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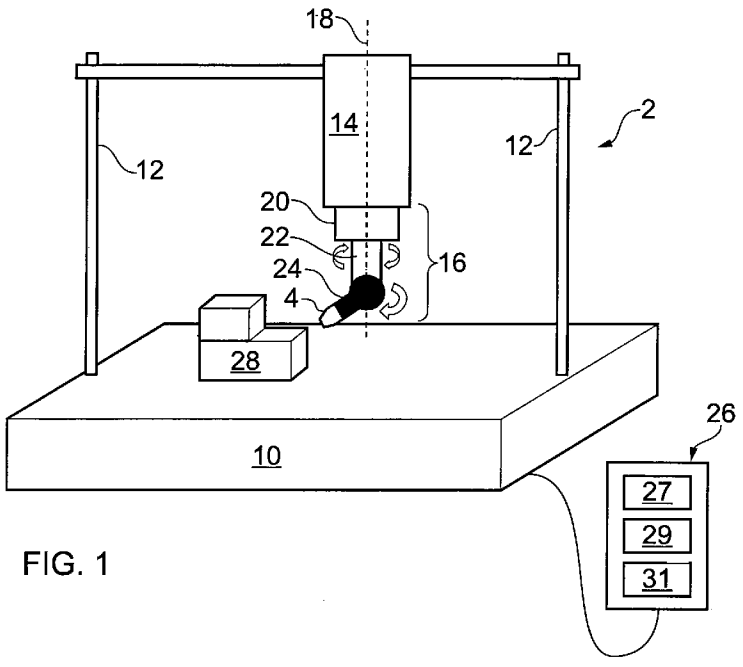


FIG. 1

(57) Abstract: A non-contact method and apparatus for inspecting an object. At least one first image of the object on which an optical pattern is projected, taken from a first perspective is obtained. At least one second image of the object on which an optical pattern is projected, taken from a second perspective that is different to the first perspective is obtained. At least one common object feature in each of the at least one first and second images is then determined on the basis of an irregularity in the optical pattern as imaged in the at least one first and second images.

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# NON-CONTACT MEASUREMENT APPARATUS AND METHOD

This invention relates to a method and apparatus for measuring an object without contacting the object.

Photogrammetry is a known technique for determining the location of certain points on an object from photographs taken at different perspectives, i.e. from different positions and/or orientations. Typically photogrammetry comprises obtaining at least two images of an object taken from two different perspectives. For each image the two dimensional coordinates of a feature of the object on the image is determined. It is then possible from the knowledge of the location and orientation of the camera(s) which took the images, and the points at which the feature is formed on the images to determine the three dimensional coordinates of the feature on the object. Such a technique is disclosed for example in US 5,251,156 the entire content of which is incorporated into this specification by this reference.

In order to perform photogrammetry it is necessary to identify features on the object which can be located on the images. It can be important that the features of the object which are to form reference points for measurement can be quickly, easily and reliably identified.

Known techniques for identifying features include attaching targets to points of interest on the object. For example, coded "bull's eyes", wherein each "bull's-eye" has a unique central point which is invariant with perspective, surrounded by a set of concentric black and white rings which code a unique identifier, can be placed on features of an to be measured. It is also known to project target features onto the object, for instance by projecting a spot or bull's eye onto the surface of the object. Automatic feature recognition methods can be used to both locate the centre of the target and also decode the unique identifier if present. By means of such targets the images can be automatically analysed and the coordinates of the

"bull's-eye" centres returned. However, disadvantages with the use of such "bull's eyes" include that such a target has to be placed or projected on each point to be measured. This can take a significant amount of time and also the measurement accuracy is limited to the accuracy with which the operator places the targets. Furthermore, the point density is limited by the size of the targets being used.

It is known to use feature recognition techniques instead of using targets to locate points on an object, such as edges and corners automatically. Such feature recognition techniques include the Hough Transform which can be used to identify straight lines, circles and ellipses. This technique can be used to identify more complex shapes, but the computation required can be demanding and the results can be sensitive to noise and lighting artefacts in the images.

The invention provides a method for inspecting an object using photogrammetry in which irregularities in an optical pattern projected on the object are identified and used as target features.

According to a first aspect of the invention there is provided a non-contact method for inspecting an object comprising, in any suitable order: i) obtaining at least one first image of the object on which an optical pattern is projected, taken from a first perspective; ii) obtaining at least one second image of the object on which an optical pattern is projected, taken from a second perspective that is different to the first perspective; and iii) identifying at least one common object feature in each of the at least one first and second images on the basis of an irregularity in the optical pattern as imaged in the at least one first and second images.

It is an advantage of the present invention that target features can be identified without the use of markers which are placed or projected on the object. Rather, they are created by the interface between the object and optical pattern, the object deforming the optical pattern imaged thereby creating irregularities in the optical

pattern. This enables highly accurate measurements of the object to be taken quickly. It also enables a high density of points to be targeted and measured. It has also been found that the method of the invention can require less processing resources to identify points on complex shaped objects than by other known image processing techniques.

At least one of the relative position and relative orientation of the object and projector of the optical pattern at step i) can be different to that of the object and projector of the optical pattern at step ii). As will be understood, as the relative position and/or orientation of the object and projector of the optical pattern at step i) can be different to the relative position and/or orientation of the object and projector of the optical pattern at step ii) the relative perspective between the object and projector of the optical pattern can be different between the steps. Accordingly, this can result in the position of the optical pattern on the object being altered between obtaining the first and at least second images. Accordingly, the position of the optical pattern on the object can be different for each image. Altering the position of the optical pattern on the object can be advantageous as it can avoid problems caused by shadowing or obstruction of the optical pattern.

The optical pattern can extend in two dimensions. The optical pattern projected can enable the determination of the topology of the surface of an object in two dimensions from a single image of the optical pattern on the object. The optical pattern can be a substantially full-field optical pattern. A substantially full-field optical pattern can be one in which the pattern extends over at least 50% of the field of view of an image sensor for obtaining at least one of the first and second images at a reference plane (described in more detail below), more preferably over at least 75%, especially preferably over at least 95%, for example substantially over the entire field of view of the image sensor at a reference plane. The reference plane can be a plane that is a known distance away from the image sensor. Optionally, the reference plane can be a plane which contains the point at which the optical pattern projector's and image sensor's optical axes intersect.

The reference plane can extend perpendicular to the image sensor's optical axis.

Preferably the pattern as imaged in the at least one first and at least one second image is projected over an area of the object. Preferably the pattern extends over an area of the object so as to facilitate the measurement of a plurality of points of the object over the area from the at least one first and at least one second images using the method of the present invention. The pattern need not be repetitive. However, preferably the pattern is a substantially repetitive pattern. Particularly preferred optical patterns comprise substantially periodic optical patterns. As will be understood, a periodic optical pattern can be a pattern which repeats after a certain finite distance. The minimum distance between repetitions can be the period of the pattern. Preferably the optical pattern is periodic in at least one dimension. Optionally, the optical pattern can be periodic in at least two perpendicular dimensions.

Suitable optical patterns for use with the present invention include patterns of concentric circles, patterns of lines of varying colour, shades, and/or tones. The colour, shades and/or tones could alternate between two or more different values. Optionally, the colour, shade and/or tones could vary between a plurality of discrete values. Preferably, the colour, shade and/or tones varies continuously across the optical pattern. Preferably, the optical pattern is a fringe pattern. For example, the optical pattern can be a set of sinusoidal fringes. The optical pattern can be in the infrared to ultraviolet range. Preferably, the optical pattern is a visible optical pattern. As will be understood, an optical pattern for use in methods such as that of the present invention is also commonly referred to as a structured light pattern.

Suitable projectors for the optical pattern include a digital light projector configured to project an image input from a processor device. Such a projector enables the pattern projected to be changed. Suitable projectors could comprise a light source and one or more diffraction gratings arranged to produce the optical

pattern. The diffraction grating(s) could be moveable so as to enable the pattern projected by the projector to be changed. For instance, the diffraction grating(s) can be mounted on a piezoelectric transducer. Optionally, the diffraction gratings could be fixed such that the pattern projected by the projector cannot be changed. Optionally the projector could comprise a light source and a hologram. Further, the projector could comprise a light source and a patterned slide. Further still, the projector could comprise two mutually coherent light sources. The coherent light sources could be moveable so as to enable the pattern projected by the projector to be changed. For instance, the coherent light sources can be mounted on a piezoelectric transducer. Optionally, the coherent light sources could be fixed such that the pattern projected by the projector cannot be changed.

As will be understood, a perspective can be a particular view point of the object. A perspective can be defined by the relative position and/or orientation of the at least one imaging device obtaining the first and second images and the object being imaged. Preferably the first and second perspectives are known relative to each other. In particular, preferably their position and orientation relative to each other is known. For instance, there could be a known offset vector and rotation matrix describing the relation between the perspectives. Optionally, position sensors could be provided which can be used to determine the perspectives. Optionally, the perspectives could be fixed. Furthermore, the perspectives could be determined from the images, for instance by looking for known reference feature and/or object.

As will be understood, preferably the first and second images contain at least partially overlapping views of the object. This is so that at least one common object feature is present in both of the images. As will be understood a common object feature can be any feature on the object which has been captured in the first and second image. The common object feature could be a single point on the object – for instance a corner feature. Optionally, the common object feature could be a plurality of points on the object. For instance, the common object feature

could be a line, such as an elongate edge of an object. The line could be straight or curved. As described in more detail below, the common object feature could be used as a target feature. In particular the common object feature could be used as a target feature in a photogrammetric measurement process.

As will be understood, at least first and second optical pattern projectors having different positions and/or orientations relative to the object can be provided. Accordingly, the optical pattern imaged in the first image can be projected by a first optical pattern projector and the optical pattern imaged in the second image can be projected by a second optical pattern projector.

Preferably, the projector of the optical pattern imaged at step i) and the projector of the optical pattern imaged at step ii) are provided by a common optical pattern projector unit comprising at least one optical pattern projector. Accordingly, the method can comprise relatively moving the object and the optical pattern projector unit between steps i) and ii). In particular this can comprise moving the optical pattern projector unit relative to the object. The optical pattern projector unit could comprise a plurality of optical pattern projectors. The plurality of optical pattern projectors could be in a fixed spatial relationship relative to each other.

More preferably, the projector of the optical pattern imaged at step ii) is the projector of the optical pattern imaged at step i). Accordingly, the method can be performed with a single optical pattern projector only. Therefore the optical pattern projector unit can comprise a single optical pattern projector only. This can be simpler than providing a plurality of optical pattern projectors. Accordingly, the method can further comprise relatively moving the object and the projector of the optical pattern between steps i) and ii). In particular, the method can comprise moving the projector of the optical pattern relative to the object.

As will be understood, the type of optical pattern projected on the object in step i) can be different to the type of optical pattern projected in step ii). For instance,

the optical pattern projected in step i) can be a plurality of concentric circles and the optical pattern projected in step ii) can be a plurality of straight lines. Preferably, the optical pattern projected on the object in step i) and step ii) is the same.

The at least one first image and the at least one second image can be obtained by at least one suitable imaging device. Suitable imaging devices can comprise at least one image sensor. For example, suitable imaging devices can comprise an optical electromagnetic radiation (EMR) sensitive detector, such as a charge-coupled device (CCD), a complementary metal-oxide-semiconductor (CMOS). Suitable imaging devices can be optically configured to focus light at the image plane. As will be understood, the image plane can be defined by the image sensor. For example, suitable imaging devices can comprise at least one optical component configured to focus optical EMR at the image plane. Optionally, the at least one optical component comprises a lens.

Suitable imaging devices can be based on the pinhole camera model which consists of a pinhole, which can also be referred to as the imaging device's perspective centre, through which optical EMR rays are assumed to pass before intersecting with the image plane. As will be understood, imaging devices that do not comprise a pinhole but instead comprise a lens to focus optical EMR also have a perspective centre and this can be the point through which all optical EMR rays that intersect with the image plane are assumed to pass.

As will be understood, the perspective centre can be found relative to the image sensor using a calibration procedure, such as those described in J. Heikkila and O. Silven, "A four-step camera calibration procedure with implicit image correction", Proceedings of the 1997 Conference in Computer Vision and Pattern Recognition (CVPR '97) and J.G Fryer, "Camera Calibration" in K. B. Atkinson (ed.) "Close range photogrammetry and machine vision", Whittles publishing (1996). Correction parameters such as those for correcting lens aberrations can be

provided and are well known and are for instance described in these two documents.

Preferably the at least one first image and the at least one second image are obtained by a common imaging device unit comprising at least one imaging device. Accordingly, the method can further comprise relatively moving the imaging device unit and object from the first perspective to the second perspective. The movement of the object and/or imaging device unit could be performed manually or automatically. The imaging device unit can comprise a plurality of imaging devices.

The at least one first and at least one second images can be obtained by a single imaging device. The single imaging device can comprise a single image sensor. Accordingly, the at least one first and at least second images can be obtained by a single image sensor. Accordingly, the object could be moved between the step of obtaining the at least one first image and at least one second image in order to obtain the first and second perspectives. Optionally, the imaging device could be moved between the step of obtaining the at least one first image and at least one second image in order to obtain the first and second perspectives. Accordingly, the method can comprise moving the imaging device from the first known perspective to the second known perspective.

Preferably the optical pattern projector unit and the imaging device unit are mounted on a coordinate positioning apparatus. Preferably the optical pattern projector unit and the imaging device unit are mounted on a coordinate positioning apparatus such that they can be moved in at least one linear degree of freedom, more preferably at least two linear degrees of freedom, especially preferably at least three linear degrees of freedom. Preferably the linear degrees of freedom are perpendicular to each other. Preferably the optical pattern projector unit and the imaging device unit are mounted on a coordinate positioning apparatus such that they can be rotated through at least one rotational degree of freedom, more

preferably rotated through at least two rotational degrees of freedom, for example through at least three rotational degrees of freedom. Preferably the at least two and at least three rotational degrees of freedom are about two substantially perpendicular axes. The rotational degrees of freedom can be provided by an articulating head on which the optical pattern projector unit and imaging device unit are mounted. Measurement devices which are moveable in three degrees of freedom and two rotational degrees of freedom are commonly referred to in the metrological industry as "five-axis" measurement devices. However, as will be understood, the invention is not limited to such systems and can be used with systems that facilitate movement through much more degrees of freedom, for instance through three, four or more rotational degrees of freedom.

Preferably the coordinate positioning apparatus is a computer controlled coordinate positioning apparatus, for example a computer numerically controlled (CNC) coordinate positioning apparatus. Suitable coordinate positioning apparatus include coordinate measuring machines (CMM) and machine tools.

Preferably, the at least one projector of the optical pattern in steps i) and ii) and the at least one imaging device for obtaining the first and second images are in a fixed spatial relationship relative to each other. Accordingly, they can be provided as a single unit. In particular they can be provided as common probe device. The common probe device can be mounted on a coordinate positioning apparatus. This can provide easy manipulation and position determination. In particular, it enables multiple known positions and orientations of the optical pattern projector unit and/or the image sensor unit to be achieved quickly, increasing the accuracy and speed of measuring the object.

Preferably the method further comprises an image analyser using the at least one first and second images to measure the common feature. Preferably, measuring the common feature comprises determining the position of the common object feature relative to the first and second perspectives. In particular, measuring the

common feature comprises determining the position of the common object feature within a measurement volume.

As will be understood, an irregularity in the optical pattern can also be referred to as discontinuity in the optical pattern.

An irregularity in the optical pattern can be a deformation of the optical pattern caused by a discontinuous feature on the object. Such a deformation of the optical pattern can, for example, be caused at the boundary between two continuous sections of an object. For instance, the boundary could be the edge of a cube at which two faces of the cube meet. Accordingly, a discontinuous feature on the object can be where the gradient of the surface of the object changes significantly. The greater the gradient of the surface relative to the optical pattern projector, the greater the deformation of the optical pattern at that point on the surface. Accordingly, an irregularity could be identified by identifying those points on the object at which the optical pattern is deformed by more than a predetermined threshold. This predetermined threshold will depend on a number of factors, including the size and shape of the object to be measured. Optionally, the predetermined threshold can be determined and set prior to operation by a user based on the knowledge of the object to be measured.

An irregularity can be can be identified by identifying in an image those points on the object at which the rate of change of the optical pattern is greater than a predetermined threshold rate of change. For instance, in embodiments in which the optical pattern is a periodic optical pattern, an irregularity can be identified by identifying in an image those points on the object at which the rate of change of the phase of the periodic optical pattern is greater than a predetermined threshold rate of change. In particular, in embodiments in which the optical pattern is a fringe pattern, an irregularity can be identified by identifying in an image those points on the object at which the rate of change of the phase of the fringe pattern is greater than a predetermined threshold rate of change.

The rate of change of the phase of an optical pattern as imaged when projected onto an object can be identified by creating a phase map from the image, and then looking for jumps in the phase between adjacent points in the phase map above a predetermined threshold. As will be understood, a phase map is a map which contains the phase a periodic pattern projected onto the object's surface for a plurality of pixels in an image. The phase map could be a wrapped phase map. The phase map could be an unwrapped phase map. Known techniques can be used to unwrap a wrapped phase map in order to obtain an unwrapped phase map.

A phase map can be created from a single image of the optical pattern object. For example, Fourier Transform techniques could be used to create the phase map.

Preferably a phase map is created from a set of images of the object from substantially the same perspective, in which the position of the optical pattern on the object is different for each image. Accordingly, a phase map can be created using a phase stepping approach. This can provide a more accurate phase map. Phase stepping algorithms known and are for example described in Creath, K. "Comparison of phase measurement algorithms" Proc. SPIE 680, 19-28 (1986). Accordingly, step i) can comprise obtaining a set of first images of the optical pattern on the object from a first known perspective. Step ii) can comprise obtaining a set of second images of the optical pattern on the object from a second known perspective. Accordingly, a set of images can comprise a plurality of images of the object from a given perspective. Preferably, a set of images comprises at least two images, more preferably at least three images, especially preferably at least four images. The position of the optical pattern on the object can be different for each image in a set.

Step iii) can comprise: a) calculating at least one first phase map from the set of first images. Step iii) can further comprise b) calculating at least one second phase map from the set of second images. The at least one first phase map and the

at least one second phase map can be wrapped phase maps. Optionally, the at least one first phase map and the at least one second phase map can be unwrapped phase maps. Step iii) can still further comprise c) identifying at least one common irregularity in the at least one first and second phase maps as a target feature.

Corresponding irregularities can be determined by known matching techniques and, for example, utilising epipolar geometry.

Step a) can comprise calculating a set of first phase maps from the set of first images. Each phase map in the set of first phase maps can be calculated using a unique order of the set of first images. Step b) can comprise calculating a set of second phase maps from the set of second images. Each phase map in the set of second phase maps can be calculated using a unique order of the set of second images. Step c) can comprise identifying at least one corresponding irregularity in each of the set of at least one first phase maps and set of at least second phase maps as a target feature.

Calculating sets of phase maps, wherein each phase map in a set is calculated using a unique order of the corresponding set of images is advantageous as it enables real and false irregularities in a phase map to be identified. Preferably, each set of phase maps comprise at least two phase maps, more preferably at least three phase maps, especially preferably at least four phase maps.

Step c) can comprise identifying at least one real irregularity in a set of phase maps. When the phase maps are wrapped phase maps, irregularities can be falsely identified due to the wrapped phase data. Accordingly, identifying at least one real irregularity can comprise comparing each of the wrapped phase maps in a set to identify those irregularity points that have been commonly identified in at least two wrapped phase maps. Any non-commonly identified irregularity points between each of the wrapped phase maps can be discarded as false irregularities.

As will be understood, irregularities can also be falsely identified due to other reasons, and for example due to shadows in the optical pattern caused by the object. Such false irregularities can be determined and discarded by comparing the images taken from different perspectives. In particular, such false irregularities can be determined and discarded by comparing the phase maps of images taken from different perspectives. As will be understood, an irregularity in a phase map caused by a shadow in an image (or set of images) from which the wrapped phase map is obtained will not be present in a wrapped phase map for a different image (or set of images) taken from a different perspective. Accordingly, such irregularities can be discarded as false irregularities.

As discussed above it can be advantageous to obtain a set of images of an object at a given perspective, in which the position of the optical pattern on the object is different in each image for wrapped phase map calculation. The position of the optical pattern on the object could be altered by changing the optical pattern emitted by an optical pattern projector. For example, the phase of an optical pattern, such as a fringe pattern, emitted by an optical pattern projector could be altered between the obtaining each image in a set of images for a given perspective.

Optionally, the position of the optical pattern on the object could be altered by relatively moving the object and the optical pattern projector which projects the optical pattern. For example, the method could comprise relatively moving the object and optical pattern projector between the obtaining of each image in a set of images. When the optical pattern projector and image sensor are fixed relative to each other, for instance provided as a single unit, the image sensor will move relative to the object as a consequence of obtaining the change in position of the optical pattern on the object. When this is the case, then it can be necessary to identify common image areas covered by each of the images in a set of images. This is so that a wrapped phase map can be created using the common image areas only. Identifying common image areas can comprise adjusting the image

coordinates to compensate for relative movement between the object and the image sensor.

The first and second known perspectives can be determined prior to operation of the method. In this case, the at least one first image and at least one second image can be obtained from static imaging devices located at predetermined positions and orientations in order to provide those perspectives. Optionally, at least one imaging device could be moved to predetermined positions and orientations in order to obtain the images at the predetermined perspectives. The at least one imaging device could be moved to the predetermined positions and orientations by a user manipulating a positioning apparatus on which the at least one imaging device is mounted. This can involve the user physically dragging the at least one imaging device to the predetermined positions and orientations. Optionally, this could involve the user controlling the positioning apparatus via an input device in order to move the at least one image sensor. The positioning apparatus could be preconfigured with the positions and orientations of the at least one imaging device and could be configured to automatically move the at least one imaging device to the predetermined positions and orientations.

Optionally, the method could comprise determining the position and orientation from which the images were obtained. In embodiments in which the at least one imaging device is mounted on a coordinate positioning machine, the position and orientation could be obtained from the coordinate positioning machine's position reporting features. For example, the coordinate position machine could comprise encoders for determining the position of relatively moveable parts of the coordinate positioning machine. In this case, the position and orientation of the imaging device could be determined from the output of the encoders.

The method can comprise the image analyser identifying in each of the at least one first image and the at least one second image a plurality of irregularities in the optical pattern formed on the object as a plurality of common object features. The

plurality of common object feature could be a plurality of target features. The method could further comprise determining the three-dimensional coordinates of each of the plurality of target features on the object within the measurement space from the at least one first image and the at least one second image.

The method can further comprise the image analyser determining topographical data regarding the surface of the object on which the optical pattern is projected. This could be done, via triangulation and/or for example via phase analysis. This can be done by the image analyser processing the deformation of the optical pattern as imaged by at least one of the first and second images. In particular, in embodiments in which the optical pattern is a periodic optical pattern, the image analyser could analyse the phase of the periodic optical pattern on the surface. There are many known techniques for determining topographical data by analysing the phase of a periodic optical pattern projected onto an object. Such techniques include the use phase stepping algorithms. For instance suitable phase stepping algorithms are described in Creath, K. "Comparison of phase measurement algorithms" Proc. SPIE 680, 19-28 (1986). As will be understood, such phase stepping algorithms require a plurality of images of the object from a substantially common perspective, in which the position of the periodic optical pattern on the object is different in each image.

Such methods can be used to generate phase maps, in particular wrapped phase maps, which can be processed to obtain topographical height information.

The position of the periodic optical pattern on the object can be changed between obtaining each of the images by changing the periodic optical pattern emitted by the projector. For instance, a projector can comprise a laser beam which is incident on a lens which diverges the beam on to a liquid crystal system to generate at least one fringe pattern on the surface to be measured. A computer can be used to control the pitch and phase of the fringe pattern generated by the liquid crystal system. The computer and the liquid crystal system can perform a phase-

shifting technique in order to change the phase of the structured light pattern.

Optionally, the position of the optical pattern on the object could be changed between obtaining each image in a set by relatively moving the object and the optical pattern projector. This still enables a phase map to be obtained by a phase stepping process. Details of a method and apparatus in which the position of an optical pattern on the object is changed between obtaining each of a plurality of images of the object, and in which topographical data is obtained by analysing those images are disclosed in the co-pending PCT application filed on the same day as the present application with the title PHASE ANALYSIS MEASUREMENT APPARATUS AND METHOD, having the applicant's reference number 742/WO/0 and claiming priority from UK Patent Application nos. 0716080.7, 0716088.0, 0716109.4.

Other known techniques include Fourier transforming an image of the periodic optical pattern to generate a phase map, in particular a wrapped phase map, which can then be processed to obtain topographical height information.

Either way, the image analyser can be configured to unwrap a wrapped phase map and to determine the topographical data from that unwrapped phase map.

The image analyser can be configured to determine the topographical data across the entire image. Optionally, the image analyser can be configured to determine the topographical data across only a part of the image. In particular, the image analyser can be configured to determine the topographical data for a continuous section of the object on which the optical pattern is projected. A continuous section of the object can be a part of the object which is enclosed by a plurality of previously identified irregularities.

As will be understood, topographical data can be data indicating the topography of at least a part of the object's surface. The topographical data can be data

indicating the height of the object's surface relative to the image sensor, at at least one point on the object, and preferably at a plurality of points on the object. The topographical data can be data indicating the gradient of the object's surface, at at least one point on the object, and preferably at a plurality of points on the object.

Details of a method and apparatus for determining topographical data of a surface of an object by phase analysis as well as identifying and determining the position of common features on an object are disclosed in the co-pending PCT application filed on the same day as the present application with the title NON-CONTACT PROBE, having the applicant's reference number 743/WO/0 and claiming priority from UK Patent Application nos. 0716080.7, 0716088.0, 0716109.4. Subject matter that is disclosed in that application is incorporated in the specification of the present application by this reference.

The method can further comprise the image analyser combining the three-dimensional coordinates of the plurality of target features with the topographical data to obtain three-dimensional model data of the object.

As will be understood, the three-dimensional coordinates of the target feature can be determined by trigonometry methods. For instance, the three-dimensional coordinates of the target feature can be determined by photogrammetry techniques. Accordingly, the method can comprise the image analyser using photogrammetry to determine the three-dimensional coordinates of the target feature on the object within the measurement space.

The method can comprise obtaining at least one third image of the optical pattern on the object from at least a third known perspective that is different to the first and second known perspectives. In this case, the method can comprise identifying an irregularity in the optical pattern in each of the at least one first, second and third images as a common object feature. The irregularity could be identified as a target feature. The method could further comprise determining the three-

dimensional coordinates of the target feature on the object within the measurement space. Of course, more images of the optical pattern on the object from further known perspectives can be obtained. Increasing the number of images obtained can improve the accuracy and reliability of the process of identifying a irregularity in the optical pattern as a target feature and determining the three-dimensional coordinates of the target feature on the object within the measurement space.

According to a second aspect of the invention, there is provided an apparatus for inspecting an object, the apparatus comprising: at least one projector configured to project from at least first and second projector perspectives an optical pattern onto an object to be measured; at least one imaging device configured to obtain from a first image perspective at least one first image of the object on which an optical pattern is projected from the first projector perspective and configured to obtain from a second image perspective at least one second image of the object on which an optical pattern is projected from the second projector perspective; and an image analyser configured to identify an irregularity in the optical pattern in each of the at least one first and second images as a common object feature.

As will be understood, a projector perspective can comprise the relative position of the projector and object. The projector perspective can comprise the relative orientation of the projector and object.

The apparatus can comprise a projector unit comprising the at least one projector. The projector unit and object can be configured to be relatively moved between the first and second projector perspectives. The apparatus can comprise an imaging device unit comprising the at least one imaging device. The imaging device unit and object can be configured to be relatively moved between the first and second image perspectives. The projector unit and imaging device unit can be configured in a fixed spatial relationship. Accordingly, the projector unit and imaging device unit can be provided as a single unit. For instance, the projector unit and imaging device unit can be provided as a probe device. The projector

unit and imaging device unit can be mounted to the moveable part of a coordinate positioning apparatus. For instance, they could be mounted to the quill of a coordinate positioning apparatus, for instance the quill of a CMM. Accordingly, for example, when the projector unit and imaging device units are provided as a single probe then the probe can be mounted to the quill of a coordinate positioning apparatus.

As will be understood, the apparatus can be configured in accordance with the above described methods and the features described in connection with the method are equally applicable to the apparatus of the invention.

According to a third aspect of the invention there is provided a computer implemented method comprising: receiving first image data representing at least one first image of an object on which an optical pattern is projected, taken from a first perspective; receiving second image data representing at least one second image of the object on which an optical pattern is projected, taken from a second perspective that is different to the first perspective; and analysing the first and second image data to identify at least one common object feature on the basis of an irregularity in the optical pattern as imaged in the at least one first and second images. As will be understood, the computer implemented method can be configured to analyse the first and second image data in accordance with the above described methods.

According to a fourth aspect of the invention there is provided a computer program code comprising instructions which, when executed by a processor device, causes the processor device to execute the methods described above. Accordingly, the computer program code can cause the processor device to control a projector, imaging device and image analyser in accordance with the above described methods. Furthermore, the computer program code can cause the processor device to process images received in accordance with the above described computer implemented method.

According to a further aspect, there is provided computer readable medium, bearing computer program code as described above.

According to a yet further aspect there is provided a machine controller, comprising: a processor; and a memory, wherein at least one of the processor and the memory is adapted to execute the above described methods.

Accordingly, the application describes a non-contact method for measuring an object comprising, in any suitable order, the steps of: i) projecting a structured light pattern onto an object to be measured, the object being located in a measurement space; ii) obtaining at least one first image of the structured light pattern on the object from a first known perspective; iii) obtaining at least one second image of the structured light pattern on the object from at least a second known perspective that is different to the first known perspective; iv) identifying a discontinuity in the structured light pattern in each of the at least one first and second images as a target feature; and v) determining the three-dimensional coordinates of the target feature on the object within the measurement space. The application also describes an apparatus for measuring an object located in a measurement space, the apparatus comprising: a projector configured to project a structured light pattern onto an object to be measured; at least one image sensor configured to obtain at least one first image of the structured light pattern on the object from a first known perspective and at least one second image of the structured light pattern on the object from at least a second known perspective that is different to the first known perspective; and an image analyser configured to identify a discontinuity in the structured light pattern in each of the at least one first and second images as a target feature and to determine the three-dimensional coordinates of the target feature on the object within the measurement space.

An embodiment of the invention will now be described, by way of example only, with reference to the following Figures, in which:

Figure 1 shows a schematic perspective view of a coordinate measuring machine on which a probe for measuring an object via a non-contact method according to the present invention is mounted;

Figure 2 illustrates various images of the object shown in Figure 1 obtained by the probe from three different perspectives;

Figure 3 illustrates a plurality of wrapped phase maps for each of the three different perspectives;

Figure 4 shows a flow chart illustrating the high-level operation of the apparatus shown in Figure 1;

Figure 5 illustrates the method of capturing a perspective image set;

Figure 6 illustrates the method of obtaining fringe shifted images;

Figure 7 illustrates the method of analysing the images;

Figure 8 illustrates the method of calculating the wrapped phase maps;

Figure 9 illustrates a first method for obtaining a height map;

Figure 10 illustrates the a second method for obtaining a height map;

Figure 11 is a schematic diagram of the components of the probe shown in Figure 1;

Figure 12 is a schematic diagram of the positional relationship of the imaging device and projector of the probe shown in Figure 11;

Figure 13 is a schematic diagram of the projector shown in Figure 11; and

Figure 14 illustrates a set of fringe shifted images, the position of the fringe on the object being different in each image;

Figure 15 illustrates the effect of moving the image sensor relative to the object;

Figure 16 illustrates how the gradient of the object surface can be determined from the phase shift;

Figure 17 illustrates obtaining fringe shifted images by causing rotation about the image sensor's perspective centre; and

Figure 18 illustrates the stand-off distance and depth of field of an imaging device.

Referring to Figure 1, a coordinate measuring machine (CMM) 2 on which a measurement probe 4 according to the present invention is mounted, is shown.

The CMM 2 comprises a base 10, supporting a frame 12 which in turn holds a quill 14. Motors (not shown) are provided to move the quill 14 along the three mutually orthogonal axes X, Y and Z. The quill 14 holds an articulating head 16. The head 16 has a base portion 20 attached to the quill 14, an intermediate portion 22 and a probe retaining portion 24. The base portion 20 comprises a first motor (not shown) for rotating the intermediate portion 22 about a first rotational axis 18. The intermediate portion 22 comprises a second motor (not shown) for rotating the probe retaining portion 24 about a second rotational axis that is substantially perpendicular to the first rotational axis. Although not shown, bearings may also be provided between the moveable parts of the articulating head 16. Further, although not shown, measurement encoders may be provided for measuring the relative positions of the base 10, frame 12, quill 14, and articulating

head 16 so that the position of the measurement probe 4 relative to a workpiece located on the base 10 can be determined.

The probe 4 is removably mounted (e.g. using a kinematic mount) on the probe retaining portion 24. The probe 4 can be held by the probe retaining portion 24 by the use of corresponding magnets (not shown) provided on or in the probe 4 and probe retaining portion 24.

The head 16 allows the probe 4 to be moved with two degrees of freedom relative to the quill 14. The combination of the two degrees of freedom provided by the head 16 and the three linear (X, Y, Z) axes of translation of the CMM 2 allows the probe 4 to be moved about five axes.

A controller 26 comprising a CMM controller 27 for controlling the operation of the CMM 2 is also provided, and a probe controller 29 for controlling the operation of the probe 4 and an image analyser 31 for analysing the images obtained form the probe 4. The controller 26 may be a dedicated electronic control system and/or may comprise a personal computer.

The CMM controller 27 is arranged to provide appropriate drive currents to the first and second motors so that, during use, each motor imparts the required torque. The torque imparted by each motor may be used to cause movement about the associated rotational axis or to maintain a certain rotational position. It can thus be seen that a drive current needs to be applied continuously to each motor of the head 16 during use; i.e. each motor needs to be powered even if there is no movement required about the associated rotational axis.

It should be noted that Figure 1 provides only a top level description of a CMM 2. A more complete description of such apparatus can be found elsewhere; for example, see EP402440 the entire contents of which are incorporated herein by this reference.

Referring now to Figure 11, the probe 4 comprises a projector 40 for projecting, under the control of a processing unit 42 a fringe pattern onto the object 28, an imaging device 44 for obtaining, under the control of the processing unit 42 an image of the object 28 onto which the fringe pattern is projected. As will be understood, the imaging device 44 comprises suitable optics and sensors for capturing images of the object 28. In the embodiment described, the imaging device comprises an image sensor, in particular a CCD defining an image plane 62. The imaging device 44 also comprises a lens (not shown) to focus light at the image plane 62.

The processing unit 42 is connected to the probe controller 29 and image analyser 31 in the controller unit 26 such that the processing unit 42 can communicate with them via a communication line 46. As will be understood, the communication line 46 could be a wired or wireless communication line. The probe 4 also comprises a random access memory (RAM) device 48 for temporarily storing data, such as image data, used by the processing unit 42.

As will be understood, the probe 4 need not necessarily contain the processing unit 42 and/or RAM 48. For instance, all processing and data storage can be done by a device connected to the probe 4, for instance the controller 26 or an intermediate device connected between the probe 4 and controller 26.

As illustrated in Figure 12, the projector's 40 image plane 60 and the imaging device's 44 image plane 62 are angled relative to each other such that the projector's 40 and imaging device's optical axes 61, 63 intersect at a reference plane 64. In use, the probe 4 is positioned such that the fringes projected onto the object's surface can be clearly imaged by the imaging device 44.

With reference to Figure 13, the projector 40 comprises a laser diode 50 for producing a coherent source of light, a collimator 52 for collimating light emitted

from the laser diode 50, a grating 54 for producing a sinusoidal set of fringes, and a lens assembly 56 for focussing the fringes at the reference plane 64. As will be understood, other types of projectors would be suitable for use with the present invention. For instance, the projector could comprise a light source and a mask to selectively block and transmit light emitted from the projector in a pattern.

In the described embodiment, the periodic optical pattern projected by the projector 40 is a set of sinusoidal fringes. However, as will be understood, other forms of structured light could be projected, such as for example a set of parallel lines having different colours or tones (e.g. alternating black and white lines, or parallel red, blue and green lines), or even for example a set of concentric circles.

Referring to Figures 2 to 10, the operation of the probe 4 will now be described.

Referring first to Figure 4, the operation begins at step 100 when the operator turns the CMM 2 on. At step 102, the system is initialised. This includes loading the probe 4 onto the articulating head 16, positioning the object 28 to be measured on the base 10, sending the CMM's encoders to a home or reference position such that the position of the articulating head 16 relative to the CMM 2 is known, and also calibrating the CMM 2 and probe 4 such that the position of a reference point of the probe 4 relative to the CMM 2 is known.

Once initialised and appropriately calibrated, control passes to step 104 at which point a set of images of the object 28 is obtained by the probe 4. This step is performed a plurality of times so that a plurality of image sets are obtained, wherein each set corresponds to a different perspective or view point of the object 28. In the example described, three sets of images are obtained corresponding to three different perspectives. The process of obtaining a set of images is explained in more detail below with respect to Figure 5.

Once all of the images have been obtained, the images are analysed at step 106 by

the image analyser 31 in the controller 26. The image analyser 31 calculates from the images a set of three dimensional ("3D") coordinates relative to the CMM 2 which describe the shape of the object 28. The method of analysing the images will be described in more detail below with reference to Figure 7. The 3D coordinates are then output at step 108 as a 3D point cloud. As will be understood, the 3D point cloud could be stored on a memory device for later use. The 3D point cloud data could be used to determine the shape and dimensions of the object and compare it to predetermined threshold data to assess whether the object 28 has been made within predetermined tolerances. Optionally, the 3D point cloud could be displayed on a graphical user interface which provides a user with virtual 3D model of the object 28.

The operation ends at step 110 when the system is turned off. Alternatively, a subsequent operation could be begun by repeating steps 104 to 108. For instance, the user might want to obtain multiple sets of measurement data for the same object 28, or to obtain measurement data for a different object.

Referring now to Figure 5, the process 104 of capturing an image set for a perspective will now be described. The process begins at step 200 at which point the probe 4 is moved to a first perspective. In the described embodiment, the user can move the probe 4 under the control of a joystick (not shown) which controls the motors of the CMM 2 so as to move the quill 14. As will be understood, the first (and subsequent) perspective could be predetermined and loaded into the CMM controller 27 such that during the measurement operation the probe 4 is automatically moved to the predetermined perspectives. Further, on a different positioning apparatus, the user could physically drag the probe 4 to the perspectives, wherein the positioning apparatus monitors the position of the probe 4 via, for example, encoders mounted on the moving parts of the apparatus.

Once the probe 4 is positioned at the first perspective, an initialising image is obtained at step 202. This involves the probe controller 29 sending a signal to the

processing unit 42 of the probe 4 such that it operates the imaging device 44 to capture an image of the object 28.

The initialising image is sent back to the image analyser 31 and at step 204, the image is analysed for image quality properties. This can include, for example, determining the average intensity of light and contrast of the image and comparing them to predetermined threshold levels to determine whether the image quality is sufficient to perform the measurement processes. For example, if the image is too dark then the imaging device 44 or projector 40 properties could be changed so as to increase the brightness of the projected fringe pattern and/or adjust the expose time or gain of the imaging device 44. The initialising image will not be used in subsequent processes for obtaining measurement data about the object 28 and so certain aspects of the image, such as the resolution of the image, need not be as high as that for the measurement images as discussed below. Furthermore, in alternative embodiments, a light sensor, such as a photodiode, separate to the imaging device could be provided in the probe to measure the amount of light at a perspective position, the output of the photodiode being used to set up the projector 40 and/or imaging device 44.

Once the projector 40 and imaging device 44 have been set up, the first measurement image is obtained at step 206. What is meant by a measurement image is one which is used in the "analyse images" process 106 described in more detail below. Obtaining the first measurement image involves the probe controller 29 sending a signal to the processing unit 42 of the probe 4 such that the processing unit 42 then operates the projector 40 to project a fringe pattern onto the object 28 and for the imaging device 44 to simultaneously capture an image of the object 28 with the fringe pattern on it.

The first measurement image is sent back to the image analyser 31 and at step 208, the first measurement image is again analysed for image quality properties. If the image quality is sufficient for use in the "analyse images" process 106 described

below, then control is passed to step 210, otherwise control is passed back to step 204.

At step 210, fringe shifted images are obtained for the current perspective. Fringe shifted images are a plurality of images of the object from substantially the same perspective but with the position of the fringes being slightly different in each image. The method this step is described in more detail below with respect to Figure 6.

Once the fringe shifted images have been obtained, all of the images are then sent back to the imager analyser 31 for analysis at step 212. As will be understood, data concerning the position and orientation that the probe 4 was at when each image was obtained will be provided to the image analyser 31 along with each image, such that 3D coordinates of the object 28 relative to the CMM 2 can be obtained as explained in more detail below. The process then ends at step 214.

As explained above, the capture perspective image set process 104 is repeated a plurality of times for a plurality of different perspectives. In this described example, the capture perspective image set process is performed three times, for first, second and third perspectives. The probe 4 is moved to each perspective either under the control of the user or controller as explained above.

With reference to Figure 6, the process 210 for obtaining the fringe shifted images will now be described. The fringes projected on the object 28 are shifted by physically moving the probe 4 by a small distance in a direction such that the position of the fringes on the object 28 are different from the previous position. As the probe 4 is shifted, the projector 40 within it, and hence the projector's optical axis 61, will also be shifted relative to the object 28. This is what provides the change in position of the fringes of the object 28.

In one embodiment, the probe 4 is moved in a direction that is parallel to the

imaging device's 44 image plane and perpendicular to the length of the fringes.

However, this need not necessarily be the case, so long as the position of the fringes on the object is moved. For example, the fringe shifting could be achieved by rotating the probe 4. For instance, the probe 4 could be rotated about an axis extending perpendicular to the projector's image plane 60. Optionally the probe could be rotated about an axis extending perpendicular to the imaging device's 44 image plane. In another preferred embodiment the probe 4 can be rotated about the imaging device's 44 perspective centre. This is advantageous because this ensures that the perspective of the features captured by the imaging device 44 across the different images will be the same. It also enables any processing of the images to compensate for relative movement of the object and image sensor to be done without knowledge of the distance between the object and image sensor.

For example, with reference to Figure 17 the probe 4 is located at a first position (referred to by reference numeral 4`) relative to an object 70 to be inspected . At this instance the probe's projector 40 is at a first position (referred to by reference numeral 40`) which projects a fringe pattern illustrated by the dotted fringe markings 72` on the object 70. An image 74 of the object with the fringe markings 72` is captured by the imaging device 44 which is at a first position referred to by reference numeral 44`.

The probe 4 is then moved to a second position, referred to by reference numeral 4``, by rotating the probe 4 relative to the object 70 about the imaging device's perspective centre. As will be understood, an imaging device's perspective centre is the point through which all light rays that intersect with the image plane are assumed to pass. In the figure shown, the perspective centre is referred to by reference numeral 76.

As can be seen, at the second position the projector, referred to by reference numeral 40``, has moved such that the position of the fringe pattern

on the object 70 has moved. The new position of the fringe pattern on the object 70 is illustrated by the striped fringe markings 72`` on the object 70. An image 74 of the object is captured by the imaging device at its second position 44``. As can be seen, although the position of the image of the object on the imaging device 44 has changed between the first 44` and second 44`` positions of the imaging device, the perspective the imaging device 44 has of the object 70 does not change between the positions. Accordingly, for example, features that are hidden due to occlusion in one image will also be hidden due to occlusion in the second. This is illustrated by the rays 78 illustrating the view the imaging device 44 has of the tall feature 80 on the object. As can be seen, because the imaging device 44 is rotated about its perspective centre, the rays 78 are identical for both positions and so only the location of the feature on the imaging device 44 changes between the positions, not the form of the feature itself.

Accordingly, rotating about the perspective centre can be advantageous as the image sensor's perspective of the object does not change thereby ensuring that the same points on the object are visible for each position. Furthermore, for any point viewed, the distance between the image points of it before and after the relative rotation of camera and object is independent of the distance to the object. That is, for an unknown object, if the camera is rotated about its own perspective centre it is possible to predict, for each imaged point before the rotation, where it will be imaged after rotation. The position of an image point after the rotation depends on the position of the initial image point, the angle (and axis) of rotation, and the internal camera parameters – all known values. Accordingly, as is described in more detail below, rotating about the perspective centre allows the relative motion to be compensated for without knowing the distance to the object.

The probe 4 is moved a distance corresponding to a fringe shift of 1/4 period at the point where the imaging device's 44 optical axis 63 intersects the reference plane 64. As will be understood, the actual distance the probe 4 is moved will depend on the period of the fringes projected and other factors such as the magnification

of the projector 40.

Once the probe 4 has been shifted, another measurement image is obtained at step 302. The steps of shifting the probe 300 and obtaining a measurement image 302 is repeated two more times. Each time, the probe is shifted so that for each measurement image the position of the fringe pattern on the object is different for all previous images. Accordingly, at the end of the obtain fringe shifted images process 210 four images of the object have been obtained for a given perspective, with the position of the fringe pattern on the object for each image being slightly different.

Reference is now made to Figure 2. Row A shows the view of the object 28 at each of the three perspectives with no fringes projected onto it. Row B illustrates, for each of the first, second and third perspectives the image 1000 that will be obtained by the imaging device 44 at step 206 of the process for capturing a perspective image set 104. Schematically shown behind each of those images 1000 are the fringe shifted images 1002, 1004 and 1006 which are obtained during execution of steps 300 and 302 for each of the first, second and third perspectives. Figures 14(a) to 14 (d) shows an example of the images 1000 – 1006 obtained for the first perspective. As shown, the relative position of the object and imaging device has moved slightly between obtaining each image in an image set for a perspective, and this needs to be taken into consideration and/or compensated for during processing of the images as described in more detail below (especially as described in connection with Figure 8).

Accordingly, once the step 104 of capturing the first, second and third image sets has been completed, the image analyser 31 will have a set of images 1000-1006 for each of the first, second and third perspectives.

The process 106 for analysing the images will now be described with reference to Figure 7. The process begins at step 400 at which point four wrapped phase maps

are calculated for each of the first, second and third perspectives. As will be understood, a wrapped phase map is a map which contains the phase of the fringes projected onto the object's surface for a plurality of pixels in one of the measurement images in a perspective image set, where the phase angle is bound within a range of 360 degrees.

For a given perspective, a wrapped phase map is obtained using each of the four phase shifted images for that perspective in a particular order. The four wrapped phase maps for a given perspective are obtained by using each of the four phase shifted images in different orders. The method for obtaining a wrapped phase map will be explained in more detail below with reference to Figure 8.

As will be understood, it need not be necessary to calculate four wrapped phase maps for each perspective. For instance, two or more wrapped phase maps could be calculated for each of the perspectives. As will be understood, the more wrapped phase maps that are calculated, the more reliable the determination of real discontinuities as explained in more detail below, but the more processing resources required.

Referring to Figure 3, columns X, Y and Z illustrate for each of the different perspectives four different wrapped phase maps 1010, 1012, 1014 and 1016. Each of those wrapped phase maps for a given perspective has been calculated using a unique order of the four different images 1002 – 1006 for that perspective. Four different wrapped phase maps 1010 – 1016 for each perspective are calculated in order to be able to distinguish between those discontinuities caused by features on the object 28 and those discontinuities caused by the wrapping of the phase, as explained in more detail below.

As can be seen from the images in row B of Figure 2, a feature, such as an edge or corner on the object 28 causes a discontinuity in the fringe pattern. For example, edge 30 on the object 28 causes a discontinuity in the fringe pattern along line 32

in the image of the object 28 with the fringe projected on it. Accordingly, it is possible to identify features of the object 28 by identifying discontinuities in the fringe pattern.

At step 402, discontinuities in the fringe pattern are identified for each of the perspectives. This is achieved by identifying discontinuities in each of the wrapped phase maps. A discontinuity in a wrapped phase map is identified by comparing the phase value of each pixel to the phase values of adjacent surrounding pixels. If the difference in the phase value between adjacent pixels is above a threshold level, then one of those pixels identifies a discontinuity point. As will be understood, it is not important which one of those pixels is selected as the discontinuity point so long as the selection criteria is consistent for the selection of all discontinuity points, e.g. always select the pixel to the left or to the top of the difference, depending on whether the differences between adjacent pixels are being calculated in the x or y direction along the image. As will be understood, the positions of the discontinuities, once found by the above described method, can be refined if required using image processing techniques, for example by looking at the gradient of the phase, or the gradient of the intensities in the measurement images in the surrounding region, in order to find the location of the discontinuity to sub-pixel accuracy, for example as described in J.R. Parker, "Algorithms for image processing and computer vision", John Wiley and Sons, Inc (1997).

The preferred threshold level depends on a number of factors including the object shape, level of noise in the image and period of the fringe pattern. The threshold level could be set by a user prior to the operation or could be calculated from an analysis of the image itself.

For example, referring to the first wrapped phase map 1010 (in Figure 3) for the first perspective, a discontinuity will be identified between adjacent pixels at point 34 due to the difference in the phase value caused by the distortion along line 32

of the fringe due to the edge 30. This discontinuity will also be identified in the other wrapped phase maps 1012, 1014 and 1016 at the same point 34.

Other discontinuities will also be identified in the wrapped phase maps 1010 – 1016, such as for example all the way along line 32, which corresponds to the edge 30.

It is possible that the above process could result in false discontinuities being identified due to the phase map being wrapped. For example, adjacent pixels might have phase values of, for instance, close to 0 degrees and 360 degrees respectively. If so, then it would appear as if there has been a large phase jump between those pixels and this would be identified as a discontinuity. However, the phase jump has merely been caused as a result of the wrapping around of the phase, rather than due to a discontinuity in the surface of the object being measured. An example of this can be seen in the first wrapped phase map 1010 for the first perspective at point 36 where the phase values jump from 360 degrees to 0 degrees (illustrated by the dark pixels and light pixels respectively). The phase value for adjacent pixels will jump significant at point 36 due to the phase map being wrapped.

Accordingly, once all discontinuities have been identified for each of the four wrapped phase maps for a given perspective, then falsely identified discontinuities are removed at step 404. This is achieved by comparing the discontinuities for each of the wrapped phase maps for a given perspective, and only keeping the discontinuities that appear in at least two of the four wrapped phase maps. As will be understood, a more stringent test could be applied by, for example, only keeping the discontinuities that appear in three or four of the wrapped phase maps. This can help overcome problems caused by noise on the images. This process 404 is performed for each of the first to third perspective image sets.

For example, as mentioned above a discontinuity would have been identified at

point 36 in the first wrapped phase map 1010 for the first perspective. However, when looking at the other wrapped phase maps 1012 to 1016 for the first perspective, a discontinuity would not have been identified at that same point 36. This is because the different wrapped phase maps have been calculated using a different order of the fringe shifted images 1000 to 1006, thereby ensuring that the phase wrapping in the wrapped phase maps occurs at different points. Accordingly, as the discontinuity identified at point 36 in the first wrapped phase map 1010 is not also identified in the other wrapped maps 1012 to 1016, then that discontinuity can be discarded.

However, as the discontinuity at point 34 in the first wrapped phase map 1010 has been confirmed by discontinuities identified at the same point 34 in all the other wrapped phase maps 1012 to 1014, point 34 is identified as a real discontinuity, i.e. a discontinuity caused by a feature on the object 28, rather than as a result of phase wrapping.

At step 406, corresponding discontinuity points between each of the perspectives are identified. Corresponding discontinuity points are those points in the wrapped phase maps which identify a discontinuity caused by the same feature on the object 28. For example, discontinuity point 38 on each of the first wrapped phase maps 1010 for each of the first, second and third perspectives all identify the same corner 39 on the object 28. Corresponding discontinuity points can be determined by known matching techniques and, for example, utilising epipolar geometry. Such known techniques are described, for example in A. Gruen, "Least squares matching: a fundamental measurement algorithm" in K. B. Atkinson (ed.), "Close range photogrammetry and machine vision", Whittles Publishing (2001). The correlated discontinuity points can then be used as target points, the 3D coordinates of which relative to the probe 4 can be determined at step 408 by known photogrammetry techniques, such as those described in, for example, M.A.R Cooper with S. Robson, "Theory of close-range photogrammetry" in K. B. Atkinson (ed.), "Close range photogrammetry and machine vision", Whittles

Publishing (2001).

Accordingly, after step 408 a number of discrete points on the object 28 will have been identified and their position relative to the probe 4 measured.

At step 410, a height map for a continuous section of the object 28 is calculated. A height map provides information on the height of the surface above a known reference plane 6 relative to the probe 4. A continuous section is an area of the object enclosed by discontinuous features, e.g. the face of a cube which is enclosed by four edges. Continuous sections can be identified by identifying those areas in the wrapped phase map which are enclosed by discontinuity points previously identified in steps 402 to 406. The height map provides measurement data on the shape of the surface between those discrete points. Methods for obtaining the height map for a continuous section are described below in more detail with respect to Figures 9 and 10. Steps 410 could be performed a plurality of times for different continuous sections for one or more of the different perspectives.

As is usual in similar fringe analysis systems, the unwrapped phase map is correct only to some unknown multiple of $2\pi$ radians, and therefore the height above the reference plane 64 may be wrong by whatever height corresponds to this unknown phase difference. This is often called $2\pi$ ambiguity. The measured 3D coordinates of the real discontinuities obtained in step 408 are used in order to resolve these ambiguities.

At this stage, the 3D coordinates of the real discontinuity points obtained in step 408 and the height map data obtained in step 410 provide the position of the object relative to a predetermined reference point in the probe 4. Accordingly, at step 412, these coordinates are converted to 3D coordinates relative to the CMM 2. This can be performed using routine trigonometry techniques as the relative position of the CMM 2 and the reference point in the probe 4 is known from

calibration, and also because the position and orientation of the probe 4 relative to the CMM 2 at the point each image was obtained was recorded with each image.

The process for calculating a wrapped phase map 400 will now be described with reference to Figure 8. Calculating a wrapped phase map comprises calculating the phase for each pixel for one of a set of fringe-shifted images. This can be done using various techniques, the selection of which can depend on various factors including the method by which the fringe-shifted images are obtained. Standard phase-shifting algorithms rely on that the relative position between the object and imaging device 44 is the same across all of the fringe-shifted images. However, if either of the methods described above (e.g. either moving the probe 4 laterally or rotating it about the imaging device's perspective centre) are used to obtain the fringe-shifted images then the imaging device 44 will have moved a small distance relative to the object. Accordingly, for each successive image in a perspective image set, a given pixel in each image will be identifying the intensity of a different point on the object. Accordingly, if standard phase-shifting algorithms are to be used it is necessary to identify across all of the fringe shifted images which pixels correspond to same point on the object, and to then compensate for this. One way of doing this when the imaging device 44 has moved laterally is to determine by how much and in what direction the imaging device 44 has travelled between each image, and by then cropping the images so that each image contains image data common to all of them. For example, if the movement of the imaging device 44 between two images means that a point on an object has shifted five pixels in one dimension, then the first image can be cropped to remove five pixel widths worth of data.

This can be seen more clearly with reference to Figure 15 which schematically illustrates corresponding rows of pixels for each of the first 1000, second 1002, third 1004 and fourth 1006 images. As can be seen, due to relative movement of the imaging device 44 and the object 28 between the images, the same point on an object is imaged by different pixels in each image. For instance, point X on the

object 28 is imaged by the 7th pixel from the left for the first image 1000, the 5th pixel from the left for the second image 1002, the 3rd pixel from the left for the third image 1004 and the 4th pixel from the left for the fourth image 1006. An effective way of compensating for the relative movement of the image sensor and object 28 is to crop the image data such that each image 1000 – 1006 contains a data representing a common region, such as that highlighted by window 51 in Figure 15.

Cropping the images is one example of a coordinate transformation, where the transformation is a linear function. This can be most accurate in situations where the distance to the object is known, or, for instance, where the stand-off distance is large compared to the depth of the measuring volume. As will be understood, and with reference to Figure 18, the stand-off distance is the distance from the imaging device's perspective centre 76 to the centre of the imaging device's measurement volume and the depth of field 65 or depth of measurement volume is the range over which images recorded by the device appear sharp. In other words, the stand-off distance is the nominal distance from the probe 4 to the object to be measured. For instance, if the ratio of stand-off distance to depth of measuring volume is around 10:1 then there can be an error of up to 10% in the compensation for some pixels. If either the stand-off distance is not large compared to the depth of the measuring volume, or if the relative motion is not a linear translation, then the most appropriate coordinate transformation to compensate for relative motion of the imaging device and the object can depend, in general on the distance to the object and the actual motion. However, it has been found that if the motion is rotation about the imaging device's 44 perspective centre then the coordinate transformation that best compensates for the motion is independent of the unknown distance to the object. This is due to the geometry of the system and the motion. Furthermore, this enables accurate compensation to be performed even if the stand-off distance is not large compared to the depth of the measuring volume, for instance in situations in which the ratio of stand-off distance to depth of measuring volume is less than 10:1, for example less than 5:1, for instance 1:1.

Accordingly, this enables measurement of an object to be performed even when the probe is located close to the object.

Once the pixel data has been compensated for the relative motion so that the same pixel in each adjusted image represents the same point on the object, the next step 502 involves using a phase-shifting algorithm to calculate the wrapped phase at each pixel. A suitable phase-shifting algorithm not requiring known phase shift, for instance the Carré algorithm, may be used to calculate the wrapped phase, phase shift and modulation amplitude.

The process for calculating a wrapped phase map 400 is repeated three further times for each perspective image set, each time using the phase shifted images in a different order, so as to obtain four wrapped phase maps for each perspective. Accordingly, in the process for calculating the wrapped phase maps 400 is performed twelve times in total.

A first process for obtaining the height map 410 will now be described with reference to Figure 9. The method involves at step 600 unwrapping the continuous section of one of the phase maps by adding integer multiples of 360 degrees to the wrapped phase of individual pixels as required to remove the discontinuities found due to the phase calculation algorithm. The method then involves converting the unwrapped phase map to a height map for that continuous section at step 602. The phase for a pixel is dependent on the relative height of the surface of the object. Accordingly, it is possible, at step 602 to create a height map for the continuous section from that phase by directly mapping the phase value of each pixel to a height value using a predetermined mapping table and procedure.

In contrast to the methods for calculating a wrapped-phase map described above in connection with Figure 8, i.e. in which the image coordinates are compensated for, it has been found that there is another way to calculate the wrapped phase when

the object and imaging device 44 are moved relative to each other which doesn't require image coordinate compensation. This method relies on the fact that a pixel of the imaging device's 44 CCD will be viewing a different point on the object for each different image. If the points viewed by a single pixel in multiple images are at different distances to the imaging device 44, then a different phase will be recorded at that pixel in each image. That is, the phase of the fringe pattern at that pixel will be shifted between each image. The actual phase shift will depend on the distance to the object and on the gradient of the object, as well as the known relative motion of the imaging device 44 and object and the fixed system parameters. The phase shift will therefore vary across the image.

As an example, with reference to Figure 16, consider an object point Xp, imaged at x in the camera plane. If the imaging device 44 is translated by some vector dX with respect the the plane, then the point imaged by the imaging device 44 will change, as show. For clarity, the projector 40 is omitted from the diagram, but it is to be understood that the imaging device 44 and projector 40 are fixed with respect to each other.

$h$ is the distance from the imaging device's 44 perspective centre to the object point imaged at $x$, and $\delta h$ is the change in this distance after translation $\delta X$. $a$ is the known direction of the imaging device's optic axis, and $X_c$ is the position of the perspective centre, also known. The change in $h$ due to the motion of the imaging device 44 only is equal to $\delta X.a$. If this quantity is zero, so that the motion is perpendicular to the imaging device axis and parallel to the image plane, then any remaining change in $h$ must be due to the object shape.

The change in $h$ is actually recorded as a change in phase, $\delta\phi$, where, again, this will consist of a component caused by the shape of the object, and a component caused by any motion of the imaging device parallel to its axis.

To measure the phase at a given pixel, we take multiple phase shifted images. The

intensity recorded at a pixel in image $k$ can be expressed as

$$I_k = A + B\cos\phi_k$$

where:

A = offset (i.e. the average intensity of the fringe pattern projected onto the object as recorded by that pixel, including any background light);

B = amplitude modulation of the light intensity recorded by that pixel; and

$$\phi_k = \phi_{k-1} + \Delta\phi_k \approx \phi_k + \underline{\nabla}\phi_{k-1}.\underline{\delta X}_k, k > 0$$

using a first order Taylor series expansion, which assumes that the translation $\delta X$ is small.

The Carré algorithm is used to calculate for each pixel in a given image in an image set, the phase and phase shift and modulation amplitude from the four phase-shifted images. The Carré algorithm assumes that the four shifts in phase are equal. This will be the case, for instance, if the motion used is a translation and the surface is planar. If this is not the case then a good approximation can be obtained by choosing motion that it small enough that the surface gradient does not vary significantly over the scale of the motion.

The phase data can be converted to height data. Optionally the phase shift data can be converted to gradient data and subsequently to height data using the method described below in connection with Figure 10.

The above described method provides optimum results when the object's reflectivity and surface gradient is substantially constant on the scale of the relative motion. Accordingly, it can be preferred that the motion between the images in an image set is small. Areas of the surface at too low or too high a gradient relative to the imaging device, or with a high degree of curvature, can be detected by inspecting the modulation amplitude returned by the Carré algorithm,

and can subsequently be measured by changing the relative motion used to induce the phase shift and if necessary by viewing the object from a different perspective.

A Carré algorithm provides both phase and phase shift data for each pixel in an image. The above methods described above in connection with Figure 9 use the phase data to obtain the height data. However, it has been possible to obtain the height information using the phase-shift data. In particular, a second process for obtaining the height map 410 will now be described with reference to Figure 10. This method begins at step 700 by, for a continuous section (which is identifiable from the discontinuities previously identified as explained above), calculating a phase shift map using a Carré algorithm on all of the images in a perspective image set. The phase shift for a pixel is dependent on the gradient of the surface of the object and how far away the object is from the probe 4. Accordingly, it is possible, at step 702 to create a gradient map for the continuous section from that phase shift by directly mapping the phase shift value of each pixel to a gradient value using a predetermined mapping table and procedure. At step 704, the gradient map is then integrated in order to get a height map for the continuous surface relative to the probe 4. The measured 3D coordinates of the real discontinuities obtained in step 408 are used in order to resolve the constant of integration to find the height above the reference plane 64.

It is an advantage of the invention that target points can be quickly identified without a user having to place markers on the object or to configure a projector to selectively project target points onto the object. Furthermore, a high density of target points can be identified.

As will be understood, the above provides a detailed description of just one particular embodiment of the invention and many features are merely optional or preferable rather than essential to the invention.

For instance, in the described embodiments the probe is mounted on a mounting

structure equivalent to the quill of a CMM. This invention is also suitable for use with planning the course of motion of a measurement device mounted on other machine types. For example, the probe 4 could be mounted on a machine tool. Further, the probe 4 may be mounted onto the distal end of an inspection robot, which may for example comprise a robotic arm having several articulating joints. Furthermore, the probe 4 might be in a fixed position and the object could be moveable, for example via a positioning machine.

Further, although the invention is described as a single probe containing a projector and imaging device, the projector and image sensor could be provided separately (e.g. so that they can be physically manipulated independently of each other). Furthermore, a plurality of imaging devices can be provided at different positions and/or orientations to each other for capturing the images for use in determining target features.

As will be understood, the description of the specific embodiment also involves obtaining and processing images to obtain topographical data via phase analysis of a periodic optical pattern. As will be understood, this need not necessarily be the case. For example, the system and method of the invention might only be configured to determine target points for photogrammetrical purposes. Furthermore, if topographical data is to be determined then techniques such as triangulation might be used instead of using phase-stepping algorithms. Furtherstill, if phase-stepping methods are to be used, the shift in the pattern could be obtained using techniques other than that described above. For instance, they could be obtained by changing the pattern projected by the projector, or by moving the object.

CLAIMS:

1. A non-contact method for inspecting an object comprising, in any suitable order:

i) obtaining at least one first image of the object on which an optical pattern is projected, taken from a first perspective;

ii) obtaining at least one second image of the object on which an optical pattern is projected, taken from a second perspective that is different to the first perspective; and

iii) identifying at least one common object feature in each of the at least one first and second images on the basis of an irregularity in the optical pattern as imaged in the at least one first and second images.

2. A method as claimed in claim 1, in which at least one of the relative position and relative orientation of the object and projector of the optical pattern at step i) is different to that of the object and projector of the optical pattern at step ii).

3. A method as claimed in claim 1 or 2, in which the projector of the optical pattern imaged at step i) and the projector of the optical pattern imaged at step ii) are provided by a common optical pattern projector unit comprising at least one projector, and in which the method further comprises relatively moving the object and the optical pattern projector unit between steps i) and ii).

4. A method as claimed in claim 3, comprising moving the optical pattern projector unit relative to the object.

5. A method as claimed in claim 3 or 4, in which the projector of the optical pattern imaged at step ii) is the projector of the optical pattern imaged at step i).

6. A method as claimed in any preceding claim, in which the optical pattern

projected on the object in step i) and step ii) is the same.

7. A method as claimed in any preceding claim, in which the at least one first image and the at least one second image are obtained by a common imaging device unit comprising at least one image sensor, and in which the method comprises moving the imaging device unit from the first perspective to the second perspective.

8. A method as claimed in claim 3 and 7, in which the optical pattern projector unit and the imaging device unit are in a fixed spatial relationship relative to each other.

9. A method as claimed in claim 8 in which the optical pattern projector unit and the imaging device unit are mounted on a coordinate positioning apparatus.

10. A method as claimed in claim 8 or 9, in which the optical pattern projector unit and the imaging device unit are provided as a single probe.

11. A method as claimed in any preceding claim, further comprising using the at least one first and second images to measure the common feature.

12. A method as claimed in claim 11, in which measuring the common feature comprises determining the position of the common feature within a measurement volume.

13. A method as claimed in any preceding claim, in which:

step i) comprises obtaining from a first perspective a set of first images of the object; and

step ii) comprises obtaining from a second perspective a set of second images of the object;

and in which the position of the optical pattern on the object is different for

each image in a set.

14. A method as claimed in claim 13, in which step iii) comprises:

a) calculating at least one first phase map from the set of first images;

b) calculating at least one second phase map from the set of second images; and

c) identifying at least one common irregularity in each of the at least one first and second phase maps as a common object feature.

15. A method as claimed in claim 14, in which:

step a) comprises calculating a set of first phase maps from the set of first images, each phase map in the set being calculated using a unique order of the set of first images;

step b) comprises calculating a set of second phase maps from the set of second images, each phase map in the set being calculated using a unique order of the set of second images; and

step c) comprises identifying at least one corresponding irregularity in the set of at least one first phase maps and set of at least second phase maps as a common object feature.

16. A method as claimed in claim 14 or 15, in which the phase maps are wrapped phase maps and in which step c) comprises discarding false irregularities caused by wrapped phase data.

17. A method as claimed in claim 16, in which discarding false irregularities comprises comparing each of the wrapped phase maps in a set and discarding non-commonly identified irregularity points between each of the wrapped phase maps.

18. A method as claimed in any preceding claim, in which identifying at least one common irregularity comprises identifying corresponding features of the object between the images of the different perspectives.

19. A method as claimed in any preceding claim, in which the method comprises identifying in each of the at least one first image and the at least one second image a plurality of irregularities in the optical pattern formed on the object as a plurality of common object features, and determining the three-dimensional coordinates of each of the common object features on the object within a measurement space from the at least one first image and the at least one second image.

20. A method as claimed in any preceding claim, further comprising determining topographical data regarding the surface of the object on which the optical pattern is projected by analysing the deformation of the optical pattern as imaged by at least one of the at least two images.

21. A method as claimed in claim 19 and 20, further comprising combining the three-dimensional coordinates of the plurality of common object features with the topographical data to obtain three-dimensional model data of the object.

22. An apparatus for inspecting an object, the apparatus comprising:

at least one projector configured to project from at least first and second projector perspectives an optical pattern onto an object to be measured;

at least one imaging device configured to obtain from a first image perspective at least one first image of the object on which an optical pattern is projected from the first projector perspective and configured to obtain from a second image perspective at least one second image of the object on which an optical pattern is projected from the second projector perspective; and

an image analyser configured to identify an irregularity in the optical pattern in each of the at least one first and second images as a common object feature.

23. An apparatus as claimed in claim 22, in which the apparatus comprises a

projector unit comprising the at least one projector and in which the projector unit and object are configured to be relatively moved between the first and second projector perspectives.

24. An apparatus as claimed in claim 22 or 23, in which the apparatus comprises an imaging device unit comprising the at least one imaging device and in which the imaging device unit and object are configured to be relatively moved between the first and second image perspectives.

25. An apparatus as claimed in claim 23 and 24, in which the projector unit and imaging device unit are in a fixed spatial relationship.

26. An apparatus as claimed in any of claims 22 to 24 in which the projector unit and imaging device unit are mounted to the moveable part of a coordinate positioning machine.

27. An apparatus as claimed in claim 25 or 26, in which the projector unit and imaging device unit are provided as a single probe.

28. A computer implemented method comprising:

receiving first image data representing at least one first image of an object on which an optical pattern is projected, taken from a first perspective;

receiving second image data representing at least one second image of the object on which an optical pattern is projected, taken from a second perspective that is different to the first perspective; and

analysing the first and second image data to identify at least one common object feature on the basis of an irregularity in the optical pattern as imaged in the at least one first and second images.

29. Computer program code comprising instructions which, when executed by a processor device, causes the processor device to execute the method of any of

claims 1 to 21 and 28.

30. A computer readable medium, bearing computer program code as claimed in claim 29.

31. A machine controller, comprising:

a processor; and

a memory, wherein at least one of the processor and the memory is adapted to execute the method of any of claims 1 to 21 and 28.

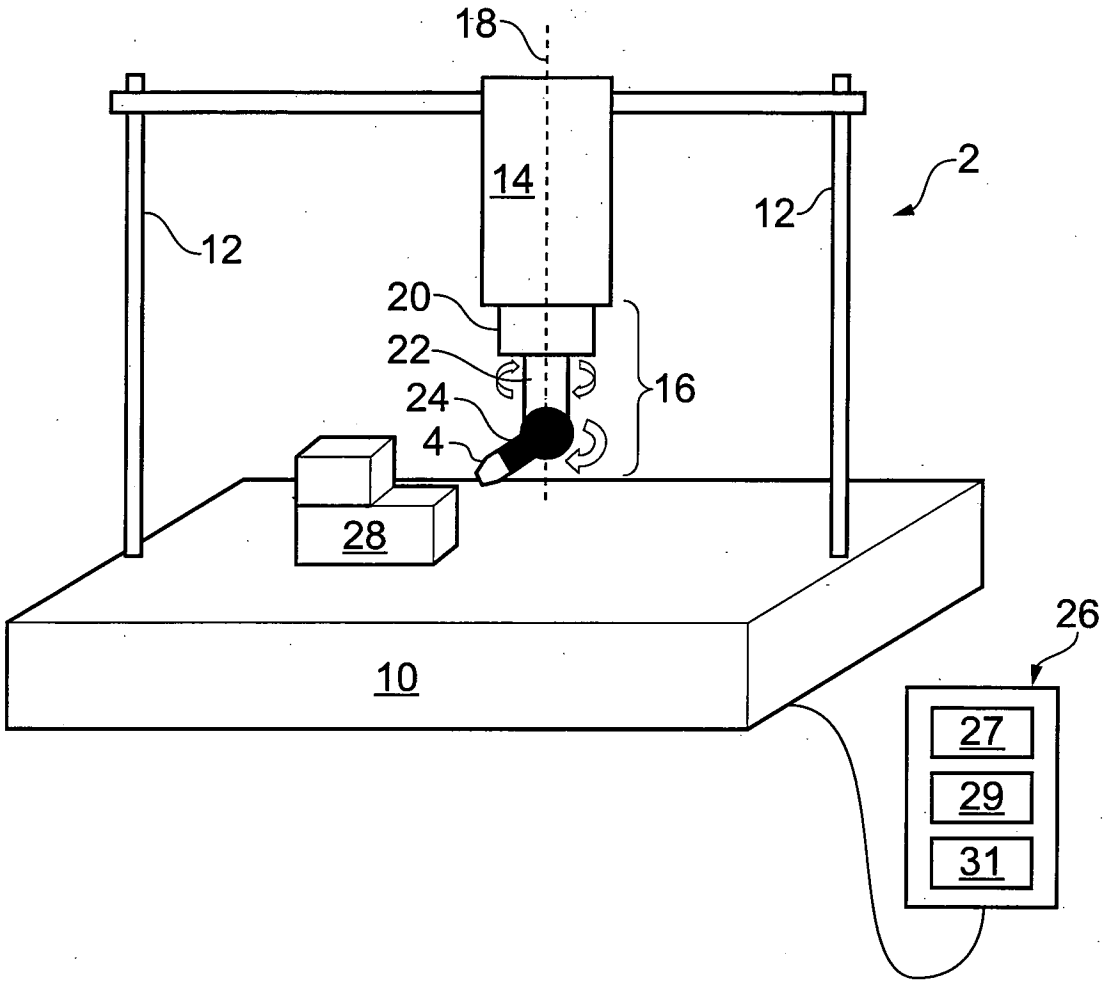


FIG. 1

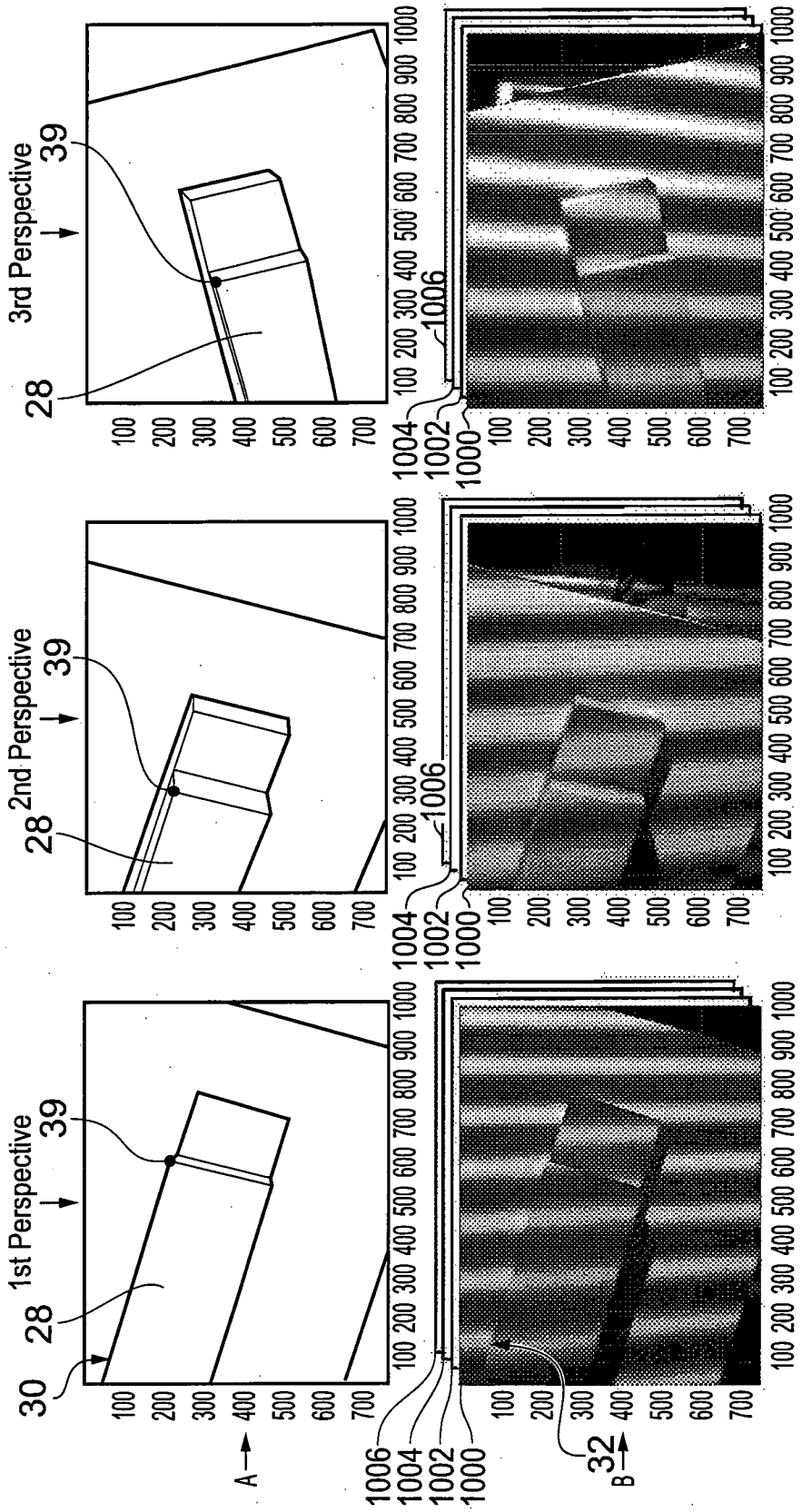
1st Perspective
2nd Perspective
3rd Perspective
39
28
30
32
A
B
1000
1002
1004
1006

FIG. 2

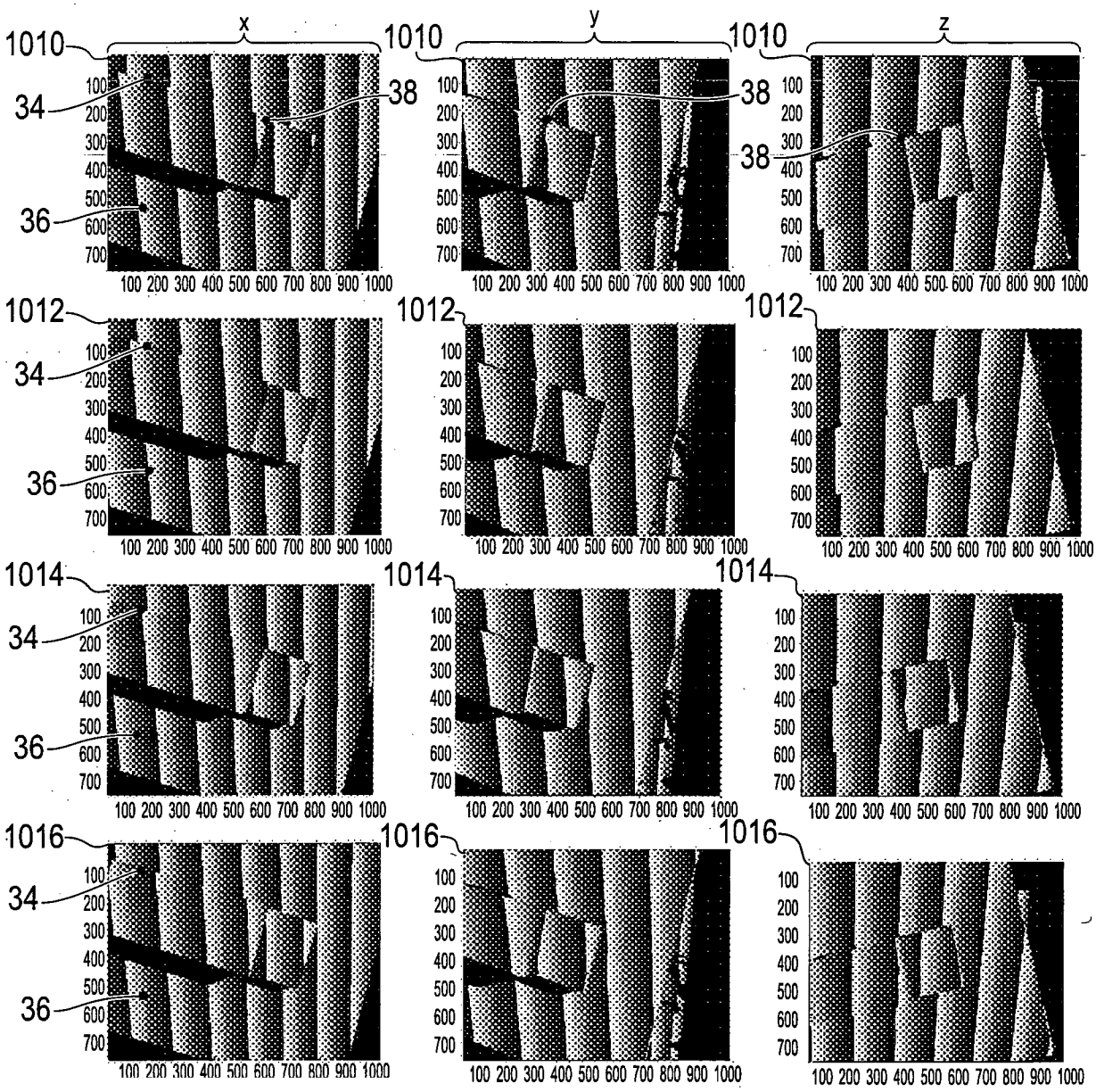
x
y
z
1010
1012
1014
1016
34
36
38
100 200 300 400 500 600 700 800 900 1000

FIG. 3

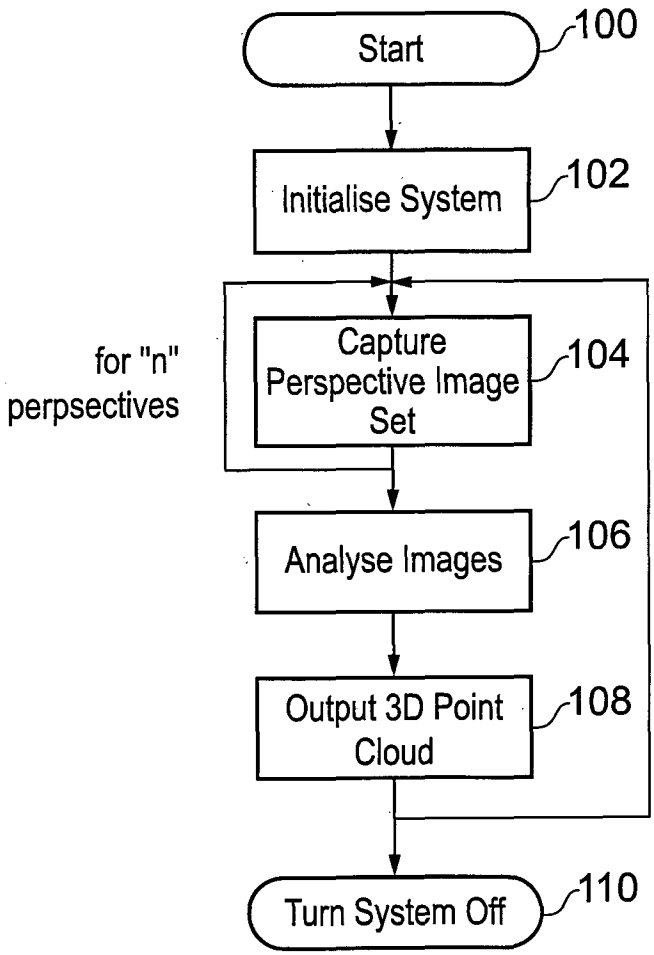
Start
100
Initialise System
102
for "n"
perpsectives
Capture
Perspective Image
Set
104
Analyse Images
106
Output 3D Point
Cloud
108
Turn System Off
110

FIG. 4

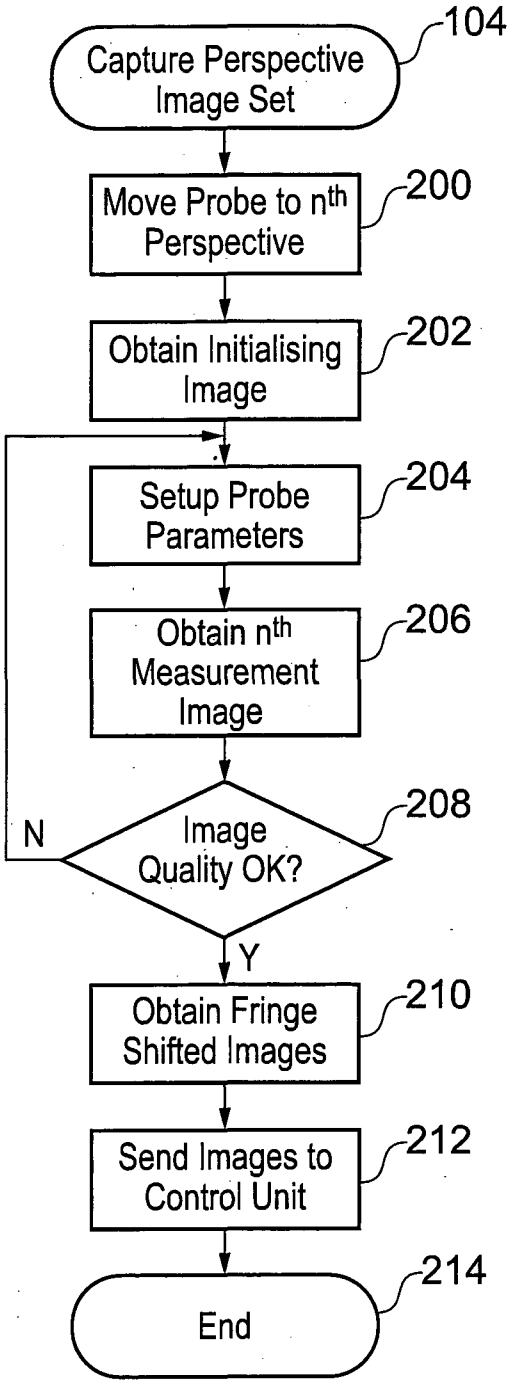
Capture Perspective Image Set
104
Move Probe to nth Perspective
200
Obtain Initialising Image
202
Setup Probe Parameters
204
Obtain nth Measurement Image
206
Image Quality OK?
208
N
Y
Obtain Fringe Shifted Images
210
Send Images to Control Unit
212
End
214

FIG. 5

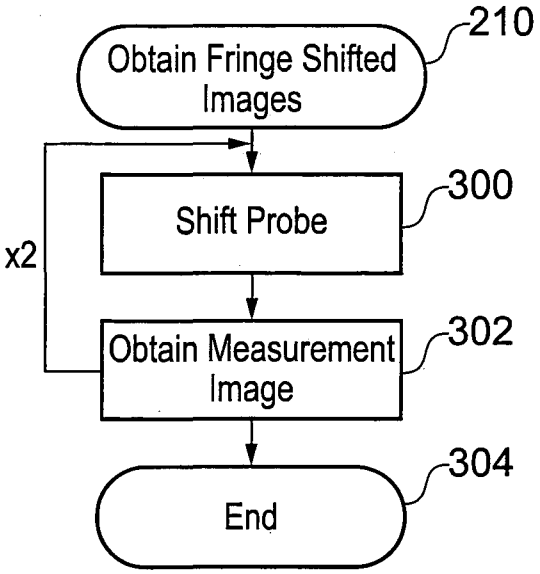
Obtain Fringe Shifted Images
210
x2
Shift Probe
300
Obtain Measurement Image
302
End
304

FIG. 6

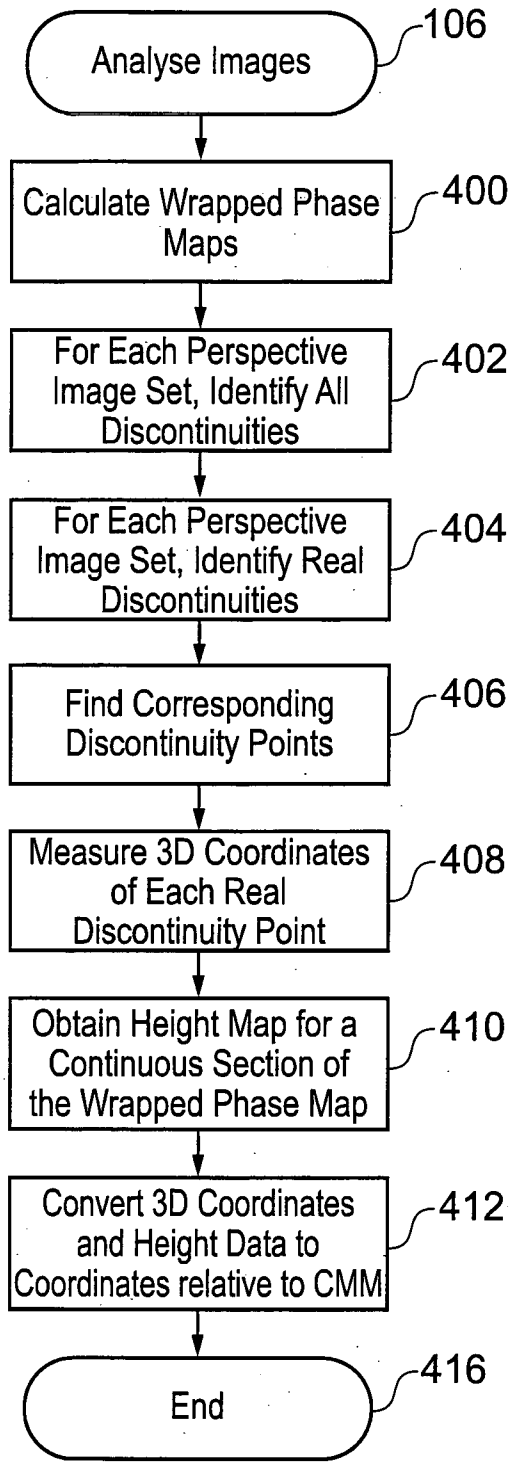
Analyse Images
106
Calculate Wrapped Phase Maps
400
For Each Perspective Image Set, Identify All Discontinuities
402
For Each Perspective Image Set, Identify Real Discontinuities
404
Find Corresponding Discontinuity Points
406
Measure 3D Coordinates of Each Real Discontinuity Point
408
Obtain Height Map for a Continuous Section of the Wrapped Phase Map
410
Convert 3D Coordinates and Height Data to Coordinates relative to CMM
412
End
416

FIG. 7

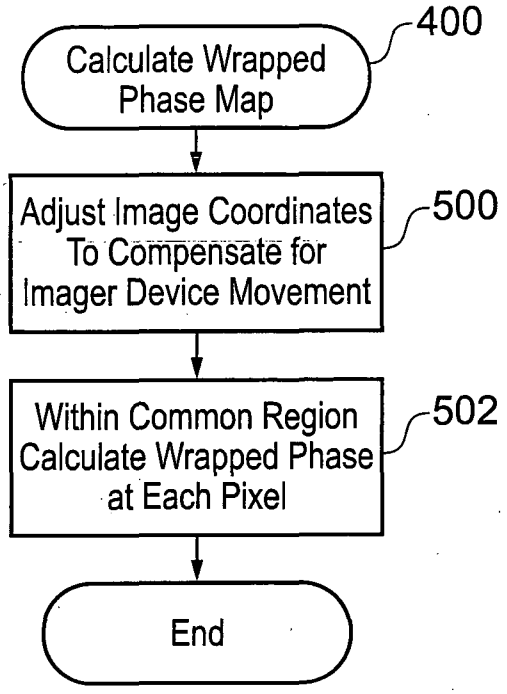


FIG. 8

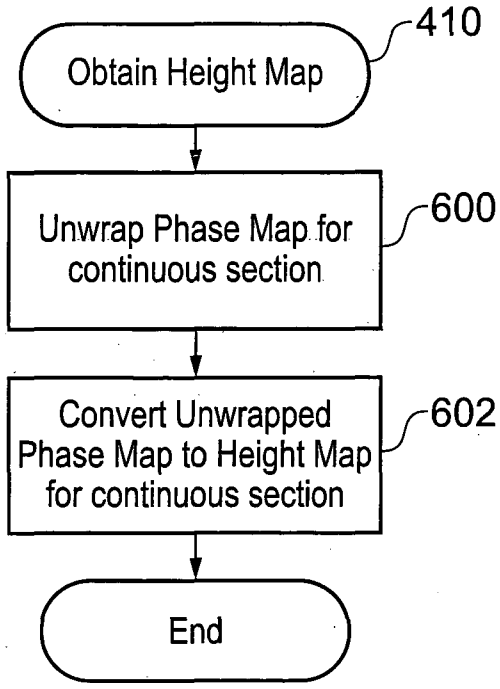


FIG. 9

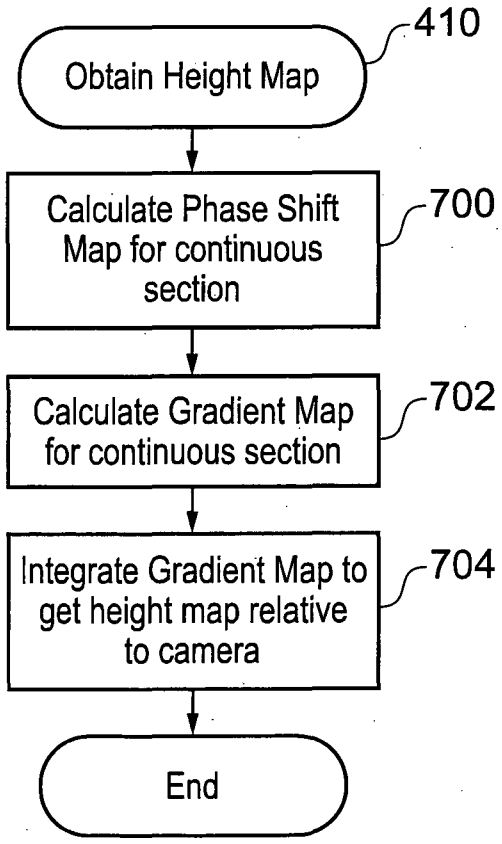


FIG. 10

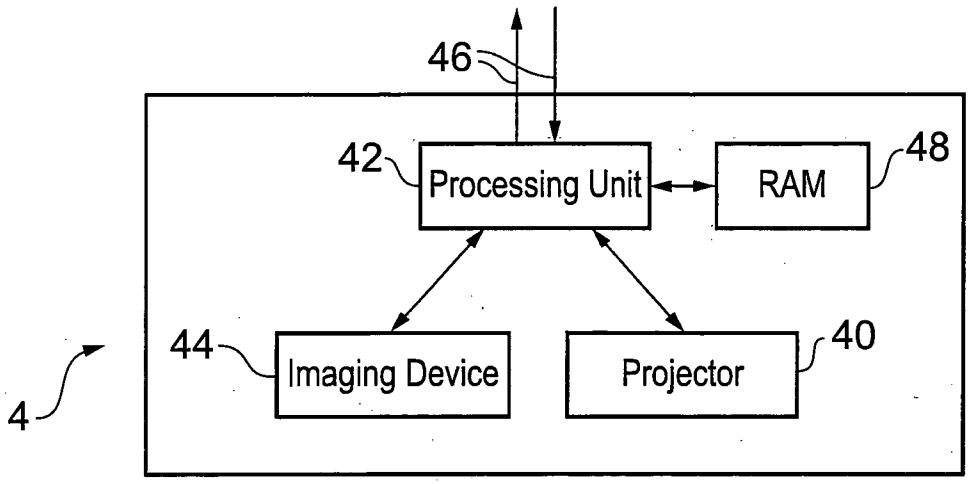
46
42
Processing Unit
RAM
48
44
Imaging Device
Projector
40
4

FIG. 11

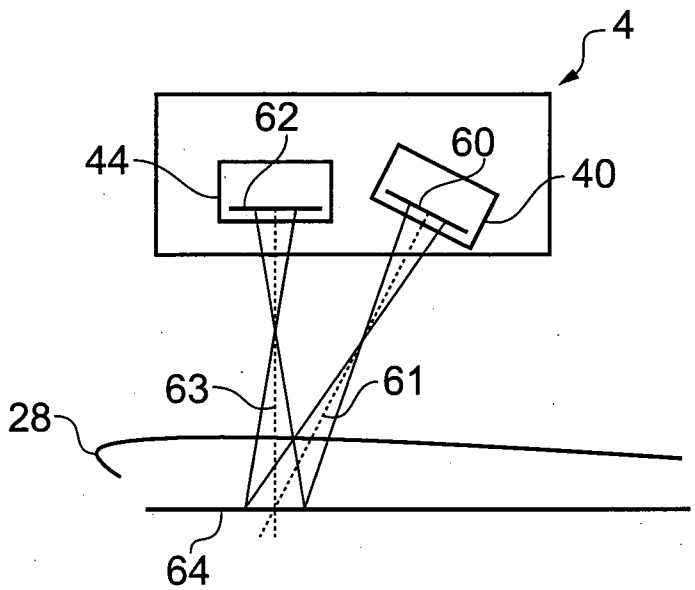
4
62
60
44
40
63
61
28
64

FIG. 12

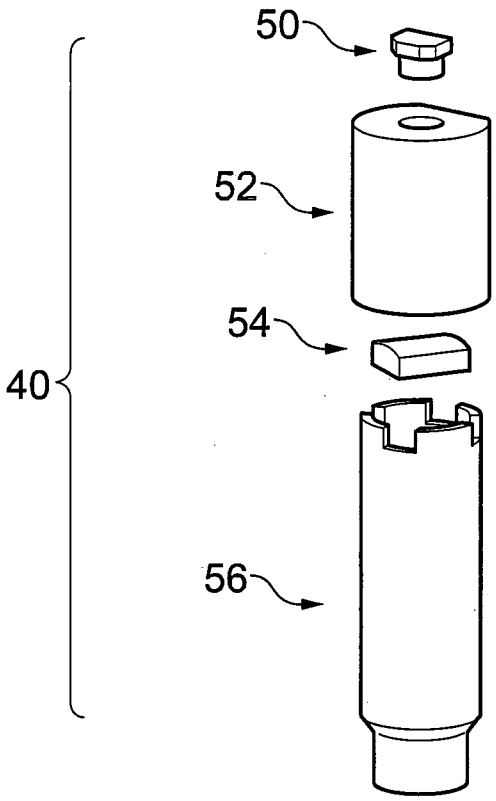


FIG. 13

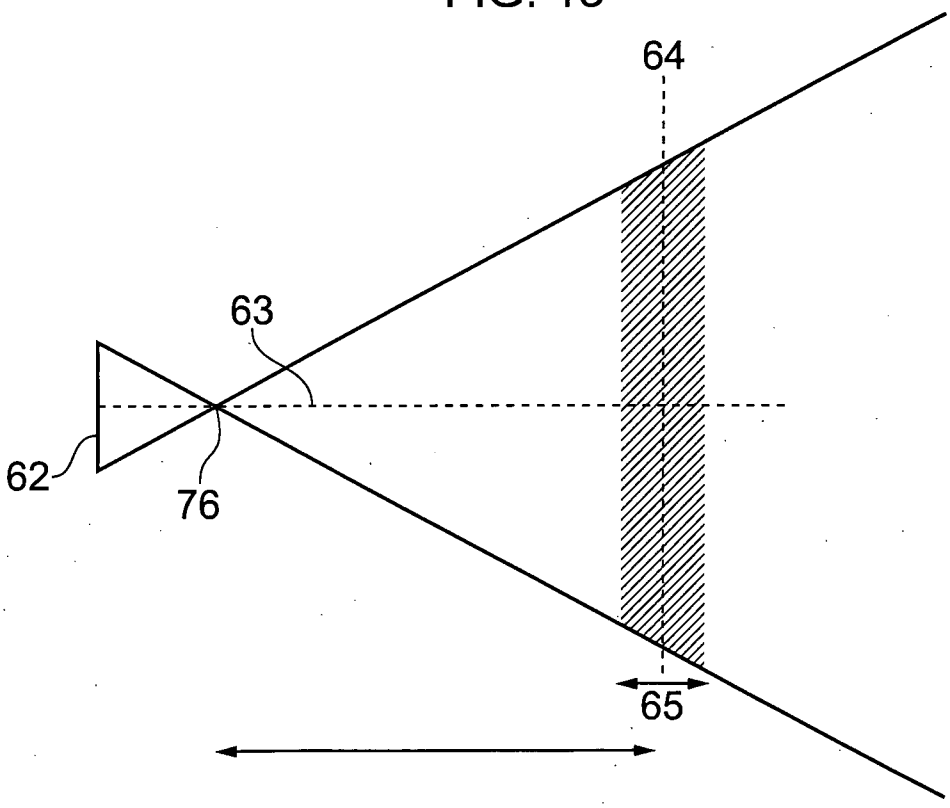


FIG. 18

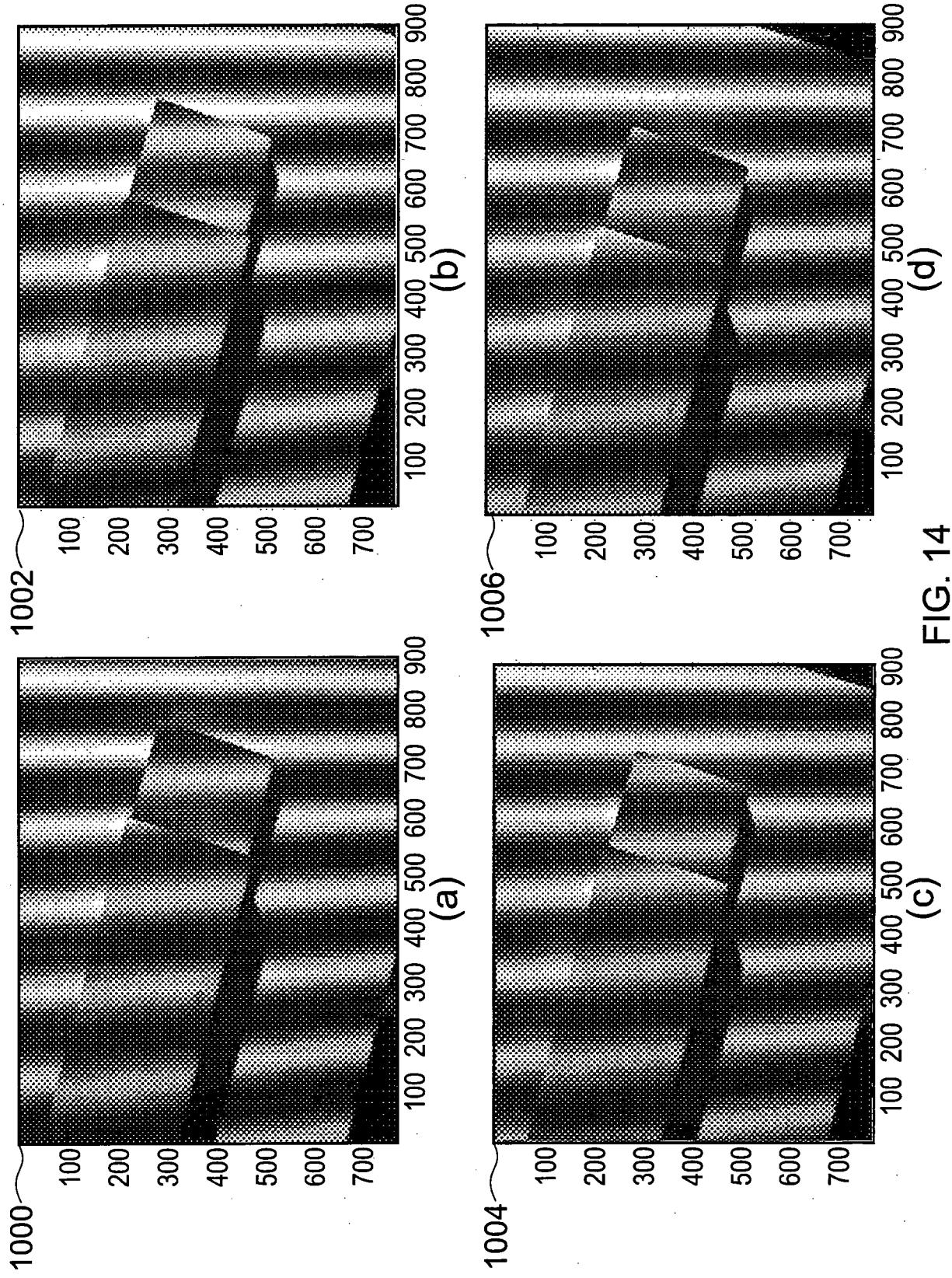
1000
1002
1004
1006
100 200 300 400 500 600 700
100 200 300 400 500 600 700 800 900
(a)
(b)
(c)
(d)

FIG. 14

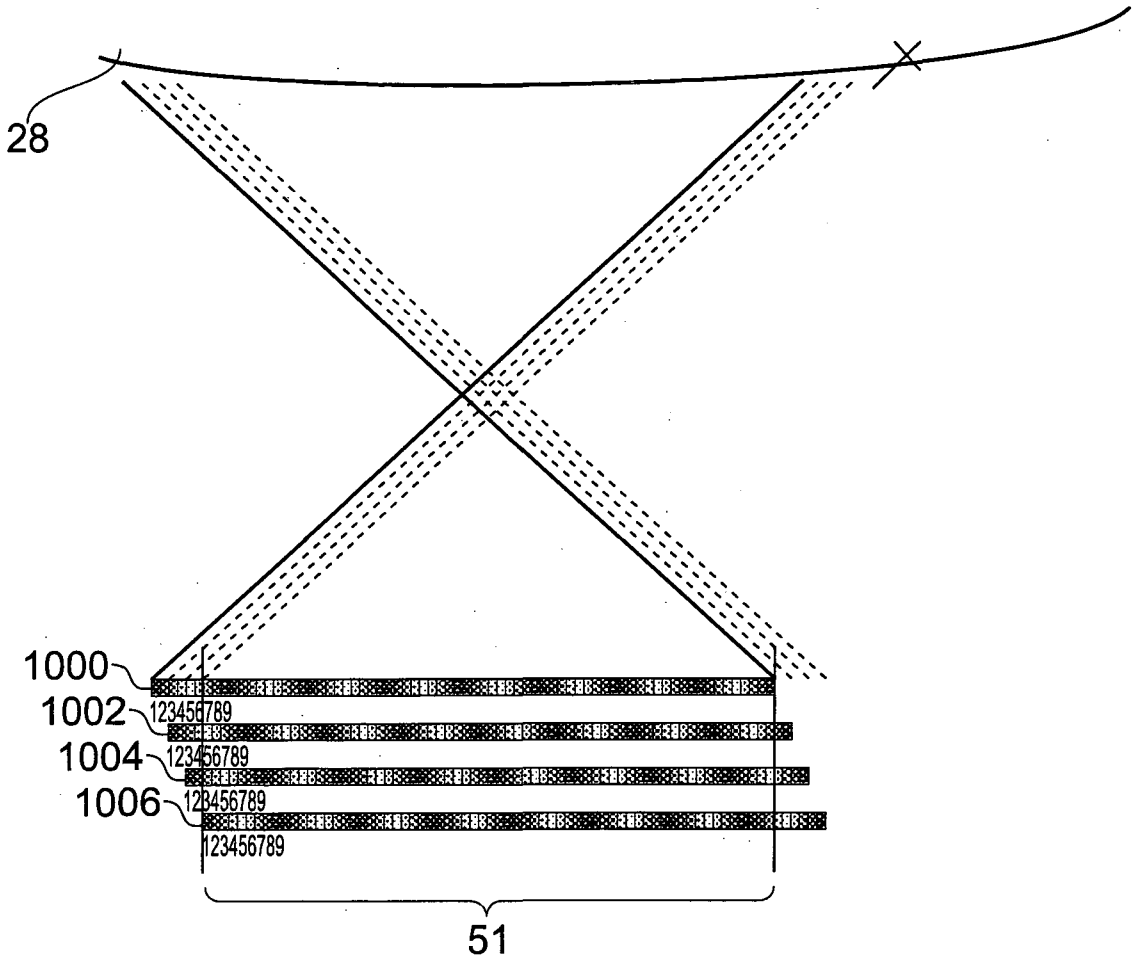
28
1000
1002
123456789
1004
123456789
1006
123456789
123456789
51

FIG. 15

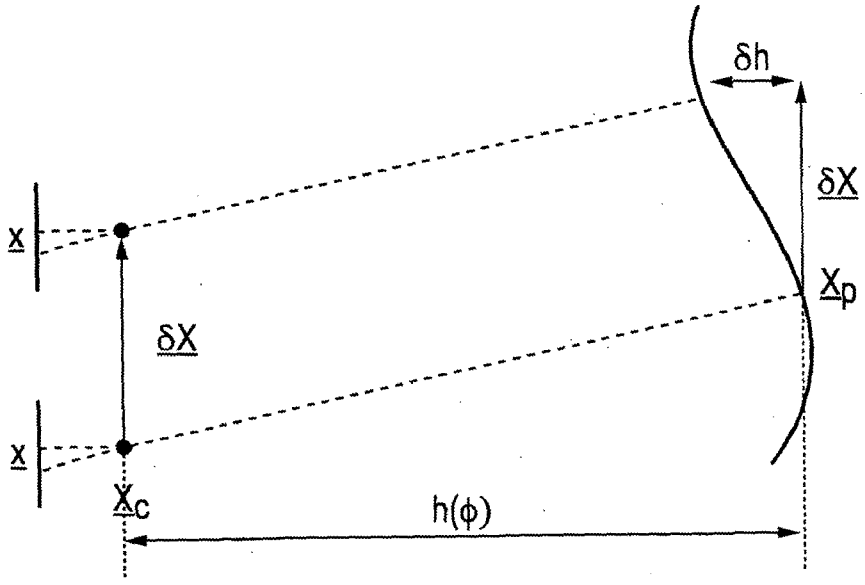


FIG. 16

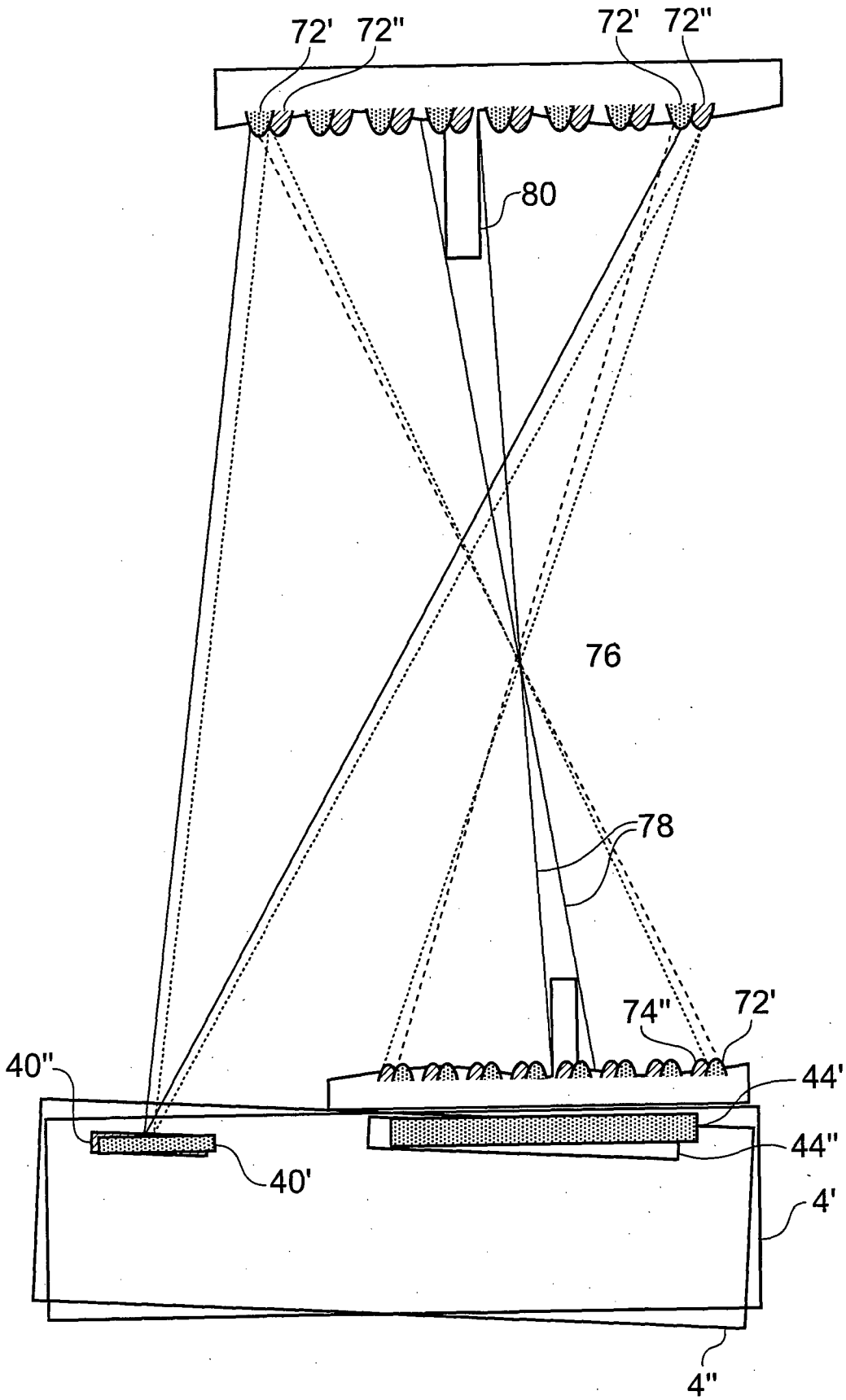


FIG. 17

# INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2008/002758

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01B11/00 G01B11/25 G01C11/02

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 H04N G01C G02B

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. |
|---|---|---|
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[X] Further documents are listed in the continuation of Box C.

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