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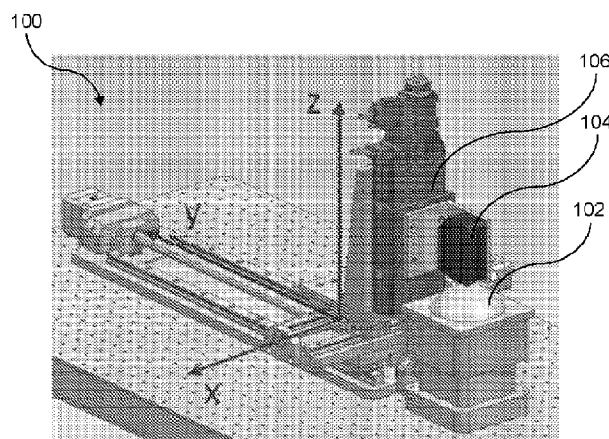


Figure 1A

(57) Abstract: The present disclosure relates to an apparatus and a method for assessing surface roughness of an object. The apparatus comprises a confocal sensor having a measurement range for measuring a plurality of locations along a surface profile of the object, and an actuation mechanism for actuating the confocal sensor. The method comprises: displacing the confocal sensor along a first axis to a current location; adjusting the confocal sensor along a second axis normal to the first axis such that the current location is within the measurement range; and measuring a set of local parameters at the current location. The method further comprises calculating a set of surface roughness parameters based on the local parameters at the plurality of locations, the surface roughness parameters for said assessing of the surface roughness of the object. The confocal sensor is adjusted for the current location based on the local parameters at one or more preceding location.

APPARATUS AND METHOD FOR ASSESSING SURFACE ROUGHNESS

Technical Field

- 5 The present disclosure generally relates to assessing surface roughness. More particularly, the present disclosure describes various embodiments of an apparatus and a method for assessing the surface roughness of an object.

Background

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Surface roughness is one of the key factors for characterizing surfaces of objects for subsequent quality inspection and evaluation of the manufacturing process to make the objects. Surface roughness is assessed by measurements of the surface topography and one commonly-used instrument to measure the surface topography
15 is a physical stylus, such as the Taylor Hobson PGI stylus profilometer. The stylus is dragged across the surface in a raster motion in order to capture the surface height deviations, but the stylus is fragile, and the measurement speed is relatively low (approximately 1 mm/s) in order to reduce tendency of the stylus jumping. Optical profilers such as coherence scanning interferometer and confocal microscope are able
20 to provide non-contact surface measurement solutions, but the narrow field of view limits their scanning range.

Fu, Shaowei, et al (A Non-Contact Measuring System for In-Situ Surface Characterization Based on Laser Confocal Microscopy) disclose a confocal
25 microscopy system that uses a laser confocal sensor moved along the surface of a specimen in order to measure the surface profile of the specimen. Although the measurement results show a good correlation with the actual surface roughness, the specimen has a substantially flat surface and the confocal microscopy system is evaluated to be suitable for flat surfaces only. The confocal microscopy system is not
30 suitable for assessing the surface roughness of non-flat surfaces or freeform objects such as aerofoils, or objects with unknown surface profiles.

Therefore, in order to address or alleviate at least one of the aforementioned problems and/or disadvantages, there is a need to provide an improved apparatus and method for assessing the surface roughness of an object.

5 Summary

According to an aspect of the present disclosure, there is an apparatus and a method for assessing surface roughness of an object. The apparatus comprises a confocal sensor having a measurement range for measuring a plurality of locations along a surface profile of the object, an actuation mechanism for actuating the confocal sensor; and a computer device comprising a control module. The control module is configured for controlling the confocal sensor and the actuation mechanism to perform the method for assessing surface roughness of the object. The method comprises: displacing the confocal sensor along a first axis to a current location; adjusting the confocal sensor along a second axis normal to the first axis such that the current location is within the measurement range; and measuring a set of local parameters at the current location. The computer device further comprises a calculation module configured for calculating a set of surface roughness parameters based on the local parameters at the plurality of locations, the surface roughness parameters for said assessing of the surface roughness of the object. The confocal sensor is adjusted for the current location based on the local parameters at one or more preceding location.

The confocal sensor is adjusted along the second axis for the current location based on the local parameters at one or more preceding location. Likewise, the local parameters at the current location can be used for adjusting the confocal sensor along the second axis for the next location. An advantage is that by relying on the local parameters at the current location, adjustment of the confocal sensor for the next location can be determined earlier, and the confocal sensor can be more quickly adjusted for the next location to be within the measurement range. This consequently improves the efficiency of tracing and measuring the surface profile for surface roughness assessment.

An apparatus and a method for assessing the surface roughness of an object according to the present disclosure are thus disclosed herein. Various features, aspects, and advantages of the present disclosure will become more apparent from the following detailed description of the embodiments of the present disclosure, by way of non-limiting examples only, along with the accompanying drawings.

Brief Description of the Drawings

Figure 1A is an illustration of an apparatus for assessing the surface roughness of an object, in accordance with embodiments of the present disclosure.

Figure 1B is an illustration of a confocal sensor of the apparatus, in accordance with embodiments of the present disclosure.

Figure 2 is a flowchart illustration of a method for assessing the surface roughness of an object, in accordance with embodiments of the present disclosure.

Figure 3A is an illustration of the confocal sensor for assessing the surface roughness of an object, in accordance with first embodiments of the present disclosure.

Figure 3B is a flowchart illustration of a method for assessing the surface roughness of an object, in accordance with first embodiments of the present disclosure.

Figure 3C is an illustration of measuring a number of local profile portions for assessing the surface roughness of an object, in accordance with first embodiments of the present disclosure.

Figure 4A is a flowchart illustration of a method for assessing the surface roughness of an object, in accordance with second embodiments of the present disclosure.

Figure 4B is an illustration of measuring a non-flat surface, in accordance with second embodiments of the present disclosure.

Figure 5 is an illustration of an object having a freeform surface.

Figure 6A is an illustration of a graph representing a surface profile measured by the apparatus, in accordance with embodiments of the present disclosure.

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Figure 6B is an illustration of a graph representing a surface profile measured by the conventional stylus.

Figure 7A is an illustration of a graph representing a surface profile measured by the apparatus and after removing the surface form, in accordance with embodiments of the present disclosure.

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Figure 7B is an illustration of a graph representing a surface profile measured by the conventional stylus and after removing the surface form.

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Figure 8 illustrates a table comparing the surface roughness parameters calculated by the apparatus and the conventional stylus.

Detailed Description

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In the present disclosure, depiction of a given element or consideration or use of a particular element number in a particular figure or a reference thereto in corresponding descriptive material can encompass the same, an equivalent, or an analogous element or element number identified in another figure or descriptive material associated therewith. The use of “/” herein, in a figure, or in associated text is understood to mean “and/or” unless otherwise indicated. The recitation of a particular numerical value or value range herein is understood to include or be a recitation of an approximate numerical value or value range.

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For purposes of brevity and clarity, descriptions of embodiments of the present disclosure are directed to an apparatus and a method for assessing the surface roughness of an object, in accordance with the drawings. While aspects of the present disclosure will be described in conjunction with the embodiments provided herein, it

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will be understood that they are not intended to limit the present disclosure to these embodiments. On the contrary, the present disclosure is intended to cover alternatives, modifications and equivalents to the embodiments described herein, which are included within the scope of the present disclosure as defined by the appended claims.

Furthermore, in the following detailed description, specific details are set forth in order to provide a thorough understanding of the present disclosure. However, it will be recognized by an individual having ordinary skill in the art, i.e. a skilled person, that the present disclosure may be practiced without specific details, and/or with multiple details arising from combinations of aspects of particular embodiments. In a number of instances, known systems, methods, procedures, and components have not been described in detail so as to not unnecessarily obscure aspects of the embodiments of the present disclosure.

In representative or exemplary embodiments of the present disclosure with reference to Figure 1A, there is an apparatus 100 for assessing the surface roughness of an object 102. The apparatus 100 includes a confocal sensor 104 and an actuation mechanism 106. The actuation mechanism 106 is configured for actuating the confocal sensor 104 along a first axis (X-axis) and a second axis (Z-axis) normal to the first axis. Optionally, the actuation mechanism 106 is further configured for actuating the confocal sensor 104 along a third axis (Y-axis) normal to the first and second axes. The first axis (X-axis), second axis (Z-axis), and third axis (Y-axis) represent the Cartesian axes of the actuation mechanism 106, and may also be respectively referred to as the longitudinal, azimuth, and lateral axes. In one embodiment, the actuation mechanism 106 has actuators for displacing the confocal sensor 104 in the respective axes, and each actuator may have a maximum actuation range (e.g. 12.7 mm) and a minimum incremental motion (e.g. 30 nm). The actuation mechanism 106 is configurable to set various parameters to achieve the desired motion, including such as the speed, acceleration, and PID (proportional–integral–derivative) control parameters.

In many embodiments, the confocal sensor 104 is a single-point laser confocal sensor, such as the Keyence LT-9010M. The confocal sensor 104 utilizes a red semiconductor laser with a wavelength of 655 nm. The laser beam spot diameter is 2 μm and the

vertical resolution of the confocal sensor 104 is 0.1 μm . The confocal sensor 104 is positioned at a measurement distance from the surface of the object 102 and is able to measure the surface of the object 102 within a measurement range. In some embodiments, the measurement distance between the confocal sensor 104 and the surface of the object 102 is 6 mm. At this measurement distance, the measurement range is 0.6 mm, i.e. the measurements are within ± 0.3 mm relative to the surface. More specifically, at this measurement range of 0.6 mm, the confocal sensor 104 is able to measure surface height deviations ± 0.3 mm from the mean line of the surface.

Figure 1B shows the working principle of the confocal sensor 104. By vertical scanning of the objective lens using the tuning fork, the detector receives the highest light intensity when the target surface of the object 102 is located at the focal distance. As used herein, the term "vertical" shall mean along the second axis (Z-axis) and is not necessarily aligned with the true vertical. The internal sensor of the tuning fork determines the target height by measuring the position of the tuning fork, thereby obtaining measurements of surface profile height deviations at the target surface.

The apparatus 100 further includes a computer device having a processor and various components / modules, including a control module and a calculation module. The control module is configured for controlling the confocal sensor 104 and the actuation mechanism 106 to perform various operations / steps of a method 200 for assessing the surface roughness of the object 102.

As used herein, the terms component and module are generally intended to refer to a computer-related entity, either hardware, a combination of hardware and software, software, or software in execution. For example, a component or a module may be, but is not limited to being, a process running on a processor, a processor, an object, an executable, a thread of execution, a program, and/or a computer. Additionally, the processor and the modules are configured for performing various operations / steps of the method 200 and are configured as part of the processor. Each module includes suitable logic / algorithm for performing various operations / steps of the method 200. Such operations / steps are performed in response to non-transitory instructions operative or executed by the processor.

With reference to Figure 2, the method 200 broadly includes an operation 210 of measuring, using the confocal sensor 104, a plurality of locations along a surface profile of the object 102. In the operation 210, the confocal sensor 104 traces the surface profile to obtain measurements for assessing the surface roughness of the traced surface profile. The surface profile may be a linear segment (e.g. a straight line), a curvilinear segment (e.g. a curve), or a combination of linear and curvilinear segment on the surface of the object 102.

The operation 210 includes a step 212 of displacing, by the actuation mechanism 106, the confocal sensor 104 along the first axis to a current location. At each location, the confocal sensor 104 is positioned at a measurement distance relative to the location, i.e. the confocal sensor 104 is separated from the location by the measurement distance. In some embodiments, the confocal sensor 104 is positioned at the measurement distance of 6 mm above the location.

The operation 210 further includes a step 214 of adjusting, by the actuation mechanism 106, the confocal sensor 104 along the second axis such that the current location is within the measurement range of the confocal sensor 104. The step 214 may be performed before, during, or after said displacing in the step 212. Specifically, the confocal sensor 104 is moved along the second axis in order to position the current location within the measurement range, which is, for example, 0.6 mm at the measurement distance of 6 mm.

The operation 210 further includes step 216 of measuring a set of local parameters at the current location. The control module is configured to analyze real-time readings from the confocal sensor 104 to ensure that the current location is within the measurement range before the local parameters are measured. The local parameters may include one or more of, but are not limited to, the X, Y, and Z values or coordinates according to the Cartesian axes of the actuation mechanism 106.

Additionally, the confocal sensor 104 is adjusted in the step 214 for the current location based on the local parameters at one or more preceding location. The adjustment of

the confocal sensor 104 based on the preceding local parameters is along the second axis only, i.e. as described in the step 214 above.

5 The method 200 further includes an operation 220 of calculating, by the calculation module, a set of surface roughness parameters from the local parameters at the plurality of locations. The measured sets of local parameters from all of the plurality of locations along the surface profile are collated to calculate the surface roughness parameters for assessing the surface roughness of the object 102. The surface roughness parameters are in accordance with the ISO 4287 standard, and may
10 include but not limited to, the arithmetic and root mean square averages of the surface profile height deviations from the mean line.

In some embodiments, the control module is further configured for controlling the confocal sensor 104 and the actuation mechanism 106 to perform additional steps of
15 the method 200 to measure one or more other surface profiles of the object 102. Specifically, the method includes a step of, after said measuring of the locations along the surface profile, displacing the confocal sensor 104 along the third axis towards another surface profile of the object 102. The method further includes a step of calculating another set of surface roughness parameters from local parameters
20 measured at locations along the other surface profile. For purpose of brevity, it will be readily understood that the various steps of the method 200 for tracing and measuring the local parameters of first surface profile apply similarly or analogously to the second and subsequent surface profiles.

25 Accordingly, in various embodiments of the present disclosure, the apparatus 100 is able to perform the method 200 to assess the surface roughness of an object 102 by tracing and measuring surface profiles on the surface of the object 102. The confocal sensor 104 is displaceable by the actuation mechanism 106 along the first axis (X-axis), the second axis (Z-axis), and optionally the third axis (Y-axis). The confocal
30 sensor 104 performs local scanning or measurements at each location along a surface profile. The actuation mechanism 106 displaces the confocal sensor 104 along the first axis to the locations along the surface profile, and also adjusts the confocal sensor 104 along the second axis such that each location is within the measurement range.

Actuation of the confocal sensor 104 along at least two perpendicular axes allows the confocal sensor 104 to trace the surface profile and measure distinct locations along the surface profile, and to adjust the confocal sensor 104 such that each location is within the measurement range, thereby improving the accuracy of the local parameters measured at each location. Additionally, adjustment of the confocal sensor 104 along the second axis advantageously enables the confocal sensor 104 to trace and measure surface profiles of freeform surfaces as well as surfaces with large surface height deviations. The apparatus 100 thus addresses the measurement range limitation of the conventional confocal microscopy system which is suitable for flat surfaces only, and can be used to assess the surface roughness of non-flat surfaces / objects such as aerofoils.

As described above, the confocal sensor 104 is adjusted along the second axis for the current location based on the local parameters at one or more preceding location. In a similar or analogous manner, the local parameters at the current location can be used for adjusting the confocal sensor 104 for the next location, i.e. adjustment of the confocal sensor 104 for the next location is calculated based on at least the current local parameters. The next location is the one immediately succeeding the current location along the same surface profile. By relying on the local parameters at the current location, adjustment of the confocal sensor 104 for the next location can be determined earlier, such as before displacing the confocal sensor 104 to the next location, and the confocal sensor 104 can be more quickly adjusted such that the next location is within the measurement range. This advantageously obviates having to continuously measure the position of the confocal sensor 104 relative to the location, which requires more time and computer processing power. Calculation of the adjustment for the next location based on at least the current local parameters thus improves the efficiency of tracing and measuring the surface profile for surface roughness assessment.

In some embodiments, the confocal sensor 104 is displaced along the third axis to trace and measure other surface profiles of the object 102. The surface profiles can be combined together to collectively build the overall surface area of the object 102.

Various three-dimensional areal or surface texture parameters in accordance with the ISO 25178-2 standard can be calculated.

First Exemplary Embodiments

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In various first embodiments of the present disclosure, each location along the surface profile of the object 102 includes a local portion of the surface profile and the confocal sensor 104 is configured for scanning the local profile portions. With reference to Figure 3A, the confocal sensor 104 includes an oscillating actuator 108 for oscillating the confocal sensor 104 along a local axis thereof to scan the respective local profile portion, the local axis corresponding to the first axis. In one embodiment, the oscillation frequency of the oscillating actuator 108 is 1.5 kHz. Scanning of each local profile portion is completed after a predefined number of oscillations or a predefined duration, such as 400 ms. Each local profile portion has the same local scan length L and adjacent local profile portions overlap with each other. By way of non-limiting examples only, the local scan length L may range from 0.1 mm to 1.1 mm and the overlap at adjacent local profile portions may range from 10% to 30%. In one embodiment, the local scan length L is 1.1 mm and the overlap at adjacent local profile portions is 20%, i.e. the overlap length is 0.2L which is equivalent to 0.22 mm. It will be appreciated that various local profile portions may have different local scan lengths.

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The local parameters at each local profile portion, such as the X, Y, and Z values or coordinates, are measured and computed in real time by the calculation module of the computer device. The local profile portions along the surface profile are subsequently combined together using a data stitching algorithm to collectively compute the local parameters and assess the surface roughness based on the measured surface profile. Measurements at all the local profile portions are completed after the combined local scan lengths of the local profile portions reaches a predefined total scan length, after a predefined duration, or when the actuation mechanism 106 reaches its maximum actuation range along the first axis. The apparatus 100 of the first embodiments is thus configured to perform a method 300 of assessing the surface roughness of the object 102 based on the local parameters measured at the various local profile portions. The method 300 may also be referred to as a piecewise scan.

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With reference to Figure 3B, in a step 302 of the method 300, the actuation mechanism 106 positions the confocal sensor 104 at the home or starting position, which represents the home local profile portion on the surface profile of the object 102. In a step 304, the actuation mechanism 106 displaces the confocal sensor 104 along the second axis such that home local profile portion is at the measurement distance (e.g. 6 mm) and within the measurement range (e.g. 0.6 mm or ± 0.3 mm). The confocal sensor 104 may be positioned at any point of the local profile portion, such as the centre or either end.

In a step 306, the confocal sensor 104 measures the set of local parameters at the home local profile portion. Specifically, the oscillating actuator 108 oscillates the confocal sensor 104 along the local axis so that the confocal sensor 104 is able to measure the home local profile portion across its local scan length L. In some embodiments, the local scan length L is 1.1 mm. The local parameters at the home local profile portion are measured and are communicated to the computer device for real-time processing. The local parameters include, but are not limited to, the X values of location points along the home local profile portion, the Z values corresponding to the same location points, and optionally the Y values. The Z values provide height information of the home local profile portion and are used as reference for adjusting the confocal sensor 104 along the second axis. The X, Y, and Z values may be set to zero at the home local profile portion to provide a reference for subsequent measurements at other local profile portions.

In a step 308, the actuation mechanism 106 actuates the confocal sensor 104 along the first axis and second axis to another local profile portion along the surface profile. For easier understanding, this is referred to as the current local profile portion. The step 308 includes the actuation mechanism 106 displacing the confocal sensor 104 along the first axis to the current local profile portion which has the same local scan length L. The displacement of the confocal sensor 104 along the first axis may be at a constant speed of, for example, approximately 1 mm/s.

The step 308 includes adjusting the confocal sensor 104 along the second axis such that the current local profile portion is within the measurement range. Said adjusting of the confocal sensor 104 along the second axis is based on the local parameters measured at the preceding local profile portion. The actuation mechanism 106 may include an optical linear encoder for accurate positioning of the confocal sensor 104. It will be appreciated that said displacing and adjusting of the confocal sensor 104 in the step 308 may be performed simultaneously or one after the other.

A subsequent step 310 determines if the measurements at the measured local profile portions are complete for assessing the surface roughness of the object 102. If the measurements are determined to be incomplete, the step 310 returns to the step 306 to measure the local parameters at the current local profile portion which has been adjusted to be within the measurement range. In the next iteration of the step 308, the confocal sensor 104 is displaced to the next local profile portion and adjusted along the second axis such that the next local profile portion is within the measurement range. In a similar or analogous manner as the current local profile portion, said adjusting of the confocal sensor 104 along the second axis for the next local profile portion is based on the local parameters measured at the current local profile portion (which precedes the next local profile portion).

Accordingly, multiple sets of local parameters at a plurality of local profile portions are obtained. It will be appreciated that the local parameters at the local profile portions are measured in a similar manner as the home local profile portion described above, and are measured relative to the home or starting position which serves as a common reference for calculating the surface roughness parameters.

The current and next local profile portions are adjacent to and overlap with each other such that the total scan length is less than $2L$. In some embodiments, the overlap is 20% and the confocal sensor 104 is displaced to the next local profile portion along the first axis for a distance equivalent to the remaining 80% of the local scan length L of the current local profile portion. As a non-limiting example, the local scan length L is 1.1 mm. The confocal sensor 104 is displaced 0.88 mm along the first axis for both local profile portions to have a 0.22 mm overlap length. Some publications have

reported that a 20% overlap gives a good trade-off between having good stitching accuracy (when combining the local profile portions) and obtaining a large measurement range with minimum data sets.

5 In some embodiments as shown in Figure 3B, in the step 310, the measurements are determined to be complete if the actuation mechanism 106 has displaced the confocal sensor 104 through a predefined total scan length, i.e. has completed the X-axis scanning length and all the measured local profile portions are within the X-axis scanning length. In some other embodiments, the measurements are determined to be complete after measuring a predefined number of local profile portions. In some other embodiments, the measurements are determined to be complete after a predefined duration, i.e. only the local profile portions measured during the predefined duration are used for surface roughness assessment. In some other embodiments, the measurements are determined to be complete when the actuation mechanism 106 reaches its maximum actuation range or displacement along the first axis. For example, the maximum displacement is 12.7 mm and only the measured local profile portions within the maximum displacement are used for surface roughness assessment.

If the measurements are determined to be incomplete, the step 310 returns to the step 306 to measure the next local profile portion which has been adjusted to be within the measurement range. In the next iteration of the step 308, the confocal sensor 104 is displaced to the another next local profile portion and adjusted along the second axis such that said another next local profile portion is within the measurement range. Accordingly, the steps 306 and 308 iteratively measure a total number of n local profile portions, as shown in Figure 3C. The local profile portions have a total scan length D , each local profile portion has a local scan length L , and the overlap at adjacent local profile portions is 20%. Measurement numbers $i-1$, i , and $i+1$ (where i is a positive integer) identify consecutive local profile portions within the total number n .

30 As described above in the step 308, and with reference to Figure 3C, adjusting of the confocal sensor 104 for the next $i+1^{th}$ local profile portion includes moving the confocal sensor 104 along the second axis based on the local parameters at the preceding (current) i^{th} local profile portion. Said moving of the confocal sensor 104 along the

second axis may be calculated using a polynomial regression algorithm. A non-limiting example is a second order polynomial regression algorithm shown in Equations 1 and 2 below which are used to best fit the current i^{th} local profile portion and determine the next $i+1^{th}$ local profile portion.

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$$z_i(x_j) = a_i x_j^2 + b_i x_j + c_i \quad [\text{Equation 1}]$$

$$z_{i+1}(x_j) = a_i (x_j + 0.8L)^2 + b_i (x_j + 0.8L) + c_i \quad [\text{Equation 2}]$$

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Where $z_i(x_j)$ represents the surface profile height of the current i^{th} local profile portion after polynomial regression, x_j represents the j^{th} data point in the respective local profile portion, and $z_{i+1}(x_j)$ represents the determined next $i+1^{th}$ local profile portion.

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After measuring the local parameters at the current i^{th} local profile portion, the actuation mechanism 106 automatically adjusts the confocal sensor 104 along the second axis such that the next $i+1^{th}$ local profile portion is within the measurement range. The adjustment along the second axis is calculated based on the local parameters at the current i^{th} local profile portion, as shown in Equation 3 below.

$$\Delta h_i = \frac{1}{2m} \sum_{j=1}^m [z_i(x_j) + z_{i+1}(x_j)] \quad [\text{Equation 3}]$$

20

Where Δh_i represents adjustment along the second axis calculated from measurement of the current i^{th} local profile portion, and m represents the number of local parameters or data points acquired from said measurement.

25

The adjustment along the second axis for the next local profile portion can thus be calculated earlier based on the local parameters of the current local profile portion. The current local parameters facilitate determination of the next local profile portion, especially if the surface profile is non-flat or freeform. The confocal sensor 104 can be more quickly adjusted for the next local profile portion to be within the measurement range.

30

The step 310 proceeds to the step 312 if the measurements at the measured local profile portions are determined to be complete. The step 312 determines if the measurements at the measured surface profiles along the third axis (Y-axis), each measured surface profile having a plurality of measured local profile portions, are complete for assessing the surface roughness of the object 102.

In some embodiments as shown in Figure 3C, the measurements are determined to be complete if the actuation mechanism 106 has displaced the confocal sensor 104 through a predefined Y-axis scanning length and all the measured surface profiles are within the Y-axis scanning length. In some other embodiments, the measurements are determined to be complete after measuring a predefined number of surface profiles. In some other embodiments, the measurements are determined to be complete after a predefined duration, i.e. only the surface profiles measured during the predefined duration are used for surface roughness assessment. In some other embodiments, the measurements are determined to be complete when the actuation mechanism 106 reaches its maximum actuation range or displacement along the third axis.

If the measurements are determined to be incomplete, the step 312 proceeds to a step 314 in which the actuation mechanism 106 displaces the confocal sensor 104 along the third axis from the current surface profile to the next surface profile. The displacement may be based on a predefined interval between the surface profiles. In one example, the predefined Y-axis scanning length is 10 mm and the predefined interval is 0.1 mm. In another example, the predefined Y-axis scanning length is 1 mm and the predefined interval is 0.01 mm.

In some embodiments, the actuation mechanism 106 displaces the confocal sensor 104 along the third axis from the starting oscillation position of the last local profile portion of the current surface profile to the next surface profile, such that the first local profile portion of the next surface profile is aligned along the third axis with the last local profile portion of the current surface profile. In some other embodiments, the actuation mechanism 106 displaces the confocal sensor 104 along the first axis from the last to the first local profile portion of the current surface profile. The actuation mechanism 106 then displaces the confocal sensor 104 along the third axis from the

starting oscillation position of the current surface profile to the next surface profile, such that the first local profile portions of both surface profiles are aligned along the third axis.

- 5 The step 314 returns to the step 306 to measure the local profile portions along the next surface profile. Each local profile portion at the next surface profile may be measured relative to the first local profile portion of the next surface profile, or relative to the home local profile portion of the current surface profile. Accordingly, multiple sets of local parameters at more than one surface profile can be measured. The
- 10 surface profiles can be combined together to collectively build the overall surface area of the object 102 and calculate various areal or surface texture parameters.

The step 314 proceeds to the step 316 if the measurements at the measured surface profiles are determined to be complete. The step 316 combines the local profile

15 portions at each surface profile, such as by using a data stitching algorithm, to build a stitched surface profile for calculating the surface roughness parameters.

The local axis of the oscillating actuator 108 corresponds to the first axis of the actuation mechanism 106 and should ideally be aligned with the first axis, such that

20 the local profile portions along a surface profile are accurately measured (by oscillation along the local axis) as the confocal sensor 104 is being displaced by the actuation mechanism 106 along the first axis. However, there may be misalignment between the confocal sensor 104 and the actuation mechanism 106, such as due to manufacturing defects. This would result in jump errors at the overlaps at adjacent local profile

25 portions, inaccuracies in the measurements of local profile portions, and consequently measurement errors in the local parameters.

The data stitching algorithm is used to reduce errors caused by the misalignment. The data stitching algorithm may be based on the method of iteratively reweighted least

30 squares. Assuming that for every pair of adjacent local profile portions, the local surface roughness in the overlap is consistent, the mismatch between the pair of adjacent local profile portions is only caused by slope and offset differences during measurement. The error propagation of the data stitching algorithm has been analyzed

in some studies and was shown that the stitching error was in the magnitude of tens of nanometres for a range longer than 50 mm stitched length, i.e. total scan length of more than 50 mm.

- 5 With reference to Figure 3C, $f(x)$ represents the whole surface profile to be measured along the total scan length D . As shown in Equations 4 below, $f_{i-1}(x)$ and $f_i(x)$ respectively represent the $i-1^{th}$ and i^{th} local profile portions. $\Delta f_i(x)$ represents the difference between $f_{i-1}(x)$ and $f_i(x)$ within the overlap at the adjacent $i-1^{th}$ and i^{th} local profile portions. As shown in Equation 5 below, a_i and b_i respectively represent the
10 slope and offset coefficients for the i^{th} local profile portion. The slope and offset coefficients are according to the least-squares linear regression equation of the method of iteratively reweighted least squares.

$$\Delta f_i(x) = f_{i-1}(x) - f_i(x) ; x \in [0.8iL, iL] \quad \text{[Equation 4]}$$

$$15 \quad \Delta f_i(x) = a_i x + b_i ; x \in [0.8iL, iL] \quad \text{[Equation 5]}$$

As shown in Equations 6 below, $f'_i(x)$ represents the shifted surface profile in the i^{th} iteration. Consequently, the n^{th} iteration of the data stitching algorithm combines total number n of local profile portions and is represented by $f'_n(x)$.

20

$$f'_1(x) = f_1(x) + a_1 x + b_1 ; x \in [0.8L, 1.8L]$$

$$f'_2(x) = f_2(x) + a_2 x + b_2 + a_1 x + b_1 ; x \in [1.6L, 2.6L]$$

.

.

25

.

$$f'_n(x) = f_n(x) + \sum_{i=1}^n (a_i x + b_i) ; x \in [0.8nL, (0.8n + 1)L] \quad \text{[Equations 6]}$$

Adding both sides of Equation 6 for the n^{th} iteration results in Equation 7 below which represents the whole stitched surface profile $f(x)$.

30

$$f(x) = f_0(x) + \sum_{i=1}^n f'_i(x) \quad \text{[Equation 7]}$$

The step 316 further includes calculating the surface roughness parameters from the whole stitched surface profile. The surface roughness parameters are subsequently used for assessing the surface roughness of the object 102, as described further below.

5 Second Exemplary Embodiments

In various second embodiments of the present disclosure, each location along the surface profile of the object 102 includes a single point and the confocal sensor 104 is configured for measuring the single points. The single points may be located at intervals of 2 μm as the laser beam spot diameter of the confocal sensor 104 is 2 μm . Continuously measuring multiple single points (also referred to as a single-point continuous scan) along the surface profile avoids the post-measurement data stitching of the piecewise scan of the first embodiments. The single-point continuous scan is suitable for use with confocal sensors 104 which have only single point measurement function. The apparatus 100 of the second embodiments is thus configured to perform a method 400 of assessing the surface roughness of the object 102 based on the local parameters measured at the respective single points. For purpose of brevity, it will be appreciated that various aspects described above in relation to the first embodiments may apply similarly or analogously to the second embodiments and vice versa.

20

With reference to Figure 4A, in a step 402 of the method 400, the actuation mechanism 106 positions the confocal sensor 104 at the home or starting position, which represents the home single point on the surface profile of the object 102. In a step 404, the actuation mechanism 106 displaces the confocal sensor 104 along the second axis such that home single point is at the measurement distance and within the measurement range. The confocal sensor 104 measures the set of local parameters, such as the X, Z, and optionally Y values, at the home single point. The X, Y, and Z values may be set to zero at the home single point to provide a reference for subsequent measurements at other single points.

30

In a step 406, the actuation mechanism 106 displaces the confocal sensor 104 along the first axis to another single point along the surface profile. For easier understanding, this is referred to as the current single point. The displacement of the confocal sensor

104 along the first axis may be at a constant speed of, for example, approximately 1 mm/s. Additionally, during said displacement, the confocal sensor 104 measures the single points along the surface profile at $2\ \mu\text{m}$ intervals due to the laser beam spot diameter. In a step 408, the confocal sensor 104 measures the set of local parameters
5 at the current single point relative to the home single point.

A step 410 determines if the local parameters, specifically the Z value, measured at the current single point exceeds a predefined threshold of the measurement range. For example, the predefined threshold is set as 80% of the limits of the measurement
10 range. If the Z value is within the predefined threshold, the step 410 returns to the step 408 and the confocal sensor 104 continues displacement along the first axis to measure the other single points.

Conversely, if the Z value reaches or exceeds the predefined threshold, i.e. at or falls
15 outside of the threshold limits of the measurement range, then in a step 412, the actuation mechanism 106 stops displacing the confocal sensor 104 along the first axis. The actuation mechanism 106 then adjusts the confocal sensor 104 along the second axis such that the current single point is within the measurement range. Said adjusting of the confocal sensor 104 includes a step 414 of moving the confocal sensor 104
20 along the second axis, such that the current single point returns to the measurement distance relative to the confocal sensor 104 and is within the measurement range. The actuation mechanism 106 may include an optical linear encoder and the control module of the computer device may include an inner-loop PID controller for accurate positioning of the confocal sensor 104. Once the current single point is within the
25 measurement range, the confocal sensor 104 measures the local parameters at the current single point. The Z value at the current single point may be measured relative to the home single point or may be reset to zero.

Figure 4B illustrates the steps 406, 408, and 410 for measuring single points along a
30 non-flat surface of an object 102. The predefined threshold of the measurement range is represented by $\pm t$. At every single point spaced apart at intervals of $d = 2\ \mu\text{m}$, the confocal sensor 104 measures the local parameters including the Z values represented by $h(i)$. When the Z value of the current single point reaches the

predefined threshold, i.e. $h(i) = t$, the confocal sensor 104 is moved (in the step 414) along the second axis (Z-axis) for adjusting the confocal sensor 104 so that current single point is within the measurement range. The magnitude of this movement along the second axis is determined as described below and is represented by $\Delta z(j)$ where j represents the j^{th} movement in the iterative adjustment process.

In the step 414, said moving of the confocal sensor 104 along the second axis may cause positioning errors of the confocal sensor 104 relative to the second axis which may be due to inherent defects of the apparatus 100. Such inherent defects include misalignment between the confocal sensor 104 and the actuation mechanism 106, the actuator straightness errors of the actuation mechanism 106, and the Abbe error of the whole apparatus 100. In a step 416, the confocal sensor 104 measures, at each single point, a set of local parameters including a positioning error of the confocal sensor 104 relative to the second axis after said moving of the confocal sensor 104 in the step 414.

Said moving of the confocal sensor 104 in the step 414 compensates for the positioning error measured at a plurality of preceding single points. In a similar or analogous manner as the current single point, moving of the confocal sensor 104 for the next single point compensates for the positioning errors measured at a plurality of preceding single points which include the current single point. In a step 418, an outer-loop PID controller of the control module calculates a compensation movement of the confocal sensor 104 for the next single point to compensate for the positioning errors measured at the preceding single points including the current single point. The outer-loop PID controller communicates the calculated compensation movement to the inner-loop PID controller so that said moving of the confocal sensor 104 in the next iteration of the step 414 for the next single point also includes this compensation movement to compensate for the positioning errors. In a similar or analogous manner as the next single point, said moving of the confocal sensor 104 for the current single point in the step 414 compensates for the positioning errors measured at a plurality of preceding single points.

A step 420 determines if the measurements at the measured single points are complete for assessing the surface roughness of the object 102. If the measurements are determined to be incomplete, the step 420 returns to the step 406 to displace the confocal sensor 104 along the first axis to the next single point. In the next iterations of the respective steps, the confocal sensor 104 measures the local parameters at the next single point in the step 408, and the step 410 determines if the Z value measured at the next single point exceeds the predefined threshold of the measurement range. If it exceeds, the confocal sensor 104 is adjusted for the next single point depending on the step 410. Said adjusting includes moving the confocal sensor 104 along the second axis which compensates for the positioning errors measured at the preceding single points. Accordingly, the steps 406, 408, 410, 412, 414, 416, and 418 iteratively measure a plurality of single points along the surface profile.

In the step 418, the confocal sensor 104 is adjusted for the next single point, by said moving along the second axis which compensates for the positioning errors measured at a plurality of preceding single points. The compensation in said moving thereof may be calculated using a discrete-time PID algorithm, as shown in Equations 8 below.

$$U(z) = \left[K_p + \frac{K_i}{1-z^{-1}} + K_d(1-z^{-1}) \right] E(z)$$

$$K_1 = K_p + K_i + K_d$$

$$K_2 = -K_p - 2K_d$$

$$K_3 = K_d$$

[Equations 8]

Where $U(z)$ and $E(z)$ represent the Z-transform of the control variable and error, respectively. K_p , K_i , and K_d respectively represent the proportional, integral and derivative gains.

In one embodiment, the compensation movement for the next $n+1^{th}$ single point is calculated based on the positioning errors measured at the current n^{th} single point and two preceding ($n-1^{th}$ and $n-2^{th}$) single points. Equations 8 can be converted to the difference equation as shown in Equation 9 below. The positioning errors are respectively represented by $e(n)$, $e(n-1)$, and $e(n-2)$ and are the inputs for the

discrete-time PID algorithm. The compensation movement for the next $n+1^{th}$ single point is represented by $u(n+1)$.

$$u(n+1) = K_1 e(n) + K_2 e(n-1) + K_3 e(n-2) \quad \text{[Equation 9]}$$

5

The compensation movement for the next single point can thus be calculated earlier based on the positioning errors of the preceding single points. The preceding single points form a small portion of the surface profile which facilitates determination of the next single point, especially if the surface profile is non-flat or freeform. The confocal sensor 104 can be more quickly adjusted for the next single point to be within the measurement range and to compensate for positioning errors.

The step 420 proceeds to the step 422 if the measurements at the measured single points are determined to be complete. The step 422 determines if the measurements at the measured surface profiles along the third axis (Y-axis), each measured surface profile having a plurality of measured single points, are complete for assessing the surface roughness of the object 102.

If the measurements are determined to be incomplete, the step 422 proceeds to a step 424 in which the actuation mechanism 106 displaces the confocal sensor 104 along the third axis from the current surface profile to the next surface profile. The step 424 returns to the step 404 to measure the single points along the next surface profile. The step 424 proceeds to the step 426 if the measurements at the measured surface profiles are determined to be complete. The step 426 includes calculating the surface roughness parameters from the local parameters measured at the single points. The surface roughness parameters are subsequently used for assessing the surface roughness of the object 102, as described below.

Surface Roughness Assessment

30

Each surface profile on the object 102 includes roughness, waviness, and surface form. Roughness is an irregularity as a result of manufacturing processes such as tearing, cutting, and surface fatigue. Waviness is a periodic texture usually caused by

vibration, chatter, or machine deflections. Surface form often results from inaccuracies of the machine elements such as elastic deformations, linear guide errors, and long-term thermal effects.

5 In order to assess the surface roughness, the surface form needs to be separated from the surface profile. To remove the surface form from the surface profile, best-fit least-squares methods are recommended in the ISO 4287 standard, such as a second order polynomial fitting method using least squares algorithm was introduced. The second order polynomial fitting method is suitable for removing the surface form
10 introduced by machining processes such as grinding, turning, and milling processes, as the surface form errors introduced by these machining processes are relatively simple, such as lines and curvatures. An example of the second order polynomial regression algorithm is shown in Equation 10 below.

$$15 \quad f(i) = a_0 + a_1x(i) + a_2x^2(i) \quad \text{[Equation 10]}$$

Where $f(i)$ represents the output element after polynomial regression, and $x(i)$ represents the i^{th} data point along the longitudinal direction (first axis) of the measured surface profile. The polynomial regression function determines the polynomial
20 coefficients a_i by minimizing the residue (RSS) according to Equation 11 below.

$$RSS = \frac{1}{n} \sum_{i=0}^{n-1} w(i) \times [f(i) - Z(i)]^2 \quad \text{[Equation 11]}$$

Where n represents the number of data points acquired the measured surface profile, $w(i)$ represents the i^{th} weighted element, and $Z(i)$ represents the i^{th} data point along
25 the height direction (second axis) of the measured surface profile. After the removal of the surface form, the levelled surface profile $Z_L(x)$ can be obtained by Equation 12 below.

$$30 \quad Z_L(i) = Z(i) - f(i) \quad \text{[Equation 12]}$$

To separate waviness including short wave components such as micro-fracture marks from surface roughness, a linear Gaussian profile filter is introduced in accordance with the ISO 16610-21 standard. The Gaussian profile filter is a phase correct filter that does not result in phase shift and asymmetrical profile distortion. The weighting function for the Gaussian profile filter is shown in Equation 13 below.

$$s(x) = \frac{1}{\alpha \times \lambda_c} \times \exp \left[-\pi \left(\frac{x}{\alpha \times \lambda_c} \right)^2 \right] \quad [\text{Equation 13}]$$

Where $s(x)$ represents the weighting function, and λ_c represents the cut-off wavelength and is determined based on the ISO 4288 standard. The value of α is 0.4697 to provide a 50% transmission characteristic of the Gaussian profile filter at the cut-off wavelength λ_c . The waviness profile is the convolution of the levelled surface profile $Z_L(x)$ and weighting function $s(x)$ and is shown in Equation 14 below.

$$Z_W(x) = \sum_{i=x-L_c\lambda_c}^{x+L_c\lambda_c} Z_L(i) s(x-i) \quad [\text{Equation 14}]$$

Where L_c is the truncation constant of the weighting function. According to the ISO 16610-21 standard, the value of L_c is 0.5 and results in a 0.76% implementation error. The surface roughness profile $Z_R(x)$ is the deduction between the levelled surface profile $Z_L(x)$ and the waviness profile $Z_W(x)$ and is shown in Equation 15 below.

$$Z_R(x) = Z_L(x) - Z_W(x) \quad [\text{Equation 15}]$$

The surface roughness parameters, such as R_a and R_q , can be calculated from the surface roughness profile $Z_R(x)$ using Equations 16 and 17 below. The surface roughness parameters R_a and R_q respectively represent the arithmetic and root mean square averages of the surface profile height deviations from the mean line. Notably, the arithmetic average R_a is one of the most commonly used surface roughness parameters.

$$R_a = \frac{1}{n} \sum_{i=1}^n |Z_R(i)| \quad [\text{Equation 16}]$$

$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^n Z_R(i)^2} \quad [\text{Equation 17}]$$

An evaluation was performed using an object 500 having a freeform surface 502 as shown in Figure 5. The measured surface profile and calculated surface roughness parameters from the freeform surface 502 and obtained by the apparatus 100 are evaluated against a stylus which was used as a reference instrument. The stylus is the Taylor Hobson PGI stylus profilometer and has an inherent measurement range limitation of 8 mm vertically, only the surface profile 504 forming part of the freeform surface was measured. As can be seen in Figure 5, the surface profile 504 has a curvilinear profile and the conventional confocal microscopy system is not suitable for measuring the curvilinear surface profile 504.

Figure 6A illustrates a graph of the local parameters, specifically the X and Z values, of the surface profile 504 measured using the apparatus 100. Figure 6B illustrates a graph of the local parameters of the surface profile 504 measured using the stylus. Figure 7A illustrates a graph of the surface profile 504, which was measured using the apparatus 100, after removing the surface form. Figure 7B illustrates a graph of the surface profile 504, which was measured using the stylus, after removing the surface form. Figure 8 illustrates a table comparing the surface roughness parameters – R_a and R_q – calculated from the measurement results of the stylus and the apparatus 100. It can be seen that the error magnitude in the surface roughness parameters are within 0.03 μm or 30 nm. In comparison, the Taylor Hobson PGI stylus profilometer has a measurement accuracy of 10 nm and a measurement limit of ± 4 mm (i.e. the stylus can measure surface deviations up to ± 4 mm from the surface mean line). The apparatus 100 is able to measure larger surface deviations of non-planar surfaces with a comparable measurement accuracy of 30 nm. Moreover, the error percentages (3.49% and 2.87% respectively) are less than the 5% error described in the background art *Fu et al.*

Although the evaluation was performed for a single surface profile 504, it will be appreciated that multiple surface profiles can be measured for surface roughness assessment. For example, if multiple surface profiles along the third axis are measured,

each surface profile can be individually assessed for surface roughness. Alternatively, all the surface profiles can be combined together to collectively build the overall surface area and assessed for surface roughness and uniformity. Various three-dimensional areal or surface texture parameters in accordance with the ISO 25178-2 standard can be calculated, such as but not limited to, the arithmetical mean (S_a) and root mean square (S_q) heights of the surface. Assessment of the overall surface area may have potential applications such as for evaluation of areal surface quality.

The evaluation showed that the apparatus 100 and the methods 200, 300, and 400 performed by the apparatus 100 can achieve substantially the same surface roughness assessment results as that of the conventional stylus, which is considered as the standard method for surface roughness assessment. Additionally, the apparatus 100 is suitable for assessing the surface roughness of non-flat surfaces or freeform objects such as aerofoils, objects with large surface height deviations, and objects with unknown surface profiles. The apparatus 100 uses the confocal sensor 104 which is suitable for non-contact and non-destructive surface measurement, addressing the disadvantages of the stylus which requires physical contact with the surface. Compared to typical stylus measurement speed of approximately 1 mm/s, the measurement speed of the confocal sensor 104 can reach up to approximately 3 mm/s, making the apparatus 100 suitable for in-situ surface roughness measurement. Therefore, the performance of the apparatus 100 is encouraging and addresses various disadvantages of other conventional instruments.

In the foregoing detailed description, embodiments of the present disclosure in relation to an apparatus and a method for assessing the surface roughness of an object are described with reference to the provided figures. The description of the various embodiments herein is not intended to call out or be limited only to specific or particular representations of the present disclosure, but merely to illustrate non-limiting examples of the present disclosure. The present disclosure serves to address at least one of the mentioned problems and issues associated with the prior art. Although only some embodiments of the present disclosure are disclosed herein, it will be apparent to a person having ordinary skill in the art in view of this disclosure that a variety of changes and/or modifications can be made to the disclosed embodiments without

departing from the scope of the present disclosure. Therefore, the scope of the disclosure as well as the scope of the following claims is not limited to embodiments described herein.

Claims

1. A method for assessing surface roughness of an object, the method comprising:
measuring, using a confocal sensor having a measurement range, a
5 plurality of locations along a surface profile of the object, comprising:
displacing the confocal sensor along a first axis to a current
location;
adjusting the confocal sensor along a second axis normal to the
first axis such that the current location is within the measurement range;
10 and
measuring a set of local parameters at the current location; and
calculating a set of surface roughness parameters from the local
parameters at the plurality of locations, the surface roughness parameters for
said assessing of the surface roughness of the object,
15 wherein the confocal sensor is adjusted for the current location based
on the local parameters at one or more preceding location.
2. The method according to claim 1, wherein each location comprises a local
profile portion, said measuring of the local parameters comprises scanning the
20 respective local profile portion by oscillating the confocal sensor along a local axis
thereof corresponding to the first axis.
3. The method according to claim 2, wherein adjacent local profile portions overlap
with each other.
25
4. The method according to claim 3, further comprising combining the local profile
portions along the surface profile using a data stitching algorithm.
5. The method according to claim 2, wherein said adjusting of the confocal sensor
30 for the current local profile portion comprises moving the confocal sensor along the
second axis based on the local parameters at the preceding local profile portion.

6. The method according to claim 5, wherein said moving of the confocal sensor along the second axis is calculated using a polynomial regression algorithm.

7. The method according to claim 1, wherein each location comprises a single point and the local parameters are measured at the respective single point, said adjusting for each single point comprising moving the confocal sensor along the second axis.

8. The method according to claim 7, further comprising measuring, at each single point, a positioning error of the confocal sensor after said moving of the confocal sensor.

9. The method according to claim 8, wherein said moving of the confocal sensor for the current single point compensates for the positioning errors measured at a plurality of preceding single points.

10. The method according to claim 9, wherein the compensation of the confocal sensor in said moving thereof is calculated using a discrete-time PID algorithm.

11. The method according to claim 1, further comprising, after said measuring of the locations along the surface profile, displacing the confocal sensor along a third axis normal to the first and second axes towards another surface profile of the object.

12. The method according to claim 11, further comprising calculating another set of surface roughness parameters from local parameters measured at locations along the other surface profile.

13. An apparatus for assessing surface roughness of an object, the apparatus comprising:

- a confocal sensor having a measurement range for measuring a plurality of locations along a surface profile of the object;
- an actuation mechanism for actuating the confocal sensor; and

a computer device comprising a control module configured for controlling the confocal sensor and the actuation mechanism to:

displace the confocal sensor along a first axis to a current location;

adjust the confocal sensor along a second axis normal to the first

5 axis such that the current location is within the measurement range; and

measure a set of local parameters at the current location; and

the computer device further comprising a calculation module configured for calculating a set of surface roughness parameters based on the local parameters at the plurality of locations, the surface roughness parameters for
10 said assessing of the surface roughness of the object,

wherein the confocal sensor for the current location is adjusted based on the local parameters at one or more preceding location.

14. The apparatus according to claim 13, wherein the confocal sensor comprises
15 an oscillating actuator for oscillating the confocal sensor along a local axis thereof corresponding to the first axis to scan a local profile portion at each location.

15. The apparatus according to claim 14, wherein said adjusting of the confocal sensor for the current local profile portion comprises moving the confocal sensor along
20 the second axis based on the local parameters at the preceding local profile portion.

16. The apparatus according to claim 13, wherein the confocal sensor is configured for measuring a single point at each location, said adjusting for each single point comprising moving the confocal sensor along the second axis.
25

17. The apparatus according to claim 16, wherein the control module is further configured for controlling the confocal sensor and actuation mechanism to measure, at each single point, a positioning error of the confocal sensor after said moving of the confocal sensor.
30

18. The apparatus according to claim 17, wherein said adjusting of the confocal sensor for the current single point compensates for the positioning errors measured at a plurality of preceding single points.

19. The apparatus according to claim 13, wherein the control module is further configured for controlling the confocal sensor and the actuation mechanism to, after said measuring of the local parameters along the surface profile, displace the confocal
5 sensor along a third axis normal to the first and second axes towards another surface profile of the object.

20. The apparatus according to claim 19, wherein the calculation module is further configured for calculating another set of surface roughness parameters from local
10 parameters measured at locations along the other surface profile.

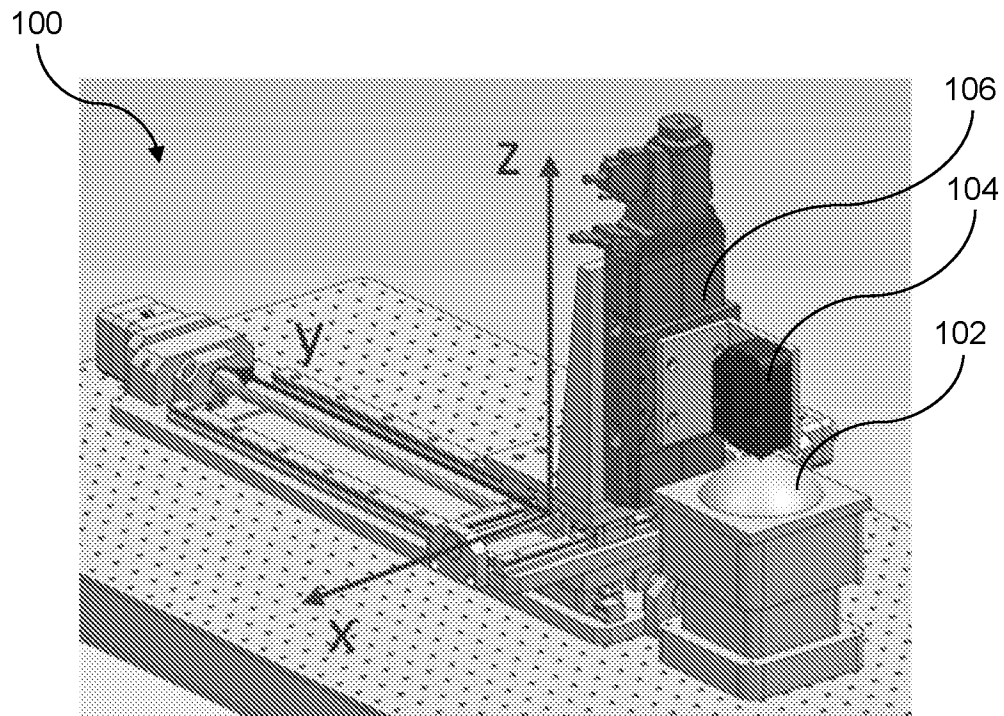


Figure 1A

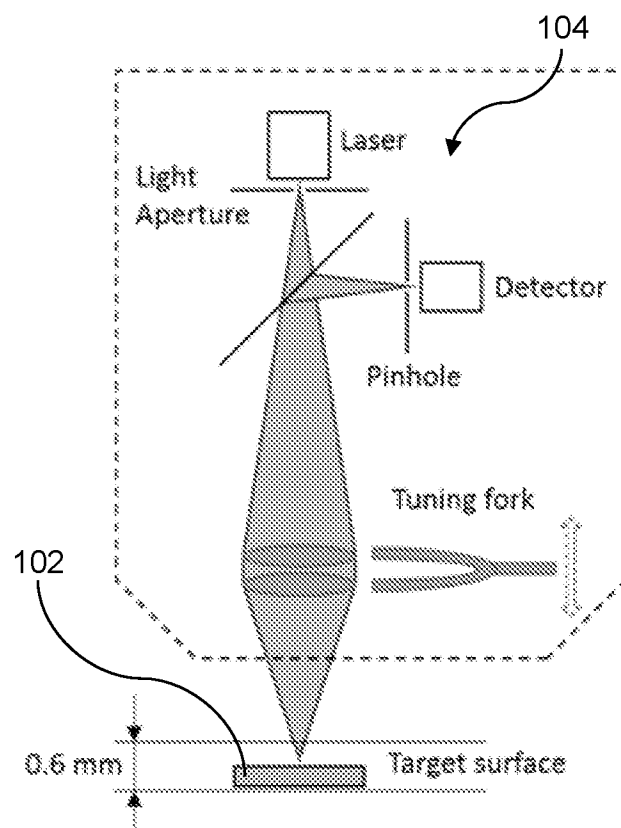


Figure 1B

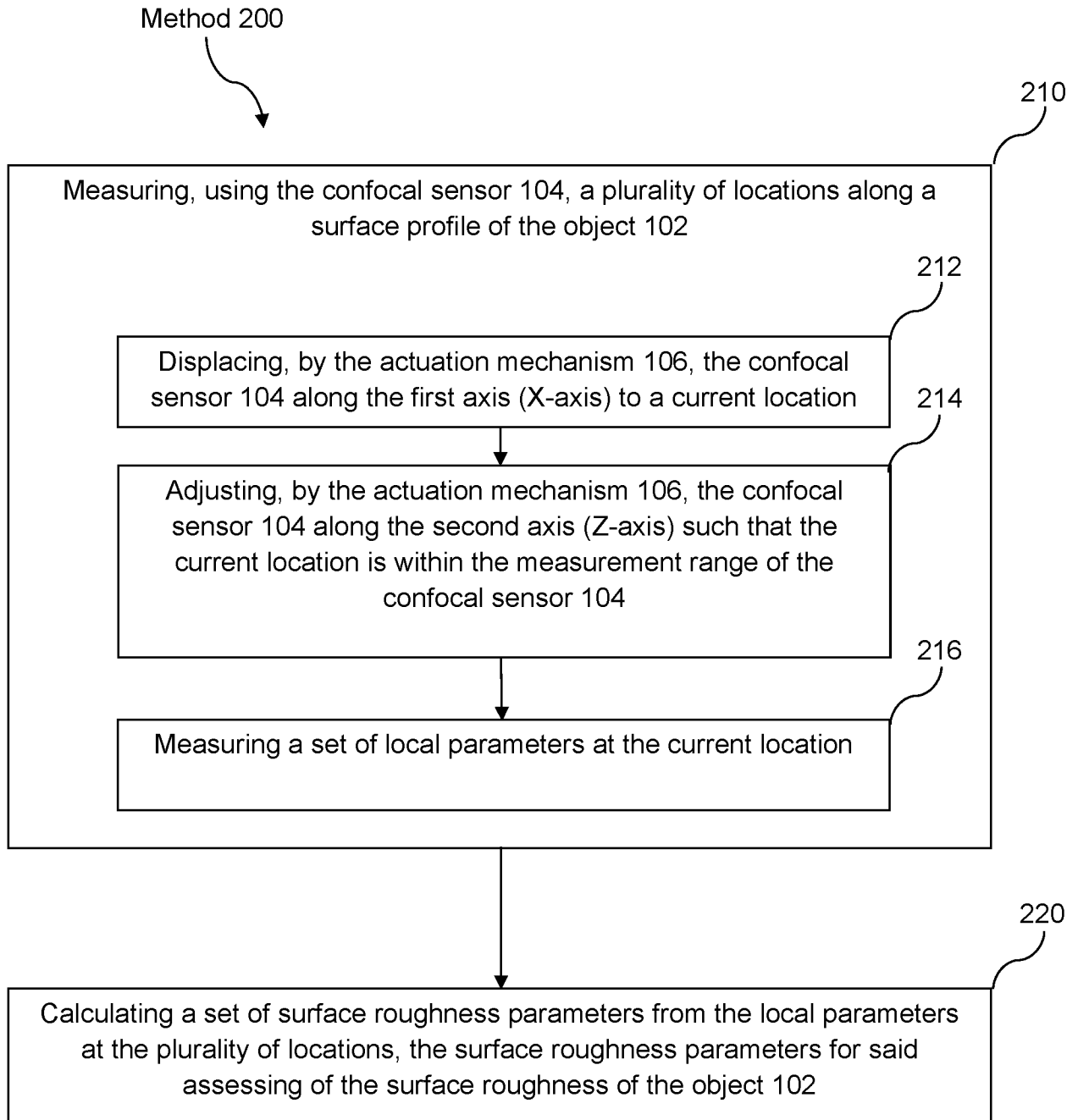


Figure 2

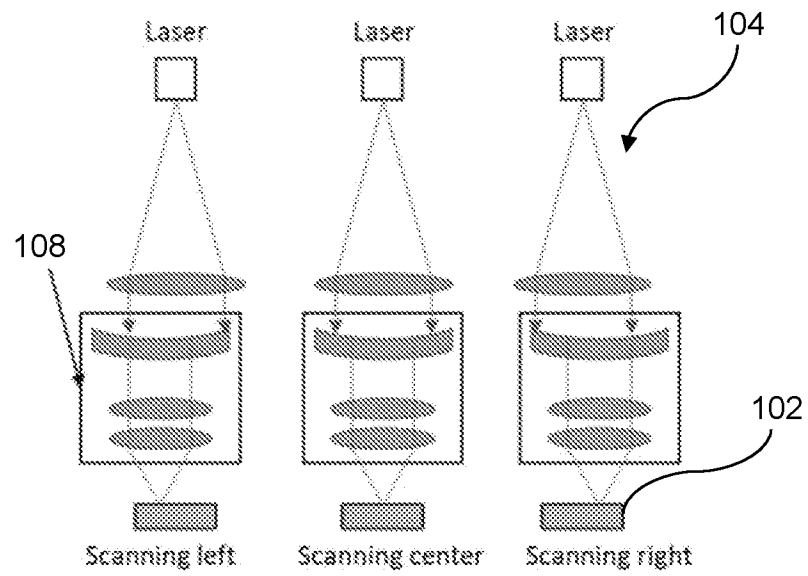


Figure 3A

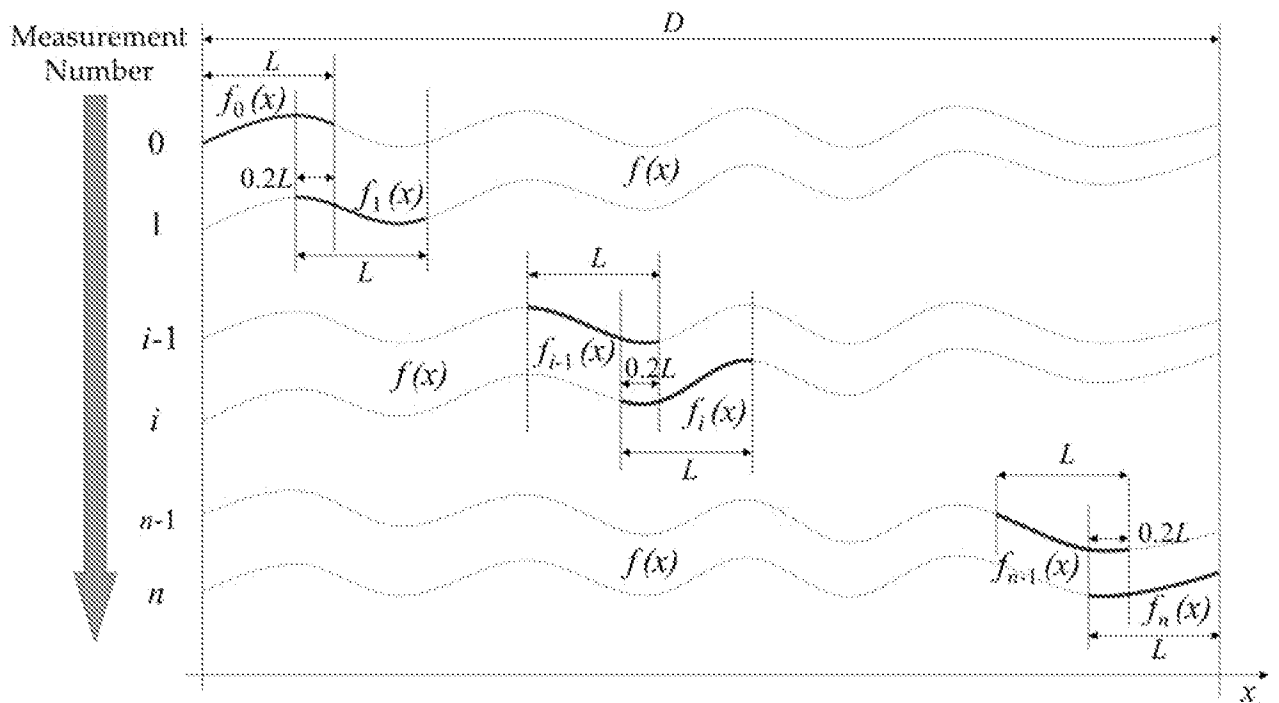


Figure 3C

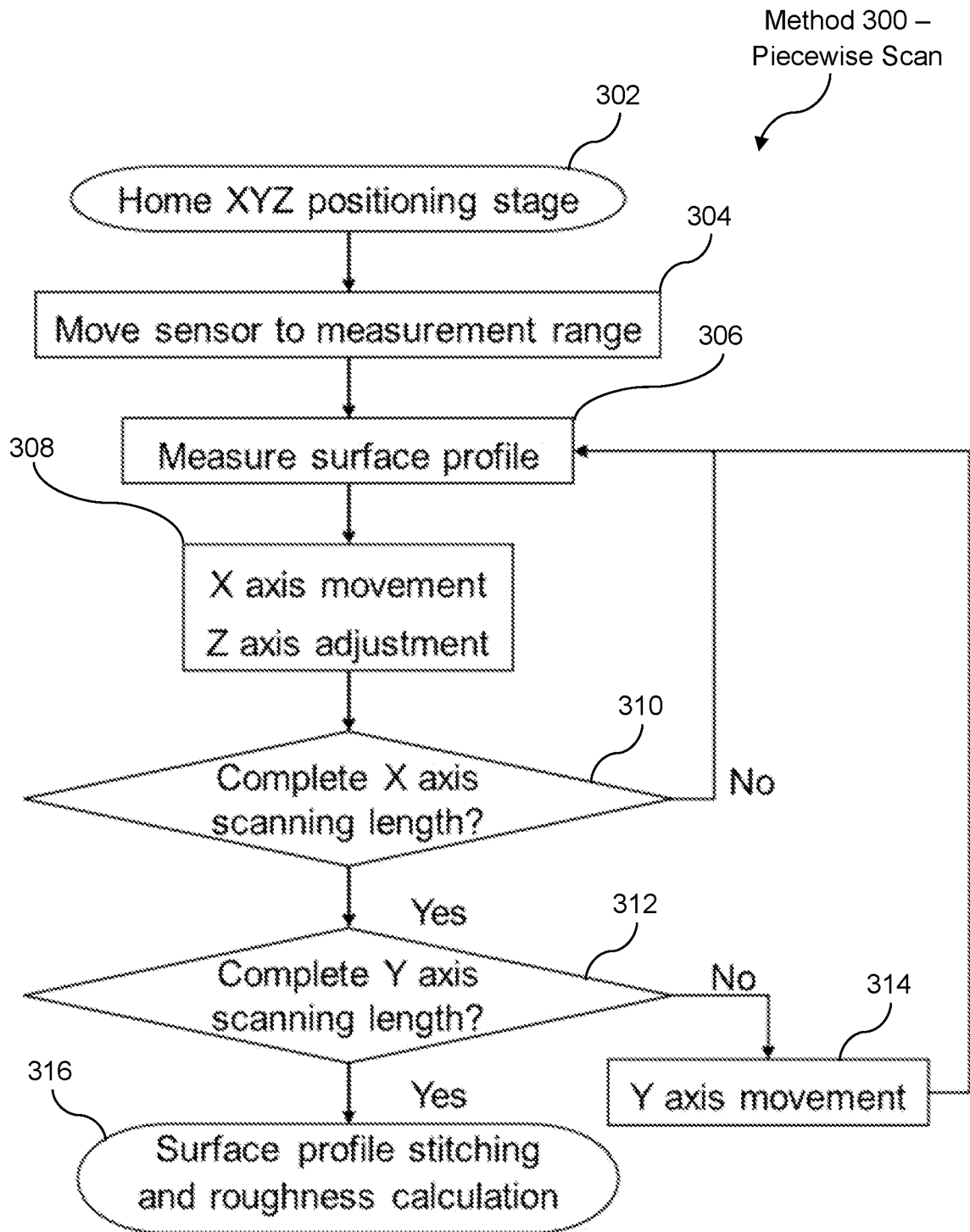


Figure 3B

Method 400 – Single-point Continuous Scan

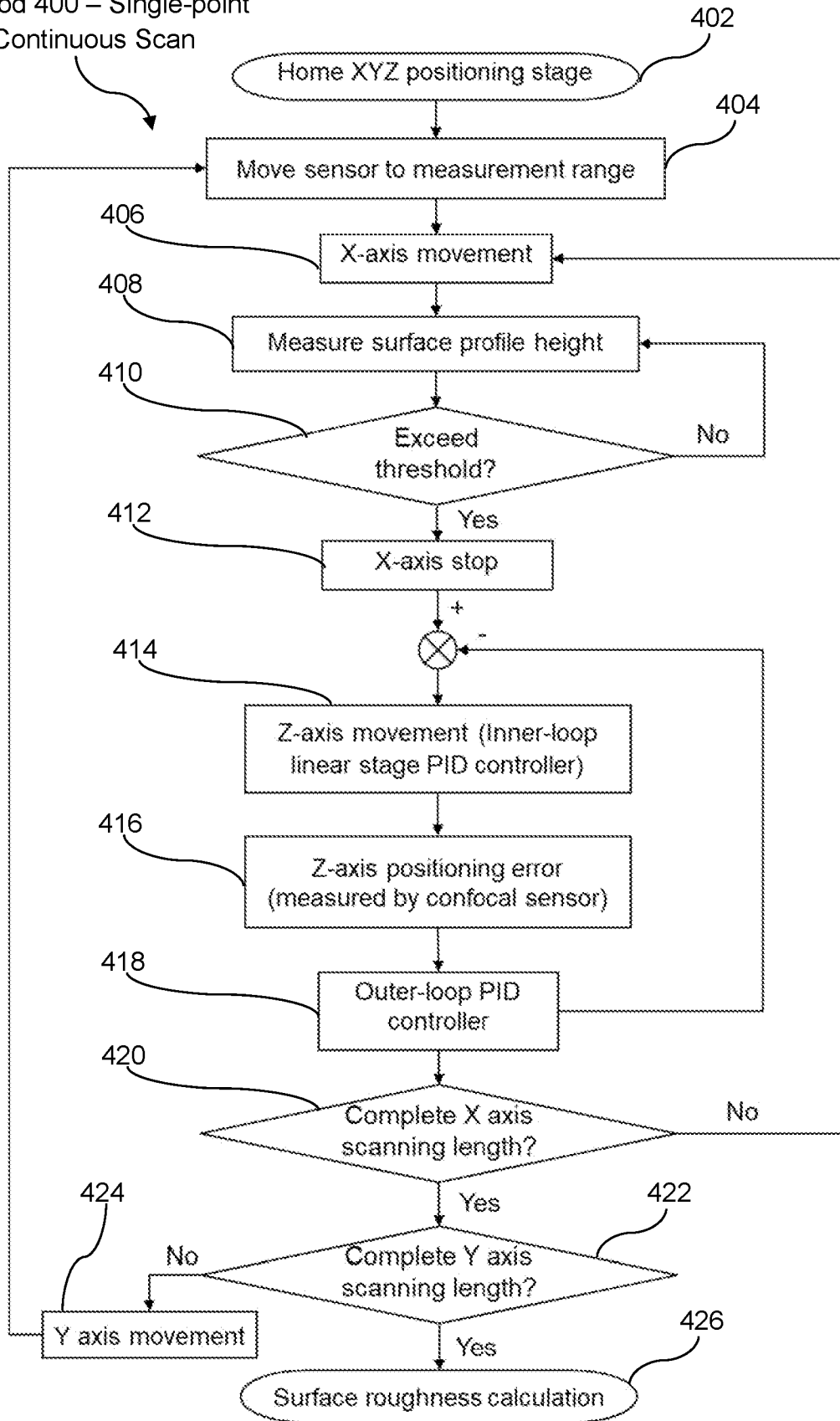


Figure 4A

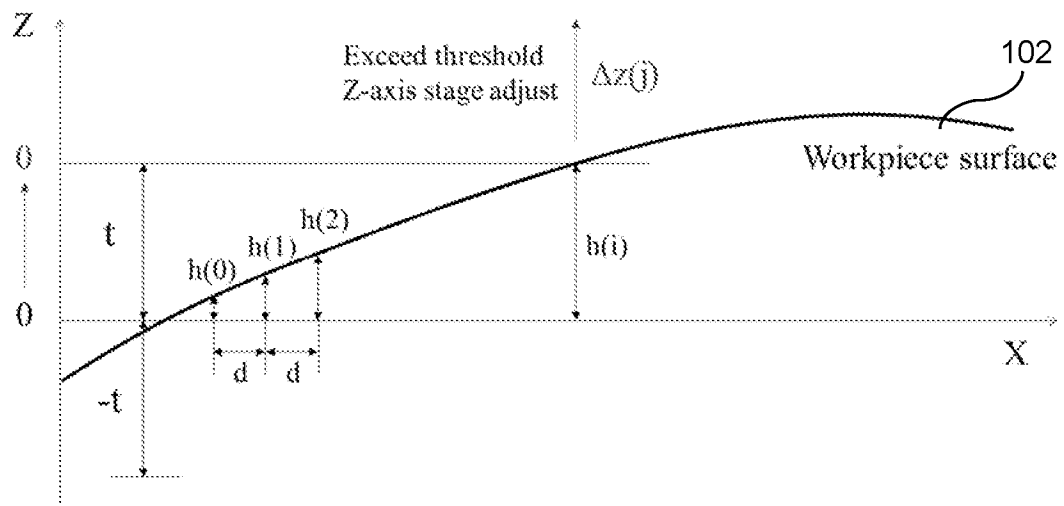


Figure 4B

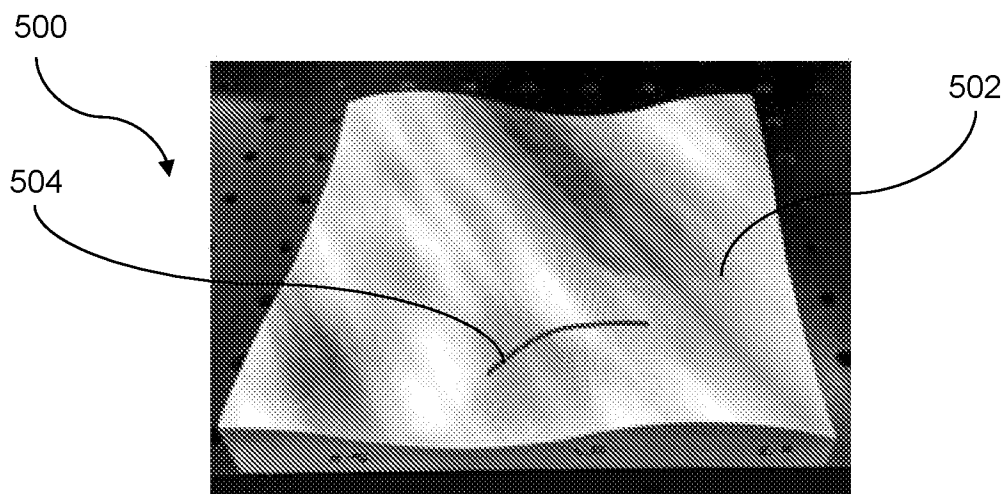


Figure 5

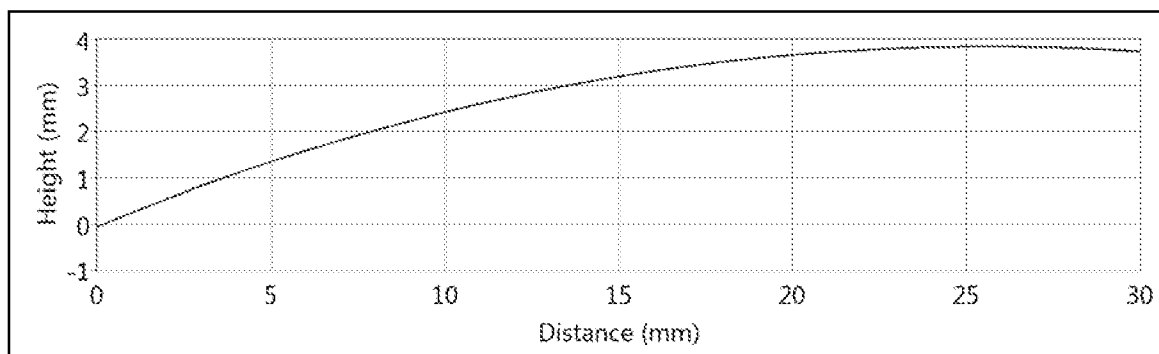


Figure 6A

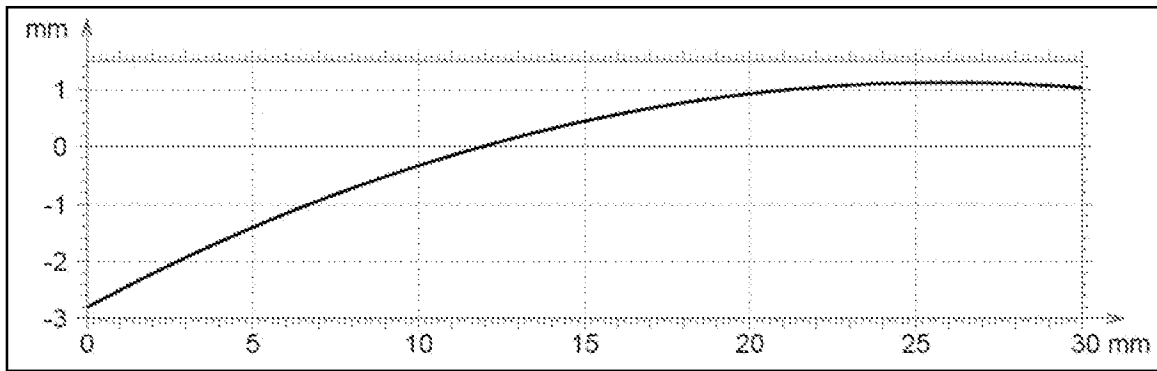


Figure 6B

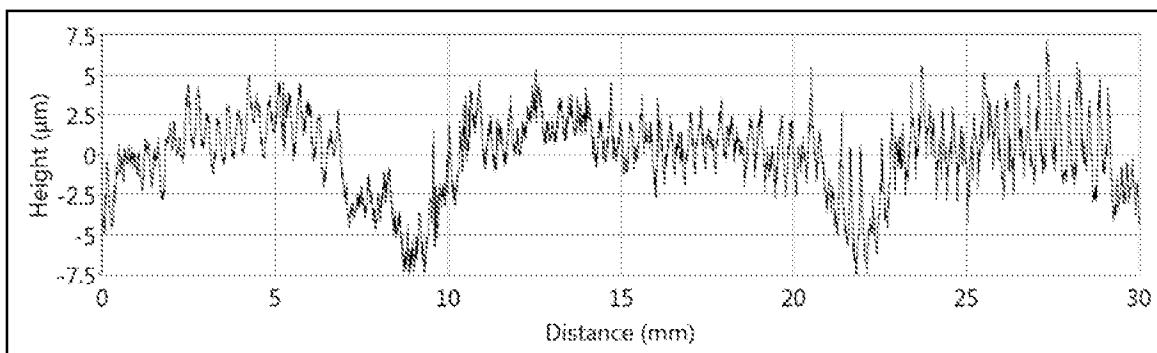


Figure 7A

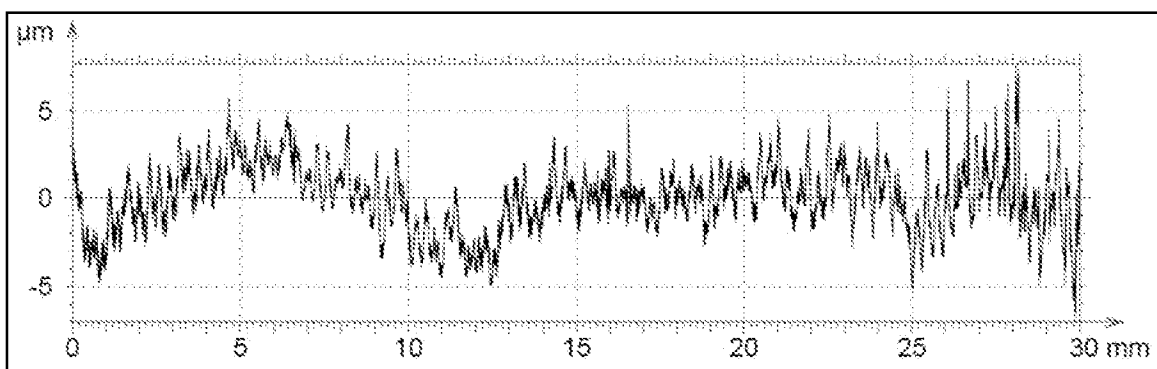


Figure 7B

Parameter	Stylus	Apparatus 100	Error Magnitude	Error Percentage
R_a	0.860 μm	0.83 μm	0.030 μm	3.49%
R_q	1.079 μm	1.11 μm	0.031 μm	2.87%

Figure 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2019/050018

A. CLASSIFICATION OF SUBJECT MATTER

G01B 11/24 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01B

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

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

FAMPAT: surface, roughness, profile, topography, confocal, sensor, location, position, preceding, previous, earlier, measurement range, scan range, working distance, 表面, 粗糙, 形状, 传感器位置, 前位, 测量量, 测量范围, 扫描范围 and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2016/0027194 A1 (ZUIDERWEG A. T. ET AL.) 28 January 2016 Abstract, paragraphs [0054], [0076]-[0087]	1-20
A	CN 105674914 A (UNIV ZHEJIANG) 15 June 2016 Whole document of the machine translation	Whole document
A	CN 104913733 A (NAT INST METROLOGY PRC) 16 September 2015 Whole document of the machine translation	

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

☒ See patent family annex.

*Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

05/03/2019

(day/month/year)

Date of mailing of the international search report

29/03/2019

(day/month/year)

Name and mailing address of the ISA/SG



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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2019/050018

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

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