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(54) Title: LASER SCANNING MEASUREMENT SYSTEMS AND METHODS FOR SURFACE SHAPE MEASUREMENT OF HIDDEN SURFACES

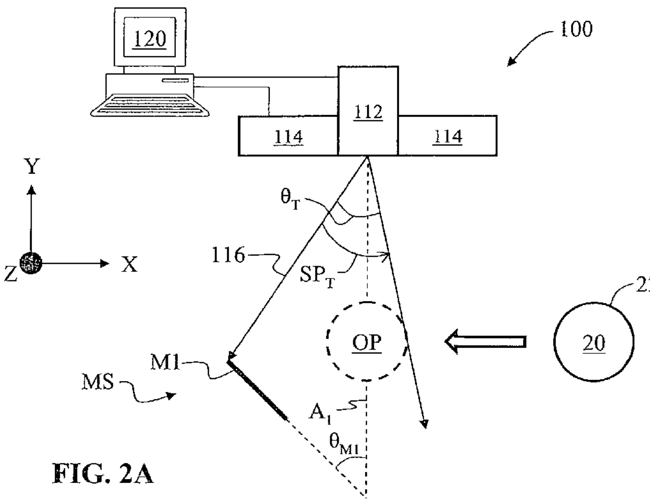

FIG. 2A

(57) Abstract: Laser scanning measurement systems and methods are disclosed that allow for surface shape measurements of otherwise hidden portions of an object's surface. The system includes a laser system that scans a laser beam over a scan path, a photodetector that detects light reflected from the object's surface, and a processor adapted to process detector signals from the photodetector to determine a two-dimensional (2D) surface shape representation and a three-dimensional (3D) surface shape profile representation. The system includes a mirror(s) configured to direct the scanned laser beam to one or more portions of the object surface that cannot be directly irradiated by the laser, and that allows the photodetector to detect light reflected from the one or more hidden portions via the mirror(s). The laser scanning measurement system is able to measure, in a single laser beam scan, some or all of the hidden portion(s) of an object rather having to rotate the object or having to use multiple scanned laser beams or multiple scanning systems.

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Laser Scanning Measurement Systems and Methods for Surface Shape Measurement of Hidden Surfaces

Related Applications

[0001] This application claims the benefit of U.S. Provisional Application No. 61/001,271 filed 10/31/2007, entitled "Laser Scanning Measurement Systems and Methods for Surface Shape Measurement of Hidden Surfaces."

BACKGROUND

[0002] The present invention relates generally to laser measurement systems for measuring surface shapes, and in particular to such laser scanning systems capable of measuring surface portions that are otherwise hidden from direct impingement of a scanning laser beam.

[0003] Laser scanning measurement systems measure the profile (shape) of the surface of an object, and are used in a variety of applications, such as art (e.g., sculpture), architecture, industrial design, and product inspection. In one type of laser scanning measurement system, a laser emits a narrow light pulse directed to the object's surface, forming a small spot on the object. A portion of the light that forms the laser spot is reflected by the surface and is detected by a photodetector. The photodetector typically includes, for example, a charge-coupled device (CCD) array, so that the location of the detected laser spot can be determined. By knowing the distance between the laser and the detector, the angle formed by the reflected laser spot and the detector, and the angle of the laser beam as formed at the laser, the relative position of the surface from which the laser spot reflected is established. By moving ("scanning") the laser spot (or in some cases, a laser line) over the surface, the entire three-dimensional (3D) surface profile can be measured.

[0004] **FIGS. 1A** through **1C** illustrate a typical measurement scenario using a laser scanning measurement system **10** to measure the shape of a surface **22** of an object **20** such as a cylinder. Laser system **10** includes a laser source **12**, a detector unit **14**, and a processor (e.g., a computer) **18** operably coupled to the laser source and detector unit. Processor **18** processes detector signals from detector unit **14**.

[0005] In the operation of system **10**, laser **12** emits a laser beam **16** over a total scan path **SP_T** having a corresponding angular range ("beam angle") **θ_T**. As shown in **FIG. 1A,** system **10** can only measure a portion of surface **22**—namely, the exposed surface portion **22A** that faces laser **12** and that subtends the beam angle **θ_T**. The other portions of surface **22,** identified as **22B** and **22C,** remain hidden from the laser beam and so remain unmeasured. To measure hidden surface portion **22B,** object **20** is rotated (or system **10** is moved) so that surface portion **22B** is within the beam angle **θ_T** of scan path **SP_T**, as shown in **FIG 1B.** A second laser scan is then taken. After this second scan, if the remainder of object **20** is to be measured, it must be rotated again to bring surface portion **22C** to within beam angle **θ_T** of scan path **SP_T**, as shown in **FIG. 1C.** Depending on the beam angle **θ_T** of scan path **SP_T,** this rotation/measurement process may need to be repeated even more times until the entire surface **22** is measured.

[0006] The different scanned views must then be pieced together (e.g., by processor **18**) to form a complete measurement of surface **22** at the given circumference. Unfortunately, this repeated process is time consuming and often does not arrive at the correct shape. Further, human intervention may be needed to perform the object rotation, which further delays and complicates the surface measurement process. Moreover, not all objects are amenable to rotation. For example, soft objects may change shape when rotated.

SUMMARY

[0007] In one aspect, a laser measurement system is disclosed herein for measuring a surface of an object held at an object position. The system comprises a laser source adapted to scan a laser beam over a scan path relative to the object position. A mirror system comprising at least one mirror is arranged relative to the laser source and to the object position such that the scanned laser beam is incident directly on an exposed portion of the object surface and is also incident via reflection by the mirror system onto at least one hidden portion of the object surface that is not directly accessible by the scanned laser beam. A photodetector is configured relative to the laser source, the mirror system and the object position, so as to detect light from the scanned laser beam that reflects directly from the exposed surface portion and that reflects from the at least one hidden surface portion to the photodetector via the mirror system.

[0008] In another aspect, a method is disclosed herein of performing a non-contact measurement of a surface of an object using a single scan of a laser beam. The method comprises scanning a first portion of the object surface with the laser beam. The method also comprises scanning a second portion of the object surface with the laser beam, wherein said second surface portion cannot be directly irradiated by the laser beam. This is accomplished by reflecting the laser beam to the second portion. The method further comprises detecting light reflected by the first surface portion and second hidden surface portion. The method also comprises determining a surface shape representation of the object surface based on the detected light. The object is preferably not moved during the scanning, for example with respect to the laser source. Preferably, the object is not rotated during the scanning.

[0009] In another aspect, a laser scanning measurement system is disclosed herein for measuring a surface of an object having a circumference. The system comprises a laser source adapted to provide a laser beam that scans over a scan path. The system has an object holder adapted to hold the object at an object position relative to the laser source such that the object has i) an exposed surface portion upon which the scanned laser beam can be made directly incident and ii) at least one hidden surface portion upon which the scanned laser beam cannot be made directly incident. A mirror system is arranged relative to the object holder and to the laser source such that the scanned laser beam can be made incident upon the at least one hidden surface portion as the laser beam is scanned over the scan path. The system also comprises a photodetector adapted to receive light reflected directly from the exposed surface portion and light reflected from the at least one hidden surface portion via said mirror system, and to generate detector signals corresponding to said detected light from said surface portions. The system further comprises a processor adapted to receive and process the detector signals to determine a surface shape representation of the object surface.

[0010] Additional features and advantages of the invention are set forth in the detailed description that follows, and will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description that follows, the claims, as well as the appended drawings.

[0011] It is to be understood that both the foregoing general description and the following detailed description present embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the invention and, together with the description, serve to explain the principles and operations of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] **FIGS. 1A-1C** are schematic diagrams of a prior art laser scanning measurement system, illustrating how multiple scans are needed to measure the hidden surface portions of an object;

[0013] **FIG. 2A** is a schematic diagram of a first exemplary embodiment of a laser scanning measurement system according to the present invention that can measure an otherwise hidden surface portion of an object;

[0014] **FIG. 2B** through **FIG. 2D** illustrate an exemplary embodiment of a surface measurement process for measuring the otherwise hidden surface portion(s) of an object using the example measurement system of **FIG. 2A**;

[0015] **FIG. 3A** is a perspective view of an example cylindrical object whose surface is to be measured, illustrating the laser spot and the scanning direction of the laser spot over the object's surface;

[0016] **FIG. 3B** is a side view of an exemplary embodiment of an object holder that holds the cylindrical object of **FIG. 3A** at its respective ends so that the entire surface can be accessed both directly and indirectly by the scanned laser beam;

[0017] **FIG. 3C** is an end-on view of an exemplary embodiment of an object holder that holds the cylindrical object of **FIG. 3A** by supporting it in a V-groove type of mount so that only a small portion of the object's surface is not accessible to the scanned laser beam;

[0018] **FIG. 4** is a flow diagram that describes an exemplary embodiment of a method of measuring both the exposed and hidden portion(s) of an object using the measurement system of **FIG. 2A** and **FIG. 6A**;

[0019] **FIG. 5** plots the resulting surface shape segments as obtained using the system of **FIG. 2A** prior to the segments being combined to form the corresponding surface shape representation, and also shows the coordinate transformation used to combine the surface shape segments to form the corresponding surface shape representation;

[0020] **FIG. 6A** is a schematic diagram of a second exemplary embodiment of a laser scanning measurement system according to the present invention that can measure an entire surface of an object using a single scan even when portions of the object surface are otherwise hidden from direct measurement by the scanning laser beam;

[0021] **FIG. 6B** is a schematic perspective diagram of an exemplary embodiment of a mirror system that comprises two plane mirror sections;

[0022] **FIG. 6C** is the same schematic diagram of **FIG. 6A**, but showing the laser beam scan path;

[0023] **FIG. 6D** is the same schematic diagram of **FIG. 6C**, but showing how the laser beam scan path of **FIG. 6C** is divided up into different scan path segments;

[0024] **FIG. 6E** through **FIG. 6I** illustrate an exemplary embodiment of a surface measurement process for measuring the otherwise hidden surface portion(s) of an object using the example measurement system of **FIG. 6A**;

[0025] **FIG. 7A** plots the resulting surface shape segments as obtained using the system of **FIG. 6A** prior to the segment being combined to form the corresponding surface shape representation;

[0026] **FIG. 7B** illustrates how the surface shape segments of **FIG. 7A** undergo a coordinate transformation and are combined to form the corresponding surface shape representation;

[0027] **FIG. 8A** is a schematic diagram similar to **FIG. 2A**, illustrating the geometry for the coordinate transformation used to combine the surface shape segments;

[0028] **FIG. 8B** is a close-up view of an example mirror of the mirror system shown in the system of **FIG. 8A**, wherein the mirror comprises opaque stripes used to indicate the mirror position in each object scan that comprises the mirror;

[0029] **FIG. 9A** is an end-on view of an example of an extruded-type particulate filter that can serve as an object whose surface can be measured by the laser scanning measurement system of the present invention;

[0030] **FIG. 9B** is a side view of the filter of **FIG. 9A**;

[0031] **FIG. 9C** is the side view similar to that of **FIG. 9A**, illustrating a bowed surface shape defect in the extruded log that forms the filter body; and

[0032] **FIG. 9D** is a side view similar to **FIG. 9C**, illustrating a flared-end surface shape defect that arises when cutting the extruded log to form the filter body.

DETAILED DESCRIPTION

[0033] Reference is now made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Whenever possible, the same or analogous reference numbers are used throughout the drawings to refer to the same or like parts.

Single-mirror embodiment

[0034] **FIG. 2A** is a schematic diagram of an exemplary embodiment of a laser scanning measurement system **100** for measuring a surface **22** of an object **20** arranged at an object position **OP**. **FIG. 2B** through **FIG. 2D** illustrate an exemplary embodiment of a surface measurement process according to the present invention. A Cartesian coordinate system is included in select Figures for the sake of reference.

[0035] **FIG. 3A** is a perspective view of an example cylindrical object **20** whose surface **22** is to be measured. Object **20** has a central axis A_C, an object surface **22** and opposite ends **23** and **24**. In an exemplary embodiment illustrated in **FIG. 3B**, object **20** is supported at ends **23** and **24** by an object holder (mount) **30** so that that access to object surface **22** is unobstructed. In another exemplary embodiment illustrated in **FIG. 3C**, object **20** is supported by a V-groove object holder **36** that runs the length of the object (or a portion of the length sufficient to support the object) so that access to object surface **22** is only marginally obstructed. In the exemplary embodiments discussed below, object surface **22** comprises three surface portions **22A, 22B** and **22C** for the sake of illustration. However, object surface **22** can be divided up into any reasonable number of surface portions, depending on the particular measurement geometry and the particular object being measured. The dividing of object surface **22** into different portions is merely for the sake of convenience and need not be related to features on the object surface *per se*.

[0036] With reference to **FIG. 2A** and **FIG. 2B**, system **100** comprises a laser source **112** adapted to form a scanned laser beam **116** over a total scan path SP_T that has an associated total beam angle θ_T. As illustrated in **FIG. 3A**, laser beam **116** forms a small laser spot **118** on object surface **22** that is scanned in a given direction **119**. A photodetector **114** is arranged relative to laser source **112** and is adapted to detect reflected light **116R** (as illustrated, for example, in FIGS. 2C and 2D) reflected from spot **118** at object surface **22**. Photodetector **114** comprises, for example, a CCD camera. Photodetector **114** is shown as residing on either side of laser source **112** so as to have a relatively wide field of view in detecting light reflected **116R** from different points on object surface **22**.

[0037] System **100** also comprises a processor **120**, such as a computer (e.g., a personal computer) that is adapted to receive electrical detector signals **SD** from photodetector **114** and process these signals to calculate one or more surface shape segments, surface shape representations, and three-dimensional surface profiles, as discussed below. In an exemplary embodiment, processor **120** comprises a microprocessor **122**, such as a field-programmable gate array (FPGA), a central processing unit (CPU) or the like, that is programmable to carry out logic operations and in particular mathematical calculations. In an exemplary embodiment, processor **120** comprises image processing software typically used in laser scanning measurement systems to calculate surface shapes and surface profiles. Processor **120** may also include a memory unit (not shown) for storing information from the various detector signals as discussed below.

[0038] System **100** further comprises a mirror system **MS**, arranged relative to object position **OP** and laser source **112.** In the present exemplary embodiment, mirror system **MS** comprises a mirror **M1.** In a preferred embodiment, mirror **M1** is a plane mirror as shown, though other mirror shapes can be used. Mirror **M1** forms an angle θ_{M1} with a system central axis A_1. Mirror system **MS** allows for a relatively large total scan path SP_T that covers a correspondingly large total beam angle θ_T. Mirror system **MS** allows for system **100** to measure a greater portion of object surface **22** in a single scan than is otherwise possible by simply scanning the portion of the object surface that faces laser source **112**.

[0039] Specifically, with reference to **FIG. 2C** and **FIG. 2D**, object **20** can be considered to have different surface portions—namely a "front" or "exposed" surface portion **22A** that faces laser source **112** and that is illuminated directly by laser source **112**, and at least one "back" or "unexposed" or "hidden" surface portion, such as two hidden surface portions **22B** and **22C**, that are not directly accessible by laser beam **116** (i.e., cannot be illuminated directly by laser beam **116**) with the system 100 and object 20 in that configuration.

[0040] Mirror **M1** of mirror system **MS** allows for a single scan path $\mathbf{SP_T}$ (i.e., a single pass of laser beam **116**) to measure the surface shape of both the exposed surface portion **22A** and the hidden surface portion **22B**. With reference now also to flow diagram **400** of **FIG. 4**, this is accomplished as follows. In one embodiment, the procedure is: place object in position OP **401**; then perform single scan Sn over n scan path segments SP_n of scan path SP_T for given orientation Zj to scan exposed surface portion and at least one hidden surface portion **402**, then detect direct reflection and mirror reflection(s) associated with n scan segments SP_n **403**, then calculate surface shapes segments SS_n for scan path segments SP_n **404**, then perform coordinate transformation to properly orient surface shapes segments SS_n **405**, then determine overlap regions for adjacent calculated surface shape segments SS_n **406**, then combine calculated surface shape segments SS_n to arrive at a surface shape representation SS_{Zn} for the given orientation **407**, then ask: Perform scan at another scan path orientation? **408**, and if the answer is yes, then change scan path orientation Z_j and return to performing the single scan **(402) 409**, and if the answer is no, calculate final 3D surface profile representation SPR_F based on the m measured 2D surface shapes representations SS_{Zm} for each scan path orientation $Z_1, \ldots Z_m$ **410**.

[0041] That is, first, in step **401**, object **20** is placed in system **100** in object position **OP** (**FIG. 2A**). This is accomplished, for example, by supporting object **20** in object holder **30** or object holder **36** (**FIG. 3B** and **FIG. 3C**, respectively). Next, in step **402**, laser beam **116** is scanned over scan path $\mathbf{SP_T}$ at a first orientation with respect to object **20**. For the sake of illustration, the scan orientations are in the X-Y plane at different Z-positions $Z_j = Z_1, \ldots Z_m$. For the first scan orientation, $Z_j = Z_1$. In step **403**, the reflected light **116R** from scanned spot **118** as formed by laser beam **116** is detected by photodetector **114**.

[0042] Scan path $\mathbf{SP_T}$ can be divided into a number n of scan path segments $\mathbf{SP_n}$. In the present exemplary embodiment, n = 2, so that there are two scan path segments $\mathbf{SP_n}$, namely $\mathbf{SP_1}$ and $\mathbf{SP_2}$. As illustrated in **FIG. 2C**, laser beam **116** is scanned over the first scan path segment $\mathbf{SP_1}$ wherein the laser beam is incident upon mirror **M1**, which is positioned to reflect the laser beam onto hidden surface portion **22B**. A portion **116R** of laser beam **116** reflects from hidden surface portion **22B** at the location where laser spot **118** is formed. This reflected light then reflects from mirror **M1** and is directed back toward photodetector **114**, which captures and detects the reflected light (e.g., images the reflected laser spot onto a one or more pixels in a CCD array). As laser beam **116** scans over scan path segment $\mathbf{SP_1}$, laser spot **118** scans across hidden surface portion **22B**, which in turn scans across photodetector **114**. In response thereto, photodetector **114** generates corresponding detector signals $\mathbf{SD_1}$. Detector signals $\mathbf{SD_1}$ contain surface shape (profile) information about hidden surface portion **22B**.

[0043] As laser beam **116** continues its scan over scan path $\mathbf{SP_T}$, it moves from first scan path segment $\mathbf{SP_1}$ to second scan path segment $\mathbf{SP_2}$. As illustrated in **FIG. 2D**, for second scan path segment $\mathbf{SP_2}$, light from scanned laser spot **118** reflects from exposed surface portion **22A** and is detected by photodetector **114**, which sends corresponding detector signals $\mathbf{SD_2}$ to processor **120**. Detector signals $\mathbf{SD_2}$ contain surface shape information about exposed surface portion **22A**.

[0044] In step **404**, processor **120** calculates surface shape segments SS_n (i.e., SS_1 and SS_2) for both the hidden and exposed surface portions **22B** and **22A** based on the information provided in corresponding detector signals $\mathbf{SD_n}$ (i.e., signals $\mathbf{SD_1}$ and $\mathbf{SD_2}$) for the corresponding scan path segments $\mathbf{SP_1}$ and $\mathbf{SP_2}$. **FIG. 5** illustrates a plot of the resulting surface shape segments SS_1 and SS_2.

[0045] Because mirror **M1** makes an angle θ_{M1} with system central axis $\mathbf{A_1}$, surface shape segment SS_1 corresponding to scan path segment $\mathbf{SP_1}$ needs to be rotated relative to surface shape SS_2 corresponding to scan path segment $\mathbf{SP_2}$. Thus, in step **405**, processor **120** performs a coordinate transformation on surface shape segment SS_2. In an exemplary embodiment, processor **120** stores surface shape segments SS_1 and SS_2 as sets of data points representing the coordinates (e.g., Cartesian coordinates) of each of the surface points measured during the laser scan. A mathematical operation is then performed to carry out the appropriate coordinate transformation, as described below.

[0046] In an exemplary embodiment, scan path segments $\mathbf{SP_1}$ and $\mathbf{SP_2}$ partially overlap so that a portion of surface **22** is measured more than once. In step **406**, the portions of surface shape segments SS_1 and SS_2 that overlap are calculated based, e.g., on the geometry of system **100**, or by comparing adjacent surface shapes in processor **120** to find surface features common to both surface shape segments. In **407**, and as illustrated in **FIG. 5**, the surface shape segments SS_1 and SS_2 are combined to form a measured surface shape representation SS_{Zj} for the first measurement orientation $\mathbf{Z_1}$. Measured surface shape representation SS_{Zn} is a two-dimensional (2D) representation of the actual shape of object surface **22** for a slice of object **20** taken at $Z = Z_j$. Note that in this particular exemplary embodiment only one of the hidden surface portions **22B** is measured, which results in a gap G_{22C} in the measured surface shape representation SS_{Zj} at the location corresponding to hidden surface portion **22C**.

[0047] Step **408** inquires as to whether another scan is to be performed at a different scan orientation other than $Z_j = Z_1$. If the answer to this inquiry is "YES," then the scan orientation is changed (e.g., from Z_1 to Z_2) in step **409** and the above-described steps **402** through **407** are repeated to generate another surface shape representation SS_{Z2} for the second scan orientation. Steps **402-407** can be repeated numerous times (say, m times) until at step **407** the answer to the inquiry becomes "NO." At this point, the process moves to step **410**, wherein a final three-dimensional (3D) surface profile representation SPR_F calculated in processor **120** by combining the m 2D surface shape representations $SS_{Z1},...SS_{Zm}$ for the various scan orientations $Z_1,...Z_m$.

[0048] Note that in the above-described non-contact surface measurement process, object **20** is not rotated (e.g. with respect to laser source **112**) in order to scan hidden object surface portion **22B**. Rather, mirror **M1** allows hidden surface portion **22B** to be measured using a single scan over scan path SP_T. This is a particularly important feature when it is preferred that object **20** not be rotated, e.g., in the case where rotation of the object can change its surface shape or other properties that need to be kept constant. As compared to known measurement processes, the overall length of scan path SP_T is greater because it needs to include mirror **M1**; however, laser beam scanning speeds are very rapid (e.g., hundreds or thousands of scans per second), and the greater length is generally not significant.

Two-mirror embodiment

[0049] **FIG. 6A** is a schematic diagram of another exemplary embodiment of the laser scanning measurement system **100** similar to that shown in **FIG. 2A**, but wherein mirror system **MS** of system **100** of **FIG. 6A** comprises an additional mirror **M2** located on the opposite side of axis A_1 from mirror **M1**. In a preferred embodiment, mirrors **M1** and **M2** are plane mirrors, as shown. Mirrors **M1** and **M2** can also be sections of a single mirror. Mirror **M2** makes an angle θ_{M2} with respect to axis A_1. In an exemplary embodiment, mirrors **M1** and **M2** are arranged symmetrically about axis A_1 such that $\theta_{M1} = \theta_{M2}$. **FIG. 6B** is a schematic perspective diagram of an exemplary embodiment of mirror system **MS** that comprises two plane mirror sections that run parallel to the Z-axis and thus along the length of axis A_1 of object **20**.

[0050] As illustrated in **FIG 6C** and **FIG. 6D**, scan path SP_T and associated beam angle θ_T cover both mirrors **M1** and **M2**. Mirrors **M1** and **M2** of mirror system **MS** allow for system **100** to measure in a single scan path SP_T (i.e., a single pass of laser beam **116**) the 2D surface shape of an entire circumference C_n of object surface **22**. Note that in the present exemplary embodiment, object surface **22** has a hidden surface portion **22C** similar to hidden surface portion **22B** but on the other side of axis A_1 (**FIG. 6C**).

[0051] With reference again to flow diagram **400** of **FIG. 5**, the surface shape of object **20** is measured in a similar manner to the first exemplary embodiment described above. First, in step **401**, object **20** is placed in system **100** in object position **OP** (**FIG. 6A**). This is accomplished, for example, by supporting object **20** in object holder **30** or object holder **36** (**FIG. 3B** and **FIG. 3C**, respectively). Next, in step **402**, as illustrated in **FIG. 6C**, laser beam **116** is scanned over scan path SP_T at a first orientation with respect to object **20**. For the sake of illustration, the first orientation is in the **X-Y** plane at $Z = Z_1$. In step **403**, the reflected light **116R** from scanned spot **118** as formed by laser beam **116** is detected by photodetector **114**.

[0052] Scan path SP_T is again divided into n scan path segments SP_n (**FIG. 6D**) for the sake of convenience and illustration. In the present exemplary embodiment, n = 5, so that there are five scan path segments $SP_n = SP_1$ through SP_5. With reference now to **FIG. 6E**, as in the first exemplary embodiment, scanning laser beam **116** over the first scan path segment SP_1 directs the laser beam to mirror **M1**, and in response thereto, photodetector **114** generates corresponding detector signals SD_1 as described above. Detector signals SD_1 contain surface shape information about hidden surface portion **22B**.

[0053] With reference now to **FIG. 6F**, as laser beam **116** continues its scan over scan path SP_T, it moves from first scan path segment SP_1 to second scan path segment SP_2. In the present exemplary embodiment, there is a first gap **G1** between mirror **M1** and object **20** through which laser beam **116** travels without reflecting from the object or the mirror. Accordingly, no detector signals SD_2 are generated for this scan path segment **SP2**.

[0054] With reference now to **FIG. 6G**, laser beam **116** continues to third scan path segment **SP_3**, wherein reflected light **116R** from scanned laser spot **118** reflects from exposed surface portion **22A**. This reflected light is detected by photodetector **114**, which sends corresponding detector signals **SD_3** to processor **120**. Detector signals **SD_3** contain surface shape information about exposed surface portion **22A**.

[0055] With reference now to **FIG. 6H**, laser beam **116** then continues to fourth scan path segment **SP_4**, which like scan path segment **SP_2**, is associated with a second gap **G2** between object **20** and mirror **M2**. Consequently, laser beam **116** travels without reflecting from the object or mirror **M2**. Accordingly, no detector signals **SD_3** are generated for this scan path segment **SP_3**.

[0056] With reference now to **FIG. 6I**, laser beam **116** then continues to fifth scan path segment **SP_5**, wherein laser beam **116** is directed to mirror **M2**, which is positioned to reflect the laser beam onto hidden surface portion **22C**. A portion **116R** of laser beam **116** reflects from hidden surface portion **22C** at the location where laser spot **118** is formed. This reflected light then reflects from mirror **M2** and is directed back toward photodetector **114**, which captures and detects the reflected light (e.g., images the reflected laser spot onto a one or more pixels in a CCD array). As laser beam **116** scans over scan path segment **SP_5**, laser spot **118** scans across hidden surface portion **22C**, which in turn scans across photodetector **114**. In response thereto, photodetector **114** generates corresponding detector signals **SD_5**. Detector signals **SD_5** contain surface shape (profile) information about hidden surface portion **22C**. Note that **FIG. 6D** illustrates the combined scan path segments **SP_1** through **SP_5** that make up the total scan path **SP_T**.

[0057] In step **404**, and as illustrated in **FIG. 7A**, processor **120** calculates surface shape segments SS_n (i.e., SS_1 through SS_5) for both the hidden surface portions **22B** and **22C** as well as exposed surface portion **22A** based on the information provided in corresponding detector signals **SD_1** through **SD_5**.

[0058] Because mirrors **M1** and **M2** make angles **θ_{M1}** and **θ_{M2}** with system central axis **A_1**, surface shape segment SS_1 corresponding to scan path segment **SP_1** and surface shape segment SS_5 corresponding to scan path segment **SP_5** need to be rotated relative to surface shape segment SS_3 corresponding to scan path segment **SP_3**. Thus, in step **405**, processor **120** performs a coordinate transformation on surface shape segments SS_1 and SS_5 relative to surface shape segment SS_3. In an exemplary embodiment, processor **120** stores surface shape segments SS_1, SS_3 and SS_5 as sets of data points representing the coordinates (e.g., Cartesian coordinates) of each of the surface points measured during the laser scan. A mathematical operation is then used to carry out the appropriate coordinate transformations, as described in detail below.

[0059] In an exemplary embodiment, scan path segments SP_1, SP_3 and SP_5 partially overlap so that portions of surface **22** are measured more than once. In step **406**, the portions of surface shape segments SS_1, SS_3 and SS_5 that overlap with the adjacent surface shape segment are calculated based, e.g., on the geometry of system **100**, or by comparing the surface shape segments in processor **120** to find surface features common to the surface shape segments. In step **407**, and as shown in **FIG. 7B**, the surface shape segments SS_1, SS_3 and SS_5 are properly overlapped and combined form a completed 2D surface shape representation SS_{Zj} for the first measurement orientation $Z_j = Z_1$ that covers most if not all of the entire circumference C_n for the given scan path orientation. The result shown in **FIG. 7B** is for the example case where an entire circumference C_n of surface **22** is scanned for the given scan path. In cases where object **20** is held by an object holder that covers or otherwise blocks access to a portion of object surface **22** by scanning laser beam **116** (e.g., V-type object holder **36**), a small portion of the object surface remains unmeasured.

[0060] Step **408** inquires as to whether another scan is to be performed at a different scan orientation other than $Z_j = Z_1$. If the answer to this inquiry is "YES," then the scan orientation is changed (i.e., from Z_1 to Z_2) in step **409** and the above-described steps **402** through **407** are repeated to generate another surface shape representation SS_{Z2} for the second scan orientation. Steps **402-407** can be repeated numerous times (say, m times) until at step **507** the answer to the inquiry becomes "NO." At this point, the process moves to step **410**, wherein a final 3D surface profile representation SPR_F is calculated in processor **120** by combining the 2D surface shape representations $SS_{Z1}, \ldots SS_{Zm}$ for the various (m) scan orientations $Z_1, \ldots Z_m$.

[0061] Again, in the above-described non-contact surface measurement process, object **20** need not be rotated in order to scan hidden object surface portions **22B** and **22C**. Rather, mirrors **M1** and **M2** allow for hidden surface portions **22B** and **22C** to be measured using a single scan of laser beam **116** over its scan path SP_T.

Coordinate transformations

[0062] **FIG. 8A** is a schematic diagram of laser scanning measurement system **100** similar to that shown in **FIG.2A**, illustrating the geometry associated with performing the coordinate transform used to piece together the different surface shape representations **SS**. The geometry is described for an example system **100** having a mirror system **MS** with a single plane mirror **M1**.

[0063] In an exemplary embodiment, the relevant geometrical information for performing the coordinate transformation is recorded by or is programmed into system **100**. This information comprises, for example, the incident angle θ_0 of laser beam **116** at mirror **M1**, and the **(X,Y)** position where laser spot **118** reflects from object surface **22**. This information is sufficient to generate a surface shape representation **SS** of exposed surface portion **22A**.

[0064] System **100** also generates reflected or "virtual" Cartesian coordinates **X'-Y'-Z'** associated with a virtual image **20'** (hereinafter, the "virtual object") of "real" object **20** as formed by mirror **M1**. Since the **Z** coordinate remains unchanged, the other two virtual object coordinates **(X',Y')** need to be transformed into the **(X,Y)** coordinates of the real object in order for the surface shapes to be combined in their proper orientation. To do this, the position and angle of mirror **M1** relative to laser beam **116** must be known.

[0065] At least two methods can be used for determining the relative position and angle of mirror **M1**. The first method is to replace the mirror with an opaque object (not shown) and then scan the opaque object's surface to generate a table of **(X, Y)** coordinates as a function of scan angle θ_0. Once the calibration is completed, the opaque object is replaced with the mirror. The coordinate table is then used to carry out the coordinate transformation **(X',Y')→ (X,Y)**.

[0066] With reference to the close-up view of **FIG. 8B, a** second method is to provide the reflective surface **179** of mirror **M1** with two opaque stripes **181** and **183** at opposite ends of the mirror, as shown. Opaque stripes **181** and **183** extend in the **Z**-direction so as not to significantly disrupt the view of object **20**. In this second method, stripes **181** and **183** show up in each object scan and provide two points that indicate the position of mirror **M1**. These two points are then used to generate the slope and intercept of the mirror plane in the **(X,Y)** coordinate space as a function of laser beam incident angle θ_0.

[0067] In addition to knowing the distance **D1** from laser source **112** to mirror **M1**, laser beam angle θ_0 and mirror angle θ_{M1}, the distance **D2** from mirror **M1** to the object at the **(X,Y)** location of laser spot **118** needs to be established.

[0068] System **100** measures the **(X',Y')** position of the virtual object surface **22'** for a given laser beam incident angle θ_0 by the equation:

$$X' = -(D1 + D2)\sin(\theta_0) \qquad \text{(Eq. 1A)}$$

$$Y' = -(D1 + D2)\cos(\theta_0) \qquad \text{(Eq. 1B)}$$

[0069] The position of the real object point in the **(X,Y)** coordinate space is then determined by the coordinate transformation:

$$X = -D1\sin(\theta_0) + D2\cos(2\theta_{M1} + \theta_0 - 90^\circ) \qquad \text{(Eq. 2A)}$$

$$Y = -D1\cos(\theta_0) + D2\sin(2\theta_{M1} + \theta_0 - 90^\circ) \qquad \text{(Eq. 2B)}$$

[0070] In the above set of equations, **D2** is unknown. However, the above equations can be combined to produce the following coordinate transformation:

$$X = -D1\sin(\theta_0) + (D1\sin(\theta_0) - X')(\cos(2\theta_{M1} + \theta_0 - 90^\circ)/\sin(\theta_0) \qquad \text{(Eq. 3A)}$$

$$Y = -D1\cos(\theta_0) + (D1\sin(\theta_0) - X')(\sin(2\theta_{M1} + \theta_0 - 90^\circ)/\sin(\theta_0) \qquad \text{(Eq. 3B)}$$

The coordinate transformation for mirror **M2** is analogous. Coordinate transformations for non-planar mirrors is more complicated but can be determined in a straightforward manner by one skilled in the art through a number of different approaches, including using ray-tracing software such as CODE V® or LightTools®, both available from Optical Research Associates, Inc., Pasadena, California.

Example application: extruded ware surface shape measurement

[0071] An example application for the laser scanning measurement system **100** of the present invention is for measuring the surface shape of extruded particulate filters. **FIG. 9A** is an end view and **FIG. 9B** is a side view of an example particulate filter body ("filter") **200** having opposite end faces **202** and **204** and an internal honeycomb structure **212** that comprises a number of cell channels **220** that extend between the end faces (see inset of **FIG. 9A**). Filter **200** has an outer surface **222**.

[0072] Versions of filter **200** are formed, for example, from an aqueous-based ceramic precursor mixture fed through an extrusion die to form a wet "log." The aqueous-based ceramic precursor mixture comprises, for example, a batch mixture of ceramic (such as cordierite) forming inorganic precursor materials, an optional pore former such as graphite or starch, a binder, a lubricant, and a vehicle. The wet log is then cut during the extrusion step into a number of pieces. These pieces are then dried to form "green" honeycomb logs.

[0073] The process of forming filter **200** further involves cutting or segmenting the green honeycomb pieces into green honeycombed structures of a desired length, and thereafter removing dust from the green honeycombed structures as formed during the cutting step. At this point, the honeycombed structure can be fired and then plugged at the ends. This may involve, for example, charging or otherwise introducing a flowable plugging cement material, such as a slurry preferably comprising a water diluted ceramic-forming solution, into selected cell channels **220** as determined by a plugging mask.

[0074] Because filter **200** is typically designed to fit into an enclosure of a very specific size and shape (e.g., the housing for a catalytic converter for an automobile), the surface shape of the filter needs to satisfy relatively tight specifications. Yet, because the extruded log does not have a hard outer surface, contact-type surface measurements can damage and/or deform the filter and change its surface shape. Thus, non-contact measurement of the surface shape of filter **200** along its various stages of manufacture is an important aspect of monitoring filter quality.

[0075] For example, if the extrusion process is not uniform, the logs **201** used to form filter **200** can have a bowed shape (**FIG. 9C**), or can have a shape that differs from its ideal shape, such as a certain dimension oval for use in catalytic converters. In addition, the cutting of log **201** into pieces can cause surface **222** at log ends **202** and **204** to have respective defects or distortions such as flares **230** due to differences in the stress-strain balance at the log ends (**FIG. 9D**). Flares **230** tend to happen within a short distance of the log ends. To the extent that shape defects occur in the manufacturing process, they need to be quickly measured and quantified to assess whether the resulting product will have a surface shape within the design tolerance. Further, the surface measurements are preferably taken over most if not all of the object's circumference. Accordingly, the surface measurements provided by the laser scanning measurement system of the present invention allow for a quick surface shape inspection of the extruded parts without having to rotate the parts. This is particularly important in the case of extruded logs since rotating the log may cause deformation of the surface shape.

[0076] In one aspect, a laser measurement system is disclosed herein comprising: a laser source adapted to scan a laser beam over a scan path relative to an object at an object position; a mirror system arranged relative to the laser source and to the object position such that the scanned laser beam is incident directly on an exposed portion of an object surface of the object and is incident via reflection by the mirror system onto at least one hidden portion of the object surface that is not directly accessible by the scanned laser beam; and a photodetector configured relative to the laser source, the mirror system and the object position so as to detect light from the scanned laser beam that reflects from the exposed surface portion and that reflects from the at least one hidden portion of the object surface. Preferably, the object does not move with respect to the laser source. Preferably, the object does not rotate. In some embodiments, the object has a circumference, and the system comprises a plurality of mirrors, and the mirrors are arranged such that the object surface is measured around the entire circumference. Preferably, the object is capable of not moving with respect to the laser source. In some embodiments, the scanning laser beam and the mirror are configured so as to provide a plurality of laser beam scans at different scan path orientations relative to the object position so as to provide a corresponding plurality of surface measurements that can be combined to form a three-dimensional surface profile representation of the object surface. In some embodiments, the system further comprises a processor adapted to receive detector signals from the photodetector corresponding to the light detected over the scanning path and process the detector signals to determine a surface shape representation of the object surface. In some embodiments, the system comprises a plurality of mirrors. In some embodiments, the mirror is a plane mirror.

[0077] In another aspect, a method is disclosed herein of performing a non-contact measurement using a laser beam, the method comprising: scanning a first portion of an object surface of an object by irradiating the first portion with the laser beam; scanning a second portion of the object surface with the laser beam by reflecting the laser beam to said second portion, wherein said second surface portion cannot be directly irradiated by the laser beam; detecting light reflected by the first surface portion and second hidden surface portion; and determining a surface shape representation of the object surface based on the detected light. In some embodiments, a single scan of the laser beam is utilized. In some embodiments, the laser beam emanates from a laser source, and the object does not move with respect to the laser source during the scanning of the first and second portions. In some embodiments, the laser beam emanates from a laser source, and the object does not rotate during the scanning of the first and second portions. In some embodiments, the reflecting of the laser beam further comprises reflecting the scanning laser beam from at least one mirror. In some embodiments, the object has a circumference, and the second surface portion plus the first surface portion substantially covers the circumference, and determining the surface shape representation further comprises determining the surface shape representation for the circumference. In some embodiments, the determining the surface shape representation based on the detected light comprises: dividing up the scan path into a number of scan path segments; calculating surface shape segments associated with the scan path segments; and combining the surface shape segments to form the surface shape representation. The method may further comprise performing a coordinate transformation to orient the surface shape segments relative to one another prior to said combining of surface shape segments. In some embodiments, a portion of each surface shape segment overlaps with an adjacent surface shape segment, and the method further comprises: determining said surface shape segment overlaps, and accounting for said overlaps when combining the surface shape segments to arrive at the surface shape representation. In some embodiments, the surface shape representation formed by a) canning a first portion of an object surface of an object by irradiating the first portion with the laser beam, (b) scanning a second portion of the object surface with the laser beam by reflecting the laser beam to said second portion, wherein said second surface portion cannot be directly irradiated by the laser beam, (c) detecting light reflected by the first surface portion and second hidden surface portion, and (d) determining a surface shape representation of the object surface based on the detected light, is a 2D surface shape representation, and the method further comprises repeating steps a) through d) for a plurality of different scan paths to form a three-dimensional (3D) object surface profile representation.

[0078] In another aspect, a laser scanning measurement system is disclosed herein comprising: a laser source adapted to provide a scanning laser beam that scans over a scan path; an object holder adapted to hold an object at an object position relative to the laser source such that the object has an object surface comprised of an exposed surface portion, upon which the scanned laser beam can be made directly incident, and at least one hidden surface portion, upon which the scanned laser beam cannot be made directly incident; a mirror arranged relative to the object holder and to the laser source such that the scanned laser beam can be made incident upon the at least one hidden surface portion as the laser beam is scanned over the scan path; a photodetector adapted to receive detected light comprised of light reflected directly from the exposed surface portion and light reflected from the at least one hidden surface portion, and to generate detector signals corresponding to said detected light from said surface portions; and a processor adapted to receive and process the detector signals to determine a surface shape representation of the object surface. In some embodiments, the object holder holds the object stationary with respect to the laser source. In some embodiments, the measurement system comprises a plurality of mirrors configured such that the scanning laser beam can be made indirectly incident upon all of the hidden surface portions so that the surface shape representation can be determined for a circumference of the object over a single laser beam scan taken over the scan path. In some embodiments, the scan path comprises a plurality of scan path segments, and wherein the processor is adapted to calculate for each scan path segment a corresponding surface shape segment and to combine the surface shape segments to form said surface shape representation. In some embodiments, the processor is further adapted to perform a coordinate transformation of at least one of the surface shape segments so as to place the surface shape segments in a spatial orientation relative to one another. In some embodiments, at least two of the scan segments overlap, and wherein the processor is adapted to calculate said overlap. In some embodiments, the processor is adapted to process detector signals for scans taken from different scan path orientations and to calculate a three-dimensional (3D) object surface profile representation based on said detector signals in order to determine the surface shape representation.

[0079] It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A laser measurement system comprising:

a laser source adapted to scan a laser beam over a scan path relative to an object at an object position;

a mirror system arranged relative to the laser source and to the object position such that the scanned laser beam is incident directly on an exposed portion of an object surface of the object and is incident via reflection by the mirror system onto at least one hidden portion of the object surface that is not directly accessible by the scanned laser beam; and

a photodetector configured relative to the laser source, the mirror system and the object position so as to detect light from the scanned laser beam that reflects from the exposed surface portion and that reflects from the at least one hidden portion of the object surface.

2. The system of claim 1 wherein the object has a circumference, wherein the system comprises a plurality of mirrors, and wherein the mirrors are arranged such that the object surface is measured around the entire circumference.

3. The system of claim 1 wherein the scanning laser beam and the mirror are configured so as to provide a plurality of laser beam scans at different scan path orientations relative to the object position so as to provide a corresponding plurality of surface measurements that can be combined to form a three-dimensional surface profile representation of the object surface.

4. The system of claim 1 further comprising:

a processor adapted to receive detector signals from the photodetector corresponding to the light detected over the scanning path and process the detector signals to determine a surface shape representation of the object surface.

5. The system of claim 1 wherein the system comprises a plurality of mirrors.

6. The system of claim 1 wherein the mirror is a plane mirror.

7. A method of performing a non-contact measurement using a laser beam, the method comprising:

scanning a first portion of an object surface of an object by irradiating the first portion with the laser beam;

scanning a second portion of the object surface with the laser beam by reflecting the laser beam to said second portion, wherein said second surface portion cannot be directly irradiated by the laser beam;

detecting light reflected by the first surface portion and second hidden surface portion; and

determining a surface shape representation of the object surface based on the detected light.

8. The method of claim 7 wherein a single scan of the laser beam is utilized.

9. The method of claim 7 wherein the laser beam emanates from a laser source, and wherein the object does not move with respect to the laser source during the scanning of the first and second portions.

10. The method of claim 7 wherein the laser beam emanates from a laser source, and wherein the object does not rotate during the scanning of the first and second portions.

11. The method of claim 7 wherein said reflecting of the laser beam further comprises reflecting the scanning laser beam from at least one mirror.

12. The method of claim 7 wherein the object has a circumference, wherein the second surface portion plus the first surface portion substantially covers the circumference, and wherein determining the surface shape representation further comprises determining the surface shape representation for the circumference.

13. The method of claim 7 wherein the determining the surface shape representation based on the detected light comprises:

dividing up the scan path into a number of scan path segments;

calculating surface shape segments associated with the scan path segments; and

combining the surface shape segments to form the surface shape representation.

14. The method of claim 13 wherein a portion of each surface shape segment overlaps with an adjacent surface shape segment, and wherein the method further comprises:

determining said surface shape segment overlaps; and

accounting for said overlaps when combining the surface shape segments to arrive at the surface shape representation.

15. The method of claim 8 wherein the method further comprises repeating the scanning of the first portion, the scanning of the second portion, the detecting light reflected, and the determining the surface shape representation, for a plurality of different scan paths to form a three-dimensional (3D) object surface profile representation.

16. A laser scanning measurement system comprising:

a laser source adapted to provide a scanning laser beam that scans over a scan path;

an object holder adapted to hold an object at an object position relative to the laser source such that the object has an object surface comprised of an exposed surface portion, upon which the scanned laser beam can be made directly incident, and at least one hidden surface portion, upon which the scanned laser beam cannot be made directly incident;

a mirror arranged relative to the object holder and to the laser source such that the scanned laser beam can be made incident upon the at least one hidden surface portion as the laser beam is scanned over the scan path;

a photodetector adapted to receive detected light comprised of light reflected directly from the exposed surface portion and light reflected from the at least one hidden surface portion, and to generate detector signals corresponding to said detected light from said surface portions; and

a processor adapted to receive and process the detector signals to determine a surface shape representation of the object surface.

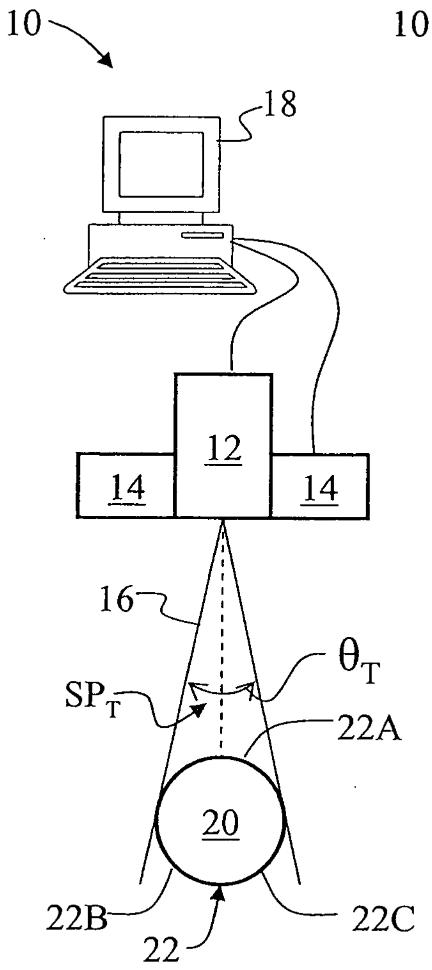
17. The system of claim 16 wherein the object holder holds the object stationary with respect to the laser source.

18. The system of claim 16 wherein the measurement system comprises a plurality of mirrors configured such that the scanning laser beam can be made indirectly incident upon all of the hidden surface portions so that the surface shape representation can be determined for a circumference of the object over a single laser beam scan taken over the scan path.

19. The system of claim 16 wherein the scan path comprises a plurality of scan path segments, and wherein the processor is adapted to calculate for each scan path segment a corresponding surface shape segment and to combine the surface shape segments to form said surface shape representation.

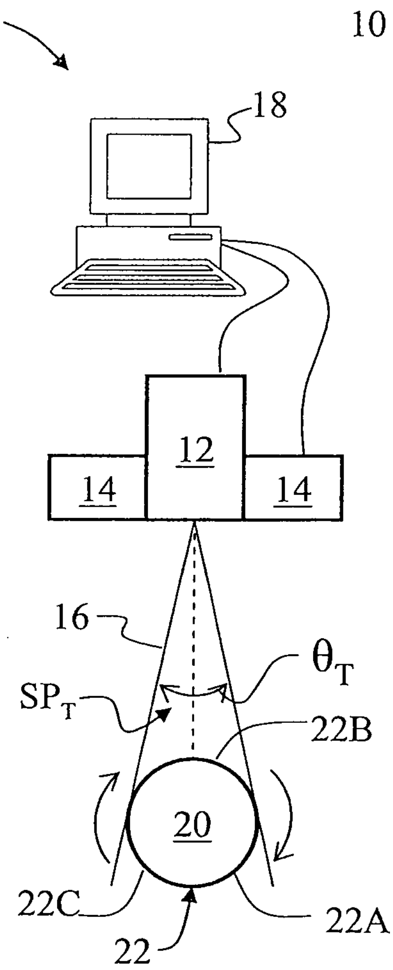
20. The system of claim 19 wherein the processor is further adapted to perform a coordinate transformation of at least one of the surface shape segments so as to place the surface shape segments in a spatial orientation relative to one another.

21. The system of claim 19 wherein the processor is adapted to process detector signals for scans taken from different scan path orientations and to calculate a three-dimensional (3D) object surface profile representation based on said detector signals in order to determine the surface shape representation.



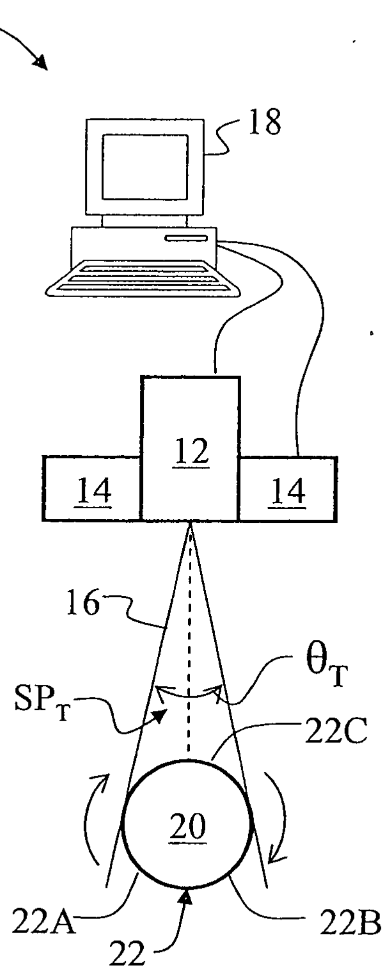
PRIOR ART

FIG. 1A



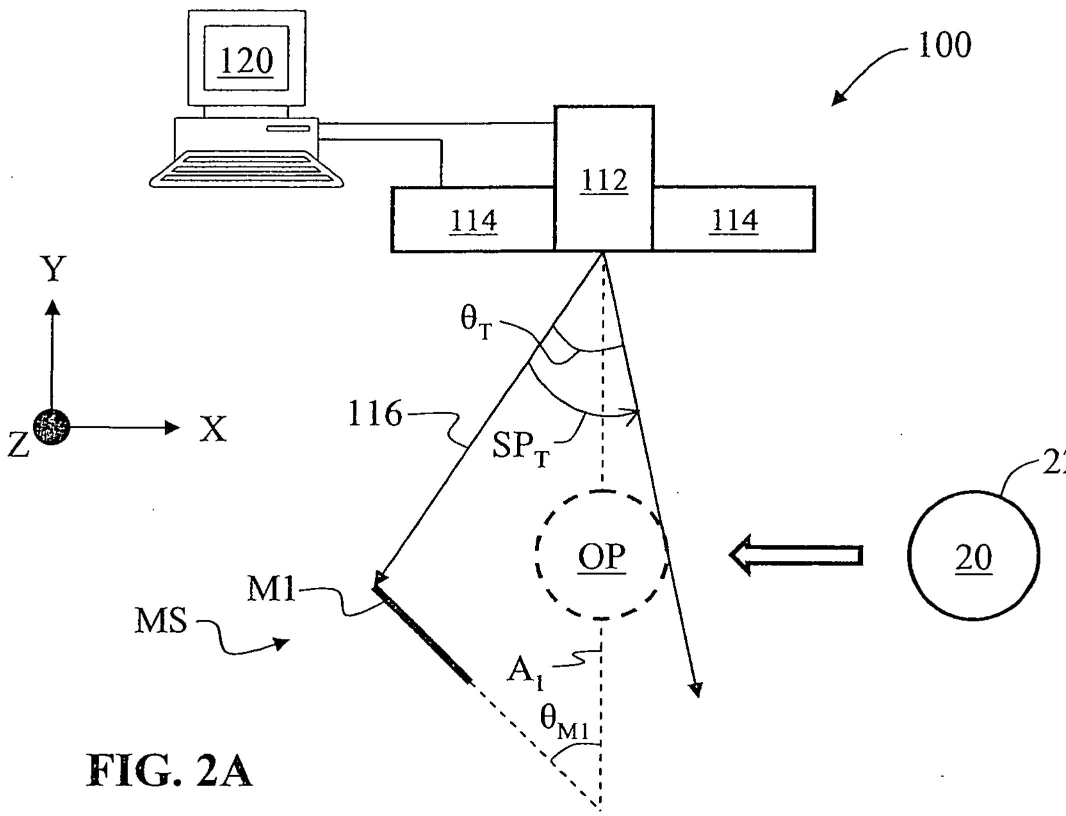
PRIOR ART

FIG. 1B



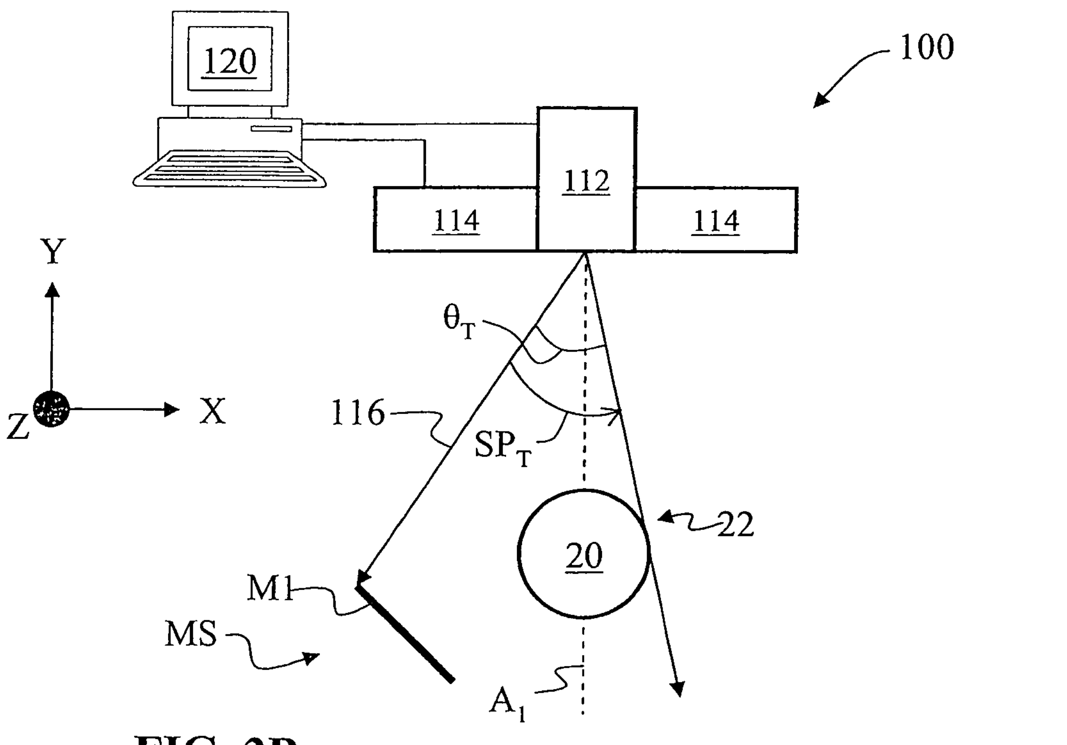
PRIOR ART

FIG. 1C



100
120
112
114
114
Y
X
Z
θ_T
116
SP_T
22
OP
20
M1
MS
A_1
θ_{M1}

FIG. 2A



100
120
112
114
114
Y
X
Z
θ_T
116
SP_T
22
20
M1
MS
A_1

FIG. 2B

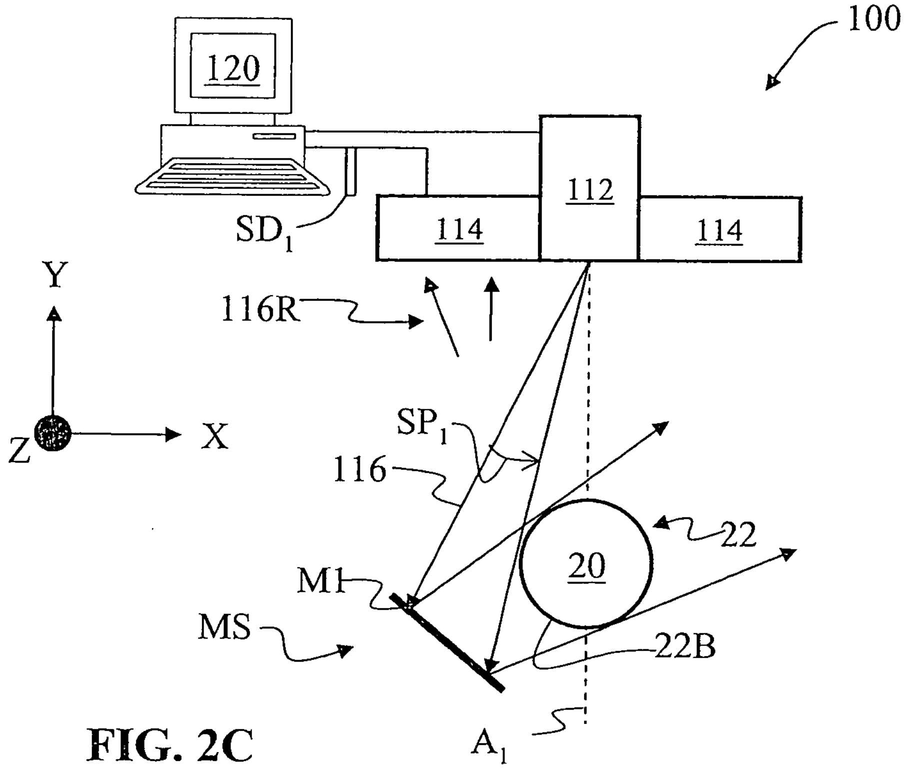

100
120
112
114
114
SD1
Y
116R
X
Z
SP1
116
22
20
M1
MS
22B
A1

FIG. 2C

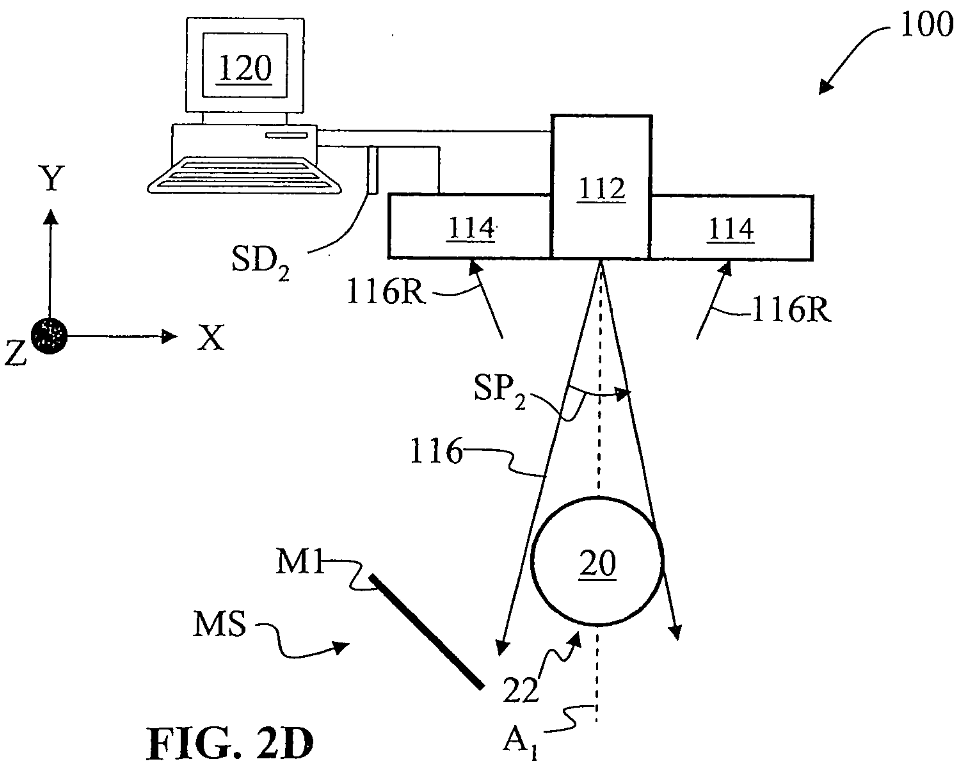

100
120
112
114
114
Y
SD2
116R
116R
X
Z
SP2
116
20
M1
MS
22
A1

FIG. 2D

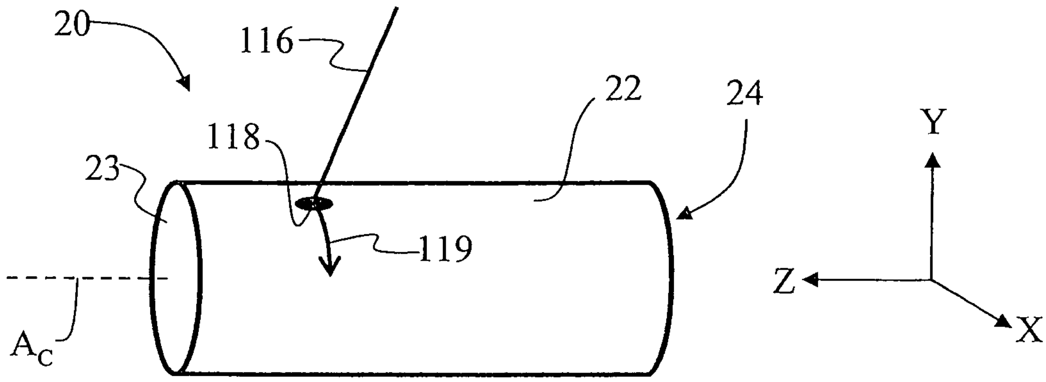


FIG. 3A

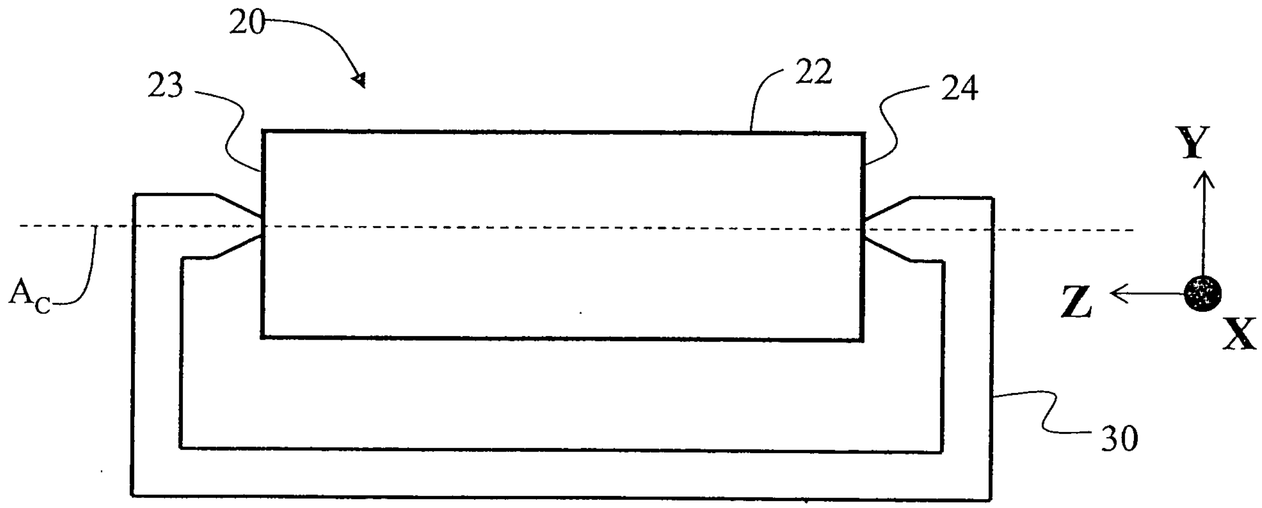


FIG. 3B

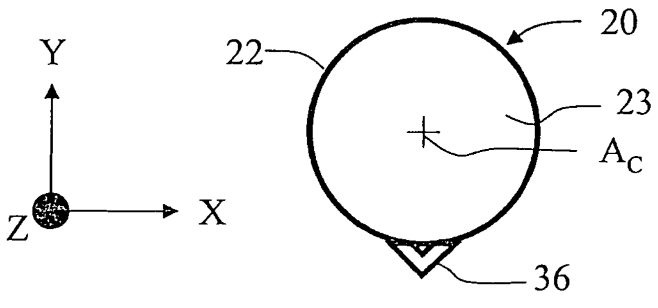

Y
X
Z
22
20
23
A_C
36

FIG. 3C

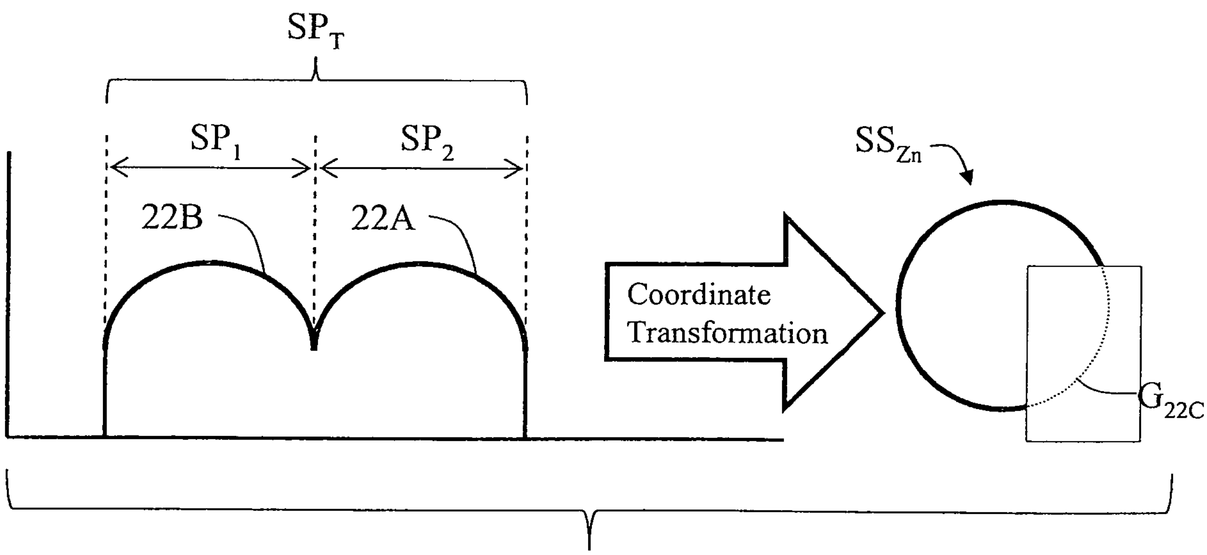

SP_T
SP_1
SP_2
22B
22A
Coordinate
Transformation
SS_{Zn}
G_{22C}

FIG. 5

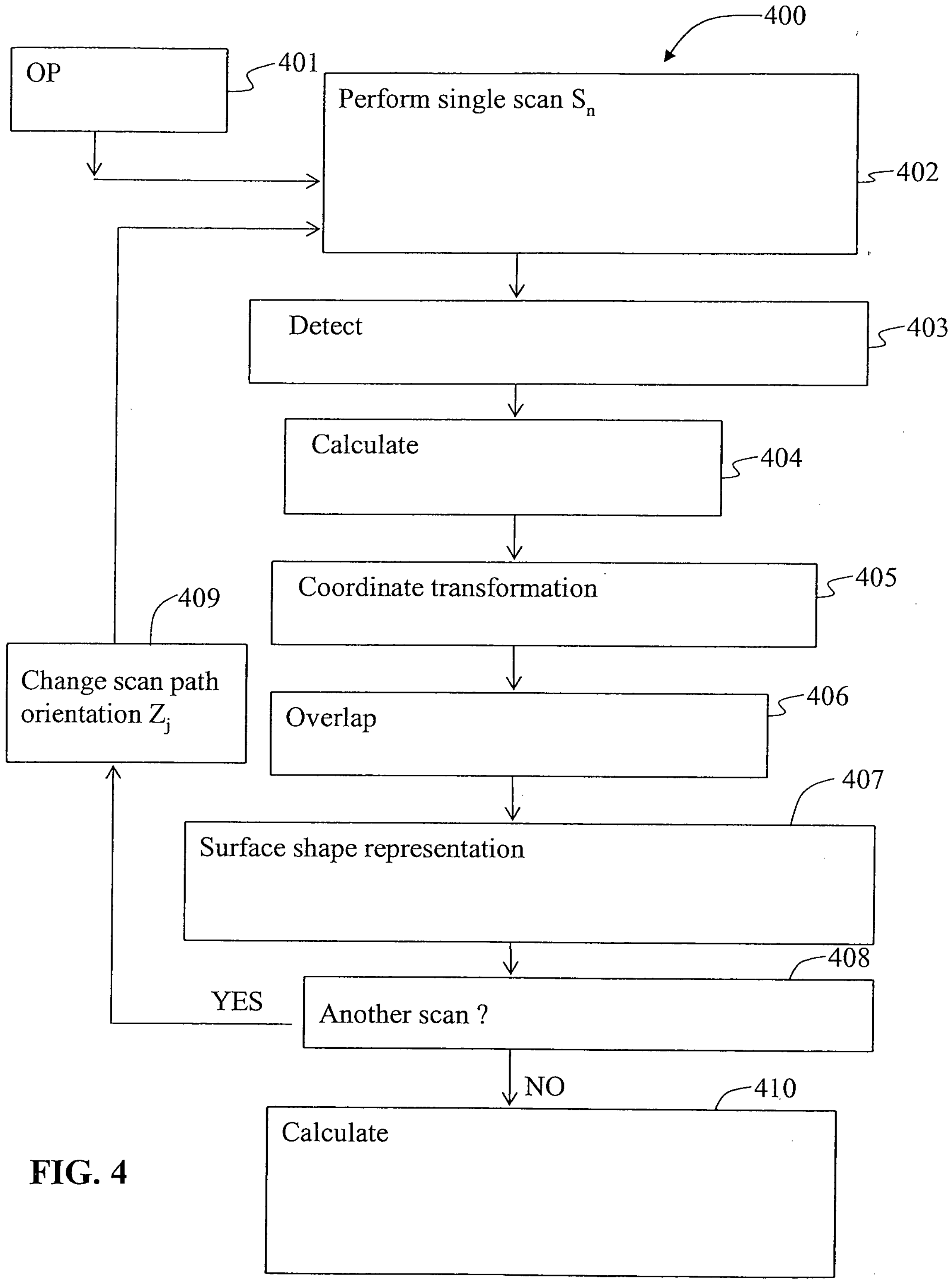
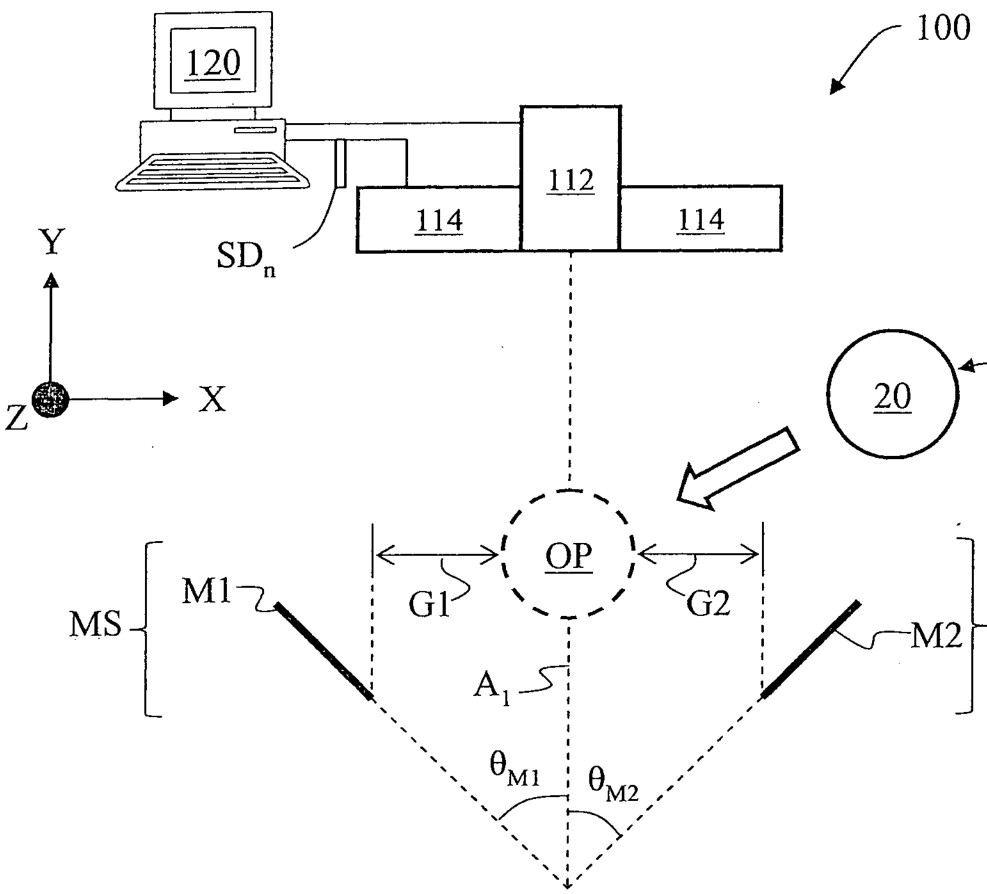
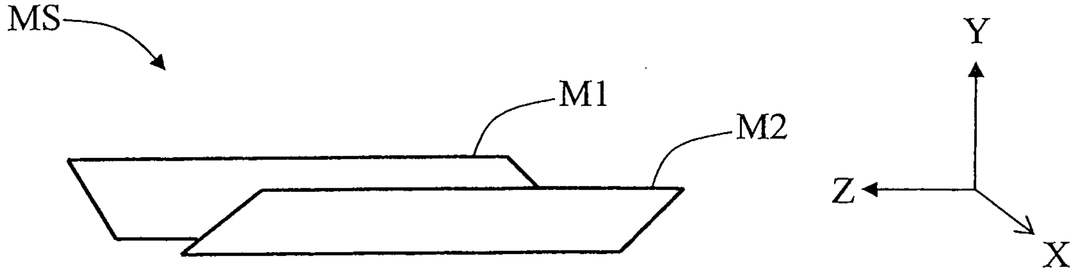

400
OP
401
Perform single scan S_n
402
Detect
403
Calculate
404
Coordinate transformation
405
409
Change scan path orientation Z_j
Overlap
406
407
Surface shape representation
408
YES
Another scan ?
NO
410
Calculate

FIG. 4



100
120
112
114
114
SD$_n$
Y
X
Z
22
20
OP
G1
G2
MS
M1
M2
A$_1$
θ_{M1}
θ_{M2}

FIG. 6A



MS
M1
M2
Y
Z
X

FIG. 6B

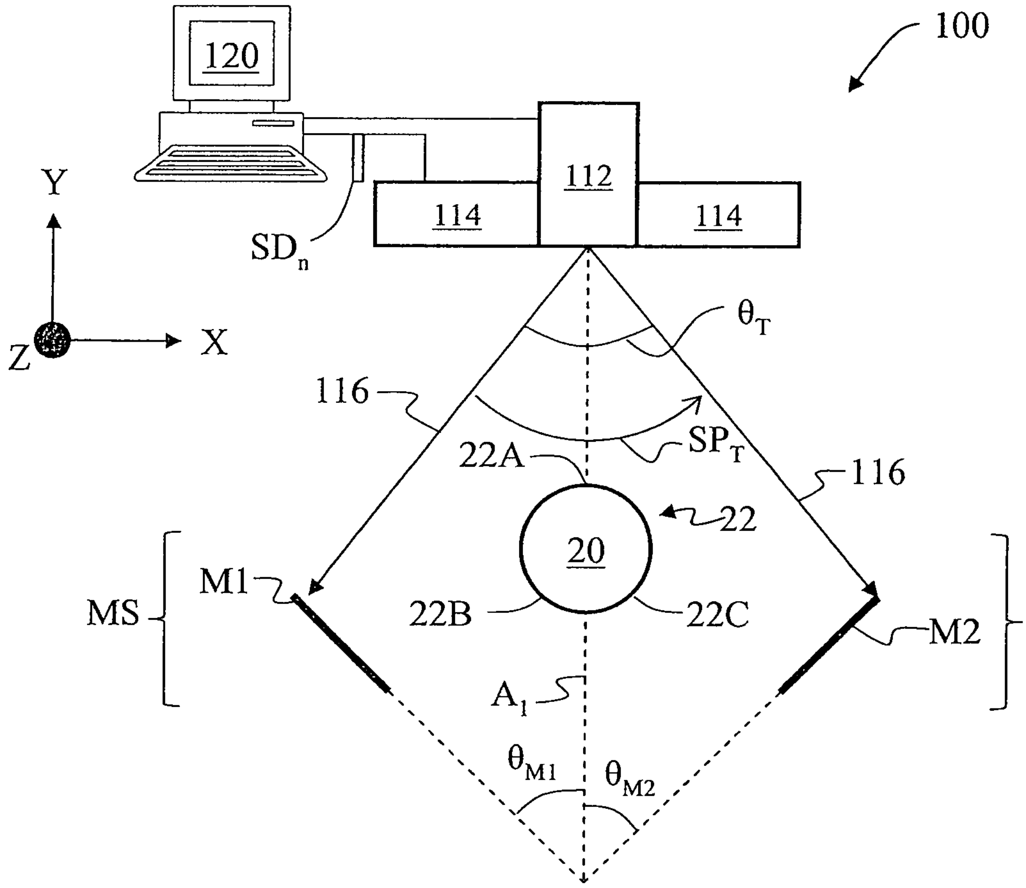

100
120
112
114
114
Y
X
Z
SDn
θT
116
SPT
116
22A
22
20
M1
MS
22B
22C
M2
A1
θM1
θM2

FIG. 6C

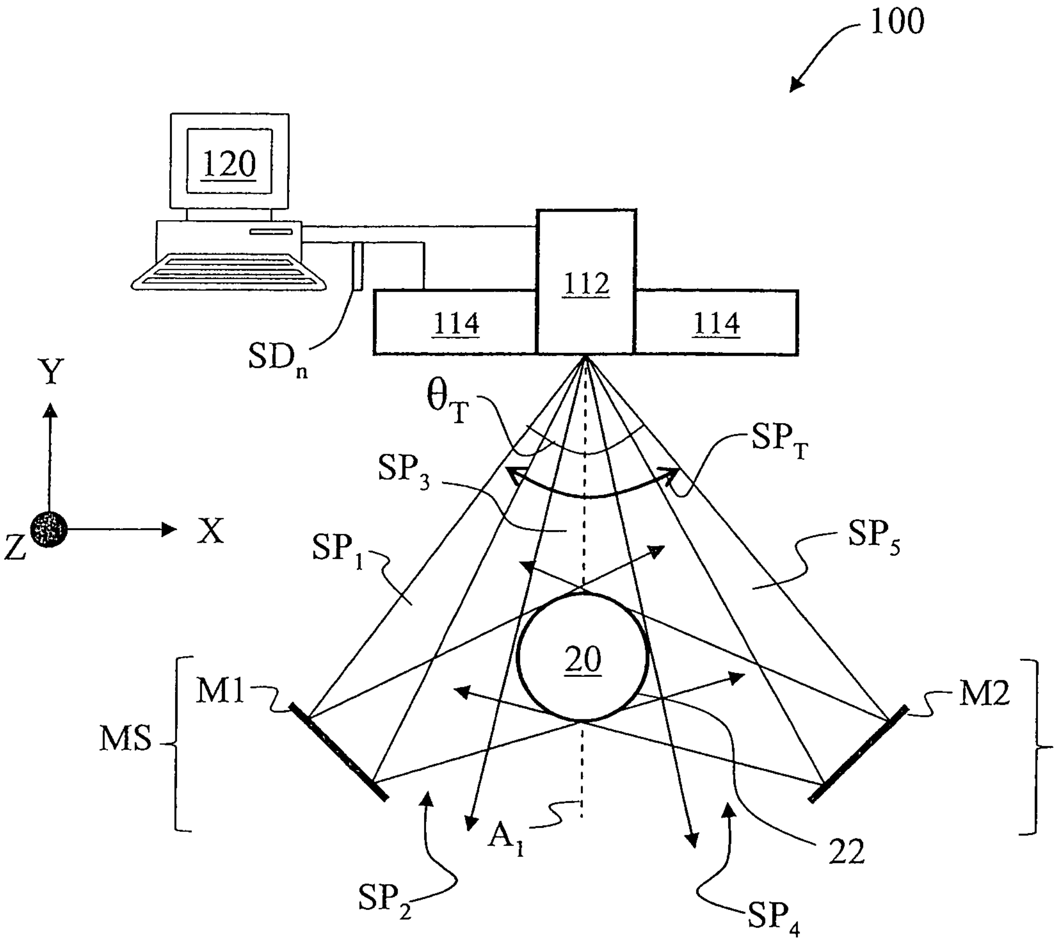

100
120
112
114
114
SD$_n$
Y
X
Z
θ$_T$
SP$_T$
SP$_3$
SP$_1$
SP$_5$
20
M1
M2
MS
A$_1$
22
SP$_2$
SP$_4$

FIG. 6D

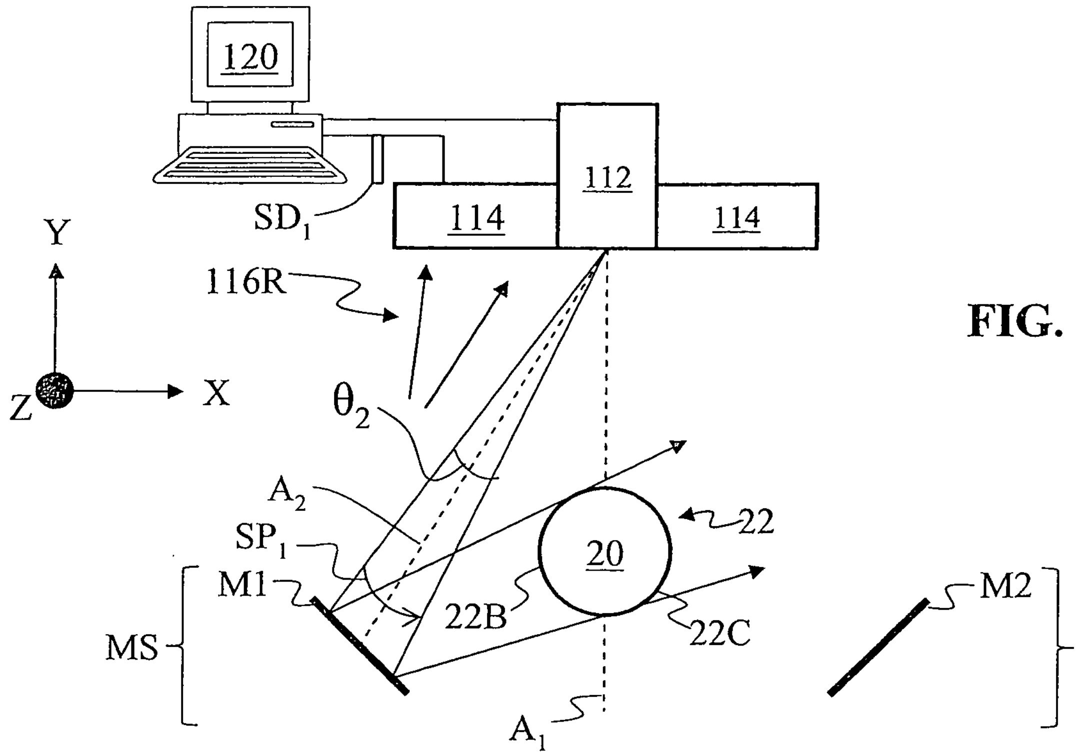

120
112
114
114
SD1
Y
116R
X
Z
θ2
A2
SP1
20
22
M1
22B
22C
M2
MS
A1

FIG. 6E

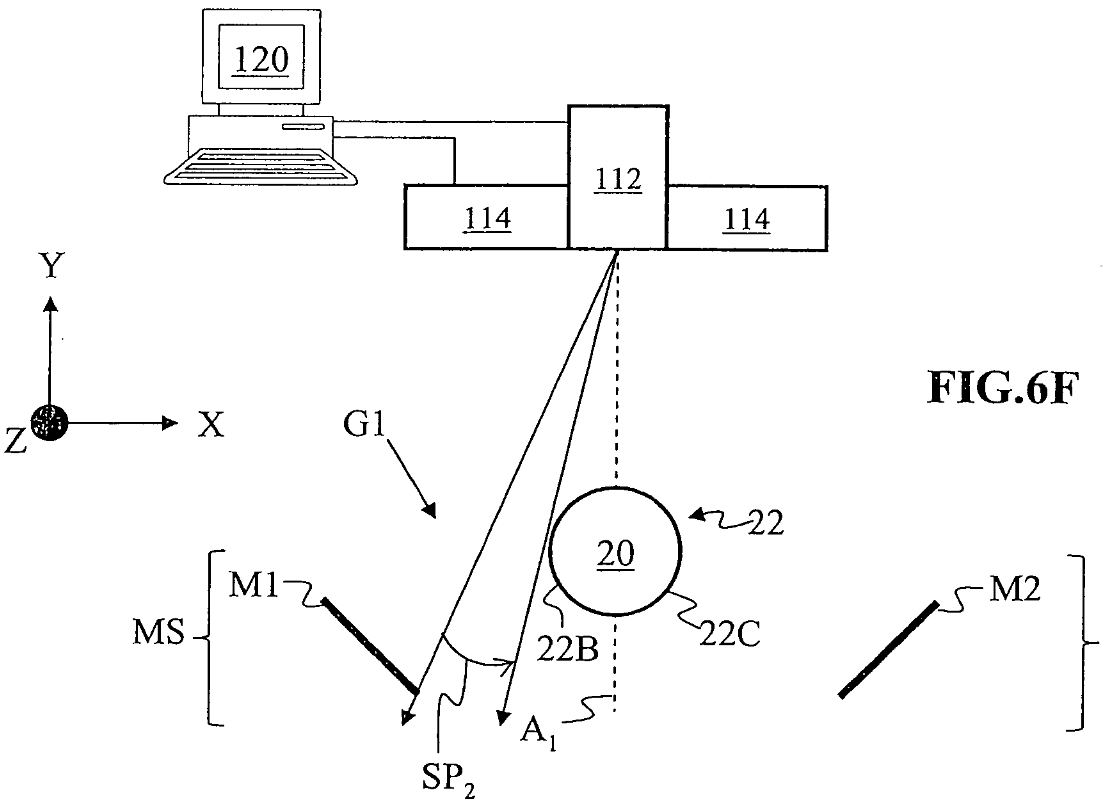

120
112
114
114
Y
X
Z
G1
20
22
M1
M2
MS
22B
22C
A1
SP2

FIG.6F

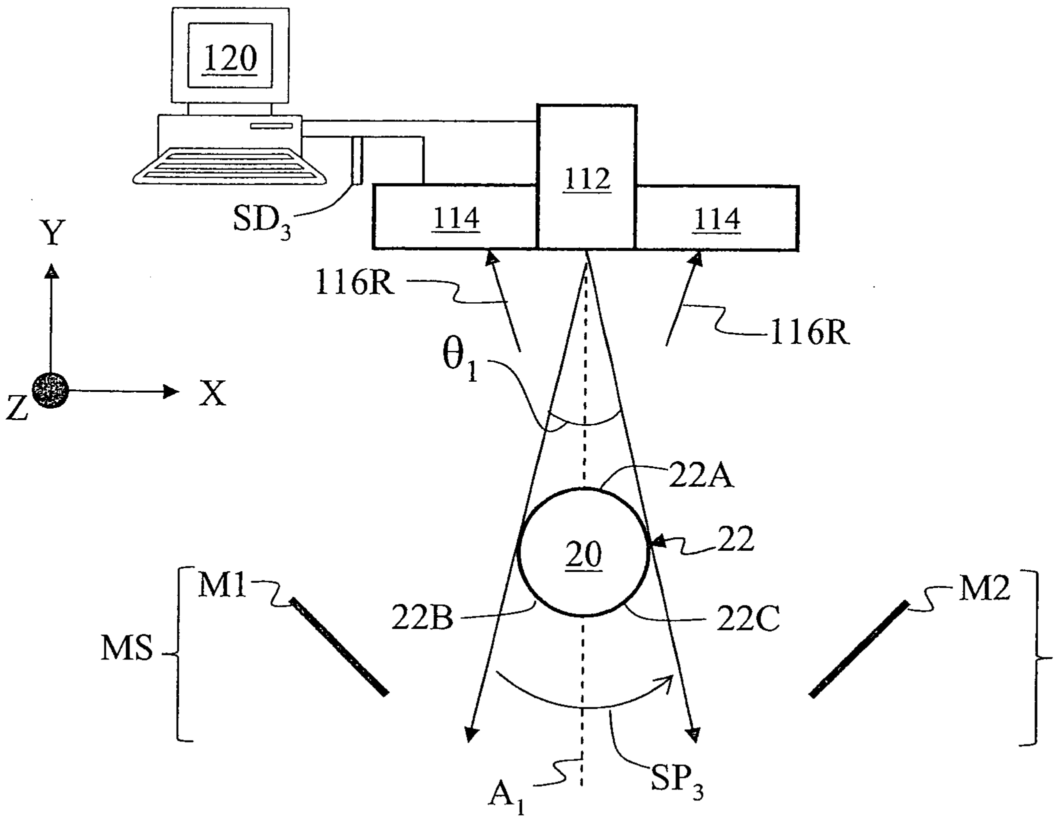

120
SD3
112
114
114
Y
116R
116R
θ1
Z
X
22A
22
20
M1
M2
MS
22B
22C
A1
SP3

FIG. 6G

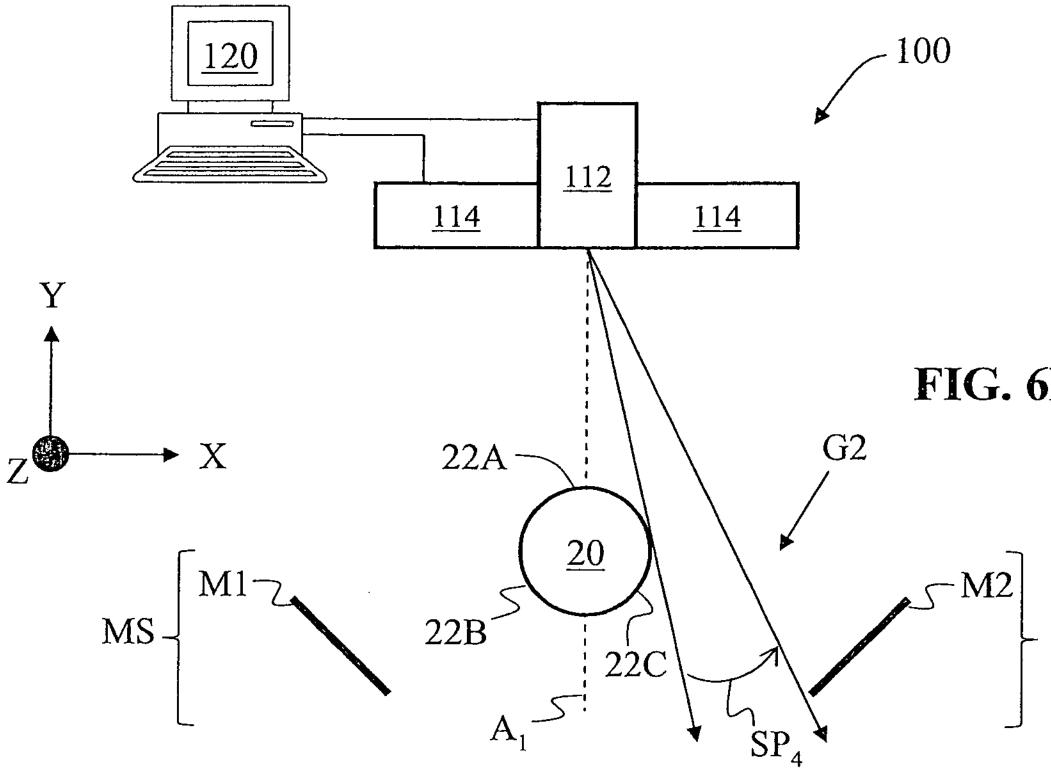

120
100
112
114
114
Y
X
Z
G2
22A
20
M1
M2
MS
22B
22C
A1
SP4

FIG. 6H

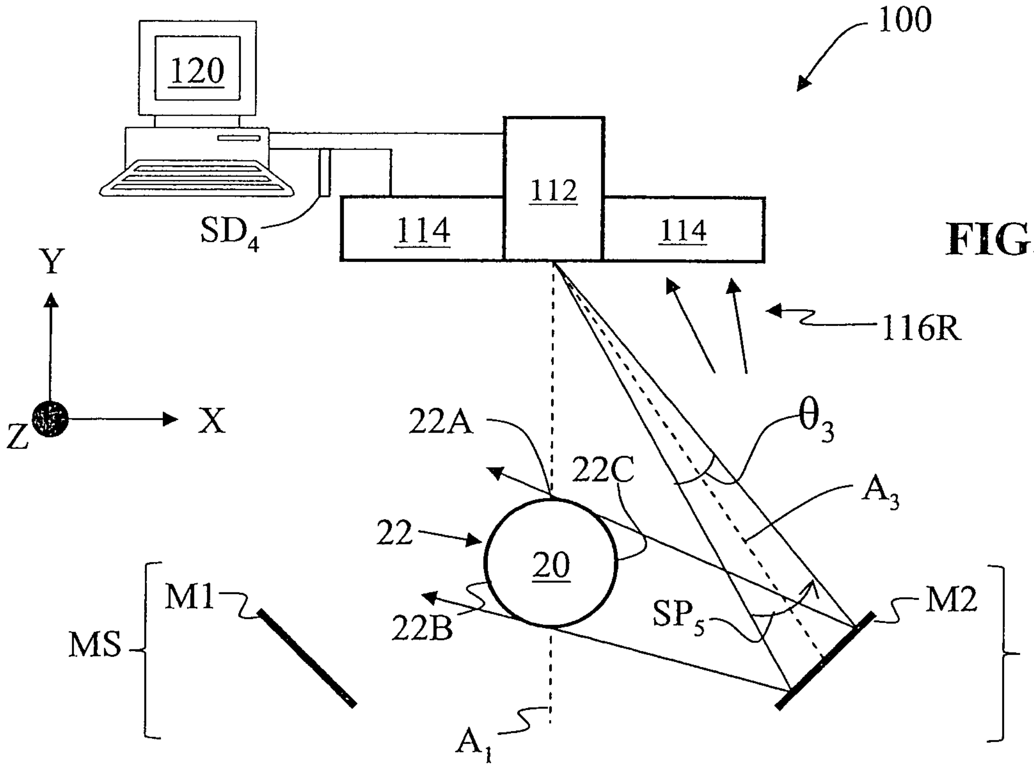

120
100
112
114
114
SD4
Y
X
Z
116R
θ3
22A
22C
A3
22
20
M1
M2
MS
SP5
22B
A1

FIG. 6I

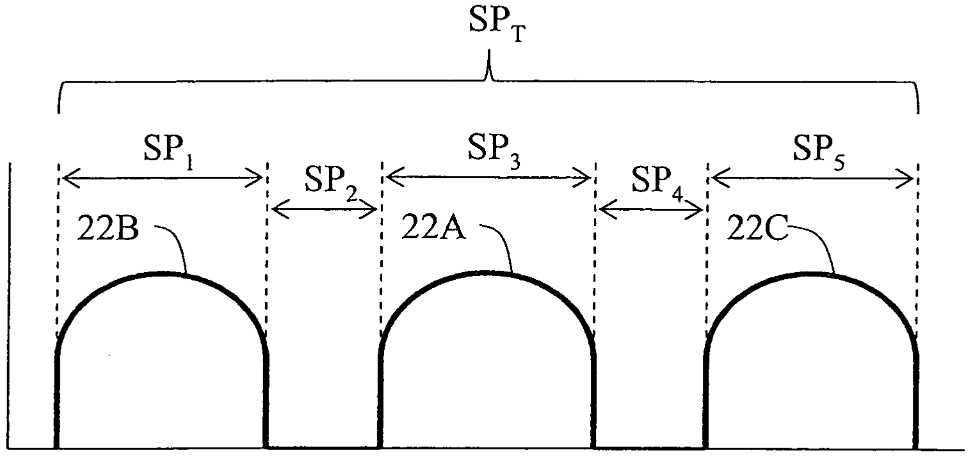


FIG. 7A

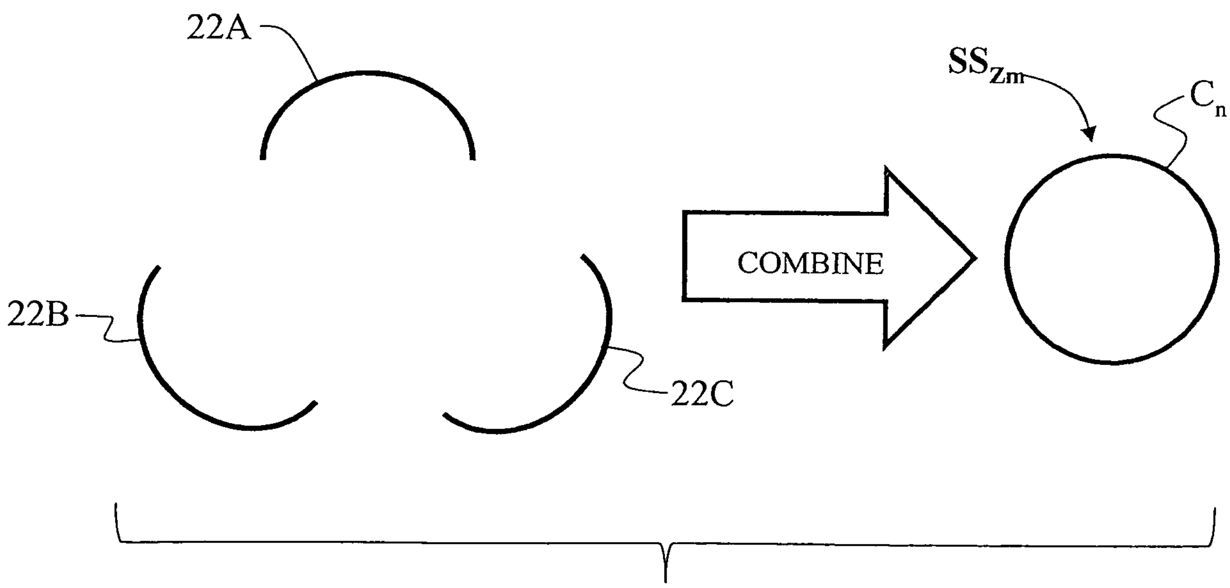


FIG. 7B

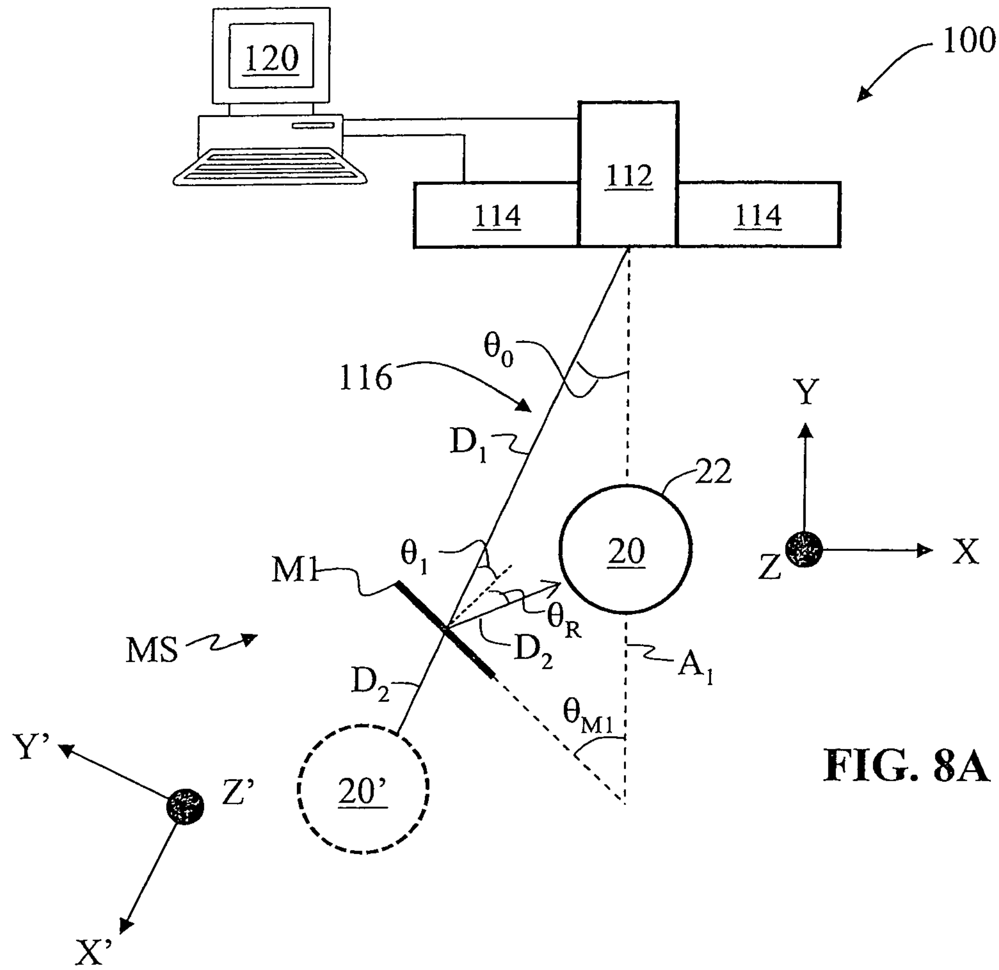

120
100
112
114
114
θ0
116
D1
Y
22
20
θ1
M1
θR
Z
X
MS
D2
A1
D2
θM1
Y'
Z'
20'
X'

FIG. 8A

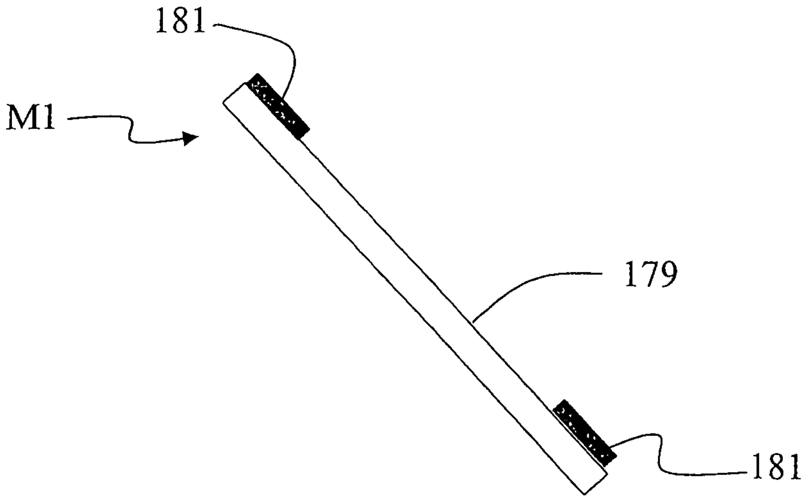

181
M1
179
181

FIG. 8B

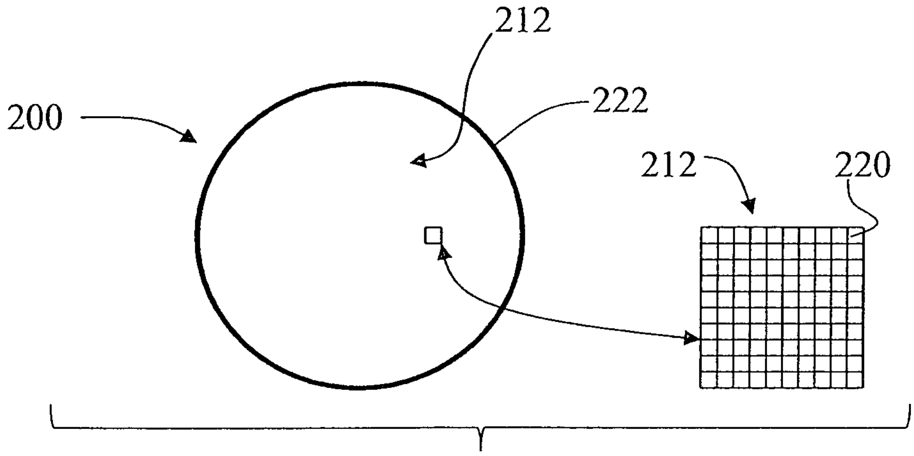


FIG. 9A

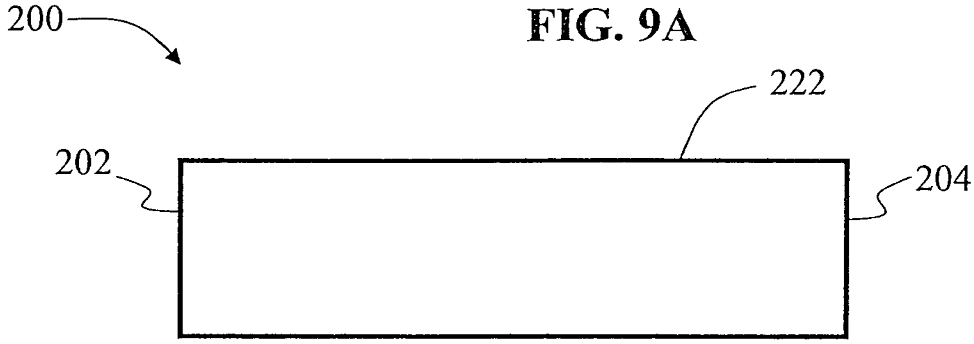


FIG. 9B

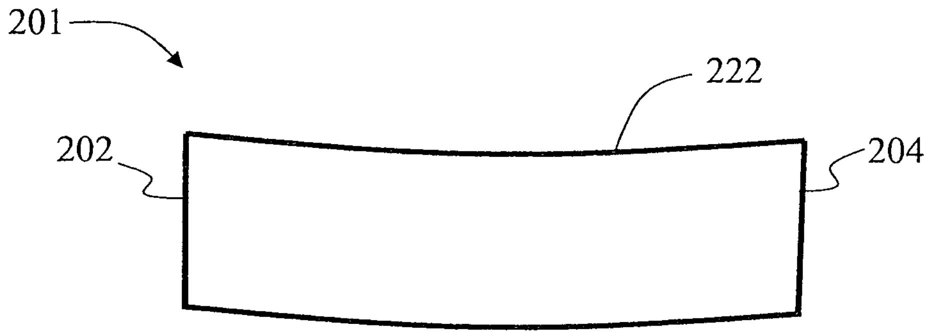


FIG. 9C

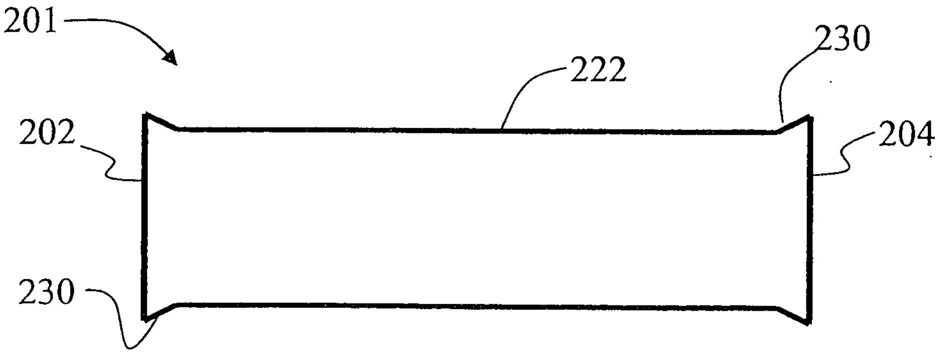


FIG. 9D

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/012194

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01B11/24 G01N21/952

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)
G01B G02B G01N

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 practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 203 673 A (BUCKSON GERALD I [US]) 20 May 1980 (1980-05-20) abstract column 3, line 6 - column 8, line 8 figures 2-4,7 -----	1-21
X	US 6 122 045 A (PIKE JOHN NAZARIAN [US] ET AL) 19 September 2000 (2000-09-19) abstract column 3, line 38 - column 6, line 61 column 9, line 63 - column 12, line 39 claims 1,14,16 figures 1,2,6-9 -----	1-21
X,P	EP 1 901 030 A (MICRO EPSILON OPTRONIC GMBH [DE]) 19 March 2008 (2008-03-19) the whole document -----	1-21

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 January 2009	30/01/2009

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Kokkonen, Jukka

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2008/012194

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 4203673	A	20-05-1980	NONE	
US 6122045	A	19-09-2000	NONE	
EP 1901030	A	19-03-2008	NONE	