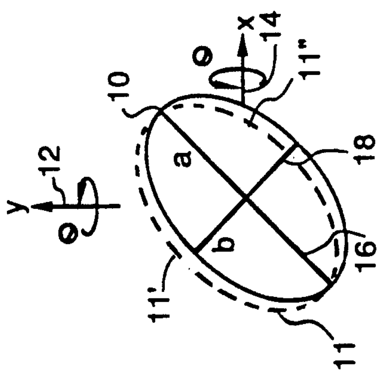

Fig. 1c

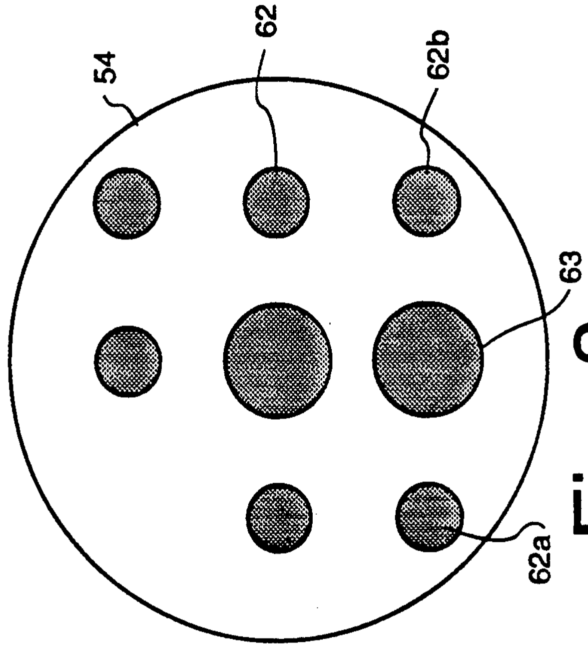

Fig. 3

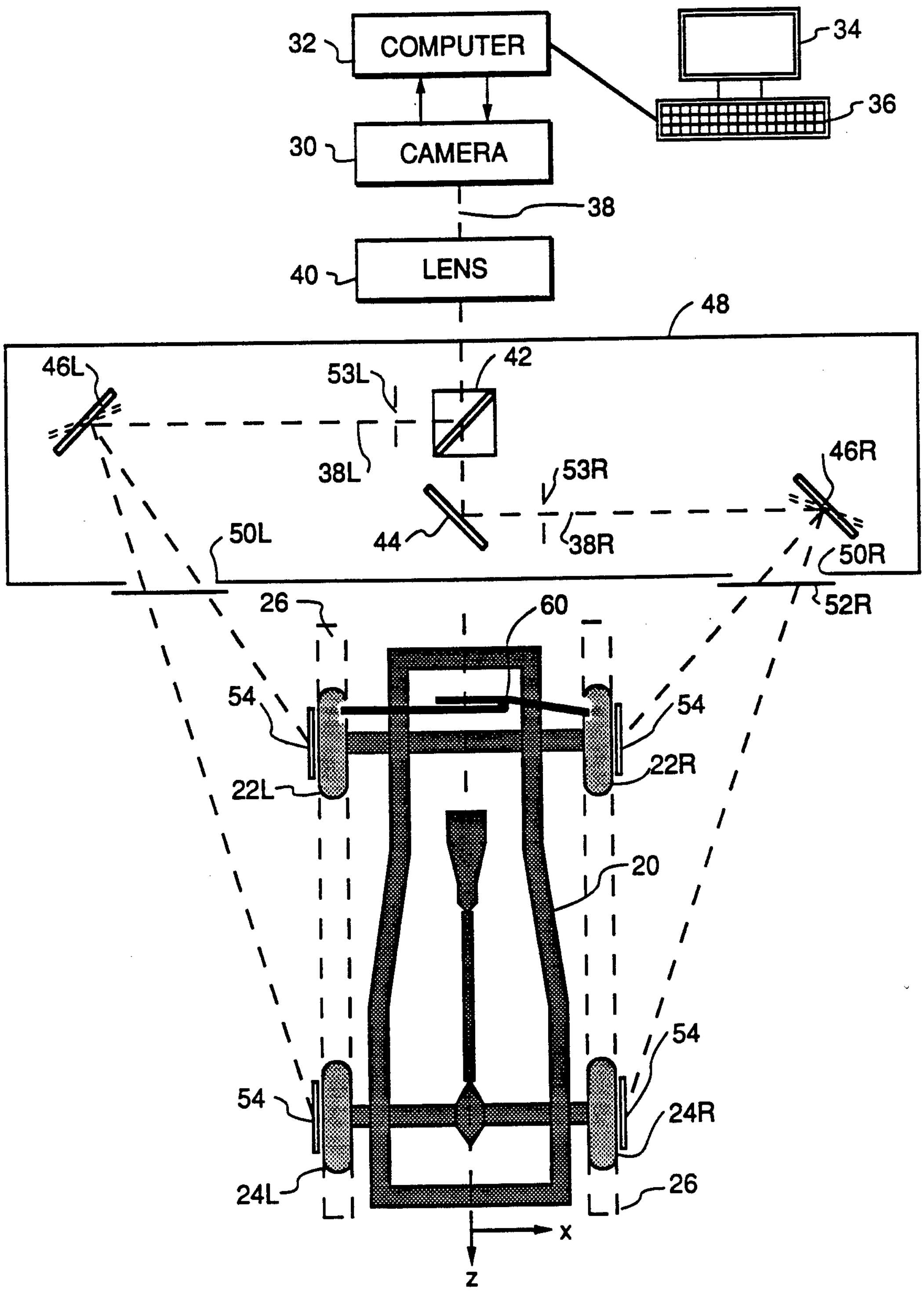
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Fig. 2

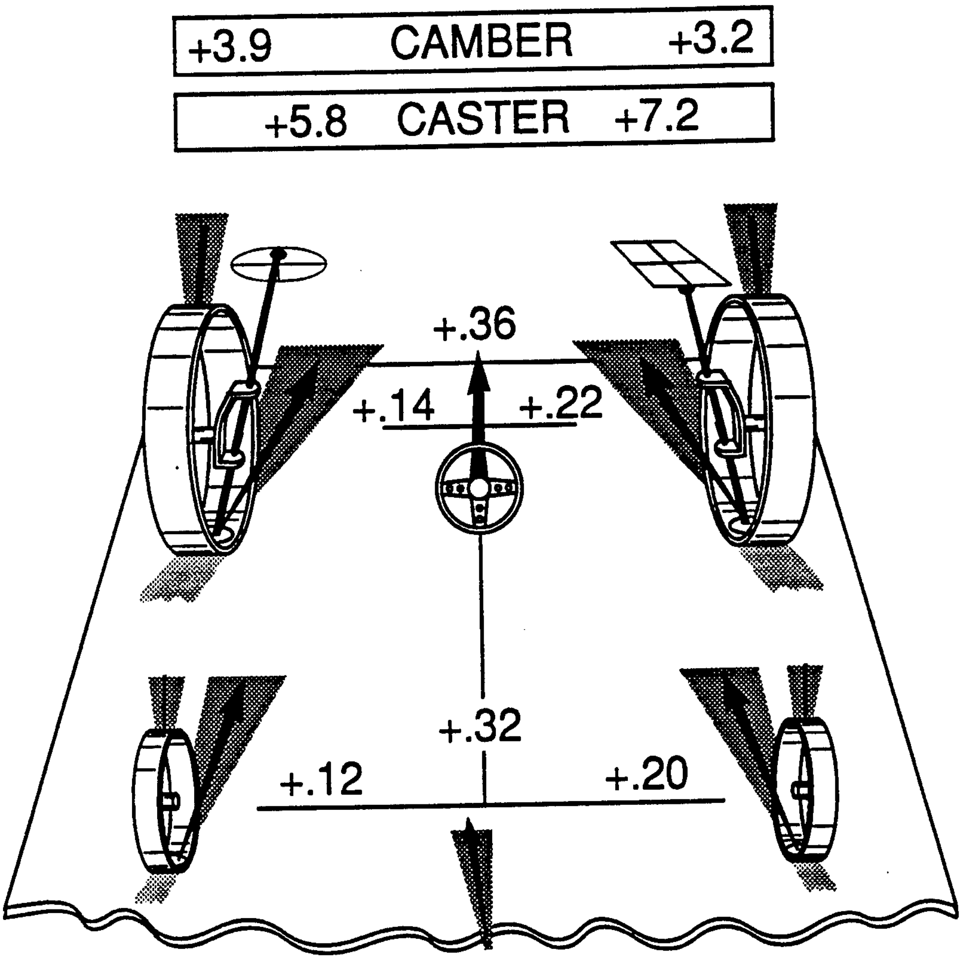

Fig 2a

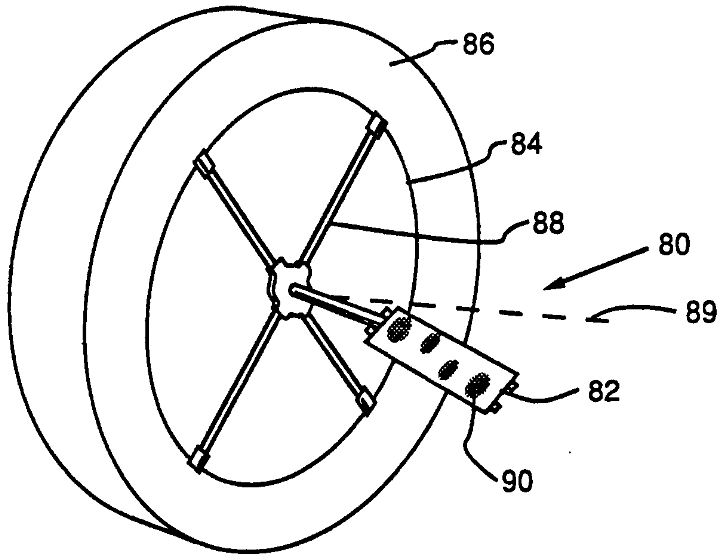

Fig. 5

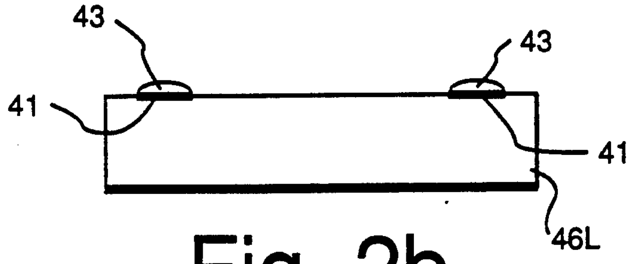

Fig. 2b

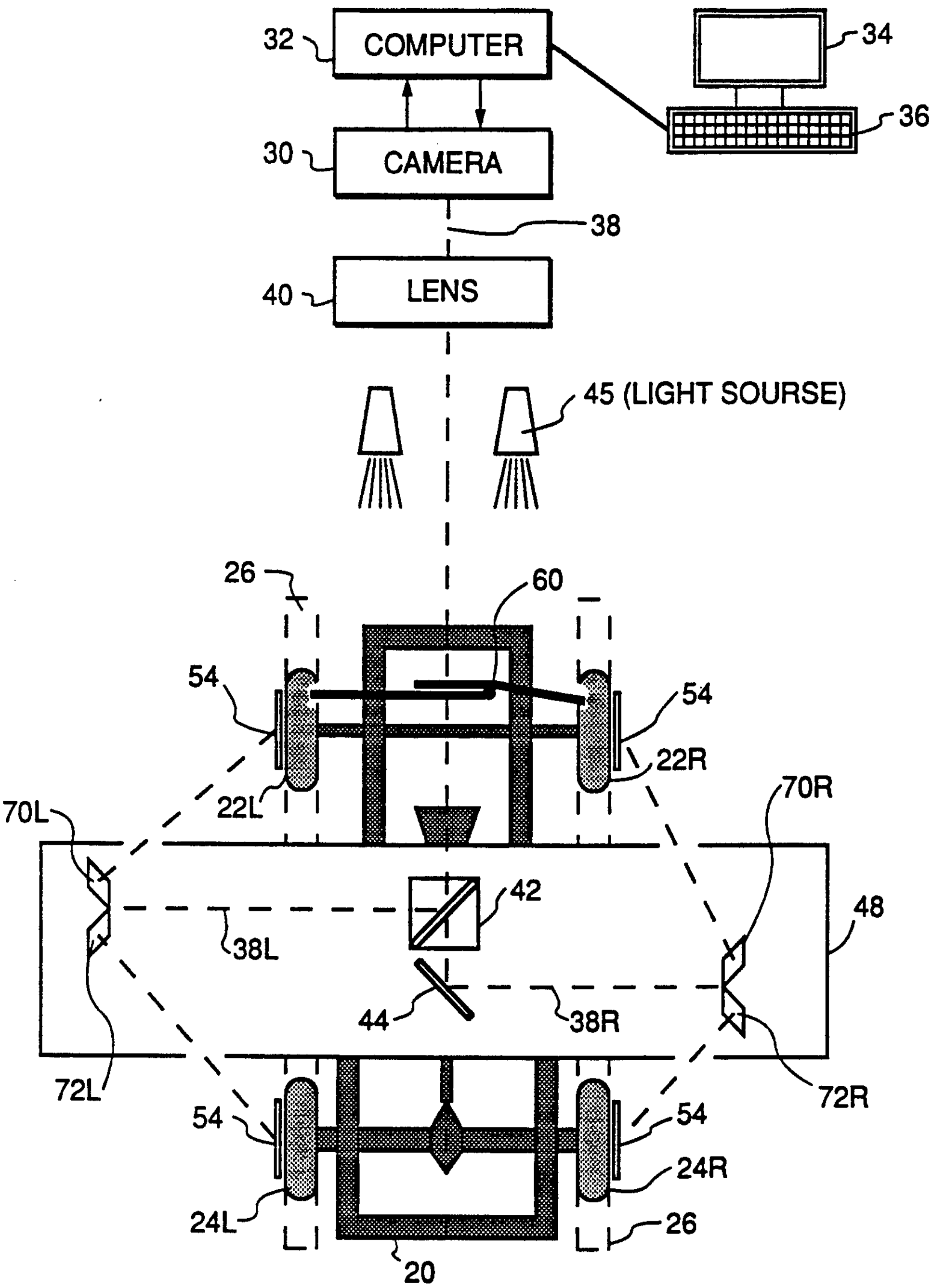
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Fig. 4

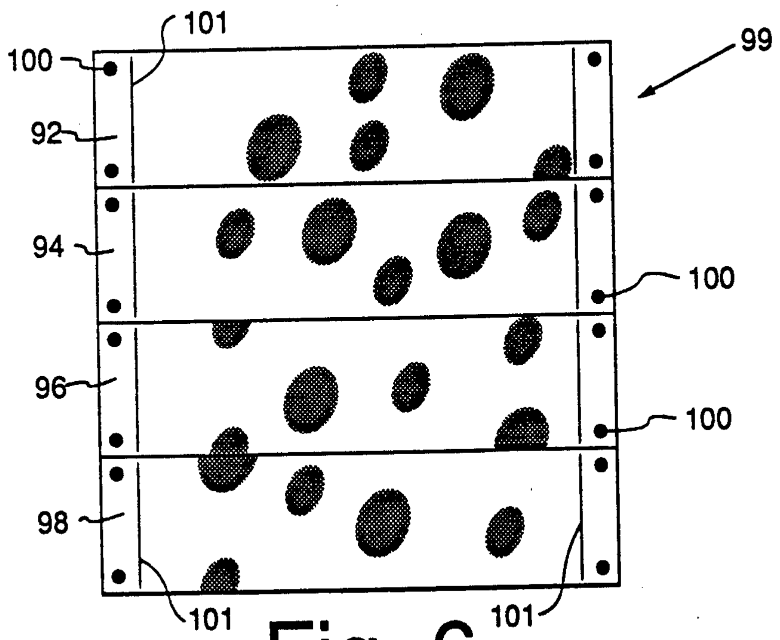

Fig. 6

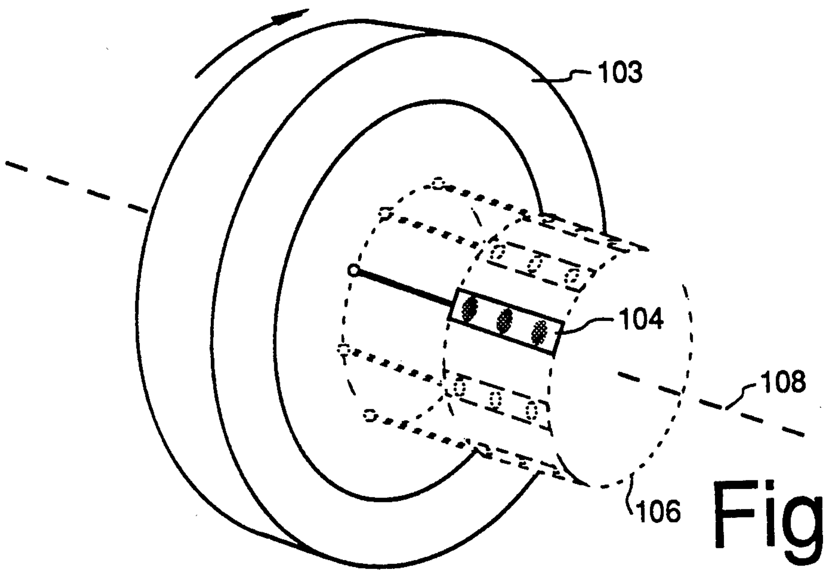

Fig. 7

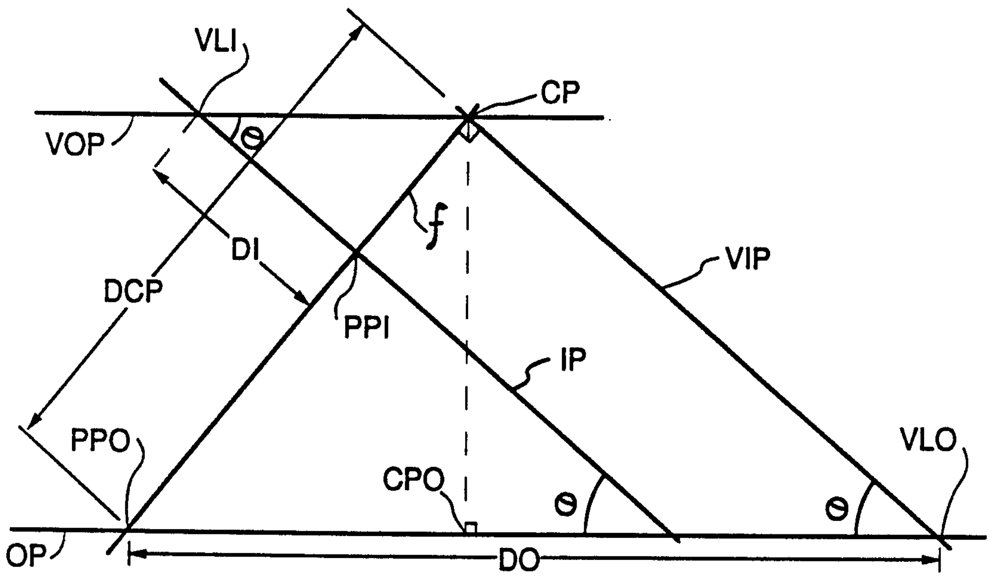

Fig. 8a

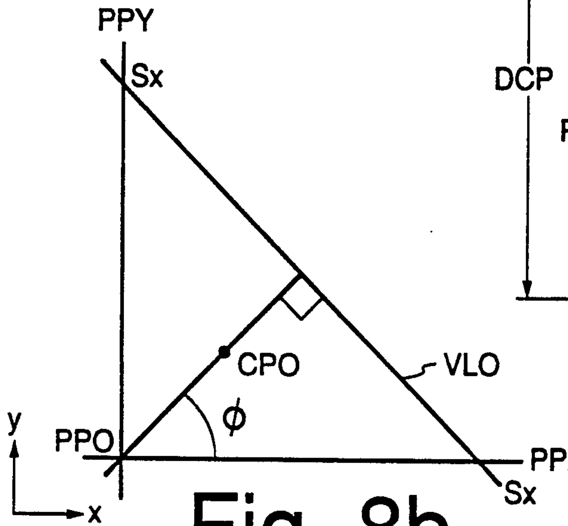

Fig. 8b

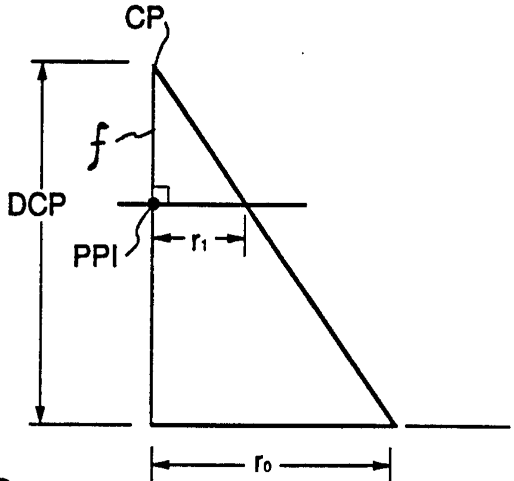

Fig. 8c

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/08333

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :Please See Extra Sheet.
US CL :33/288,203.19,203
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 33/288,203.19,203,286,203.18,203.2;358/107,101;356/155;382/8

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	DE, A, 29 48 573 (Siemens) 04 June 1981, see entire document	1-3,16-18, 20,25,27 ---- 4,5,19,21-23,26
Y	US, A, 5,048,954 (Madey et al) 17 September 1991, see entire document	4,19,21-23
Y	US, A, 4,180,915 (Lill et al) 01 January 1980, see abstract	5,26

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be part of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search 21 October 1993	Date of mailing of the international search report NOV 05 1993
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Authorized officer Sheila Veney for CHRISTOPHER W. FULTON
Facsimile No. NOT APPLICABLE	Telephone No. (703)308-0771

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/08333

A. CLASSIFICATION OF SUBJECT MATTER:
IPC (5):

G01B 11/275