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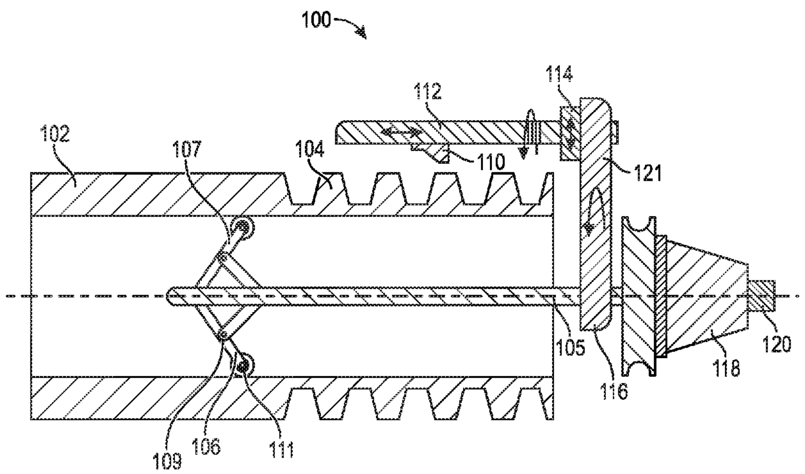


**FIG. 1**

**(57) Abstract:** A thread-inspection apparatus and method, of which the apparatus includes a sensor unit configured to measure a distance between the sensor unit and a point on a threadform of a cylindrical member, a plurality of actuators coupled to the sensor unit and configured to move the sensor unit radially, axially, and rotationally with respect to the cylindrical member, and a processor configured to generate a point cloud based on measurements taken by the sensor unit. The point cloud represents the threadform in three dimensions.

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# ON-MACHINE THREAD INSPECTION APPARATUS AND METHOD

## Cross-Reference To Related Applications

**[0001]** This application claims priority to U.S. Provisional Patent Application having Serial No. 62/847560, which was filed on May 14, 2019 and is incorporated herein by reference in its entirety.

## Background

**[0002]** Pipes are commonly used in the oil and gas industry and in many other industries. Generally, the pipes are coupled together, end-to-end, to form strings. To couple the pipes together, threads are cut into the ends of the pipes. In some instances, pipes may have external threads on both ends, and are then connected together using a collar. In other cases, the pipes may have external threads on one end, and internal threads on the other end, allowing the pipes to be directly connected together.

**[0003]** To ensure integrity and safety of the coupling connection, and whether an adequate seal is formed therebetween, the threaded surfaces of the pipes are inspected. The threaded surface may be formed in one of many different profiles to comply with different thread standards, which may be industry or application specific.

**[0004]** Generally, inspecting the threads includes gauging and measuring of the external/internal threaded surfaces using sets of manual gauges and tools. Examples of such tools include a thread pitch gauge for measuring pitch, a thread height gauge for measuring thread height, and a rubber mold for replicating the thread, among other tools.

**[0005]** Accordingly, the thread inspection process is typically performed manually. The threaded surface inspection and measurements may thus be tedious and time-consuming. Further, when defects are detected on the threaded surface during the final quality control phase, it may be too late to conduct any correction process to correct the defects, which may lead to wasted product.

## Summary

**[0006]** This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

**[0007]** Embodiments of the disclosure may provide a thread-inspection apparatus. The apparatus includes a sensor unit configured to measure a distance between the sensor unit and a point on a threadform of a cylindrical member, a plurality of actuators coupled to the sensor unit and configured to move the sensor unit radially, axially, and rotationally with respect to the cylindrical member, and a processor configured to generate a point cloud based on measurements taken by the sensor unit. The point cloud represents the threadform in three dimensions.

**[0008]** Embodiments of the disclosure may also provide a method including measuring a plurality of distances between a sensor unit and a plurality of points of a threadform of a cylindrical member. Each of the plurality of points is offset from each other of the plurality of points. Measuring includes moving the sensor unit axially, radially, and rotationally with respect to the cylindrical member. The method also includes generating a point cloud based on the plurality of distances. The point cloud represents the threadform in three dimensions. The method also includes comparing the point cloud to an engineering model to determine whether the threadform is within tolerance of the engineering model.

**[0009]** Embodiments of the disclosure may further provide a thread-inspection apparatus. The apparatus includes a sensor unit configured to measure a distance between the sensor unit and a point on a threadform of a cylindrical member, a plurality of actuators coupled to the sensor unit and configured to move the sensor unit radially, axially, and rotationally with respect to the cylindrical member, a processor in communication with the sensor unit and the plurality of actuators, and a non-transitory, computer-readable medium storing instructions, that when executed by the processor, cause the thread-inspection apparatus to perform operations. The operations include measuring a plurality of distances between the sensor unit and a plurality of points of a threadform of the cylindrical member. Each of the plurality of points is offset from each other of the plurality of points. Measuring comprises moving the sensor unit axially, radially, and rotationally with respect to the cylindrical member. The operations also include generating a point cloud based on the plurality of distances. The point cloud represents the threadform in three dimensions. The operations further include comparing one or more axial cross-sections of the point cloud to one or more axial cross-sections of an engineering model to determine whether the threadform is within tolerance of the engineering model.

## Brief Description of the Drawings

**[0010]** The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the present teachings and together with the description, serve to explain the principles of the present teachings. In the figures:

**[0011]** Figure 1 illustrates a side, cross-sectional view of a thread inspection apparatus inspecting an externally-threaded pipe, according to an embodiment.

**[0012]** Figure 2 illustrates a side, cross-sectional view of the thread inspection apparatus inspecting an internally-threaded pipe, according to an embodiment.

**[0013]** Figure 3 illustrates a conceptual view of a laser triangulation configuration employed by the thread inspection apparatus, according to an embodiment.

**[0014]** Figure 4 illustrates a view of a raw three-dimensional (3D) point cloud of a thread, according to an embodiment.

**[0015]** Figure 5 illustrates a flowchart of a method for determining threadform characteristics, e.g., using the thread inspection apparatus, which may be employed to control or otherwise affect a thread-forming process, according to an embodiment.

**[0016]** Figure 6 illustrates a conceptual view of the point cloud overlaid on the engineering design, according to an embodiment.

**[0017]** Figure 7 illustrates a cross-sectional view of the point cloud overlaid on the engineering design, according to an embodiment.

**[0018]** Figure 8 illustrates a schematic view of a computing system, according to an embodiment.

## Detailed Description

**[0019]** The following disclosure describes several embodiments for implementing different features, structures, or functions of the invention. Embodiments of components, arrangements, and configurations are described below to simplify the present disclosure; however, these embodiments are provided merely as examples and are not intended to limit the scope of the invention. Additionally, the present disclosure may repeat reference characters (e.g., numerals) and/or letters in the various embodiments and across the Figures provided herein. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed in the Figures. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact. Finally, the embodiments presented below may be combined in any combination of ways, e.g., any element from one exemplary embodiment may be used in any other exemplary embodiment, without departing from the scope of the disclosure.

**[0020]** Additionally, certain terms are used throughout the following description and claims to refer to particular components. As one skilled in the art will appreciate, various entities may refer to the same component by different names, and as such, the naming convention for the elements described herein is not intended to limit the scope of the invention, unless otherwise specifically defined herein. Further, the naming convention used herein is not intended to distinguish between components that differ in name but not function. Additionally, in the following discussion and in the claims, the terms “including” and “comprising” are used in an open-ended fashion, and thus should be interpreted to mean “including, but not limited to.” All numerical values in this disclosure may be exact or approximate values unless otherwise specifically stated. Accordingly, various embodiments of the disclosure may deviate from the numbers, values, and ranges disclosed herein without departing from the intended scope. In addition, unless otherwise provided herein, “or” statements are intended to be non-exclusive; for example, the statement “A or B” should be considered to mean “A, B, or both A and B.”

**[0021]** Embodiments of the present disclosure may provide a digital inspection apparatus that measures both the external and internal threaded surfaces of the pipes. The measurements include major diameter, minor diameter, pitch diameter, thread length, thread profile, thread lead, thread height, thread taper, and thread standoff. Standoff is a specific API (American Petroleum Institute) thread measurement. Based on the measurement data, a 3D point cloud model may be generated so that the threaded surface GD&T (Geometric Dimensioning and Tolerancing) can be verified and validated. In at least one embodiment, the digital inspection apparatus may be configured to measure a pipe with diameter range of 50–350 mm with a ±25 μm accuracy. The measurable thread length can be up to 150 mm.

**[0022]** Figure 1 illustrates a side, cross-sectional view of a measurement apparatus 100 disposed on an end of a cylindrical (e.g., tubular) member 102, according to an embodiment. In particular, the cylindrical member 102 may have a helical threadform (e.g., “threads”) 104 formed thereon, e.g., such as by cutting with a lathe or another machining operation. In Figure 1, the threadform 104 is formed on the outside of the cylindrical member 102, extending from an axial end thereof, such that this end forms a male half of a threaded coupling. Figure 2 illustrates a side, cross-sectional view of the measurement apparatus 100 disposed on an end of another cylindrical member 102, which has a threadform 104 formed therein, e.g., a female half of a threaded coupling. The apparatus 100 may be equally capable of measuring the threadforms 104 of both.

**[0023]** The measurement apparatus 100 may include a central rod 105 on which a centralizer 106 is positioned. The centralizer 106 may include two or more expandable arms 107, 109, each of which may include a roller 111 coupled thereto and positioned at a distal end thereof. The centralizer 106 may be retractable, and may be configured to maintain the concentricity alignment of the apparatus 100 to the cylindrical member 102. Various different centralizers 106 may be employed, and may variously include spring-loaded arm, bow springs, etc. Other designs that could hold the inspection embodiment in the center of the cylindrical member 102 may also be used.

**[0024]** Accordingly, the centralizer 106 may thus bear against an inner diameter surface of the cylindrical member 102, so as to maintain the rod 105 in a central position relative to the cylindrical member 102. With the rod 105 held in position, a remainder of the measurement apparatus 100 may be provided with a stationary platform from which to measure the position of various points on the cylindrical member 102 as will be discussed in greater detail below.

**[0025]** The measurement apparatus 100 may also include a sensor unit 110, and a plurality of actuators, such as an axial actuator 112, a radial actuator 114, and a rotary actuator 116. Further, the apparatus 100 may include a machine interface 118 and a communications device 120. The communications device 120 may include communication components (e.g., an antenna or ports for wired connections). The communications device 120 may, e.g., continuously, transmit measurements to the software through wireless connection using any wireless protocol, such as WiFi®, ZIGBEE®, and/or BLUETOOTH® etc.

**[0026]** The machine interface 118 may include a processor for processing measurement data collected, e.g., by the sensor unit 110. The measurement data may, for example, be transmitted to the processor at substantially the same time as it is collected, e.g., in real-time. Additional details of such a processor and processing measurement data are provided below.

**[0027]** The sensor unit 110 may include a beam laser sensor, or a dual configuration of a beam laser sensor, and/or a laser profiler, and/or a chromatic confocal sensor. The sensor unit 110 may be configured to measure the distance from the sensor unit 110 to a point on the surface of the threadform 104.

**[0028]** The axial actuator 112, the radial actuator 114, and the rotary actuator 116 may cooperatively move the sensor unit 110 across the circumferential surface of the threadform 104 (e.g., the inner diameter surface or outer diameter surface of the cylindrical member 102, depending on where the threadform 104 is located). For example, the axial actuator 112 may have a translational range of motion along the axial direction (e.g., parallel to a central longitudinal axis of the cylindrical member 102). Accordingly, the axial actuator 112 may be configured to move the sensor unit 110 along the axial direction to measure the entire axial span of the threadform 104. The axial actuator 114 may include any form of linear mechanism with suitable motion accuracy, such as linear guide rail, linear bearing, worm drive, rack-and-pinion, etc. Further, the axial actuator 112 may be configured to sense or otherwise determine a precise axial position of the sensor unit 110, e.g., relative to a stationary datum such as an end of the cylindrical member 102, and may provide a signal representative of such axial position.

**[0029]** The radial actuator 114 may be coupled to the axial actuator 112 and may have a translational range of motion along a radial direction with respect to the cylindrical member 104. The radial actuator 114 may move the axial actuator 112 and the sensor unit 110 along the radial direction, e.g., toward or away from the cylindrical member 102, to compensate for diameter changes in the cylindrical member 102, and/or to move the sensor unit 110 so that it is positioned to measure an external threadform (e.g., Figure 1) or an internal threadform (e.g., Figure 2). The radial actuator 114 may be or include any form of linear mechanism with acceptable motion accuracy, such as linear guide rail, linear bearing, worm drive, rack-and-pinion, etc. In an embodiment, the axial actuator 112 may be mounted on the radial actuator 112. Further, the radial actuator 114 may be configured to sense, record, or otherwise transmit a radial location of the sensor unit 110, e.g., with respect to a stationary datum such as the central axis of the cylindrical member 102. Further, the radial actuator 114 may be configured to translate along at least a portion of the radial actuator 116, e.g., an arm 121 thereof, with the arm 121 being connected to the rod 105.

**[0030]** The rotary actuator 116 may be coupled to the radial actuator 114 and may have a rotational range of motion and drives the radial and axial actuators 112, 114 and the sensor unit 110 to rotate around the central axis of the cylindrical member 102. For example, the rotary actuator 112 may rotate around the center shaft 105, which, as noted above, is held generally centralized or along the central axis, within the cylindrical member 102. The rotary actuator 116 may be or include any suitable rotation-imparting actuator, such as a motor with an encoder, which may serve to record or otherwise determine a rotary position of the sensor unit 110.

**[0031]** In an embodiment, the radial actuator 114 may be coupled to the rotary actuator 116 at different points, e.g., depending on whether internal or external threadforms are being inspected. For example, the radial actuator 114 may be coupled to a first, radially-outward point when an external threadform 104 (Figure 1) is being examined, and a second, radially-inward point when internal threadform 104 (Figure 2) is being examined.

**[0032]** Further, the axial actuator 112 may be coupled to the radial actuator 114 via a rotary joint 118. The rotary joint 118 may permit the axial actuator 112, and thus the sensor unit 110, to rotate such that the sensor unit 110 may face in a radial inward direction as the rotary actuator 116 rotates the axial actuator 112, radial actuator 114, and the sensor unit 110 about the cylindrical member 102. In some embodiments, the rotary joint 118 may include a suitable motor and encoder, with the motor being configured, e.g., automatically, to point the sensor unit 110 radially inward. Although the embodiment described herein has the axial actuator 112 coupled immediately to the sensor unit 110, the radial actuator 114 coupled to the axial actuator 112, and the radial actuator 114 coupled to the rotary actuator 116, it will be appreciated that this arrangement may be readily modified without departing from the scope of the present disclosure. For example, the axial actuator 112 may be coupled between the radial actuator 114 and the rotary actuator 116, to name just one variation among many contemplated.

**[0033]** Returning to the embodiment illustrated in Figures 1 and 2, as the sensor unit 110 moves, it may measure the distance between the sensor unit 110 and many points along the surface of the threadform 104. These measurements may be transmitted to a processor, either on-board the apparatus 100 or external thereto, e.g., via the machine interface 118.

**[0034]** The machine interface 118 may be used to effect a change in a computer numerical control (CNC) machine, such that on-machine threaded surface inspection can be achieved. The machine interface can also be used as an interface for a robot to grip, so that a robot mounted inspection application can be formed.

**[0035]** Figure 3 illustrates a diagrammatic view of the sensor unit 110, according to an embodiment. The sensor unit 110 may include a laser diode 300 (or other emitter) that directs a laser beam 302 to a point 304 on the surface of the threadform 104. The laser beam 302 is reflected back to a photodetector 306 of the sensor unit 110, e.g., via an imaging lens 308. Depending on the location of the laser diode 300 projection on the photodetector, the distance between the sensor unit 110 and the point on the surface of the threadform 104 may be measured from the constructed triangulation laser beam structure. One or more of the actuators 112, 114, 116 may then move the sensor unit 110 to direct the laser beam to a new location, and thereby measure another distance.

**[0036]** Figure 4 illustrates a "point cloud" 400 that is generated based in part on the measurements taken by the sensor unit 110, according to an embodiment. In particular, the point cloud 400 illustrates the actual measurements of the threadform 104 in three dimensional space, e.g., based on the location measurements provided by the actuators 112-116 and the distance measurement provided by the sensor unit 110.

**[0037]** The apparatus 100 (e.g., the machine interface 118, as discussed above) may also include a processor configured to execute software which may interpret the point cloud 400 and use the point cloud 400 to make determinations about the threadform 104. For example, the point cloud 400 may be compared to an ideal design, e.g., an engineering design of a threadform that the CNC machine undertaking the cutting of the threadform 104 endeavors to follow. The locations of the point cloud 400 may be compared to locations on the engineering design to determine deviations therefrom, and thereby determine not only whether the threadform 104 as a whole is within acceptable tolerance, but whether individual locations of the threadform 104 are within tolerance. In an embodiment, the comparison may proceed by a user manually selecting one or more datum points or surfaces of the engineering design, and one or more corresponding datum of the point cloud 400. For example, a last thread (e.g., last 360 degrees of the helical threadform 104) and/or a threaded shoulder may be selected for both the engineering design and the point cloud, and the comparisons between points of each may be based therefrom. In another embodiment, the comparison may be made automatically, by the processor executing software that picks corresponding datum points/planes on the engineering design and the point cloud 400.

**[0038]** Accordingly, the processor may operate in an "on-machine" mode, in which the measurements are taken during cutting, and cutting operations may be modified/corrected on-the-fly. In the on-machine mode, the processor causes the apparatus 100 to analyze the measurement in real-time and feedback a defects coordinates back to the CNC machine through communication protocols such as MTConnect or OPC-UA. If applicable, the CNC machine can correct the threaded surface with defects using the measurement.

**[0039]** The processor may also be configured to operate in an "off-machine" mode. In the off-machine mode, the apparatus 100 can either be used as a portable hand-held inspection tool for final quality control or be used as an inspection tool held by a robot as the in-line inspection of an automated machine tending application. The measurement and coordination data may be indexed and recorded in a database at the control of the software being executed. The measurement data can be later reconstructed in a 3D point cloud format, which can be overlaid on a desired thread, so that it can be verified against with the existing thread standards or engineering CAD models.

**[0040]** The processor may also be configured to calculate API standoff and/or other thread characteristics, without relying upon a master gauge. As discussed above, such thread characteristics are generally determined manually using gauges. API standoff measurements, for example, generally involve a heavy ring or pin plug (collectively referred to as "master gauges") to form a thread assembly with the pipe. The ring or pin plug is to be hand-tightened to the threaded connection being inspected. However, this is a subjective determination. Thus, human errors and inconsistency are brought into the measurement as various torque applied to the thread assembly by different operators.

**[0041]** Figure 5 illustrates a flowchart of a method 500 for determining characteristics of the threadform 104 using the apparatus 100, which may then lead to modifications to the threadform 104 or otherwise control or affect a thread-forming process, according to an embodiment. The method 500 may obviate the potential for the aforementioned human error and/or avoid spending time using manual measurement devices to quantify the characteristics of the threadform 104.

**[0042]** The method 500 may include measuring points of points of a threadform that is cut (and/or being cut) into a cylindrical member 102, as at 502. This may proceed generally as discussed above. In addition, the method 500 may include generating a point cloud based on the measured positions, as at 504. As noted above, an example of such a point cloud 400 is shown in Figure 4.

**[0043]** The point cloud 400 may be overlaid on (or otherwise compared to) an engineering design (e.g., a digital model), as at 506. The engineering design may specify the dimensions for the threadform, and threadforms that are cut within a specified tolerance of the engineering design may be considered acceptable, with those that are outside the tolerance being unacceptable or otherwise requiring remediation. Figure 6 illustrates an example of this overlaying of the point cloud 400 onto an engineering design 600 of an external threadform. This overlay may be displayed or otherwise visualized to a user, e.g., with color-coding (in the depiction of the drawings, this is shown using different hatching) to indicate regions where the point cloud 400 deviates from the engineering design 600 by more than the specified tolerance. This may assist users in quickly determining whether and where out-of-specification regions exist. For example, in Figure 6, the closer-hatched regions on the lead flank of the threadform indicates that the threadform 104, as represented by the point cloud 400, has deviated in position outside of tolerance, and thus correction of the threadform 104 may be undertaken. Based on such an overlaying of the point cloud 400 to the engineering design 600, it can be noted where threadform remediation is called for, rather than, potentially, cutting the entirety of the threadform 104 or rejecting the threadform 104 and starting over.

**[0044]** The overlay of the point cloud 400 on the digital model of the engineering design 600 may permit for a rapid determination of a binary, "go/no go" acceptability of the threadform 104, as at 507. For example, if the whole threadform 104 is within tolerance, and there are no areas that are out of tolerance, the threadform 104 may be accepted, as at 509. It will be appreciated that some deviation from tolerances might be acceptable in some situations, and thus the prior sentence should not be considered limiting. If one or more sections, areas, features, etc., of the threadform 104 are out of specification (e.g., outside of tolerance), the method 500 may proceed with a more detailed analysis, which may be used, e.g., to determine how to adjust the threadform 104 to bring it within acceptable dimensions.

**[0045]** For example, the method 500 may include defining one or more axial cross-sections of the threadform 104, as represented by the point cloud 400, e.g., overlaid on the engineering design 600, as at 508. Figure 7 illustrates an axial cross-section of the point cloud 400. The axial cross-section may extend axially at an angle relative to the central axis, and one or more, potentially many, cross-sections may be analyzed. Any number of axial cross-sections may be considered, from one to as many as desired. Generally, the number of axial cross-sections to be considered may be input by a user or otherwise predetermined, so as to find a balance between precision in the determination and computational intensity.

**[0046]** The method 500 may also include determining one or more thread characteristics of the threadform 104 using the cross-section(s) of the point cloud 400, as at 510. For example, for both the external and internal threadforms, characteristics such as major diameter, minor diameter, pitch diameter, thread pitch, thread length, thread lead, thread height, thread taper, and thread standoff may be determined based on the location measurements in the point cloud 400. By knowing the precise position of the locations of the threadform 104 in cross-section, the threadform characteristics may be determined with accuracy on par with the accuracy of the measurements, e.g., within about 25 μm in some cases.

**[0047]** In an embodiment, the method 500 may further include determining whether the threadform 104 is within a specification (e.g., within tolerance) based on the one or more axial cross-sections, as at 510. For example, thread characteristics such as thread form, height, pitch, taper, and lead may be determined using the axial cross section of the point cloud 400. These characteristics may be compared to the specifications for the threadform 104, in order to determine whether the threadform 104 characteristics are within tolerance.

**[0048]** Another thread characteristic is thread standoff; however, standoff generally cannot be directly measured from the geometry of the threadform 104, but is measured using a manual gauge. The manual gauge, and measurements based thereon, provide a rough estimate of whether the threadform as a whole is within design specifications. In embodiments of the present disclosure, however, such rough standoff determinations may be omitted. Rather, the axial cross-sections at potentially many different regions can be analyzed to determine whether the threadform 104 is within design specifications. If the axial cross-sections do not evidence out-of-tolerance areas, the standoff specification may be considered met, as the threadform 104 passing more rigorous analyzation of the threadform by the present method means that it would also pass the rougher analyses using a manual gauge. This may avoid using mechanical tools to measure standoff, as a rough proxy for precision in the thread-forming process.

**[0049]** As noted above, if the threadform is out of tolerance, it may be remediated, e.g., by manipulating a CNC machine and/or robot used to form the threadform 104. After such remediation, the threadform 104 may be re-inspected for compliance with the engineering design specifications, and passed along for use or further fabrication processes once meeting the design specifications. Thus, the method 500 may affect or otherwise control the threadforming process by controlling the inspection thereof.

**[0050]** In one or more embodiments, the functions described (e.g., as executed by a processor) can be implemented in hardware, software, firmware, or any combination thereof. For a software implementation, the techniques described herein can be implemented with modules (e.g., procedures, functions, subprograms, programs, routines, subroutines, modules, software packages, classes, and so on) that perform the functions described herein. A module can be coupled to another module or a hardware circuit by passing and/or receiving information, data, arguments, parameters, or memory contents. Information, arguments, parameters, data, or the like can be passed, forwarded, or transmitted using any suitable means including memory sharing, message passing, token passing, network transmission, and the like. The software codes can be stored in memory units and executed by processors. The memory unit can be implemented within the processor or external to the processor, in which case it can be communicatively coupled to the processor via various means as is known in the art.

**[0051]** As described above, the apparatus 100 may include or otherwise be in communication with a processor, which may be part of a computing system configured to determine measurements based on sensor readings, interface with a CNC machine or another external processor, or otherwise execute software, so as to execute an embodiment of any of the methods or processes discussed herein. Figure 8 illustrates an example of such a computing system 800, in accordance with some embodiments. The computing system 800 may include a computer or computer system 801A, which may be an individual computer system 801A or an arrangement of distributed computer systems. The computer system 801A includes one or more analysis module(s) 802 configured to perform various tasks according to some embodiments, such as one or more methods disclosed herein. To perform these various tasks, the analysis module 802 executes independently, or in coordination with, one or more processors 804, which is (or are) connected to one or more storage media 806. The processor(s) 804 is (or are) also connected to a network interface 807 to allow the computer system 801A to communicate over a data network 809 with one or more additional computer systems and/or computing systems, such as 801B, 801C, and/or 801D (note that computer systems 801B, 801C and/or 801D may or may not share the same architecture as computer system 801A, and may be located in different physical locations, e.g., computer systems 801A and 801B may be located in a processing facility, while in communication with one or more computer systems such as 801C and/or 801D that are located in one or more data centers, and/or located in varying countries on different continents).

**[0052]** A processor can include a microprocessor, microcontroller, processor module or subsystem, programmable integrated circuit, programmable gate array, or another control or computing device.

**[0053]** The storage media 806 can be implemented as one or more computer-readable or machine-readable storage media. Note that while in the example embodiment of Figure 8 storage media 806 is depicted as within computer system 801A, in some embodiments, storage media 806 may be distributed within and/or across multiple internal and/or external enclosures of computing system 801A and/or additional computing systems. Storage media 806 may include one or more different forms of memory including semiconductor memory devices such as dynamic or static random access memories (DRAMs or SRAMs), erasable and programmable read-only memories (EPROMs), electrically erasable and programmable read-only memories (EEPROMs) and flash memories, magnetic disks such as fixed, floppy and removable disks, other magnetic media including tape, optical media such as compact disks (CDs) or digital video disks (DVDs), BLURAY® disks, or other types of optical storage, or other types of storage devices. Note that the instructions discussed above can be provided on one computer-readable or machine-readable storage medium, or can be provided on multiple computer-readable or machine-readable storage media distributed in a large system having possibly plural nodes. Such computer-readable or machine-readable storage medium or media is (are) considered to be part of an article (or article of manufacture). An article or article of manufacture can refer to any manufactured single component or multiple components. The storage medium or media can be located either in the machine running the machine-readable instructions, or located at a remote site from which machine-readable instructions can be downloaded over a network for execution.

**[0054]** In some embodiments, computing system 800 contains one or more thread measurement module(s) 808. In the example of computing system 800, computer system 801A includes the thread measurement module 808. In some embodiments, a single thread measurement module may be used to perform some or all aspects of one or more embodiments of the methods. In alternate embodiments, a plurality of thread measurement modules may be used to perform some aspects of the methods disclosed herein.

**[0055]** It should be appreciated that computing system 800 is only one example of a computing system, and that computing system 800 may have more or fewer components than shown, may combine additional components not depicted in the example embodiment of Figure 8, and/or computing system 800 may have a different configuration or arrangement of the components depicted in Figure 8. The various components shown in Figure 8 may be implemented in hardware, software, or a combination of both hardware and software, including one or more signal processing and/or application specific integrated circuits.

**[0056]** Further, the steps in the processing methods described herein may be implemented by running one or more functional modules in information processing apparatus such as general purpose processors or application specific chips, such as ASICs, FPGAs, PLDs, or other appropriate devices. These modules, combinations of these modules, and/or their combination with general hardware are all included within the scope of protection of the disclosure.

**[0057]** Geologic interpretations, models and/or other interpretation aids may be refined in an iterative fashion; this concept is applicable to embodiments of the present methods discussed herein. This can include use of feedback loops executed on an algorithmic basis, such as at a computing device (e.g., computing system 800, Figure 8), and/or through manual control by a user who may make determinations regarding whether a given step, action, template, model, or set of curves has become sufficiently accurate for the evaluation of the subsurface three-dimensional geologic formation under consideration.

**[0058]** The foregoing description, for purpose of explanation, has been described with reference to specific embodiments. However, the illustrative discussions above are not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. Moreover, the order in which the elements of the methods are illustrated and described may be re-arranged, and/or two or more elements may occur simultaneously. The embodiments were chosen and described in order to explain the principals of the invention and its practical applications, to thereby enable others skilled in the art to utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated.

**CLAIMS**

*What is claimed is:*

1. A thread-inspection apparatus, comprising:

a sensor unit configured to measure a distance between the sensor unit and a point on a threadform of a cylindrical member;

a plurality of actuators coupled to the sensor unit and configured to move the sensor unit radially, axially, and rotationally with respect to the cylindrical member; and

a processor configured to generate a point cloud based on measurements taken by the sensor unit, wherein the point cloud represents the threadform in three dimensions.

2. The apparatus of claim 1, further comprising an interface coupled to the processor and communicable with a CNC machine as an on-machine inspection tool or a robot for post-machine thread inspection.

3. The apparatus of claim 1, wherein the sensor unit comprises a sensor selected from the group consisting of a confocal sensor, a laser line profiler, and a confocal sensor.

4. The apparatus of claim 1, further comprising a centralizer configured to maintain a position of the sensor unit relative to the cylindrical member except when moved by one or more of the plurality of actuators.

5. The apparatus of claim 4, wherein the centralizer is configured to be received into the cylindrical member and to bear against an inner diameter surface thereof.

6. The apparatus of claim 1, wherein the plurality of actuators comprise a rotary actuator configured to rotate the sensor unit about a central axis of the cylindrical member, a radial actuator coupled to the rotary actuator and configured to move the sensor radially toward and away from the central axis, and an axial actuator coupled to the radial actuator and configured to move the sensor unit parallel to the central axis.

7. The apparatus of claim 6, wherein the rotary actuator comprises a first connection configured to connect to the axial actuator when the threadform is an external thread, and a second connection configured to connect to the axial actuator when the thread is an internal thread, the second connection being radially inward of the first connection.

8. The apparatus of claim 6, further comprising a rotary joint between the axial actuator and the radial actuator, wherein the rotary joint is configured to point the sensor unit in a radially-inward direction at any rotational position of the sensor unit.

9. The apparatus of claim 1, further comprising a data transmission unit in communication with the sensor unit, wherein the data transmission unit is configured to transmit data representing the point cloud that represents the threadform to the processor, and wherein the processor is configured to detect defects in the thread based on the point cloud.

10. The apparatus of claim 1, wherein the processor is configured to:

compare the point cloud to an engineering model of a threadform;

calculate a distance between points in the point cloud and corresponding points of the engineering model;

determine that the distance is larger than an acceptable tolerance; and

initiate a remediation action to reduce the distance.

11. The apparatus of claim 1, wherein the processor is further configured to:

define an axial cross-section of the point cloud; and

determine one or more physical characteristics of the threadform based on the axial cross-section.

12. The apparatus of claim 11, further comprising determining that the threadform meets a standoff specification based on the one or more physical characteristics of the threadform determined based on the axial cross-section meeting one or more specifications corresponding thereto.

13. A method, comprising:

measuring a plurality of distances between a sensor unit and a plurality of points of a threadform of a cylindrical member, wherein each of the plurality of points is offset from each other of the plurality of points, and wherein measuring comprises moving the sensor unit axially, radially, and rotationally with respect to the cylindrical member;

generating a point cloud based on the plurality of distances, wherein the point cloud represents the threadform in three dimensions; and

comparing the point cloud to an engineering model to determine whether the threadform is within tolerance of the engineering model.

14. The method of claim 13, further comprising modifying the threadform when the threadform is out of tolerance.

15. The method of claim 13, wherein comparing the point cloud to the engineering model comprises overlaying the point cloud onto the engineering model.

16. The method of claim 15, further comprising visualizing the point cloud overlaid on the engineering model using a computer display.

17. The method of claim 13, further comprising:

determining that the threadform is not within tolerance of the engineering model; and

in response to determining that the threadform is not within tolerance of the engineering model:

generating one or more axial cross-sections of the threadform; and

determining one or more physical characteristics of the threadform based on the one or more axial-cross sections.

18. The method of claim 17, wherein comparing comprises comparing the one or more axial cross-sections of the threadform to one or more corresponding axial cross-sections of the engineering model.

19. The method of claim 18, further comprising determining that the threadform meets a standoff specification based on the one or more physical characteristics of the threadform determined based on the axial cross-section meeting one or more specifications corresponding thereto.

20. A thread-inspection apparatus, comprising:

a sensor unit configured to measure a distance between the sensor unit and a point on a threadform of a cylindrical member;

a plurality of actuators coupled to the sensor unit and configured to move the sensor unit radially, axially, and rotationally with respect to the cylindrical member;

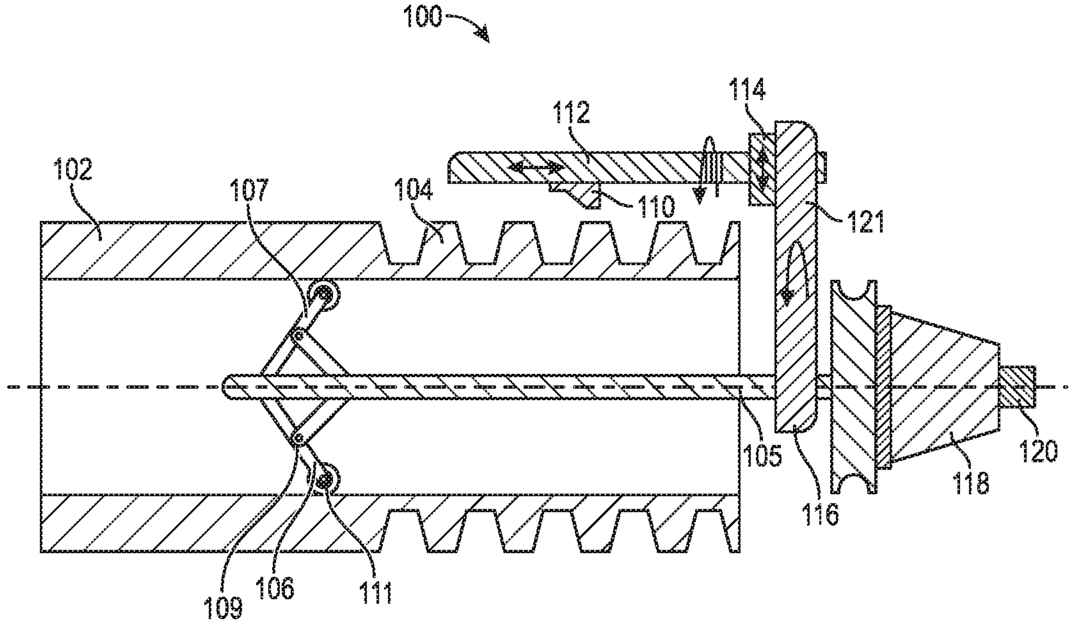
a processor in communication with the sensor unit and the plurality of actuators; and

a non-transitory, computer-readable medium storing instructions, that when executed by the processor, cause the thread-inspection apparatus to perform operations, the operations comprising:

measuring a plurality of distances between the sensor unit and a plurality of points of a threadform of the cylindrical member, wherein each of the plurality of points is offset from each other of the plurality of points, and wherein measuring comprises moving the sensor unit axially, radially, and rotationally with respect to the cylindrical member;

generating a point cloud based on the plurality of distances, wherein the point cloud represents the threadform in three dimensions; and

comparing one or more axial cross-sections of the point cloud to one or more axial cross-sections of an engineering model to determine whether the threadform is within tolerance of the engineering model.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111

FIG. 1

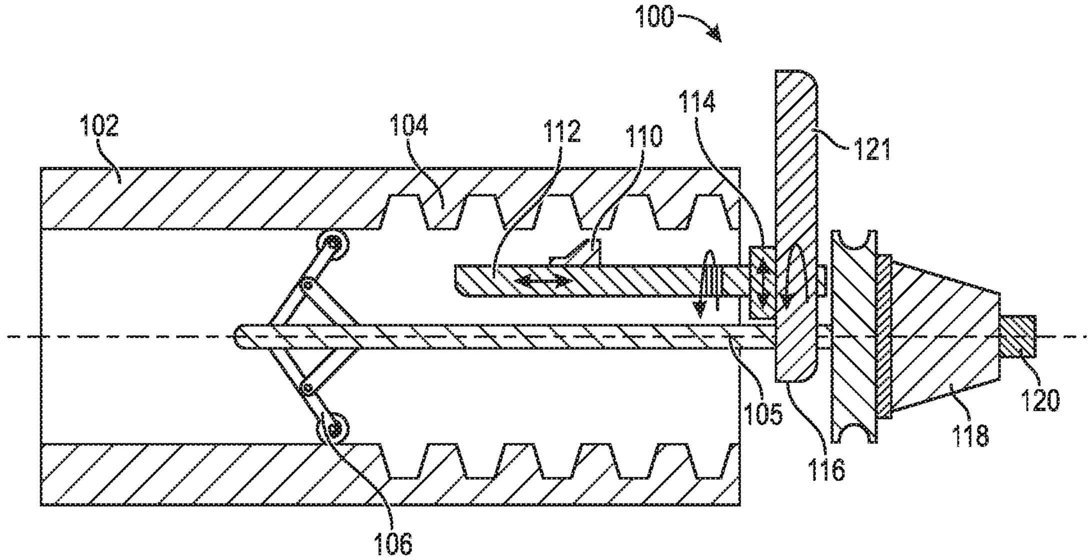
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FIG. 2

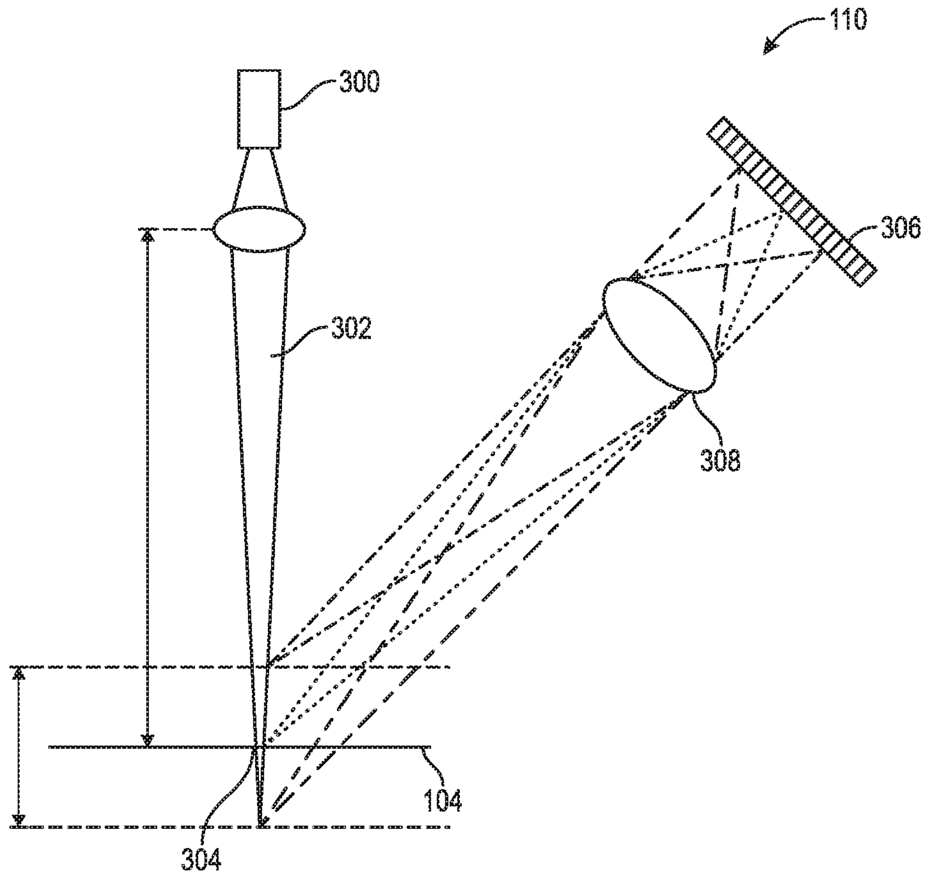


FIG. 3

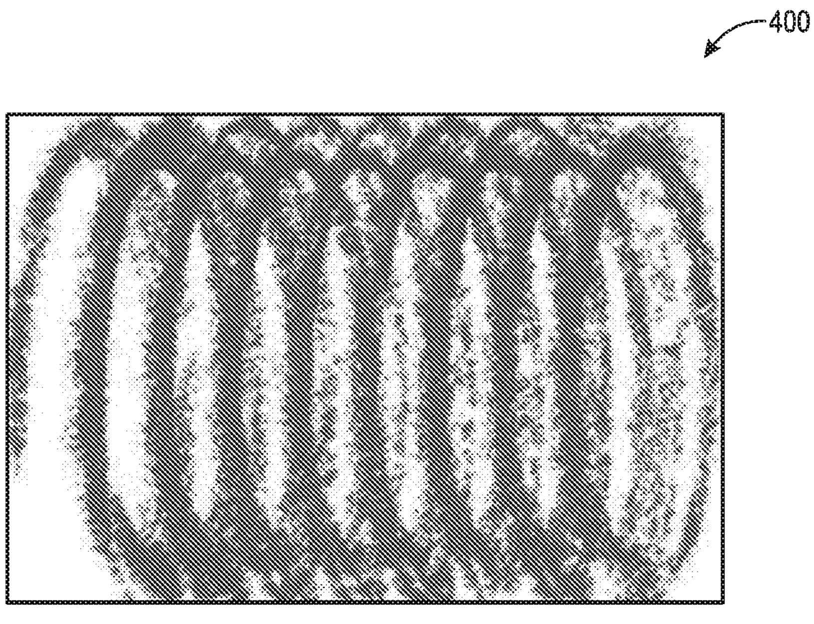


FIG. 4

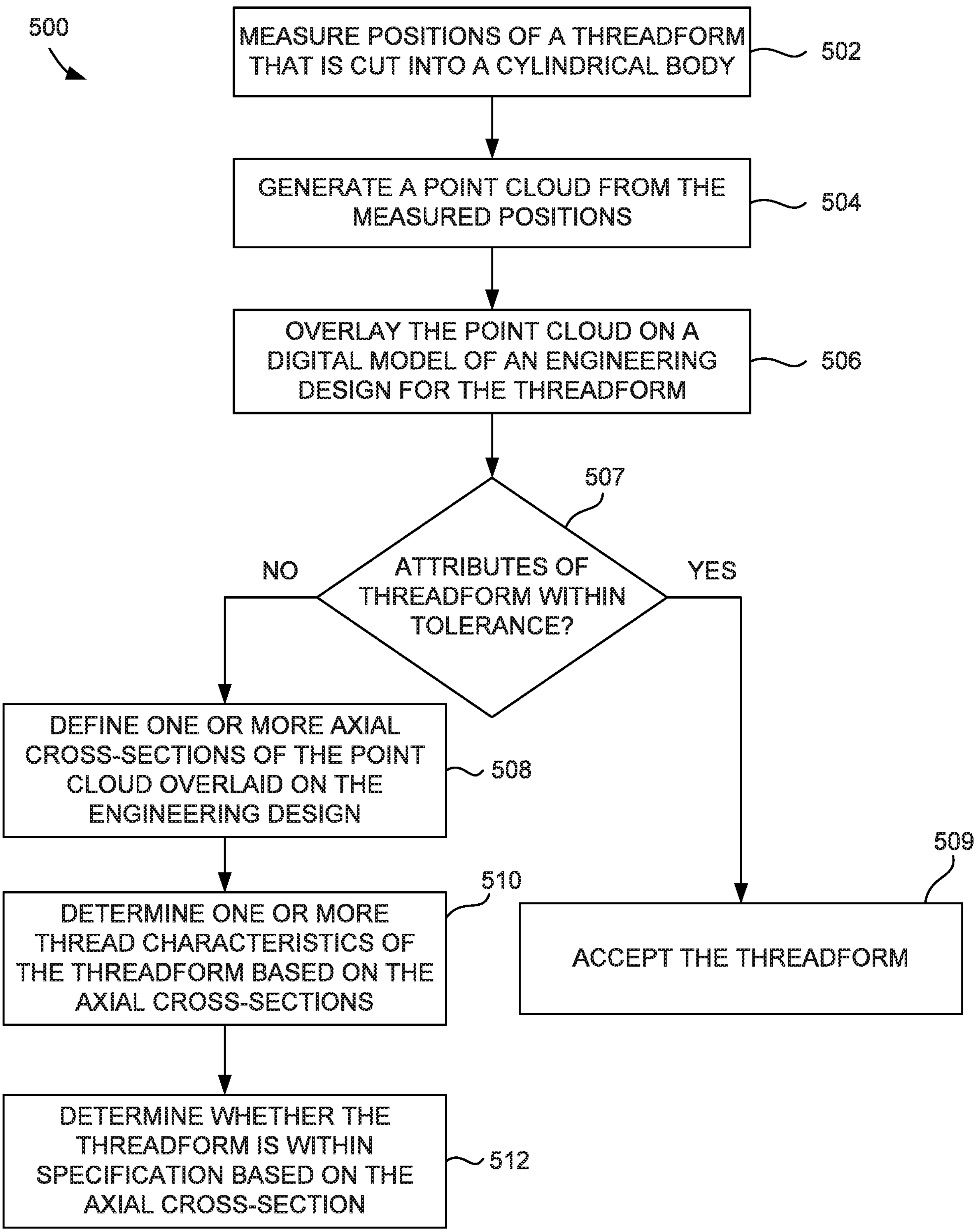
500
MEASURE POSITIONS OF A THREADFORM THAT IS CUT INTO A CYLINDRICAL BODY
502
GENERATE A POINT CLOUD FROM THE MEASURED POSITIONS
504
OVERLAY THE POINT CLOUD ON A DIGITAL MODEL OF AN ENGINEERING DESIGN FOR THE THREADFORM
506
507
ATTRIBUTES OF THREADFORM WITHIN TOLERANCE?
NO
YES
DEFINE ONE OR MORE AXIAL CROSS-SECTIONS OF THE POINT CLOUD OVERLAID ON THE ENGINEERING DESIGN
508
DETERMINE ONE OR MORE THREAD CHARACTERISTICS OF THE THREADFORM BASED ON THE AXIAL CROSS-SECTIONS
510
DETERMINE WHETHER THE THREADFORM IS WITHIN SPECIFICATION BASED ON THE AXIAL CROSS-SECTION
512
ACCEPT THE THREADFORM
509

FIG. 5

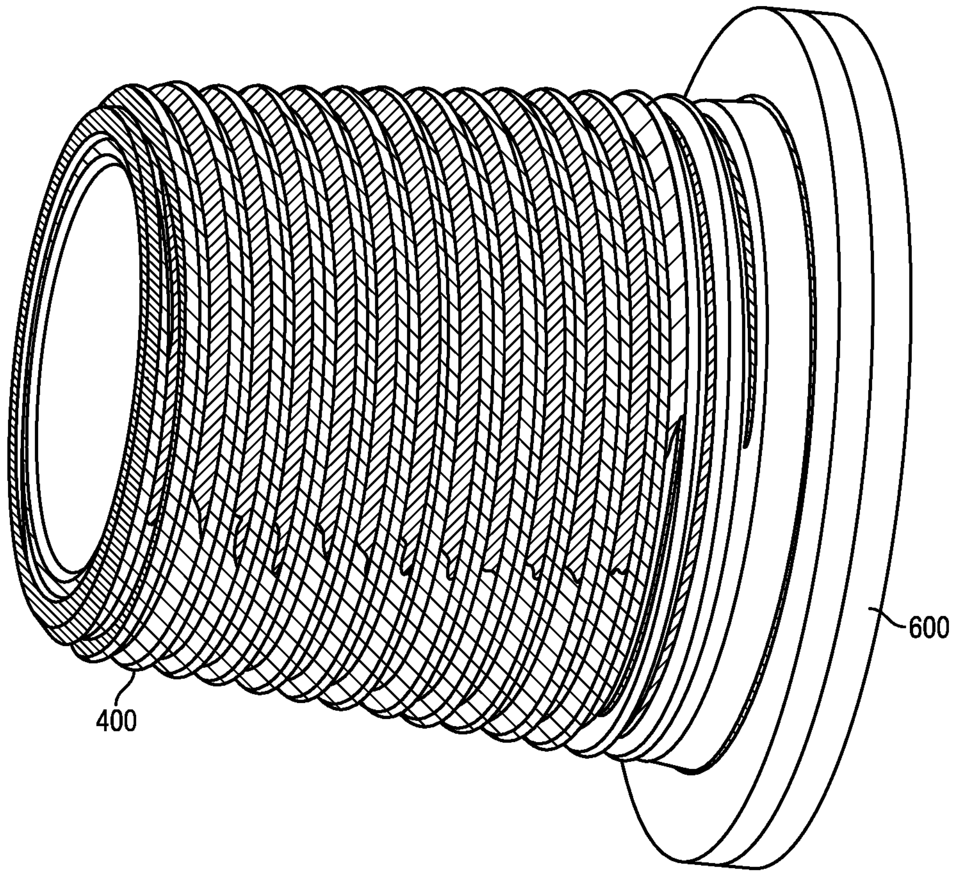


**FIG. 6**

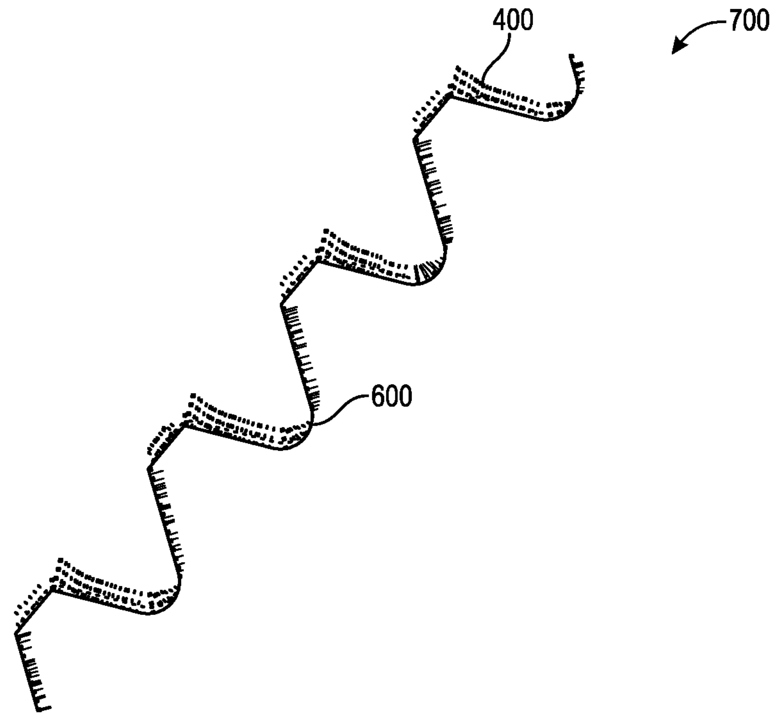


**FIG. 7**

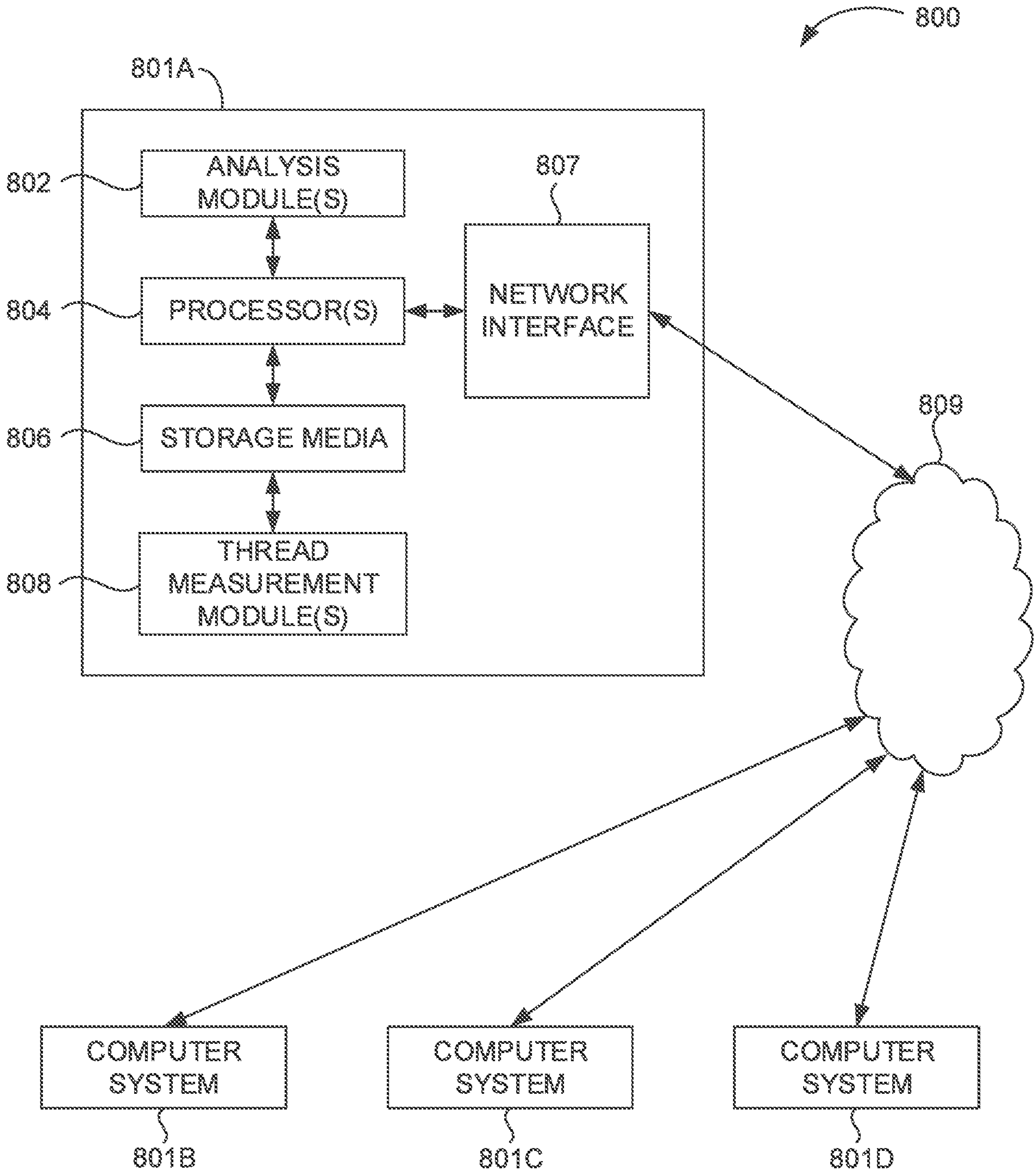
800
801A
802
ANALYSIS MODULE(S)
804
PROCESSOR(S)
806
STORAGE MEDIA
808
THREAD MEASUREMENT MODULE(S)
807
NETWORK INTERFACE
809
COMPUTER SYSTEM
801B
COMPUTER SYSTEM
801C
COMPUTER SYSTEM
801D

FIG. 8

**INTERNATIONAL SEARCH REPORT**

International application No.
**PCT/US2020/032557**

**A. CLASSIFICATION OF SUBJECT MATTER**

**G01B 11/24(2006.01)i**

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 11/24; F21V 8/00; G01B 1/00; G01B 11/04; G01B 11/22; G01B 3/48; G06F 15/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: thread, pipe, sensor, insepction, actuator

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | US 2013-0247398 A1 (DURIVAULT et al.) 26 September 2013<br>paragraph [0032]; and claims 18, 32-33 | 1-20 |
| Y | US 2011-0295550 A1 (BONADEO et al.) 01 December 2011<br>paragraphs [0065]-[0078]; claim 10; and figure 18 | 1-20 |
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| A | KR 10-1675467 B1 (SEOUL METAL CO., LTD.) 14 November 2016<br>claim 1; and figures 1-8 | 1-20 |

☐ 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
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"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 | Date of mailing of the international search report |
|---|---|
| 11 August 2020 (11.08.2020) | **12 August 2020 (12.08.2020)** |


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