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(54) **DETERMINING GEOMETRIC CHARACTERISTICS OF REFLECTIVE SURFACES**

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CPC ***G01B 11/24*** (2013.01)

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(Continued)

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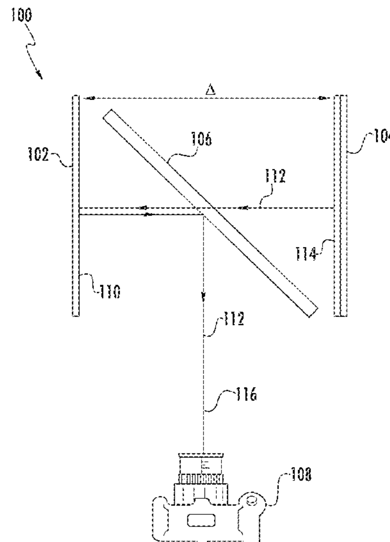
(57) **ABSTRACT**

Illustrative embodiments of determining geometric characteristics of reflective surfaces are disclosed. In at least one illustrative embodiment, a method of determining geometric characteristics of reflective surfaces includes sensing electromagnetic waves with a sensor, where the electromagnetic waves have been reflected off a reflective surface of a specimen from a target structure including a feature point. The method further includes determining a displacement of the feature point of the target structure indicated by the sensed electromagnetic waves relative to reference data indicating a reference location for the feature point and determining a surface slope of a point of the reflective surface based on the determined displacement of the feature point of the target structure.

20 Claims, 10 Drawing Sheets



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(58) **Field of Classification Search**
USPC 356/612
See application file for complete search history.

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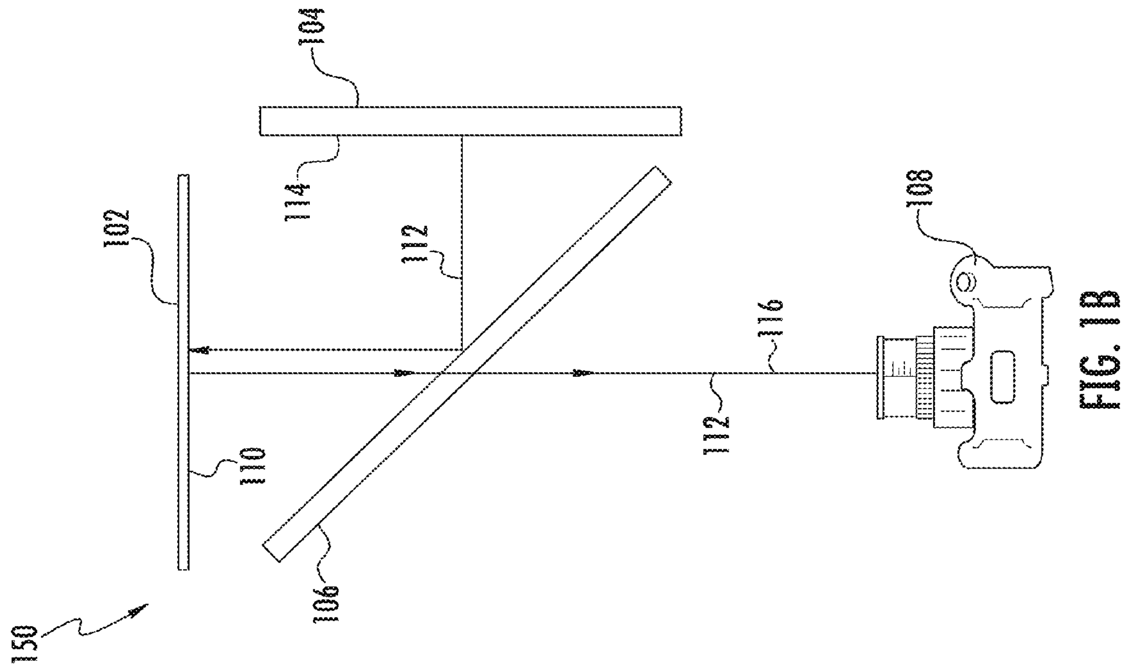


FIG. 1B

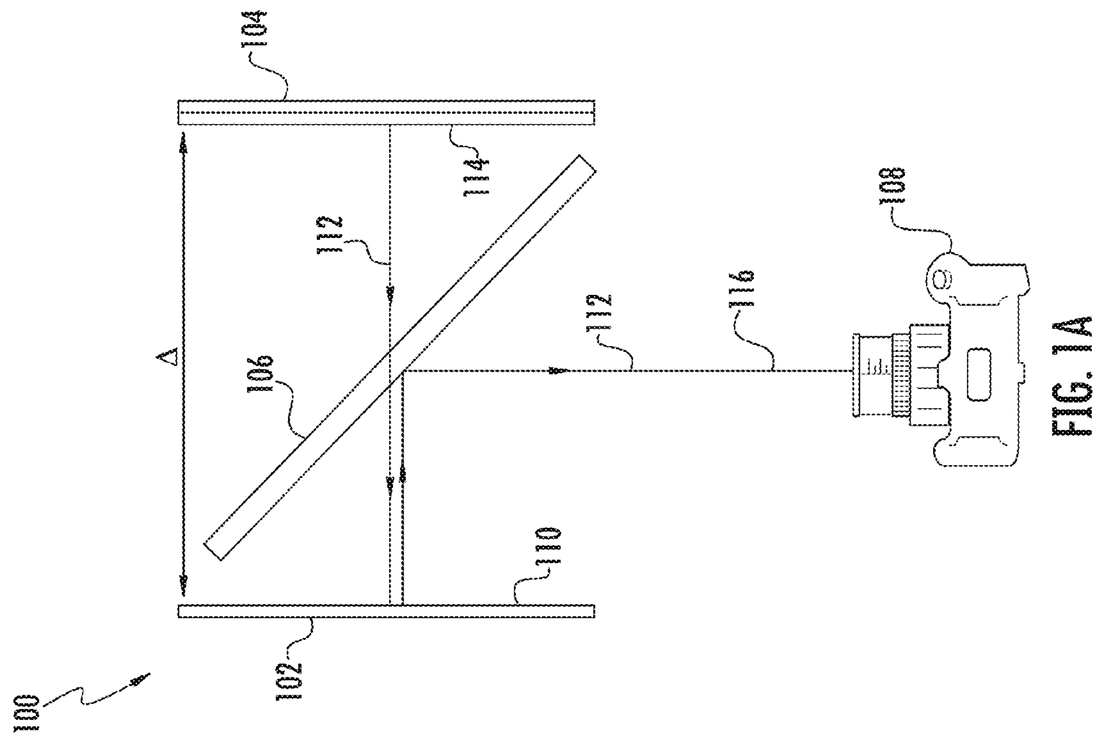


FIG. 1A

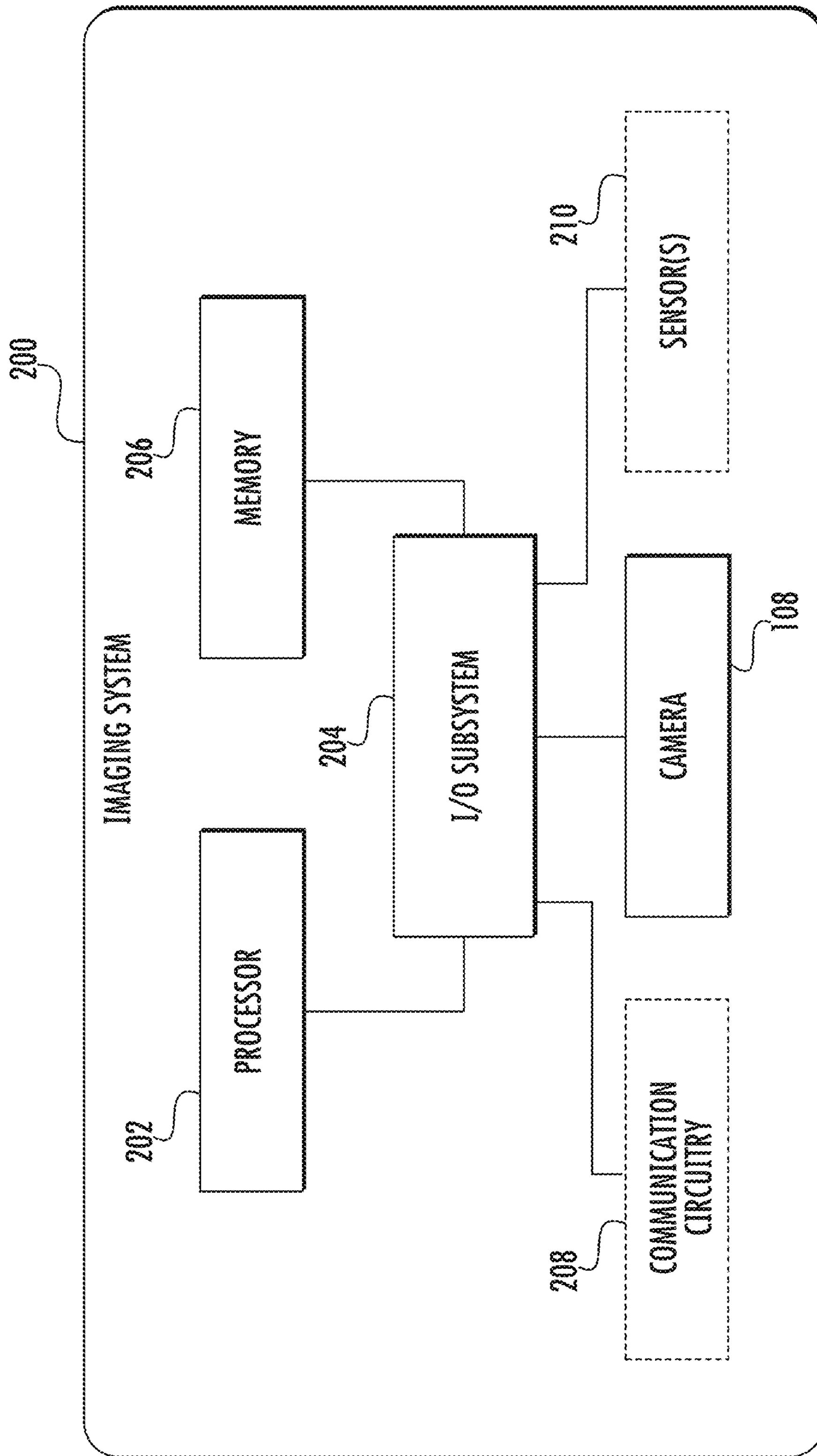


FIG. 2

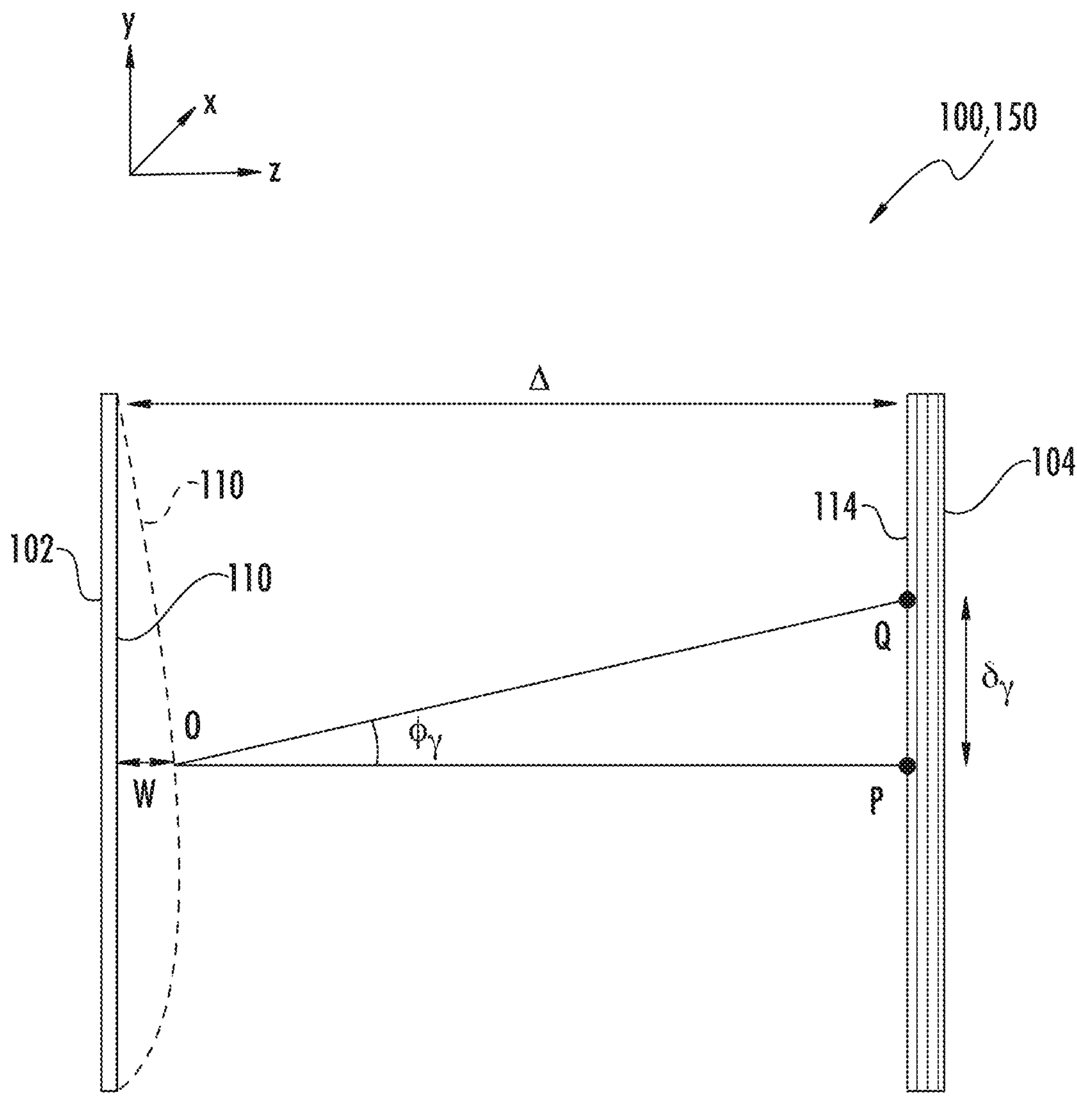


FIG. 3A

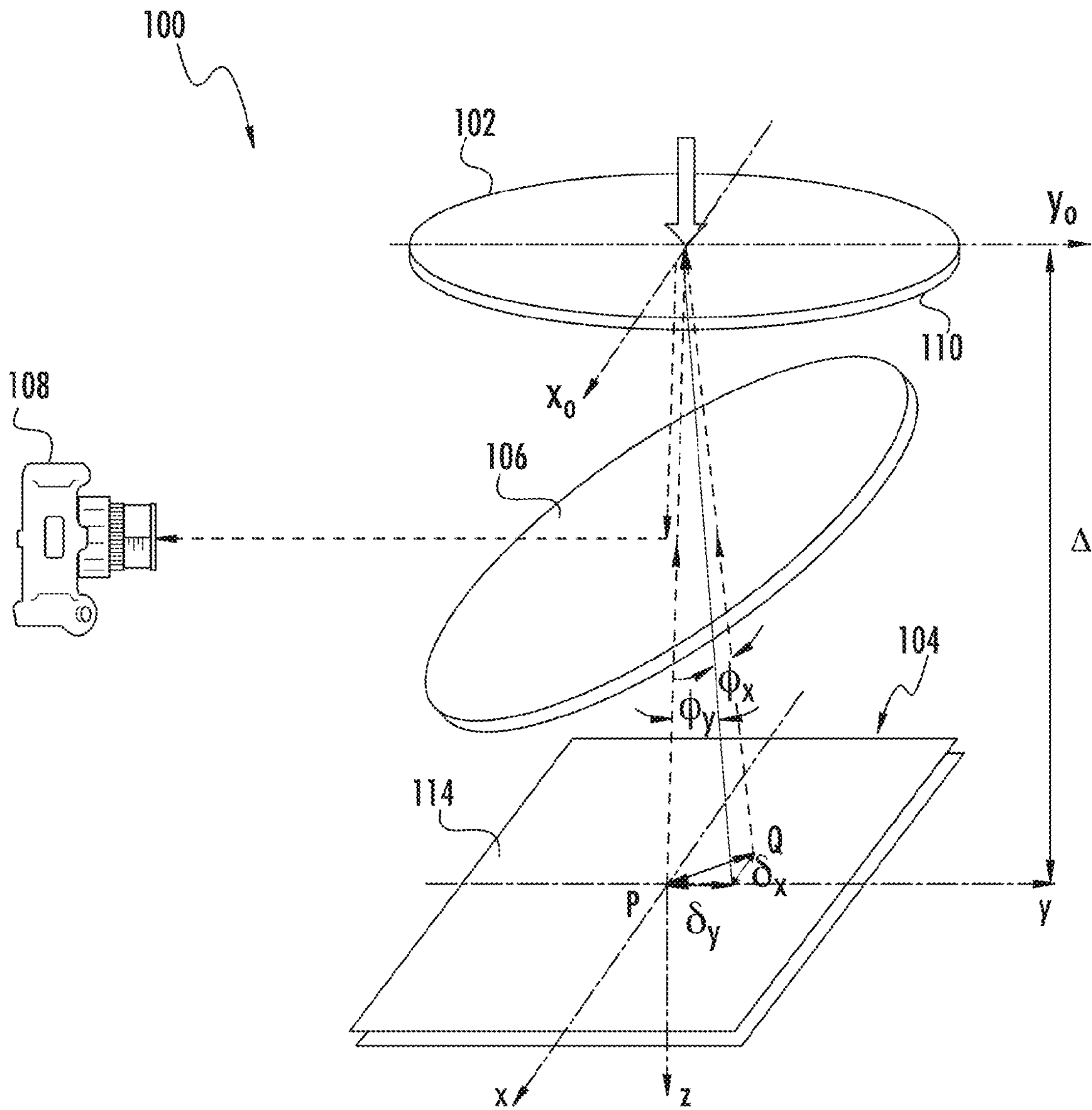


FIG. 3B

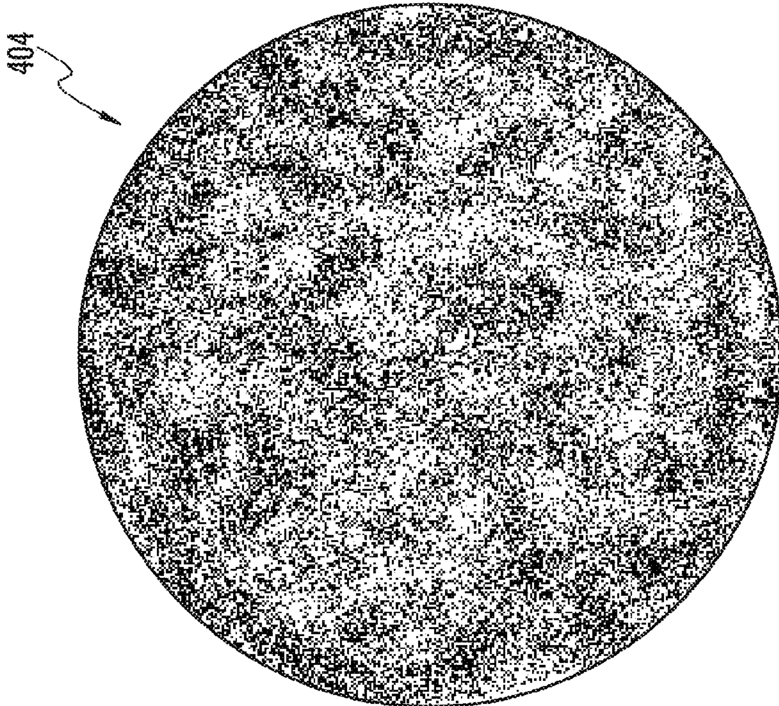


FIG. 4B

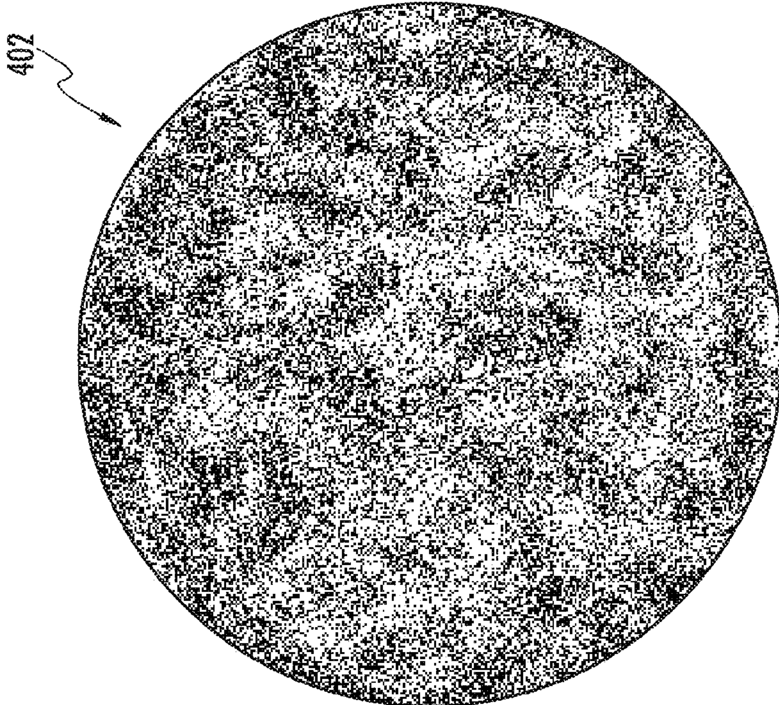


FIG. 4A

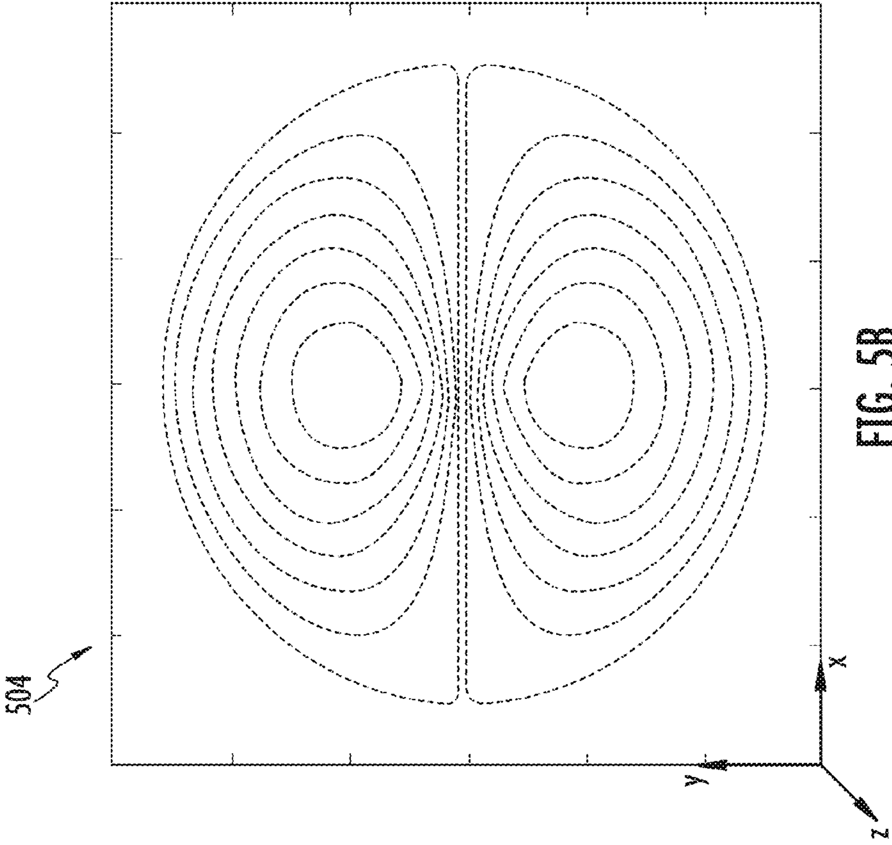


FIG. 5B

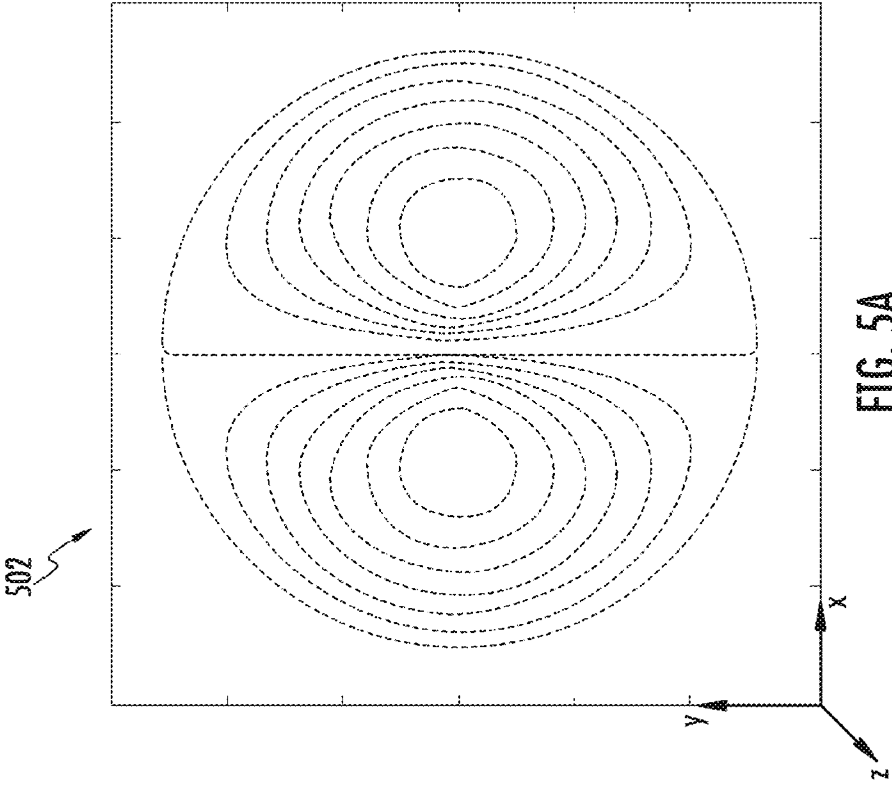


FIG. 5A

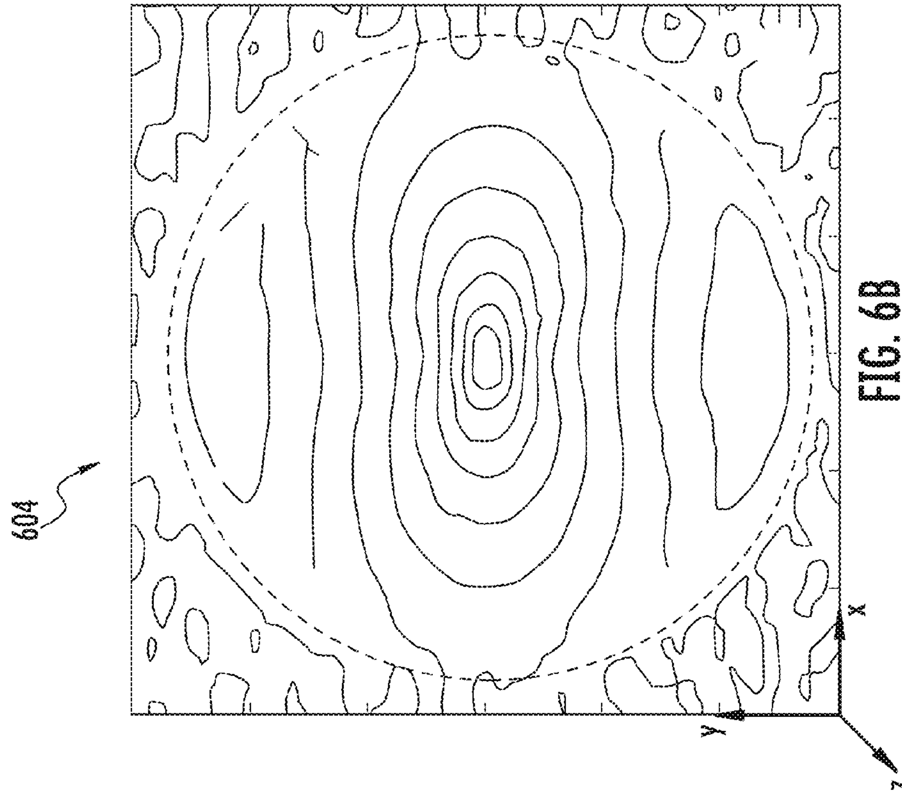


FIG. 6B

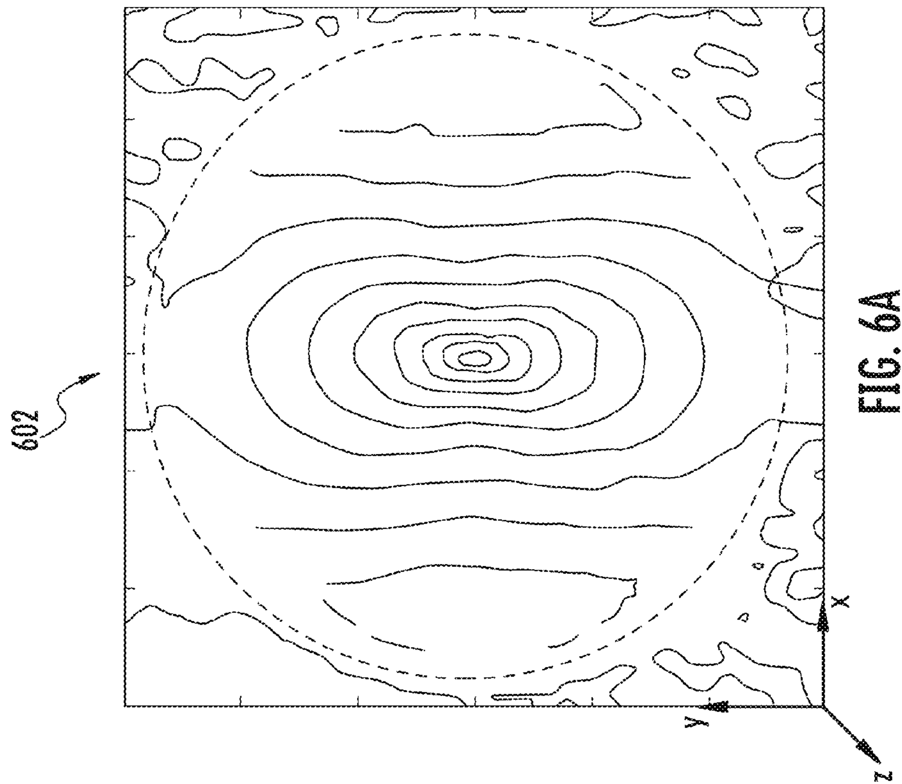


FIG. 6A

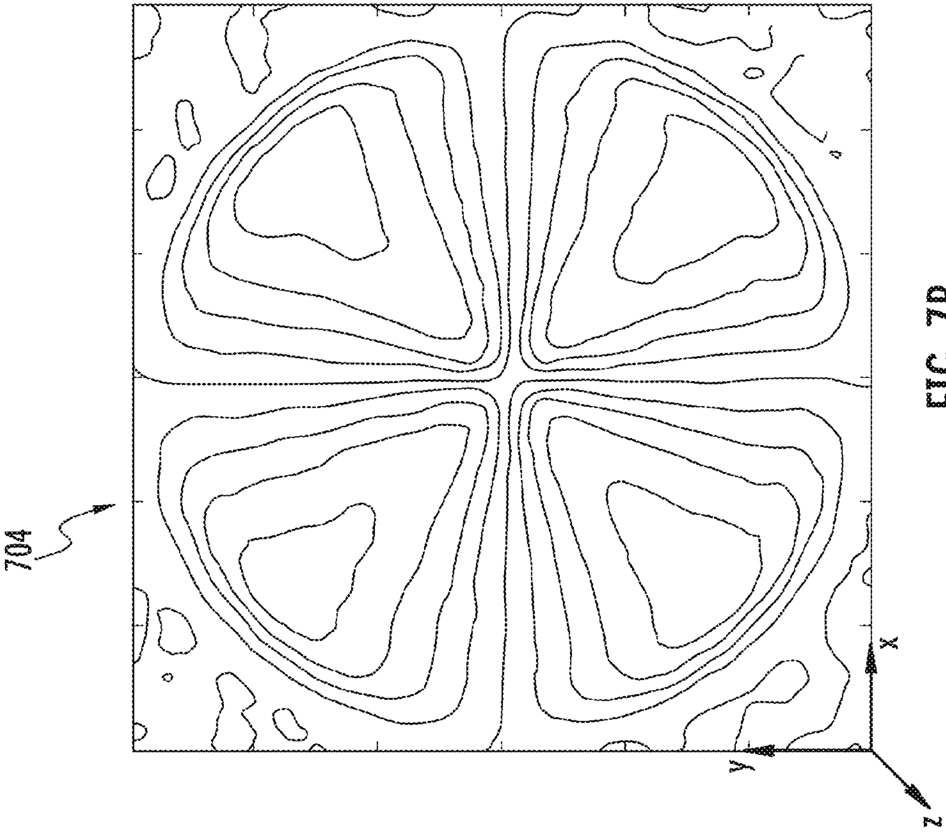


FIG. 7B

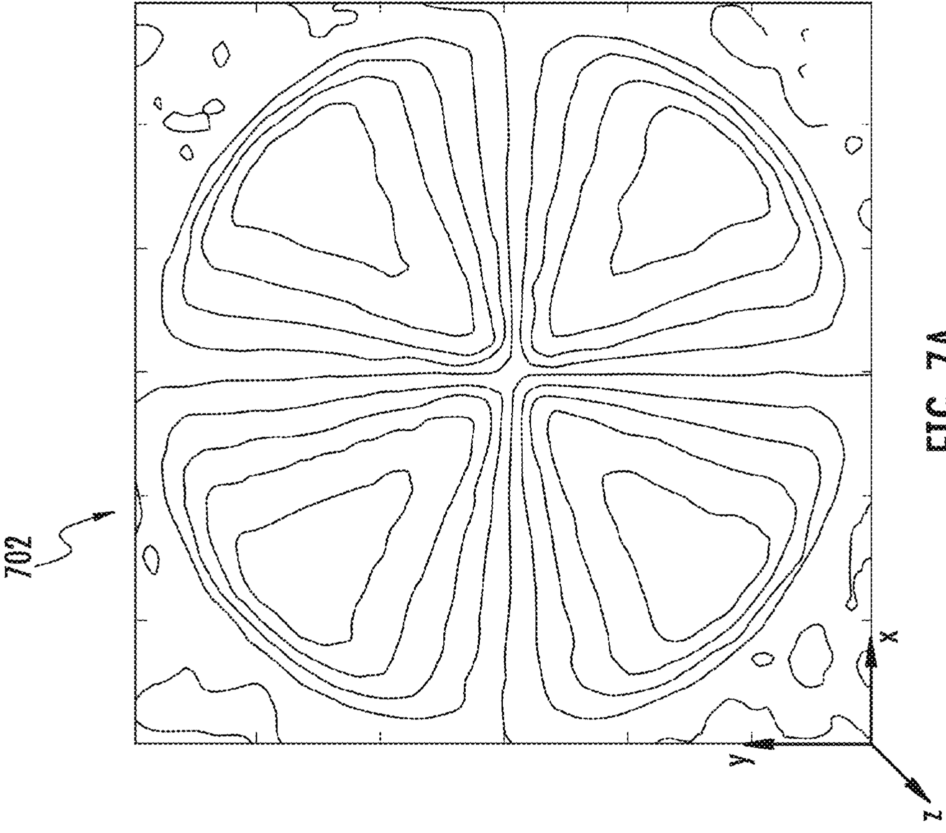


FIG. 7A

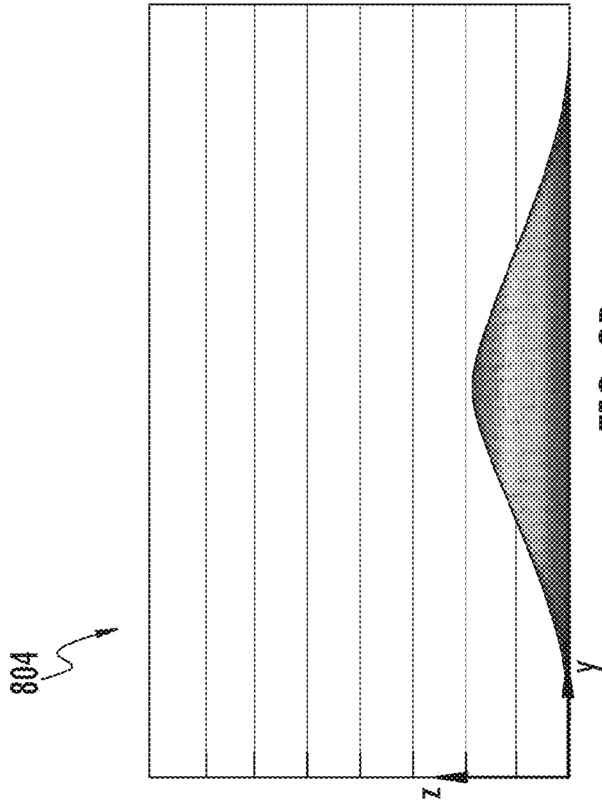


FIG. 8B

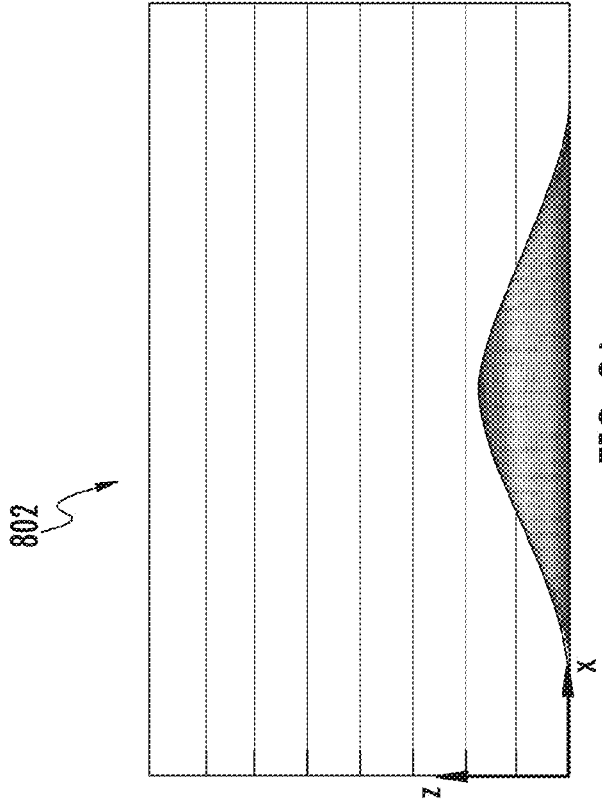
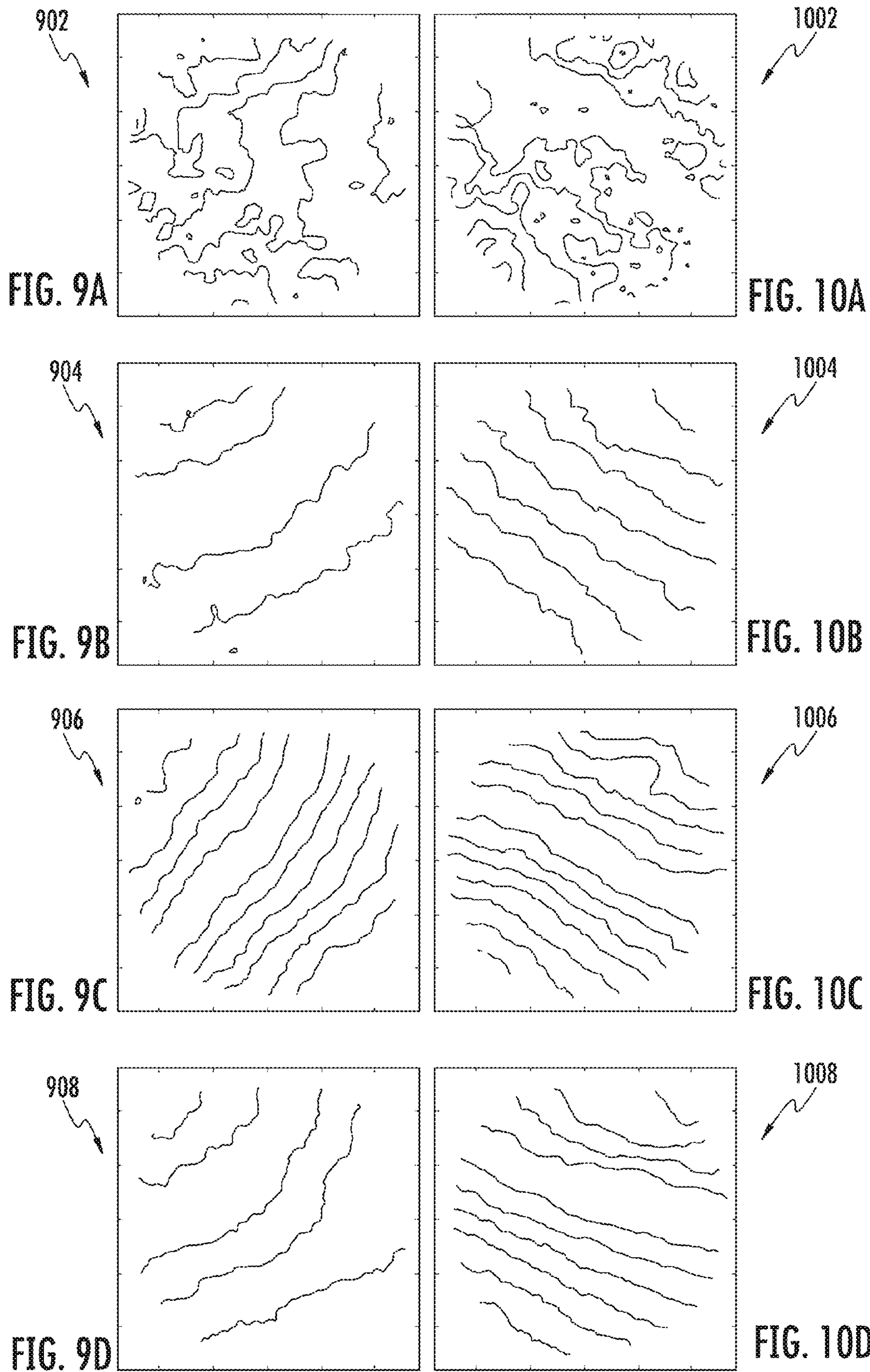


FIG. 8A


902
1002
FIG. 9A
FIG. 10A
904
1004
FIG. 9B
FIG. 10B
906
1006
FIG. 9C
FIG. 10C
908
1008
FIG. 9D
FIG. 10D

DETERMINING GEOMETRIC CHARACTERISTICS OF REFLECTIVE SURFACES

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority under 35 U.S.C. §119(e) to U.S. Provisional Patent Application Ser. No. 61/844,157, filed on Jul. 9, 2013, and entitled "A Full-Field Digital Gradient Sensing Method for Optically Measuring Slopes and Curvatures of Thin Reflective Structures," the entire disclosure of which is incorporated herein by reference.

BACKGROUND

Physical structures and, in particular, thin structures in aerospace, electronics, and other industries are often subjected to thermo-mechanical stresses and/or other loads that cause the surface of those structures to change. In other words, applied loads cause the surface topography and therefore the curvature of the structures to change. Such applied loads may be the result of a process over time (e.g., the drying of an epoxy or coating on the surface of the structure) or an instantaneously applied thermal or mechanical load (e.g., from another object applying a mechanical force to the structure over a particular region). Oftentimes, it is critical to a particular application to know whether the surface of the structure is flat or otherwise.

In the past, optical metrology tools such as shearing interferometry and moiré-based methods have been employed to quantify surface slopes and curvatures of a structure's surface. However, those methods generally require special conditions and/or destructive or contact testing of the structure to make such a determination. For example, depending on the particular implementation, the method may require Ronchi rulings or grid patterns, monochromatic coherent (e.g., laser) light, transparent structures, and/or coating the structure with a thin metallic film or other substance (e.g., having a specific pattern) in order to deduce the surface geometry.

SUMMARY

According to one aspect of the present disclosure, a system for determining geometric characteristics of reflective surfaces may include a specimen, a target structure, an imaging system, and a beam splitter. The specimen may include a reflective surface, and the target structure may include a plurality of feature points configured to be reflected in the reflective surface. The imaging system may include a camera configured to capture an image of the reflective surface, the captured image including the plurality of features points of the target structure. The beam splitter may configured to direct light from the target structure to the reflective surface and from the reflective surface to the camera.

In some embodiments, the imaging system may be further configured to determine one or more surface slopes of the reflective surface based on displacements of the plurality of feature points in the captured image relative to a reference image including the plurality of feature points. The imaging system may determine the one or more surface slopes of the reflective surface by applying a digital image correlation algorithm to the captured image and the reference image. In some embodiments, the imaging system may be further configured to determine a directional curvature of the reflective surface at one or more points based on the one or more surface slopes. The imaging system may be further configured to determine a twist curvature of the reflective surface at one or more points based on the one or more surface slopes and/or determine a surface topography of the reflective surface at one or more points based on the one or more surface slopes.

In some embodiments, the camera is configured to capture a first image of the reflective surface with an applied load and a second image of the reflective surface without the applied load, wherein the second image is the reference image. At least one of the target structure or the reflective surface may be positioned on a plane that is not perpendicular to an optical axis of the camera. The reflective surface may be configured to reflect light of one or more wavelengths from the target structure to the camera. The beam splitter may be positioned at a forty-five degree angle relative to each of the reflective surface, the target structure, and an optical axis of the camera.

According to another aspect of the present disclosure, a method of determining geometric characteristics of reflective surfaces may include capturing an image of a reflective surface of a specimen with a camera, wherein a plurality of feature points of a target structure are reflected in the reflective surface such that the plurality of features points are present in the captured image, and determining one or more surface slopes of the reflective surface based on displacements of the plurality of feature points in the captured image relative to a reference image including the plurality of feature points. In some embodiments, determining the one or more surface slopes of the reflective surface may include applying a digital image correlation algorithm to the captured image and the reference image and/or determining the one or more slopes based on a distance traveled by light directed from the target structure to the specimen.

In some embodiments, the distance traveled by the light directed from the target structure to the specimen may be equal to a sum of a distance between the target structure and a beam splitter and a distance between the beam splitter and the specimen. The method may further include determining at least one of a curvature or a surface topology of the reflective surface based on the one or more surface slopes. In some embodiments, the method may further include determining displacements of the plurality of features points in each of two perpendicular directions within a plane coincident with the target structure.

According to yet another aspect of the present disclosure a method for determining geometric characteristics of reflective surfaces may include sensing electromagnetic waves with a sensor, wherein the electromagnetic waves have been reflected off a reflective surface of a specimen from a target structure including a feature point, determining a displacement of the feature point of the target structure indicated by the sensed electromagnetic waves relative to reference data indicating a reference location for the feature point, and determining a surface slope of a point of the reflective surface based on the determined displacement of the feature point of the target structure.

In some embodiments, sensing the electromagnetic waves may include capturing an image with a camera. The method may further include determining at least one of a curvature or a surface topology of the reflective surface based on the surface slope. In some embodiments, determining the surface slope of the point of the reflective surface may include

determining the surface slope based on a distance traveled by electromagnetic waves directed from the target structure to the specimen.

BRIEF DESCRIPTION OF THE DRAWINGS

The concepts described in the present disclosure are illustrated by way of example and not by way of limitation in the accompanying figures. For simplicity and clarity of illustration, elements illustrated in the figures are not necessarily drawn to scale. For example, the dimensions of some elements may be exaggerated relative to other elements for clarity. Further, where considered appropriate, reference labels have been repeated among the figures to indicate corresponding or analogous elements. The detailed description particularly refers to the accompanying figures in which:

FIGS. **1**A and **1**B are simplified schematic diagrams of two embodiments of a system for determining geometric characteristics of reflective surfaces;

FIG. **2** is a simplified block diagram of an imaging system employed by the system of FIGS. **1**A and **1**B;

FIG. **3**A is a simplified two-dimensional spatial diagram illustrating an optical path between a target structure and a specimen of the systems of FIGS. **1**A and **1**B;

FIG. **3**B is a simplified three-dimensional spatial diagram illustrating an optical path from the target structure to the camera of the system of FIG. **1**A;

FIGS. **4**A and **4**B are exemplary images of the target structure captured by the camera of the systems of FIGS. **1**A and **1**B;

FIGS. **5**A and **5**B are simplified contour diagrams of determined slopes of a surface of the specimen of FIGS. **1**A and **1**B;

FIGS. **6**A and **6**B are simplified contour diagrams of determined curvatures of the surface of the specimen of FIGS. **1**A and **1**B;

FIGS. **7**A and **7**B are simplified contour diagrams of determined twist curvatures of the surface of the specimen of FIGS. **1**A and **1**B;

FIGS. **8**A and **8**B are simplified two-dimensional diagrams of a determined surface topography of the surface of the specimen of FIGS. **1**A and **1**B; and

FIGS. **9**A-**9**D and **10**A-D are simplified contour diagrams of determined slopes of the surface of the specimen of FIGS. **1**A and **1**B monitored over a period of time during a process applied to the specimen.

DETAILED DESCRIPTION OF THE DRAWINGS

While the concepts of the present disclosure are susceptible to various modifications and alternative forms, specific exemplary embodiments thereof have been shown by way of example in the drawings and will herein be described in detail. It should be understood, however, that there is no intent to limit the concepts of the present disclosure to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present disclosure.

References in the specification to "one embodiment," "an embodiment," "an example embodiment," etcetera, indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to effect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

Referring now to FIG. **1**A, a simplified schematic diagram of one illustrative embodiment of a system **100** for determining geometric characteristics of reflective surfaces is shown. As shown, the illustrative system **100** includes a specimen **102**, a target structure **104**, a beam splitter **106**, and a camera **108**. In use, as discussed in more detail below, the system **100** is configured to determine various geometric characteristics of a reflective surface **110** of the specimen **102**. For example, the system **100** may determine the slope, curvature, twist, and/or surface topography of the specimen **102** resulting from an applied load (e.g., a process, environment-based load, mechanical load, or a combination thereof). More specifically, in the illustrative embodiment, the system **100** employs optical metrology (i.e., uses light as a measuring probe) to determine microscopic angulations associated with a slope of the reflective surface **110**. In other embodiments, the system **100** may utilize photogeometry or another suitable technique for using electromagnetic waves (e.g., light) as a measuring probe.

In some embodiments, the system **100** may determine the amount by which the surface **110** of the specimen **102** has deformed relative to a flat surface, whereas in other embodiments, the system **100** may determine the amount by which the surface **110** has deformed relative to some other reference shape's surface (e.g., a previous shape of the specimen **102** prior to undergoing a process). In the illustrative embodiment, the system **100** makes those calculations and/or determinations using an imaging system **200** (see FIG. **2**). As described below, in some embodiments, the imaging system **200** may include the camera **108**, may be communicatively coupled to the camera **108**, or may be embodied as the camera **108**.

It should be appreciated that, in the illustrative embodiment, the system **100** determines the geometric characteristics of the reflective surface **110** of the specimen **102** without applying a coating (e.g., grid pattern) or otherwise damaging the specimen **102**. As such, in such embodiments, the specimen **102** may be used for its designed purpose subsequent to the system **100** determining its geometric characteristics.

The specimen **102** may be embodied as any structure having a reflective surface **110** capable of reflecting an information carrier **112** (e.g., light) and that is otherwise suitable for use with the system **100** as described herein. As indicated above, the system **100** determines (with the imaging system **200**) the geometric characteristics of the reflective surface **110** of the specimen **102**. Accordingly, the specimen **102** may be any physical structure having a reflective surface **110** for which one may be interested in determining its shape. For example, in various embodiments, the specimen **102** may be embodied as a silicon wafer, a mirror, a solar panel, an antenna, or another reflective structure. In some embodiments, the reflective surface **110** of the specimen **102** is generally flat when a load (e.g., thermodynamic or mechanical) is not applied to the specimen **102**. Additionally, the reflective surface **110** may be nominally reflective relative to the wavelength(s) of light **112** directed from the target structure **104** to the specimen **102** and to the camera **108**. For example, in some embodiments, the "roughness" of the reflective surface **110** is less than those wavelengths of light **112**.

Although the system **100** is generally described herein as involving reflected light **112**, in other embodiments, the

information carrier may be an electromagnetic wave **112** of any combination of wavelengths (e.g., a singleton or linear combination of wavelengths) provided that the reflective surface **110** (e.g., by itself or by means of coating it with a reflective material) can reflect that combination of electromagnetic waves **112** and its intensity pattern can be recorded by the camera **108** or another suitable sensor **210**. In such embodiments, it should be appreciated that the system **100** includes a target structure **104** having corresponding features that can be reflected in the reflective surface **110** by those particular electromagnetic waves **112** (e.g., at those combinations of wavelengths) and a sensor **210** that is configured to sense and process (e.g., digitize) those electromagnetic waves **112**. Additionally, a surface that appears visually to be a matte or non-reflective surface may be reflective at other wavelengths. For example, a black matte finished surface may not reflect "white light" but likely does reflect infrared waves. Accordingly, the system **100** may be configured for use with different electromagnetic waves **112** and corresponding target structures **104** (e.g., depending on the particular specimen **102**). For ease of discussion, the system **100** is described herein primarily with respect to light **112** and corresponding light reflections; however, it should be appreciated that the techniques described herein may be similarly employed with different electromagnetic waves **112** and corresponding sensors **210** and target structures **104**.

The illustrative target structure **104** includes a plurality of distinguishable feature points that may be captured in an image (by the camera **108**) such that the captured image/data may be compared to a reference image/data to determine the displacement of the feature point locations in the captured image relative to their corresponding locations in the reference image. The target structure **104** may be illuminated by a broad-band white light source. In some embodiments, the target structure **104** is embodied as a target plate or subplane that is coated with a random black and white speckle "pattern" on a surface **114** facing the beam splitter **106** (see, for example, FIGS. **4**A-B). In particular, in the illustrative embodiment, the feature points on the target structure **104** are nonlinearly and randomly distributed across the target structure **104**. In other words, when photographed, the target structure **104** may be captured as a stochastic grayscale image of varying intensities. As discussed above, the target structure **104** may include feature points that may be reflected in the reflective surface **110** of the specimen **102** depending on the particular electromagnetic waves **112** employed with the system **100**. For example, in embodiments involving infrared (IR) light **112**, the surface **114** of the target structure **104** includes an "IR signature" that serves as the speckles or feature points.

The beam splitter **106** may be embodied as any structure configured to direct light **112** partially from the target structure **104** to the reflective surface **110** of the specimen **102** and from the reflective surface **110** of the specimen **102** to the camera **108**. That is, the beam splitter **106** is configured to allow a portion of light **112** (e.g., half) to pass through the beam splitter **106** and to reflect another portion of light **112** off the beam splitter **106**. For example, in some embodiments, the beam splitter **106** may be embodied as a partial mirror. The system **100** is configured to permit the camera **108** to capture images of the target surface **114** (e.g., the speckle pattern) reflected in the reflective surface **110** of the specimen **102** by virtue of light **112** passing through the beam splitter **106**. In embodiments of the system **100** in which other electromagnetic waves **112** are utilized, the beam splitter **106** is configured to perform similar functions.

In the illustrative embodiment, the beam splitter **106** is positioned at a forty-five degree angle relative to each of the reflective surface **110** of the specimen **102** (in an unloaded state) and the surface **114** of the target structure **104** as shown in FIG. **1**A; however, in other embodiments, the beam splitter **106** may be positioned in another suitable orientation. In yet other embodiments, it will be appreciated that the specimen **102**, the target structure **104**, and the camera **108** may be oriented relative to one another such that the beam splitter **106** may be omitted from the system **100** and the techniques described herein may still be employed (e.g., using slightly modified geometric calculations).

The camera **108** may be embodied as any peripheral or integrated device suitable for capturing images, such as a still camera, a video camera, or other device capable of capturing images. For example, in embodiments involving IR light **112**, the camera **108** may be embodied as an IR camera or be otherwise configured to capture the IR light **112**. Further, in embodiments in which other electromagnetic waves **112** are utilized, the camera **108** may be replaced or supplemented with one or more sensors **210** configured to sense those waves **112**. In the illustrative embodiment, the beam splitter **106** is positioned at a forty-five degree angle relative to an optical axis **116** of the camera **108** as shown in FIG. **1**A. As described below, in some embodiments, the camera **108** may form a portion of an imaging system **200**, which is not shown in FIG. **1**A for clarity.

As shown in FIG. **1**A, in the illustrative system **100**, the target structure **104** is oriented within a plane that is parallel to a corresponding plane within which the reflective surface **110** of the specimen (in an unloaded state) is oriented and that is parallel to the optical axis **116** of the camera **108**. Further, neither the target structure **104** nor the specimen **102** is positioned along the optical axis **116** of the camera **108**. The distance, Δ, between the reflective surface **110** of the specimen **102** and the surface **114** of the target structure **104** is predetermined in the illustrative embodiment and may vary depending on the particular embodiment. The distance, Δ, may be used in determining various geometric characteristics of the reflective surface **110** as described below.

It should be appreciated that a system **150** having the configuration shown in FIG. **1**B may also be used to employ the techniques described herein. The system **150** of FIG. **1**B may use the same components as the system **100** of FIG. **1**A but arranged in a different orientation. In particular, in the illustrative system **150**, the optical axis **116** of the camera **108** passes through the specimen **102**, and the reflective surface **110** (in an unloaded state) is oriented orthogonally to the optical axis **116**. Additionally, the target surface **114** is positioned within a plane parallel to the optical axis **116**. It should be appreciated that, in each of the systems **100**, **150**, the distance, Δ, may be determined as the sum of the distance between the target surface **114** and the beam splitter **106** and the distance between the beam splitter **106** and the reflective surface **110**. For ease of discussion, the techniques may be described herein with reference to the system **100** of FIG. **1**A; however, it should be appreciated that the techniques equally apply to the system **150** of FIG. **1**B. Further, in some embodiments, the components of the system **100** may be positioned in other suitable orientations relative to one another (e.g., using angles other than ninety and forty-five degrees).

As indicated above, the system **100** may determine various geometric characteristics of the reflective surface **110** of the specimen (e.g., slopes, curvatures, twists, topology, etc.) with the imaging system **200**. Referring now to FIG. **2**, the

illustrative imaging system **200** may be embodied as any type of computing device(s) capable of performing the functions described herein. The imaging system **200** includes a number of electronic components commonly associated with imaging systems. In the illustrative embodiment, the imaging system **200** includes a processor **202**, an input/output ("I/O") subsystem **204**, a memory **206**, and the camera **108**. As described below, the imaging system **200** may also include communication circuitry **208** (e.g., to communicate with remote devices). Further, in some embodiments, the imaging system **200** may include one or more sensors **210** (e.g., in addition to, or in place of, the camera **108**). It will be appreciated that the imaging system **200** may include additional or different components, such as those commonly found in an imaging system and/or computing device. Additionally, in some embodiments, one or more of the illustrative components of the imaging system **200** may be incorporated in, or otherwise form a portion of, another component of the imaging system **200** (e.g., as with a microcontroller).

The processor **202** of the imaging system **200** may be embodied as any type of processor(s) capable of performing the functions described herein. For example, the processor **202** may be embodied as one or more single or multi-core processors, digital signal processors, microcontrollers, or other processors or processing/controlling circuits. Similarly, the memory **206** may be embodied as any type(s) of volatile or non-volatile memory or data storage device capable of performing the functions described herein. The memory **206** stores various data and software used during operation of the imaging system **200**, such as operating systems, applications, programs, libraries, and drivers. For instance, the memory **206** may store instructions in the form of a software routine (or routines) which, when executed by the processor **202**, allows the imaging system **200** to control operation of the imaging system **200** (e.g., to capture images with the camera **108**) and process the images to compute the various surface characteristics of the specimen.

The memory **206** is communicatively coupled to the processor **202** via the I/O subsystem **204**, which may be embodied as circuitry and/or components to facilitate I/O operations of the imaging system **200**. For example, the I/O subsystem **204** may be embodied as, or otherwise include, memory controller hubs, I/O control hubs, firmware devices, communication links (e.g., point-to-point links, bus links, wires, cables, light guides, printed circuit board traces, etc.), and/or other components and subsystems to facilitate the I/O operations. In the illustrative embodiment, the I/O subsystem **204** includes an analog-to-digital ("A/D") converter, or the like, that converts analog signals from the camera **108** and the sensors **210** of the imaging system **200** into digital signals for use by the processor **202** (i.e., to digitize the sensed data). It should be appreciated that, if any one or more of the camera **108** and/or the sensors **210** associated with the imaging system **200** generate a digital output signal, the A/D converter may be bypassed. Similarly, the I/O subsystem **204** may include a digital-to-analog ("D/A") converter, or the like, that converts digital signals from the processor **202** into analog signals for use by various components of the imaging system **200**.

In some embodiments, the data captured by the camera **108** and/or the sensors **210** may be transmitted to a remote computing device (e.g., a cloud computing device) for analysis. In other words, the determination of the geometric characteristics of the reflective surface **110** may be determined by a remote computing device based on the sensed data. Accordingly, the imaging system **200** may include communication circuitry **208**, which may be embodied as any communication circuit, device, or collection thereof, capable of enabling communications between the imaging system **200** and remote devices. The communication circuitry **208** may be configured to use any one or more communication technology (e.g., wireless or wired communications) and associated protocols (e.g., Ethernet, Bluetooth®, Wi-Fi®, WiMAX, etc.) to effect such communication.

As indicated above, the system **100** may be configured to use any electromagnetic wave **112** that may be reflected off the reflective surface **110** of the specimen **102**. In such embodiments, the system **100** may utilize sensors **210**, different from the camera **108**, to capture the electromagnetic waves **112**. As such, the sensors **210** may be embodied as any type of sensors suitable for capturing such electromagnetic waves **112**.

Referring now to FIG. **3**A, a simplified spatial diagram illustrating optical paths between the target structure **104** and the specimen **102** of the system **100** and corresponding geometric relationships is shown. Although the system **100** is only shown in two dimensions (i.e., as a top view), it should be appreciated that the target structure **104** and the specimen **102** are generally three-dimensional structures. For example, it will be appreciated that FIG. **3**B is a three-dimensional representation of FIG. **3**A. More specifically, FIG. **3**B illustrates the optical path from the target structure **104** to the camera **108** in at least one embodiment of the system **100** of FIG. **1**A. In the illustrative embodiment, the reflective surface **110** of the specimen **102** is generally flat and undeformed when a load is not applied to the surface **110**. In such circumstances, the incident and reflected rays of the reflective surface **110** of the specimen **102** are collinear and may be considered to be parallel to the optical axis **116** of the camera **108** due to the beam splitter **106**. In other words, $\overline{OP}$ is coincident with $\overline{OQ}$.

When the reflective surface **110** undergoes an out-of-plane deformation, w, (e.g., a "bulge" due to an applied load), the light ray $\overline{OP}$ is deflected to $\overline{OQ}$ by an angle ϕ_y, which is equal to the angle of incidence plus the angle of reflection. Similarly, $\overline{OP}$ is deflected by an angle ϕ_x in an orthogonal direction (e.g., in an x-z plane). Accordingly, the point Q is brought into focus instead of the point P, which was originally in focus. That is, after deformation, the point P is replaced by the point Q, so the point Q is now captured through the point O on the reflective surface **110**. In other words, the camera **108** captures the feature point(s) located at point Q on the target structure **104** for the particular image pixel rather than the feature point(s) located at point P on the target structure **104**. Of course, it should be appreciated that the other image pixels captured by camera **108** may similarly vary due to the deflection.

As indicated above, the surface **114** of the target structure **104** includes a plurality of feature points that are, for example, stochastically distributed. Accordingly, in the illustrative embodiment, the imaging system **200** applies a digital image correlation (DIC) algorithm to determine the displacements δ_y and/or δ_x, which are the relative displacements associated with the deflections by the angles ϕ_y and ϕ_x discussed above. More specifically, in order to determine those displacements δ_y and/or δ_x, the imaging system **200** compares an image **402** captured by the camera **108** of the target surface **114** during (or after) the applied load (see FIG. **4**A) to a reference image **404** of the target surface **114** prior to or otherwise without enduring the applied load (see FIG. **4**B). Some illustrative DIC algorithms are described in Chen et al., "Digital Speckle-Displacement Measurement Using a

Complex Spectrum Method," 32 Appl. Opt. 1839-49 (1993); Chu et al., "Application of Digital Image Correlation Techniques to Experimental Mechanics," 25 Exp. Mech. 232-44 (1985); and Sutton et al., "Image Correlation for Shape, Motion, and Deformation Measurements," Berlin: Springer (2009). In other embodiments, the imaging system **200** may utilize any other suitable feature matching algorithm (instead of DIC) for determining the relative displacements.

It should be appreciated that the feature points represented in the image **402** are shifted relative to the feature points in the reference image **404** due to the deformation of the reflective surface **110** of the specimen **102**. In some embodiments, the reference image **404** may be captured by the camera **108** prior to the reflective surface **110** enduring the applied load. In other embodiments, the specimen **102** may be temporarily replaced with, for example, an optical trial of the general shape (e.g., flat) against which the shape of the reflective surface **110** of the specimen **102** is to be compared, and the camera **108** captures the reference image **404** of the target surface **114** reflected in the optical trial rather than the reflective surface **110**. In yet other embodiments, the reference image **404** may be otherwise generated or provided (e.g., as a standalone reference image associated with the target surface **114**). Of course, in embodiments in which images are not used in the system **100**, **150**, other suitable reference data may be used.

It should be appreciated that, in some embodiments, each of the two images **402**, **404** is stored and/or processed as a two-dimensional array of light intensities. For example, in a monochromatic (i.e., grayscale) digital image, each pixel represents an intensity value of the captured light **112** (e.g., between 0 and 255 for an 8-bit image). In the illustrative embodiment, the imaging system **200** analyzes the images **402**, **404** (e.g., using DIC) to determine a distance that each point has been displaced (e.g., in the x and/or y direction(s)) in the captured image **402** relative to the reference image **404**. In other words, the imaging system **200** may determine how much each point has been displaced relative to its location with the specimen **102** in its original, undeformed state. In some embodiments, the displacements δ_y and δ_x are generated by the imaging system **200** as distance values in a two-dimensional array. As indicated above, such displacements are a result of light **112** incident on the reflective surface **110** of the specimen **102** being deflected proportionally to the curvature or slope of the surface **110**.

In the illustrative embodiment, the imaging system **200** calculates the local surface slopes

$$\frac{\partial w}{\partial x} \text{ and } \frac{\partial w}{\partial y}$$

according to

$$\frac{\partial w}{\partial x{:}y} = \frac{1}{2}\tan(\phi_{x:y}).$$

However, as discussed above, the system **100**, **150** is configured to determine microscale changes in the slope of the reflective surface **110** and therefore tan

$$(\phi_{x:y}) \cong \frac{\delta_{x:y}}{\Delta}$$

due to the small angles. Accordingly, the imaging system **200** may calculate the local surface slopes

$$\frac{\partial w}{\partial x} \text{ and } \frac{\partial w}{\partial y}$$

according to

$$\frac{\partial w}{\partial x{:}y} \cong \frac{1}{2}\frac{\delta_{x:y}}{\Delta}$$

based on the displacements δ_y and δ_x and the distance Δ between the reflective surface **110** and the target surface **114**. That is, the imaging system **200** may calculate the slope

$$\frac{\partial w}{\partial x}$$

of the reflective surface **110** in the x-direction as

$$\frac{1}{2}\frac{\delta_x}{\Delta}$$

and the slope

$$\frac{\partial w}{\partial y}$$

of the reflective surface **110** in the y-direction as

$$\frac{1}{2}\frac{\delta_y}{\Delta}.$$

In the illustrative embodiment, coordinates on a plane coincident with the reflective surface **110** of the specimen **102** (in an unloaded state) are utilized to determine the slopes, but the displacements are determined based on coordinates of the surface **114** of the target structure **104**. Accordingly, in such embodiments, the imaging system **200** may utilize a linear mapping of coordinates between the planes of the reflective surface **110** and the target surface **114** to account for this. At least one technique for doing so is described in Periasamy, et al., "A Full-Field Digital Gradient Sensing Method for Evaluating Stress Gradients in Transparent Solids," 51 Appl. Opt. 2088-97 (2012). Further, in some embodiments, the determined slopes

$$\frac{\partial w}{\partial x} \text{ and } \frac{\partial w}{\partial y}$$

may be stored by the imaging system **200** as, for example, a two-dimensional array of slope values and may be represented visually by contour diagrams **502**, **504**, respectively, as shown in FIGS. **5**A and **5**B.

It should be appreciated that the diagrams **502**, **504** of FIGS. **5**A-B (as well as diagrams **602**, **604**, **702**, **704**, **802**,

808 of FIGS. 6A-8B, described further below) correspond with the geometry associated with a mechanical load being applied to the center of a circular silicon wafer. In other words, a small (e.g., microscale) bulge is identified by the imaging system 200 due to the mechanical load. It should further be appreciated that, unlike optical interferometric and moiré methods, the imaging system 200 permits the slope fields to be determined using a single pair of data corresponding with the reflective surface 110 in undeformed and deformed states.

As discussed above, the imaging system 200 may utilize the slopes

$$\frac{\partial w}{\partial x} \text{ and } \frac{\partial w}{\partial y}$$

to determine various other geometric characteristics of the reflective surface 110 of the specimen 102. For example, in the illustrative embodiment, the imaging system 200 utilizes numerical differentiation and/or another suitable algorithm or technique to determine various curvatures of the reflective surface 110 (e.g., directional curvatures and/or twist curvatures) based on the determined slopes. It should be appreciated that it may be desirable to determine the curvatures for any number of reasons including, for example, to determine the imposed or residual stress in a reflective substrate (e.g., a silicon wafer) which, if too high, may damage the substrate over time (e.g., by cracking). In particular, the imaging system 200 may calculate the directional curvature

$$\frac{\partial^2 w}{\partial x^2}$$

according to

$$\frac{\partial^2 w}{\partial x^2} = \frac{1}{2}\frac{\partial}{\partial x}\left(\frac{\delta_x}{\Delta}\right),$$

which is represented by the contour diagram 602 of FIG. 6A. Similarly, the imaging system 200 may calculate the directional curvature

$$\frac{\partial^2 w}{\partial y^2}$$

according to

$$\frac{\partial^2 w}{\partial y^2} = \frac{1}{2}\frac{\partial}{\partial y}\left(\frac{\delta_y}{\Delta}\right),$$

which is represented by the contour diagram 604 of FIG. 6B.

In some embodiments, the imaging system 200 may also utilize cross-partial differentiation to determine the twist curvature of the reflective surface 110 of the specimen 102. Specifically, the imaging system 200 may determine the twist curvature

$$\frac{\partial^2 w}{\partial x \partial y}$$

according to

$$\frac{\partial^2 w}{\partial x \partial y} = \frac{1}{2}\frac{\partial}{\partial x}\left(\frac{\delta_y}{\Delta}\right),$$

which is represented by the contour diagram 702 of FIG. 7A. Similarly, the imaging system 200 may determine the twist curvature

$$\frac{\partial^2 w}{\partial y \partial x}$$

according to

$$\frac{\partial^2 w}{\partial y \partial x} = \frac{1}{2}\frac{\partial}{\partial y}\left(\frac{\delta_x}{\Delta}\right),$$

which is represented by the contour diagram 704 of FIG. 7B. It will be appreciated that the contour diagrams 702, 704 are nearly identical, which is expected from the cross-partial differentiation of continuous functions (i.e., the surface topography of the reflective surface 110).

In the illustrative embodiment, the imaging system 200 also utilizes numerical integration and/or another suitable algorithm of technique to determine the surface topography of the reflective surface 110 (i.e., its shape) based on the determined slopes. For example, the imaging system 200 may integrate the determined x-directional slope

$$\frac{\partial w}{\partial x}$$

over x in a region of interest between limits a and b (e.g., the entire surface 110 of the specimen 102) to determine the surface topography of the reflective surface 110. In particular, the imaging system 200 may determine the surface topography as

$$\int_a^b \frac{\partial w}{\partial x} dx.$$

The imaging system 200 may also determine the surface topography of the reflective surface 110 in terms of the y-directional slope

$$\frac{\partial w}{\partial y}$$

as

$$\int_a^b \frac{\partial w}{\partial y} dy.$$

As shown in FIGS. **8**A and **8**B, the diagrams **802**, **804** represent the determined surface topology of the reflective surface **110** according to integration in terms of x and integration in terms of y, respectively. As expected, the diagrams **802**, **804** are nearly identical (with any deviation resulting from numerical, rounding, and/or other system errors).

In some embodiments, the imaging system **200** may determine various geometric characteristics of the reflective surface **110** of the specimen **102** over time (e.g., during a process). For example, in an embodiment, a polymer film (e.g., an epoxy film) may be applied to a silicon wafer, and the imaging system **200** may determine the surface slopes of the silicon wafer at various point in time as the polymer film cures on the wafer. Referring now to FIGS. **9**A-**10**D, various contour diagrams are shown that represent those surface slopes. In particular, a contour diagram **902** represents the local slope

$$\frac{\partial w}{\partial x}$$

of the reflective surface **110** of the silicon wafer at a first point in time (e.g., after 25 minutes from application of the polymer film). Similarly, a contour diagram **904** represents the local slope

$$\frac{\partial w}{\partial x}$$

of the reflective surface **110** of the silicon wafer at a second later point in time (e.g., 35 minutes). Further, a contour diagram **906** represents the local slope

$$\frac{\partial w}{\partial x}$$

of the reflective surface **110** of the silicon wafer at a third even later point in time (e.g., 45 minutes), and a contour diagram **908** represents the local slope

$$\frac{\partial w}{\partial x}$$

of the reflective surface **110** at a fourth even later point in time (e.g., 55 minutes). Similarly, contour diagrams **1002**, **1004**, **1006**, **1008** represent the local slope

$$\frac{\partial w}{\partial y}$$

of the reflective surface **110** of the silicon wafer at the first point in time, at the second point in time, at the third point in time, and at the fourth point in time, respectively. It will be appreciated that the slopes

$$\frac{\partial w}{\partial x} \text{ and } \frac{\partial w}{\partial y}$$

initially appear somewhat awry but converge to distinct slopes values over time, because the magnitudes of the slopes increase with time as the curing epoxy bends the silicon wafer in space.

While certain illustrative embodiments have been described in detail in the figures and the foregoing description, such an illustration and description is to be considered as exemplary and not restrictive in character, it being understood that only illustrative embodiments have been shown and described and that all changes and modifications that come within the spirit of the disclosure are desired to be protected. There are a plurality of advantages of the present disclosure arising from the various features of the apparatus, systems, and methods described herein. It will be noted that alternative embodiments of the apparatus, systems, and methods of the present disclosure may not include all of the features described yet still benefit from at least some of the advantages of such features. Those of ordinary skill in the art may readily devise their own implementations of the apparatus, systems, and methods that incorporate one or more of the features of the present disclosure.

The invention claimed is:

1. A system for determining geometric characteristics of a reflective surface of a specimen, the system comprising:

a target structure including a plurality of feature points configured to be reflected in the reflective surface of the specimen;

an imaging system including a camera, the camera comprising a lens and an image sensor, the lens configured to focus light from the reflective surface on the image sensor and the image sensor configured to capture an image including the plurality of feature points of the target structure; and

a beam splitter configured to direct light (i) from the target structure to the reflective surface and (ii) from the reflective surface to the camera.

2. The system of claim **1**, wherein the imaging system is further configured to determine one or more surface slopes of the reflective surface based on displacements of the plurality of feature points in the captured image relative to a reference image including the plurality of feature points.

3. The system of claim **2**, wherein to determine one or more surface slopes of the reflective surface comprises to apply a digital image correlation algorithm to the captured image and the reference image.

4. The system of claim **2**, wherein the imaging system is further configured to determine a directional curvature of the reflective surface at one or more points based on the one or more surface slopes.

5. The system of claim **2**, wherein the imaging system is further configured to determine a twist curvature of the reflective surface at one or more points based on the one or more surface slopes.

6. The system of claim **2**, wherein the imaging system is further configured to determine a surface topography of the reflective surface at one or more points based on the one or more surface slopes.

7. The system of claim **2**, wherein the captured image is of the reflective surface with a thermodynamic or mechanical load applied and the reference image is of the reflective surface without the thermodynamic or mechanical load applied.

8. The system of claim **1**, wherein at least one of the target structure or the reflective surface is positioned on a plane that is not perpendicular to an optical axis of the camera.

9. The system of claim **1**, wherein the reflective surface is configured to reflect light of one or more wavelengths from the target structure to the camera.

10. The system of claim **1**, wherein the beam splitter is positioned at a forty-five degree angle relative to each of the reflective surface, the target structure, and an optical axis of the camera.

11. The system of claim **1**, wherein the target structure comprises a surface with a plurality of light regions and a plurality of dark regions, and wherein each feature point of the plurality of feature points comprises a point at an interface between a light region of the plurality of light regions and a dark region of the plurality of dark regions.

12. The system of claim **11**, wherein the imaging system is further configured to determine one or more surface slopes of the reflective surface based on displacements of the plurality of feature points in the captured image relative to a reference image including the plurality of feature points.

13. The system of claim **12**, wherein the target structure is illuminated by a broad-band white light source, wherein the image sensor is configured to capture the image formed by light from the broad-band white light source, and wherein to determine the one or more surface slopes of the reflective surface based on displacements of the plurality of feature points in the captured image comprises to determine the one or more surface slopes of the reflective surface based on displacements of the plurality of feature points in the captured image formed by light from the broad-band white light source.

14. The system of claim **12**, wherein to determine the one or more surface slopes of the reflective surface comprises to determine the surface slopes of substantially all of the reflective surface.

15. A method of determining geometric characteristics of a reflective surface of a specimen, the method comprising:

capturing an image of the reflective surface of the specimen with a camera of an imaging system, wherein the camera comprises a lens and an image sensor, the lens configured to focus light from the reflective surface on the image sensor, wherein a plurality of feature points of a target structure are reflected in the reflective surface such that the plurality of features points are present in the captured image, using a beam splitter that directs light (i) from the target structure to the reflective surface and (ii) from the reflective surface to the camera; and

determining one or more surface slopes of the reflective surface based on displacements of the plurality of feature points in the captured image relative to a reference image including the plurality of feature points.

16. The method of claim **15**, wherein determining the one or more surface slopes of the reflective surface comprises applying a digital image correlation algorithm to the captured image and the reference image.

17. The method of claim **15**, wherein determining the one or more slopes of the reflective surface comprises determining the one or more slopes based on a distance traveled by light directed from the target structure to the specimen.

18. The method of claim **17**, wherein the distance traveled by the light directed from the target structure to the specimen is equal to a sum of a distance between the target structure and the beam splitter and a distance between the beam splitter and the specimen.

19. The method of claim **18**, further comprising determining at least one of a curvature or a surface topology of the reflective surface based on the one or more surface slopes.

20. The method of claim **15**, further comprising determining displacements of the plurality of features points in each of two perpendicular directions within a plane coincident with the target structure.

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