



(43) International Publication Date
20 February 2014 (20.02.2014)

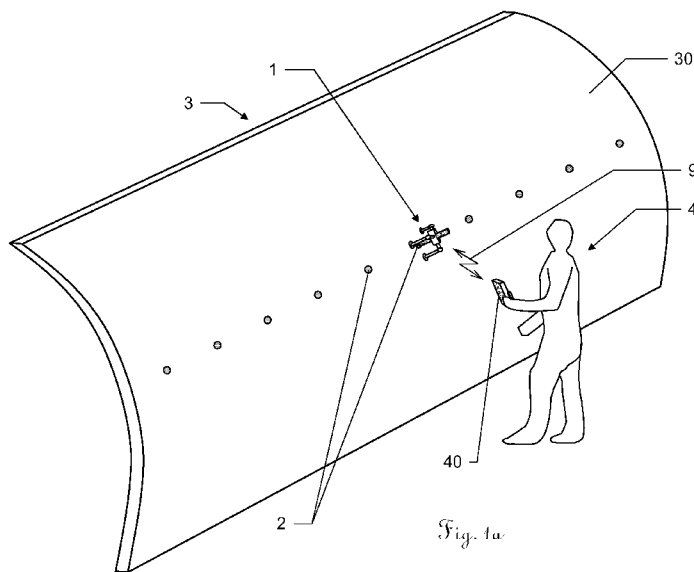
- (51) International Patent Classification:
G01B 11/00 (2006.01) *G01B 21/04* (2006.01)
- (21) International Application Number:
PCT/EP2013/066912
- (22) International Filing Date:
13 August 2013 (13.08.2013)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
12180720.0 16 August 2012 (16.08.2012) EP
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- (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CL, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— with international search report (Art. 21(3))

(54) Title: METHOD AND SYSTEM FOR DETERMINING SPATIAL COORDINATES WITH A MOBILE COORDINATE MEASURING MACHINE



(57) Abstract: The invention pertains to a method for determining at least one spatial coordinate of a measurement point of a local structure (2,2') of an object (3), providing a mobile coordinate measuring machine (1), the method comprising at least placing the mobile coordinate measuring machine (1) on a surface (30) of the object (3) to be measured, approaching the measurement point with a sensing head (21,26), and determining at least one spatial coordinate of the at least one measurement point, characterized by establishing a defined spatial relation between the coordinate measuring machine (1) and the local structure (2,2') wherein the defined spatial relation is established by means of a mechanical fixation of the coordinate measuring machine (1) to the object (3), and/or a continuous determination of position and orientation of the coordinate measuring machine (1) relative to the object (3). The invention furthermore pertains to a mobile coordinate measuring machine (1) and a computer programme product for execution of said method.

WO 2014/026989 A1

**Method and System for
Determining Spatial Coordinates with a
Mobile Coordinate Measuring Machine**

The present invention relates to a method and a system for
5 measuring local structures, such as the inner wall of a
cavity of an object, in particular for measuring a
cylindrical boring of a workpiece, making use of a mobile,
portable coordinate measuring machine (CMM).

10 It is common practice to inspect workpieces subsequent to
production on a coordinate positioning apparatus, such as a
coordinate measuring machine having a movable probe head
within a working volume of the machine.

In a conventional 3-D measurement machine, the probe head is
supported for movement along three mutually perpendicular
15 axes (in directions X, Y and Z). Thereby, the probe head can
be guided to any arbitrary point within the working volume
of the measuring device.

Stationary measuring devices for measuring local structures
such as cylindrical cavities are known from prior art. These
20 machines allow accurate measurement of local structures of
an object. However, the measuring rate of measuring machines
of this kind is conventionally very low. Additionally, this
type of coordinate measuring machine usually can only be
used stationarily - the respective object to be measured has
25 to be brought to the measuring machine. These machines,
therefore, cannot be used for measuring structures of
particularly large objects, for example boreholes in
aircraft assembly parts, such as the fuselage or the wings.

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A hand held coordinate measuring device for the measuring of cavities is disclosed, for example, in EP 1 797 813. This document describes an optical measuring device for measuring the inner wall of a cavity formed in an object according to the confocal imaging principle. A weakness of the described solution is the rather imprecise positioning and orientation of the hand held device during the measurement. Though adaptation means with mechanical coupling elements for a defined positioning of the device during the measurement are disclosed, these cannot eliminate measurement errors caused by holes not orthogonal to the surface of the object or unevenly shaped surfaces.

It is therefore an object of the present invention to provide an improved mobile coordinate measuring machine and an improved method and system for determining spatial coordinates of measurement points of local structures of a large workpiece with higher accuracy.

It is a particular object of the present invention to provide such a mobile coordinate measuring machine and method for determining spatial coordinates of measurement points of a cavity, such as a borehole.

At least one of these objects is achieved by the method for determining spatial coordinates according to Claim 1, the coordinate measuring system according to Claim 5, the mobile coordinate measuring machine according to Claim 14 and/or the dependent claims of the present invention.

According to the present invention, a method for determining at least one spatial coordinate of a measurement point of a local structure of an object to be measured comprises the steps of

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- situating or placing a mobile coordinate measuring machine on a surface of the object to be measured,
- establishing a defined spatial relation between the coordinate measuring machine and the local structure,
- 5 • approaching the measurement point with a sensing head of the mobile coordinate measuring machine, and
- determining at least one spatial coordinate of the at least one measurement point.

The defined spatial relation according to the invention is established either by means of a mechanical fixation of the
10 coordinate measuring machine to the object, or a continuous determination of a position and orientation of the coordinate measuring machine - either relative to the object or together with the object relative to a common reference
15 coordinate system.

Therefore, a system with a mobile, portable coordinate measuring machine (CMM) according to the invention which is designed for determining at least one spatial coordinate of a measurement point of a local structure of an object
20 comprises means for fixation of the CMM to a surface of an object and/or means for dynamical determination of the CMM's position and orientation with respect to the object or a reference coordinate system.

According to the invention the mobile CMM comprises a base,
25 sensor means for measuring the measurement point and generating measurement data, and a drive mechanism, adapted to drive the sensor means or parts thereof, in particular a sensing head, relative to the base for approaching the measurement point. According to the invention, during the
30 measuring a position and orientation of the base or the sensor means is defined relative to the local structure or

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relative to a reference coordinate system, the latter in particular by means of an external surveying instrument. The sensor means, for instance, can be tactile sensor means or, preferably, optical sensor means.

5 Preferably, the mobile CMM comprises placing means, which allow placing or situating the mobile CMM on a surface of the object, in particular in a standing or suspended manner, in such a way that the CMM remains in this position autonomously. In a preferred embodiment the placing means
10 are built as standing means enabling (under the influence of gravity) the mobile CMM to stand on the surface autonomously, for instance on at least three stands (or feet), in particular having a non-slip texture. In another preferred embodiment the placing means are built as
15 suspending means enabling the mobile CMM to be suspended below the surface.

Advantageously, the standing or suspending means have connecting means for connecting the standing or suspending means fixedly to the surface of the object, so that the
20 mobile CMM is enabled to stand on vertically oriented surfaces or even to hang headfirst below the surface. In particular, the fixed connection is achieved by means of magnets or a vacuum, for example with electromagnets or permanent magnets, suction pads or vacuum pumps. Also other
25 means for fixedly connecting the standing or suspension means to the object are possible: For instance, the fixed connection can be established by adhesive bonding, such as cement, glue, one- or two-component-adhesives or permanently tacky adhesives, or - if the CMM is built very light
30 weighted - by connecting means similar to that of Gecko feet through Van der Waals forces. The connecting means can also be designed for a defined mechanical connection with certain

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features of the object. These features e.g. could be screw threads, pins or rails so that the mechanical connection could be achieved by means of screws or rail bonds. Also, when measuring a local structure of an object, the
5 connecting means even could use this very structure, for instance a borehole, for establishing a fixed and defined connection to the object.

Furthermore advantageously, the connecting means are designed to provide a defined spatial relation between the
10 CMM and the local structure. In particular the accuracy of the spatial relation is at least as high as that of the measurement of the sensor means, i.e. the tolerance of the defined spatial relation is smaller than the tolerance of the determining of the at least one spatial coordinate of
15 the at least one measurement point, in particular at least two orders of magnitude smaller.

Preferably, the CMM comprises damping means for active compensation or absorption of vibrations that occur in the object or in the CMM, for instance due to a movement of the
20 sensing head. Said damping means, which e.g. can comprise piezo actuators, as such are known from prior art.

For a preferred embodiment the local structure is a cavity of an object, in particular a borehole, and the mobile coordinate measuring machine is designed for determining at
25 least one spatial coordinate of a measurement point inside the cavity.

In another preferred embodiment the mobile CMM comprises optical sensor means with a stylus for approaching measurement points, the sensor means having emitter means
30 and receiver means for determining spatial coordinates of

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the measurement points. Preferably, the base comprises a drive mechanism, adapted to rotate the stylus and to drive the stylus in such a way that it is capable to move relative to the base and to be introduced into a hole of the object.

5 Preferably, a first measurement beam is emitted perpendicular to the rotational axis in order to measure the distances to the hole's outer wall.

In order to measure a diameter of the hole, the stylus of the mobile coordinate measuring machine advantageously has

10 to be introduced into the hole along the hole's central axis, so that the measurement beam measures in a plane orthogonal to the central axis. Otherwise, the diameters of a measured section of a circular hole would be perceived as an ellipse. Also, the stylus must be positioned in or at

15 least near the middle of the hole.

Therefore, the mobile CMM in an advantageous embodiment comprises positioning means for dynamical autonomous positioning of the base relative to the local structure.

When the mobile coordinate measuring machine is placed on

20 the object's surface on top of a local structure, such as a hole, accurate positioning is crucial for the provision of accurate measurement data and the reduction of recalculation efforts. If the object's surface is not absolutely flat - for instance being curved or irregular - the vertical axis

25 of the device will not be parallel to the central axis of the hole.

A mechanical positioning will never be absolutely perfect, so that in a preferred embodiment additional software compensation is provided, which for instance can convert

30 elliptic measurements into circular measurements. In order to minimize recalculation efforts, the probe head on the one

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hand needs to be driven basically parallel to the central axis and on the other hand with a minimized distance to the central axis.

Therefore, advantageously, positioning means with a
5 positioning functionality are provided that are designed in such a way that the base can be positioned centrally over the hole so that the vertical axis of the device - at least approximately - is made coaxial with a central axis of the hole, and the stylus can be introduced into the hole along
10 the central axis. In particular, the positioning means are designed for tilting the base of the mobile CMM and moving it along the directions X and Y.

In a preferred embodiment the positioning means are designed as articulated legs, the legs connecting the base to the
15 stands and comprising each at least two members being movable with respect to each other, to the base and/or to the stands. The movable members have encoder means to detect a position and/or orientation of the single members with respect to each other, to the base and/or to the stands.
20 Articulated legs as such are known from prior art and, for instance, disclosed in EP 2 016 473.

In another preferred embodiment the base comprises hole centring means for centring the base over the hole. The hole centring means comprises at least three centring members
25 attached to the base and designed for entering the hole and then expanding towards the outside homogeneously for applying pressure to the outer wall of the hole in order to move the base in a position centrally over the middle of the hole so that the stylus can be introduced along a central
30 axis of the hole.

Preferably, the mobile CMM uses a laser measurement beam with a frequency-modulated, i.e. tuneable laser source and with an interferometric measuring principle. Such a measuring principle, for instance, is disclosed in the document EP 2 185 890. The measurements then are effected in the frequency level. Deviations from perpendicular incidence of the laser beam on the surface in the distance measurement are taken into account algorithmically or with control during probing of the optical probe head as a measuring sensor. For the intended field of use of the optical system in a coordinate measuring device with free-beam measurements of a few centimetres using compact probe heads having diameters in the region of ruby spheres, the abovementioned interferometric method is preferable. In this frequency-modulated interferometry, a source which should permit broadband tuning in a short time is used. Moreover, narrow-band characteristics with a coherence length of a few centimetres are required. The tuning of the source is referenced via a calibration interferometer, the length of which being known very precisely. In order to eliminate or reduce environmental influences, such as, for example, temperature changes or vibrations originating from the measuring machine, in the measuring interferometer, the reference surface is placed on a surface as far as possible within the optical probe head, or such a surface is used as the reference surface so that a common path interferometer is realized. It is advantageous here if a sufficient quantity of light is input from this surface back into a monomodal fibre, whereas other optical transitions as far as possible should not feed back the signal into this fibre. The laser source is preferably in the form of a fibre ring laser having an optical semiconductor amplifier as an amplifying medium and a tuneable filter element. The

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tuneable element may be formed, for example, as a Fabry-Perot filter or as an acoustically tuneable fibre Bragg grating. Further elements are optical couplers or insulators, the use and integration of which in such a system are known to the person skilled in the art. If higher repetition rates are desired in the measurement, the fibre ring laser can be extended by a fibre length of several kilometres, the repetition rate corresponding to the inverse of the transit time of the light in the fibre ring.

As with coordinate measuring machines known from prior art, for calibration of the mobile coordinate measuring machine according to the invention a standardized calibration object can be used. If the CMM of the present invention is adapted for measuring drill holes, a calibration object formed as a hollow cylinder can be used. At least one, but preferably a multitude of different calibration objects, i.e. hollow cylinders of different diameters, should be used for calibration. With this calibration process reproducible measurement errors, such as errors of measuring linearity, the beam orientation or a wobble, can be compensated.

In a preferred embodiment the sensor means is designed for simultaneously emitting more than one measurement beam. For instance, in the case of measuring inside a hole, two measurement beams emitted by the stylus in opposite directions (with an angle of 180°) can be used to solve the wobble problem. With two measurement beams emitted parallel to each other, it is possible to detect if the stylus' rotational axis is parallel to the hole's central axis. An additional vertical measurement beam can detect the distance to the bottom of the hole and thus the hole's depth. With a multitude of measurement beams, i.e. six or more measurement beams, emitted in different directions at the same level, a

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complete rotation of the stylus is not necessary, but only a rotation of 360° divided by the number of measurement beams. With a large enough number of measurement beams a rotation of the stylus would be completely dispensable.

5 In a preferred embodiment the stylus or the whole sensor means unit is exchangeable. Thus, with the same CMM different measurement tasks could be performed, for example by optical means as well as by tactile means. Alternatively, the stylus can be built adaptable. For instance, with an
10 adaptable stylus the user can choose whether the direction of a second measurement beam should be parallel to the first measurement beam or orthogonal.

Preferably the base can comprise scanner means for scanning the surface of the object or the feature to be measured. The
15 scanner means in particular comprise a line laser rotatable around the same rotary axis as the stylus. The scanning means can be used for measuring certain surface features, which cannot be measured by the stylus. This way production errors and damages of the surface and its features can be
20 detected. For instance, a head of a countersunk bolt and its alignment with the surface of the object can be measured with a diagonally aligned laser line beam. A gap between the bolt head and the surface of the countersunk hole - being an indicator for a badly inserted bolt - then can be detected.
25 Also, the scanner means can be used to measure an alignment of the CMM with respect to the surface or a feature.

In a preferred embodiment the mobile coordinate measuring machine comprises storing and calculation means, in particular for storing the measured data and/or measuring
30 programmes and for calculating compensations for known reproducible errors.

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Preferably, the mobile coordinate measuring machine comprises wireless communication means for exchanging data with external devices, such as hand held display and control devices, local or remote computers, or peripheral surveying
5 equipment. The wireless communication means for example can be based on Bluetooth or Wireless Local Area Network connections.

In a preferred embodiment the mobile coordinate measuring machine comprises active and/or passive means that enable an
10 accurate determination of its position and orientation relative to the object or with respect to a reference coordinate system.

Active means can be internal surveying means, allowing to actively determine a position and orientation of the CMM
15 relative to the object, for instance relative to a local structure to be measured or relative to visible features on the object. Also, the internal surveying means could determine a position and orientation of the CMM relative to external surveying means that determines a relative position
20 and orientation of the object.

Additionally or alternatively, also passive means can be provided. For instance, the passive means can be visible features that are detectable by external surveying
equipment, such as stereo camera systems or laser trackers.
25 The detection of the visible features enables a detection of the position and orientation of the mobile coordinate measuring machine relative to the surveying equipment, preferably in six degrees of freedom (6-DoF). For instance, this can be achieved with a camera or a plurality of
30 cameras, i.e. a stereo camera system, or a laser tracker with an additional camera. A laser tracker system of this

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kind is, for instance, disclosed in the European patent application with the filing number 11192216.7. The external surveying equipment can also be designed to determine a position and orientation of the object and, thus, the local structure. For this purpose, detectable visible features could also be placed fixedly on the surface of the object.

In a further preferred embodiment the mobile coordinate measuring machine is capable of autonomously detecting local structures, such as holes, on the surface of an object, for instance by means of a camera. Alternatively or additionally, the position of the local structures can be provided by pre-stored CAD-data or by an external camera system. The mobile coordinate measuring machine preferably also comprises an autonomous movement unit to autonomously move over the surface to a detected local structure, to autonomously measure the local structure, particularly after having positioned itself relative to the structure - e.g. centrally over a hole - and then to autonomously move on to the next local structure. The standing means can comprise wheels and/or rolls that can be driveable by motor means to move the mobile CMM on the surface. These wheels and/or rolls also can be retractable in order to ensure a reliable and defined stand. Alternatively, the autonomous movement unit comprises a walking functionality in which legs of the mobile CMM can be moved in such a way that the mobile coordinate measuring machine can be repositioned by "walking" on the surface to a distant position, in particular to a detected local structure. Also, means for driving the CMM along a rail can be provided, the rail being a part of the object - temporarily or permanently - or of a structure temporarily attached to the object and connecting local structures to be measured.

The invention in the following will be described in detail by referring to exemplary embodiments that are accompanied by figures, in which:

5 Figs. 1a-b show a mobile CMM according to the invention placed on a large object;

Figs. 2a-c show an exemplary embodiment of a mobile CMM according to the invention in a sectional view;

10 Figs. 3a-c show two preferred embodiments of the positioning means of a mobile CMM according to the invention;

Figs. 4a-b show a first embodiment of a stylus of a mobile CMM according to the invention with optical sensor means;

15 Figs. 5a-c show further embodiments of a stylus of a mobile CMM according to the invention with optical sensor means;

Figs. 6a-b show an embodiments of a stylus of a mobile CMM according to the invention with tactile sensor means;

20 Figs. 7a-b show two preferred embodiments of the system according to the invention, the CMM having visual features for determining its position and orientation; and

25 Figs. 8a-b show two more embodiments of the the system according to the invention, the CMM and the object having visual features for determining the position and orientation of the CMM relative to the surface.

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In Figure 1a a mobile CMM 1 is depicted which has been placed on a surface 30 of a large object 3 - here a part of a fuselage - by a user 4, the object 3 having a multitude of drill holes 2. The mobile CMM 1 is centred over one of the
5 drill holes 2, autonomously measuring the inner surfaces of the drill hole 2.

The measurement results are sent to an external display and control device 40 by means of a wireless connection 9 and displayed to the user 4. As the mobile CMM 1 is standing on
10 the surface 30 by itself, the user 4 has his hands free during the measuring process. The user 4 can also control functions of the mobile CMM 1 with the external display and control device 40 by means of a wireless connection 9.

In Figure 1b, additionally, a surveying instrument is
15 provided for detecting structures of the large object 3, determining the position of the holes 2 of the object 3 and/or determining the actual position and orientation of the mobile CMM 1 relative to the nearest hole 2 or to a reference coordinate system. In this example, the surveying
20 instrument is as a laser tracker device 6. For evaluation, the measurement results of the mobile CMM 1 and the laser tracker device 6 are sent to an external computer 45 by means of wireless connection 9,9'. Obviously, the wireless connections 9,9' could also be replaced by wire-based
25 connections.

In Figures 2a to 2c a first embodiment of a mobile CMM 1 according to the invention is depicted in a schematic sectional view.

Figure 2a shows the mobile CMM 1 placed on the surface 30 of
30 a workpiece and positioned over a drilling hole 2 to be

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measured. The surface 30 around the hole 2 is even and the central axis 8 of the hole 2 is orthogonal to the surface 30. The mobile CMM 1 comprises a base 10 and a primary vertical member 20 being movable to the base 10 along a rotational axis 7 by means of a drive mechanism 12. 5 A stylus 21 is attached to a secondary vertical member 22 which is attached to the primary vertical member 20 - the secondary vertical member 22 is optional, the stylus 21 could also be attached directly to the vertical member 20. 10 The stylus 21 and the vertical members 20,22 are movable in a telescopic or extendible manner with respect to each other along the rotational axis 7 so that the stylus 21 can be introduced deeply into the hole 2. By means of the drive mechanism 12 the vertical member 20 together with the 15 stylus 21 can be rotated around the rotational axis 7.

Emitter means 23 and receiver means 24 are provided for emitting two measurement beams, in particular laser beams, through the stylus 21 into the hole 2 and receiving reflected light for the deduction of measurement point coordinate 20 data. The stylus is adapted for guiding the emitted measurement beams 82,83 into the hole 2 by means of optical elements, such as mirrors, and/or by means of optical fibres (not shown). A first measurement beam 83 is emitted orthogonally to the rotational axis 7 against a wall 28 of 25 the hole 2. A vertical measurement beam 82 is emitted towards the bottom of the hole 2. Reflections of the beams are then guided through the stylus 21 to the receiver means 24 for evaluation and deduction of distance values. The evaluation, for instance, can be based on interferometric methods. 30

The CMM 1 rests on the surface 30 by standing means 18. In this embodiment the standing means 18 are built as a

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multitude of (at least three) stands that are connected to the base 10 by means of legs. The legs comprise leg members 15,17 that are movable with respect to each other, the base 10 and/or the stands 18. The stands 18 comprise
5 connecting means 19, for instance magnets or suction caps, for secure connection of the stands 18 with the surface 30. In this figure, the surface 30 around the hole 2 is even, so that the rotational axis 7 equals the central axis 8 of the hole 2.

10 The base 10 comprises rechargeable battery means 11 as a source of electric energy for the other components.

In Figures 2b and 2c the same CMM 1 of Figure 2a is shown, the surface 30 on which the CMM 1 is placed now being uneven and irregular, as it is not entirely orthogonal to the
15 central axis 8 of the hole 2.

The CMM 1 shown in Figure 2b due to this irregularity of the surface 30 is not positioned correctly. Thus, the rotational axis 7 of the CMM 1 differs from the central axis 8 of the hole 2. Based on distance values from the hole 2 received
20 through measurements with the measurement beams 82,83 calculation means of the CMM 1 can calculate an angular and positional dislocation between the rotational axis 7 and the central axis 8 and start a positioning procedure by giving positioning commands to positioning means of the CMM 1.
25 Also, additional perception means (not shown) on the base 10, such as a camera pointed towards the hole 2, could provide data for the calculation of a dislocation of the CMM 1 - even before the stylus 21 is introduced into the hole 2.

30 In Figure 2c the CMM 1 is shown after having been positioned

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correctly over the hole 2. The positioning means 15',17' of one of the legs of the mobile CMM 1 have been rearranged with respect to the situation depicted in Figure 2b in order to position the CMM 1, so that the rotational axis 7 of the stylus 21 now coincides with the hole's central axis 8.

In Figures 3a to 3c two further exemplary embodiments of a mobile CMM 1 according to the invention are depicted.

Figure 3a shows a second embodiment of the mobile CMM 1 according to the invention. It is placed on the surface 30 of an object to be measured. The CMM 1 comprises a base 10 which is centred over a hole 2. A vertical member 20 is provided at the base 10 being movable along a rotational axis with respect to the base 10. A secondary vertical member 22 is provided on the vertical member 20 and introduced into the hole 2. A stylus (not shown) is provided on the secondary vertical member 22 and rotatable around the rotational axis. The CMM 1 stands autonomously on the surface 30 by means of three stands 18 connected to the base by three legs, each having three leg members 15,16,17 being movable with respect to another and having encoder means (not shown) for detecting a position and/or orientation of the single members 15,16,17 with respect to each other, to the base 10 and/or to the stands 18. In this embodiment the three leg members 15,16,17 of each of the three legs are designed as positioning means of the CMM 1.

Figures 3b and 3c show a third embodiment of the mobile CMM 1 according to the invention. As a difference to the second embodiment of Figure 3a this embodiment comprises hole centring means 25 for positioning of the CMM 1. These can be provided as positioning means alternatively or additionally to the leg members 15,16,17. The hole centring

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means 25 comprises at least three centring members (only two are visible due to the perspective view) attached to the base 10 and designed for entering the hole 2 and then expanding towards the outside homogeneously for applying
5 pressure to the outer wall of the hole 2 in order to move the base 10 in a position centrally over the middle of the hole 2.

In Figure 3b the hole centring means 25 are shown in their initial position, partially retracted into the base 10. As
10 the mobile CMM 1 is not positioned centrally over the hole 2, the rotational axis of the CMM 1 differs from the central axis of the hole 2. Based on distance values from measurements inside the hole 2 calculation means of the CMM 1 can calculate an angular and/or positional dislocation
15 between the rotational axis and the central axis and start a positioning procedure by giving positioning commands to positioning means of the CMM 1. Also, additional perception means (not shown) on the base 10, such as a camera pointed towards the hole 2, could provide data for the calculation
20 of a dislocation of the CMM 1 - even before the stylus is introduced into the hole 2.

In Figure 3c the positioning procedure of the CMM 1 using the hole centring means 25 is illustrated by arrows indicating movement directions. First, the hole centring
25 means 25 are retracted from the base 10 towards the surface 30 and, thus, partially enter the hole 2 (vertical arrows). Then the members of the hole centring means 25 move towards the outer walls of the hole 2 (diagonal arrows). As the CMM 1 is not centred, the members do not reach the wall
30 at the same time. The member that reaches the wall first applies a pressure to the outer wall of the hole 2, thus pushing the CMM 1 into the opposite direction (horizontal

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arrows). The stands 18 for easier movement on the surface 30 can comprise wheels or rollers which also can be retractable in the stands 18. The members of the hole centring means 25 move homogenously, so that in the end the base 10 is positioned centrally over the hole 2 so that the stylus can be introduced into the hole 2 along the central axis of the hole 2.

In Figures 4a and 4b an exemplary embodiment of a stylus according to the invention is depicted being introduced into a hole 2 of a workpiece. The stylus 21 is adapted to emit two measurement beams 82,83 into the hole 2 and to rotate around a rotational axis 7. The stylus 21 is attached to a secondary vertical member 22 which is attached to a primary vertical member 20, all of which being movable in a telescopic or extendible manner with respect to each other - and to a base of the CMM (not shown) - along the rotational axis 7. The stylus is introduced into a hole 2 having an outer wall 28 and a bottom 29.

In Figure 4a the rotational axis 7 equals the central axis 8 of the hole 2. This is the ideal arrangement of the two axes 7,8 for the measurement of the hole 2, as no recalculation of the measurement data has to be carried out. The emitting segment of the stylus 21 is positioned centrally in the hole 2 and the first measurement beam 83 is emitted in an angle of 90° to the hole's central axis 8. While continuously or repeatedly emitting the first measurement beam 83 the stylus 21 is rotated around the central axis 7, thus emitting the first measurement beam 83 to a plurality of measurement points on a wall of the hole 2.

In Figure 4b the rotational axis 7 differs from the central axis 8 of the hole 2. The distances measured with the

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rotating first measuring beam 83 will, thus, lead to the false appearance of an elliptic hole. Based on measurements at different depths of the hole 2 calculation means of the CMM (not shown) can calculate a deviation of the rotational axis 7 from the hole's central axis 8 and have positioning means of the CMM (not shown) to reposition the CMM.

In Figures 5a to 5c three further exemplary embodiments of styluses of a mobile CMM 1 according to the invention are depicted. Each stylus 21 is attached to a secondary vertical member 22 which is attached to a primary vertical member 20, at least partially being introduced into a hole 2. The holes 2 have an outer wall 28 and a bottom 29.

In Figure 5a the stylus 21 is adapted to emit three measurement beams 82,83,84 and to rotate around a rotational axis 7. As a difference to the embodiment depicted in Figure 4a an additional measurement beam 84 is emitted parallel to the first measurement beam 83. This parallel measurement beam 84 is emitted at a different depth of the hole 2, but parallel and in the same direction as the first measurement beam 83. With these two measurement beams 83,84 emitted parallel to each other, it is possible to detect if the rotational axis 7 is parallel to the hole's central axis 8.

In Figure 5b the stylus 21 is adapted to emit two measurement beams 83,85 in opposite directions (with an angle of 180°) and to rotate around a rotational axis 7. With the two measurement beams 83,85 emitted in opposite directions a wobble (shaking, trembling, vibration, etc.) of the stylus 21 can easily be detected.

In Figure 5c the stylus 21 is adapted to emit a multitude of measurement beams 83,85,85a-e. Instead of two measurement

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beams as shown in Figure 5b, a multitude of measurement beams 83,85,85a-e is emitted at the same level of the stylus 21 into different directions. Here, six measurement beams are shown, but of course even more are possible. With
5 this multitude of measurement beams 83,85,85a-e emitted in various different directions at the same level, no complete rotation of the stylus 21 is necessary for complete measuring of the hole's outer wall 28 but only a rotation of 360° divided by the number of measurement beams. Here with
10 six beams, a swivel of the stylus 21 of 60° forth and back would be sufficient. With a large enough number of measurement beams a rotation of the stylus 21 could also be completely dispensable.

Naturally, the different measurement beams 82-85,85a-e of
15 the depicted exemplary embodiments can be combined with each other. Preferably, the stylus 21 and/or the secondary vertical member 22 can be exchangeable, so that different arrangements of measurement beams 82-85,85a-e can be used on the same CMM 1. Alternatively, the stylus 21 can be
20 adaptable so that the measurement beams 82-85 can be emitted from the same stylus 21 in different directions according to the needed measurement.

The Figures 6a and 6b show another embodiment of the stylus 21 being equipped with a tactile sensing head 26,
25 i.e. a ruby sphere. The primary vertical member 20 is rotatable around the rotational axis 7 and connected with the secondary vertical member 22 by a hinge 27 so that the stylus 21 with the tactile sensing head 26 is tiltable towards the measuring point. The hinge 27 is adjustable
30 manually or, preferably, by actuator means. A position of the hinge 27 can be calibrated automatically by means of an integrated calibration system, particularly comprising a

- 22 -

camera or a tactile system.

In Figure 6a the stylus 21 is depicted measuring a measuring point on the outer wall 28 of a hole 2, the rotational axis 7 equalling the central axis 8 of the hole 2. In Figure 5 6b the stylus 21 is depicted measuring a measuring point on a raised local structure 2' on the surface 30 of the object.

In Figures 7a and 7b two preferable embodiments of a system for determining spatial coordinates of a measurement point of a local structure of an object are depicted, wherein the 10 mobile CMM 1 comprises visible features 50,60 that are built in such a way, that they are identifiable by peripheral surveying means 5,6 so that a position and orientation of the mobile CMM 1 relative to the surveying means 5,6 is derivable.

15 In Figure 7a the surveying means is a stereo camera system 5 having a multiplicity of cameras (or alternatively a single camera), and the visible features are identifiable in an image of the stereo camera system 5. The visible features are an arrangement of passive visible features such as one 20 or more geometrical objects 50 of well defined shape and/or colour. They can also comprise fluorescent or retro reflective surfaces. For example, they can provide contrast faces and/or a known shape or geometry for making them identifiable in the image of the cameras of the stereo 25 camera system 5. The visible features can be naturally occurring features which are visible and identifiable in the image, for example textures, edges, differently coloured sections, etc. They can also be embodied by artificially applied visible features such as markers attached by means 30 of sticking, magnets, adhesion, suction cups, glue, screws, bolts, clamps, etc.

The visible features can also be active light points, for example in form of optical emitters such as light bulbs, LEDs, lasers, fluorescent material, etc. which are emitting continuous or pulsed light. As a single visible feature, in particular of unknown shape and size, is in general not sufficient to determine a spatial reference in five or six degrees of freedom, a set of multiple visible features is used for referencing by the cameras. The mobile CMM 1 can for a example be equipped with an arrangement of multiple LEDs as active visible features, wherein the arrangement is built in such a way that its position and orientation can be determined uniquely, for example assisted by blinking codes, different colours, etc.

In Figure 7b the surveying means is a laser tracker system having a laser tracker and a camera. The visible features are built as a measuring aid 60 comprising a retro-reflector traceable by the laser tracker for measuring a position of the mobile CMM 1 and other features, in particular active light points that are identifiable in the image of the camera for deriving an orientation of the mobile CMM 1.

The depicted laser tracker 6 by means of a laser beam measures the distance to the retro-reflector of the measuring aid 60. The depicted measuring aid 60 furthermore comprises a multitude of target markers, for instance built as reflecting or active light points which are arranged in a known configuration with respect to the base 10 of the CMM 1. The laser tracker 6 comprises a measuring camera, in particular built as a focusable camera system with variable zoom, for detection of the target markers of the measuring aid 60. Based on the detected positions of the target markers the orientation of the measuring aid 60 and, thus, of the CMM 1 is derivable.

Figures 8a and 8b depict two further exemplary embodiments of the system of Figures 7a-b. These illustrate how a defined spatial relation between the mobile CMM 1 and the local structure 2 can be established through dynamical determination of a position and orientation of the CMM 1 and of the object 3 with respect to a common coordinate system. Surveying means 5,6,6' are provided to detect visible features 50,60 on the CMM 1 as well as visible features 53,63 on the object 3.

10 In Figure 8a the surveying means is a stereo camera system 5 and the visible features are built as arrangements 50,53 of passive visible features such as one or more geometrical objects of well defined shape and/or colour (as described in Figure 7a). A first arrangement of geometrical objects 50 is placed on the CMM 1, and a second arrangement of geometrical objects 53 is placed on the surface 30 of the object 3. The stereo camera system 5 is designed for dynamically detecting a position and orientation of the CMM 1 as well as of the object 3. Thus, a spatial relation between the CMM 1 and the local structure 2 of the object 3 is determinable with high precision.

In Figure 8b the surveying means comprises two laser tracker systems 6,6' and the visible features are built as measuring aids 60,63 (as described in Figure 7b) comprising a retro-reflector traceable by the laser trackers for measuring a position of the mobile CMM 1 and the object 3, respectively, and other features, in particular active light points, that are identifiable in the image of the cameras for deriving an orientation of the mobile CMM 1 and of the object 3, respectively. The first laser tracker system 6 is designed for dynamically detecting a position and orientation of the CMM 1, and the second laser tracker system 6' is designed

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for dynamically detecting a position and orientation of the object 3. Both laser tracker systems 6,6' are referenced in a common coordinate system, so that a spatial relation between the CMM 1 and the local structure 2 of the object 3 is determinable with high precision.

All visible features 50,53,60,63 shown in the Figures 7a-b and 8a-b can be attached to the CMM 1 or the surface 30, respectively, by means of sticking, magnets, adhesion, suction cups, glue, screws, bolts, clamps, etc. Preferably, the accuracy of the spatial relation between the visible features 50,53,60,63 and the CMM 1 or the surface 30, respectively, is at least as high as that of the measurement of the sensor means.

Particularly, the tolerance of the defined spatial relation between the CMM 1 and the local structure 2 to be measured is smaller than a characteristic resolution of the applied method for determining spatial coordinates of the measurement points of the local structure 2, in particular at least two decimal orders of magnitude smaller. As a result, possible imprecision in establishing the spatial relation is not relevant when compared with the typical measurement errors of the CMM 1. If the tolerance of the defined spatial relation is at least two orders of magnitude smaller, occurring errors are so small that they are generally not recognizable in the "random noise" of the measurement inaccuracies of the CMM 1. For example, if the measurement of the CMM 1 is accurate to a millimeter, the accuracy tolerance of the spatial relation would have to be smaller than that, e.g. a tenth of a millimeter (one order of magnitude smaller) or a hundredth of a millimeter (two orders of magnitude smaller).

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Although the invention is illustrated above, partly with reference to some preferred embodiments, it must be understood that numerous modifications and combinations of different features of the embodiments can be made. All of
5 these modifications lie within the scope of the appended claims.

Patent Claims

1. Method for determining at least one spatial coordinate of a measurement point of a local structure (2,2') of an object (3), providing a mobile coordinate measuring machine (1), the method comprising at least
- 5
- placing the mobile coordinate measuring machine (1) on a surface (30) of the object (3) to be measured,
 - approaching the measurement point with a sensing head (21,26), and
 - 10 • determining at least one spatial coordinate of the at least one measurement point,
- characterized by**
- establishing a defined spatial relation between the coordinate measuring machine (1) and the local
- 15 structure (2,2'), wherein the defined spatial relation is established by means of
- a mechanical fixation of the coordinate measuring machine (1) to the object (3), and/or
 - a continuous determination of position and
 - 20 orientation of the coordinate measuring machine (1) relative to the object (3).
2. Method according to Claim 1,
- characterized by**
- positioning the mobile coordinate measuring machine (1)
- 25 relative to the local structure (2,2') and maintaining the position, in particular
- fully autonomously by positioning means (15,16,17,25) of the mobile coordinate measuring machine (1) and/or
 - in such a way that a position and orientation of the
 - 30 base (10) and/or the sensor means is continuously

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determined relative to the local structure (2,2')
and/or relative to an external surveying
instrument (5,6).

3. Method according to Claim 1 or Claim 2,

5 **characterized in that**

the local structure is a hole (2), in particular a
borehole, and approaching the measurement point
comprises introducing a stylus (21) of the mobile
coordinate measuring machine (1) into the hole (2), in
10 particular basically along a central axis (8) of the
hole (2).

4. Method according to Claim 3,

characterized in that

15 said determining of at least one spatial coordinate of
the at least one measurement point comprises

- rotating the stylus (21) around a rotational
axis (7),
- emitting a first measurement beam (83) to a plurality
of measurement points on a wall of the hole (2),
- 20 • receiving reflections of the first measurement
beam (83) from the plurality of measurement points,
and
- determining spatial coordinates of the plurality of
measurement points based on the reflections.

25 5. Method according to any of the preceding claims,

characterized in that

the defined spatial relation has a tolerance smaller
than a characteristic resolution of the applied method
for determining the at least one spatial coordinate of
30 the at least one measurement point, in particular at
least two orders of magnitude smaller.

6. Method according to any of the preceding claims,
characterized in that

the position and orientation of the coordinate measuring machine (1) and of the object (3) are determined by at least one external surveying instrument (5,6,6') and/or
5 with respect to a reference coordinate system.

7. Coordinate measuring system for determining at least one spatial coordinate of a measurement point of a local structure (2,2') of an object (3), comprising
10 a mobile coordinate measuring machine (1) designed for being placed on a surface (30) of the object (3) and comprising

- a base (10),
- sensor means for measuring the measurement point and for generating measurement data, comprising a sensing head (21,26), and
15
- a drive mechanism (12), adapted to drive the sensing head (21,26) relative to the base (10) for approaching the measurement point,

20 **characterized by**

means for establishing a defined spatial relation between the mobile coordinate measuring machine (1) and the local structure (2,2'), wherein the defined spatial relation is achieved by means of

- a mechanical fixation of the mobile coordinate measuring machine (1) to the object (3), and/or
25
- a continuous determination of a position and orientation of the coordinate measuring machine (1) relative to the object (3).

30 8. Coordinate measuring system according to Claim 7,
characterized in that

the means for establishing the defined spatial relation have a tolerance smaller than a tolerance of the measurement of the sensor means, in particular at least two orders of magnitude smaller.

5 9. Coordinate measuring system according to Claim 7 or Claim 8,

characterized in that

- the coordinate measuring machine (1) comprises
 - alignment determination means, in particular a stereo camera system, for actively determining a position and orientation of the base (10) and/or of the sensor means relative to the local structure (2,2') and/or relative to an external surveying instrument (5,6), and/or
 - 10
 - 15
 - scanner means, in particular a line laser, for scanning the surface (30) of the object (3) or the local structure (2,2'),
 - the sensor means comprise a tactile sensing head (26), in particular a ruby sphere, being tiltable towards a measuring points by means of a hinge (27), and/or
 - 20
 - the sensor means comprise
 - emitter means (23), in particular an LED or a laser diode, for emitting an optical measurement beam,
 - 25
 - receiver means (24), in particular comprising an interferometer, for receiving reflections of the measurement beam, and
 - analyzing means for generating the measurement data based on the reflections, wherein spatial
 - 30

coordinates of a measurement point are derivable from the measurement data.

10. Coordinate measuring system according to any one of Claims 7 to 9,

5 **characterized in that**

the coordinate measuring machine (1) comprises damping means for absorption or compensation of vibrations, in particular comprising piezo actuators.

11. Coordinate measuring system according to any one of Claims 7 to 10,

10

characterized in that

the coordinate measuring machine (1) comprises positioning means (15,16,17,25) for autonomous positioning of the base (10) relative to the local structure (2,2'), the positioning means (15,16,17,25) in particular being designed to position the base (10) relative to the local structure (2,2') according to the measurement data, in particular to centre the base over a central point of the local structure (2,2').

15

12. Coordinate measuring system according to any one of Claims 7 to 11,

20

characterized by

placing means, enabling the coordinate measuring machine (1) to maintain a position at the surface (30)

25

autonomously, particularly comprising

- connecting means (19) for connecting the placing means fixedly to the surface (30), in particular comprising at least an electromagnet, a permanent magnet, a suction pad or a vacuum cup with a vacuum pump, and/or

30

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- standing means (18) for enabling the coordinate measuring machine (1) to stand on the surface (30) autonomously, in particular wherein the standing means (18)
 - 5 • are linked to the base (10) by at least three legs, wherein each leg comprises a set of leg members (15,16,17) as positioning means, wherein the leg members (15,16,17) are movable with respect to another in such a way that the base
10 (10) is positionable relative to the local structure (2,2'), and/or
 - comprise wheels and/or rollers, in particular retractable and/or drivable by motor means.
13. Coordinate measuring system according to any one of
15 Claims 7 to 12,
characterized in that
- it is designed for determining at least one spatial coordinate of a measurement point of a hole (2) of an object (3), in particular a borehole,
20 • the sensing head is a stylus (21) for approaching the measurement point, and
 - the drive mechanism (12) is adapted to rotate the stylus (21) around a rotational axis (7) and to drive the stylus (21) in such a way that the stylus (21) is
25 capable to move relative to the base (10) along the rotational axis (7),
- wherein the stylus (21) is introducible into the hole (2) in such a way that at least one spatial coordinate of a measurement point of the hole (2) is
30 determinable.

14. Coordinate measuring system according to Claim 13,

characterized in that

a first measurement beam (83) is emittable from the stylus (21) orthogonally to the rotational axis (7).

15. Coordinate measuring system according to Claim 14,

5 **characterized in that**

- a second measurement beam (85) is emittable, wherein the first measurement beam (83) and the second measurement beam (85) are emitted into opposite directions, in particular with an angle of 180°,
- 10 • a parallel measurement beam (84) is emittable parallel to the first measurement beam (83), and/or
- a vertical measurement beam (82) is emittable orthogonal to the first measurement beam (83), in particular along the rotational axis (7).

15 16. Coordinate measuring system according to any one of Claims 13 to 15,

characterized in that

the coordinate measuring machine (1) comprises hole centring means (25), comprising at least three centring
20 members designed for entering the hole (2) and expanding towards the outer wall (28) of the hole (2) in order to position the base (10) centrally over the hole (2).

17. Coordinate measuring system according to any one of Claims 7 to 16,

25 **characterized in that**

the coordinate measuring machine (1) comprises visible features (50,60) that are identifiable by external surveying means (5,6) so that a position and orientation of the coordinate measuring machine (1) relative to the
30 surveying means (5,6) is determinable, in particular in six degrees of freedom, in particular wherein

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- the visible features (50,60) are a set of geometrical objects (50) of well defined shape and/or colour, and the surveying means is a camera or a stereo camera system (5), or
- 5 • the visible features (50,60) are a retro-reflector system (60) with a retro-reflector and active or passive lighting means, and the surveying means is a laser tracker (6) having camera means.

18. Coordinate measuring system according to any one of
10 Claims 7 to 17,
characterized by
data transfer means for sending data wireless to an external device and/or receiving data wireless from the external device, the external device in particular being
15 a display and control device (40), a computer (45) or surveying means (5,6).

19. Coordinate measuring system according to any one of
Claims 7 to 18,
characterized by
20 an autonomous detection unit for autonomous detection of local structures (2,2') to be measured on the surface (30) of the object (3), in particular comprising at least one detection camera.

20. Coordinate measuring system according to any one of
25 Claims 7 to 19,
characterized in that
the mobile coordinate measuring machine (1) comprises an autonomous movement unit for autonomous movement on the surface (30), in particular for a movement of the mobile
30 coordinate measuring machine (1) to a detected local structure (2,2').

21. Coordinate measuring machine (1), in particular according to any one of Claims 7 to 20 and adapted for use in the method according to any one of Claims 1 to 6, comprising

- 5
- a base (10),
 - sensor means for measuring the measurement point and for generating measurement data, comprising a sensing head (21,26), and
 - a drive mechanism (12), adapted to drive the sensing
- 10 head (21,26) relative to the base (10) for approaching the measurement point,

characterized by

means for establishing a defined spatial relation with respect to the local structure (2,2').

- 15 22. Computer programme product, having computer-executable instructions for performing the method of one of the Claims 1 to 6, in particular when run on a storing and calculation means of a mobile coordinate measuring machine according to Claim 21 or a mobile coordinate
- 20 measuring system according to one of the Claims 7 to 20.

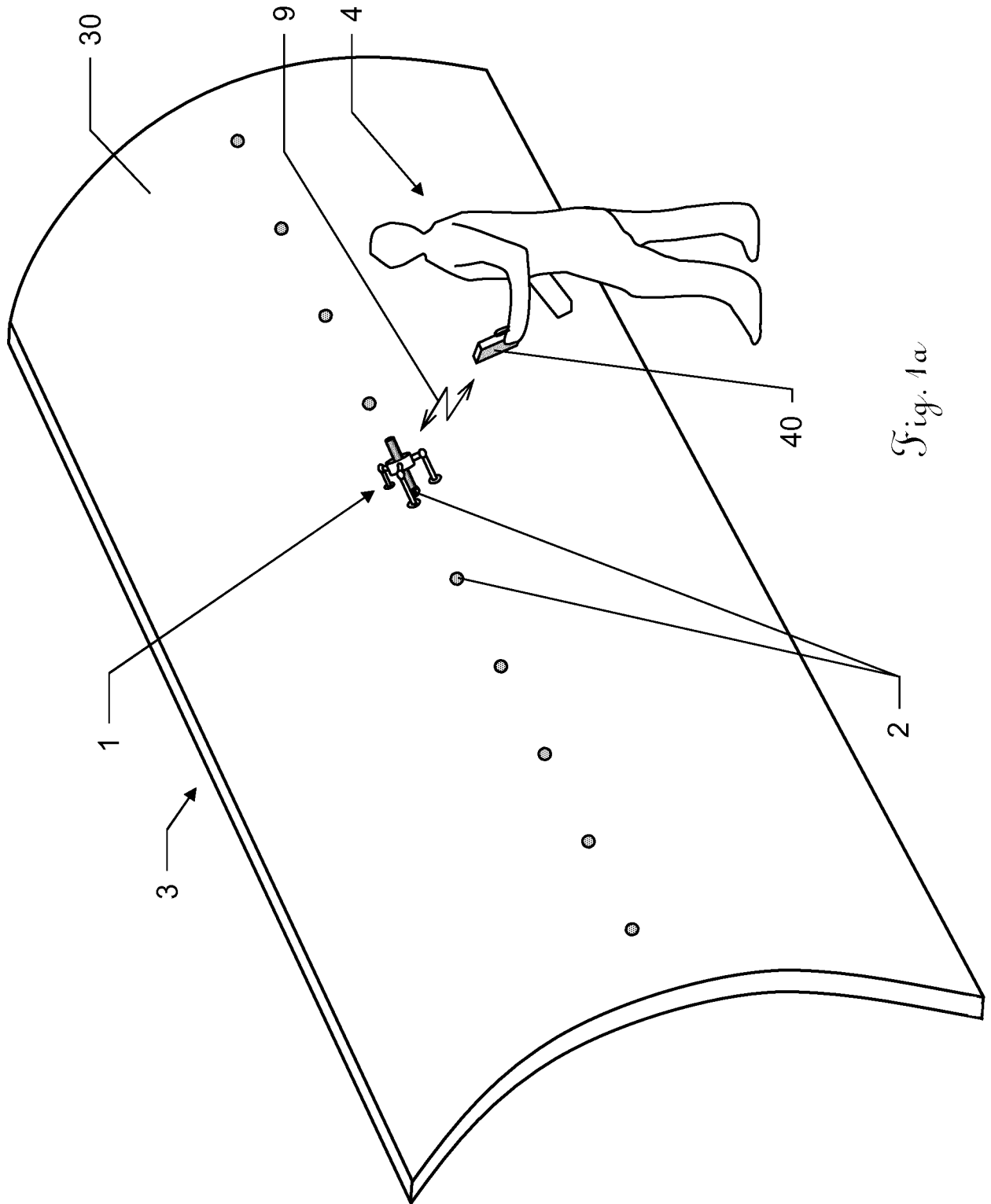


Fig. 1a

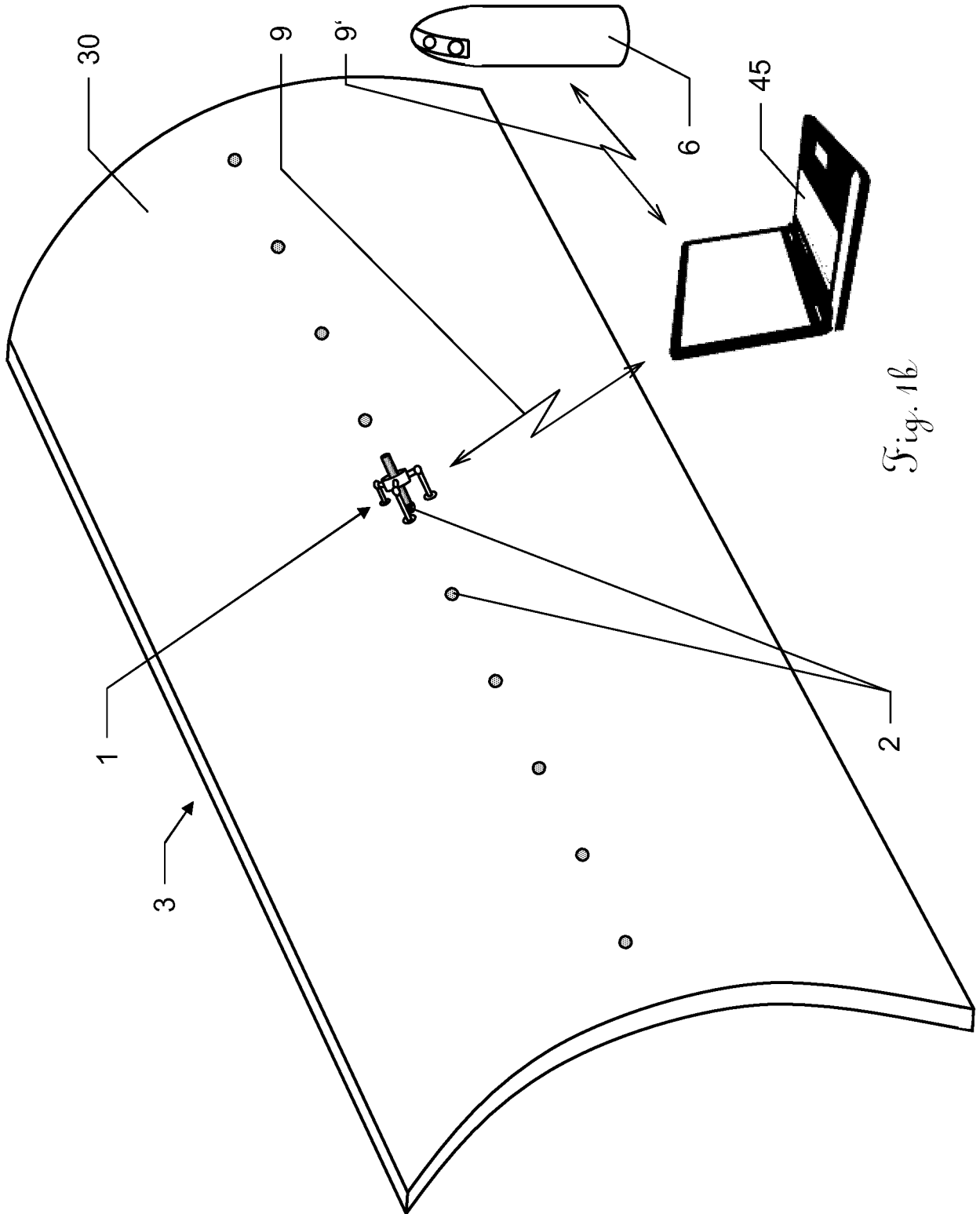
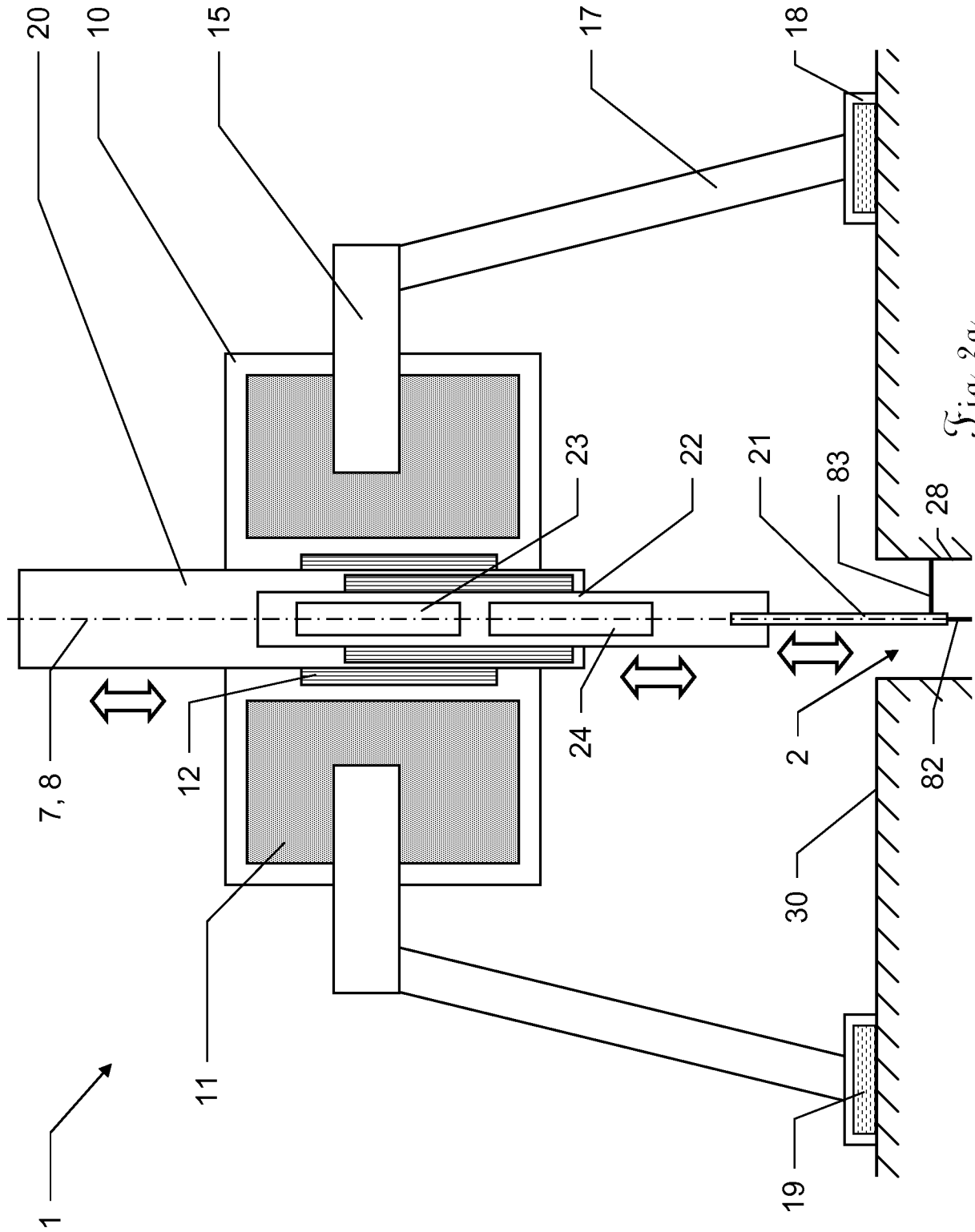
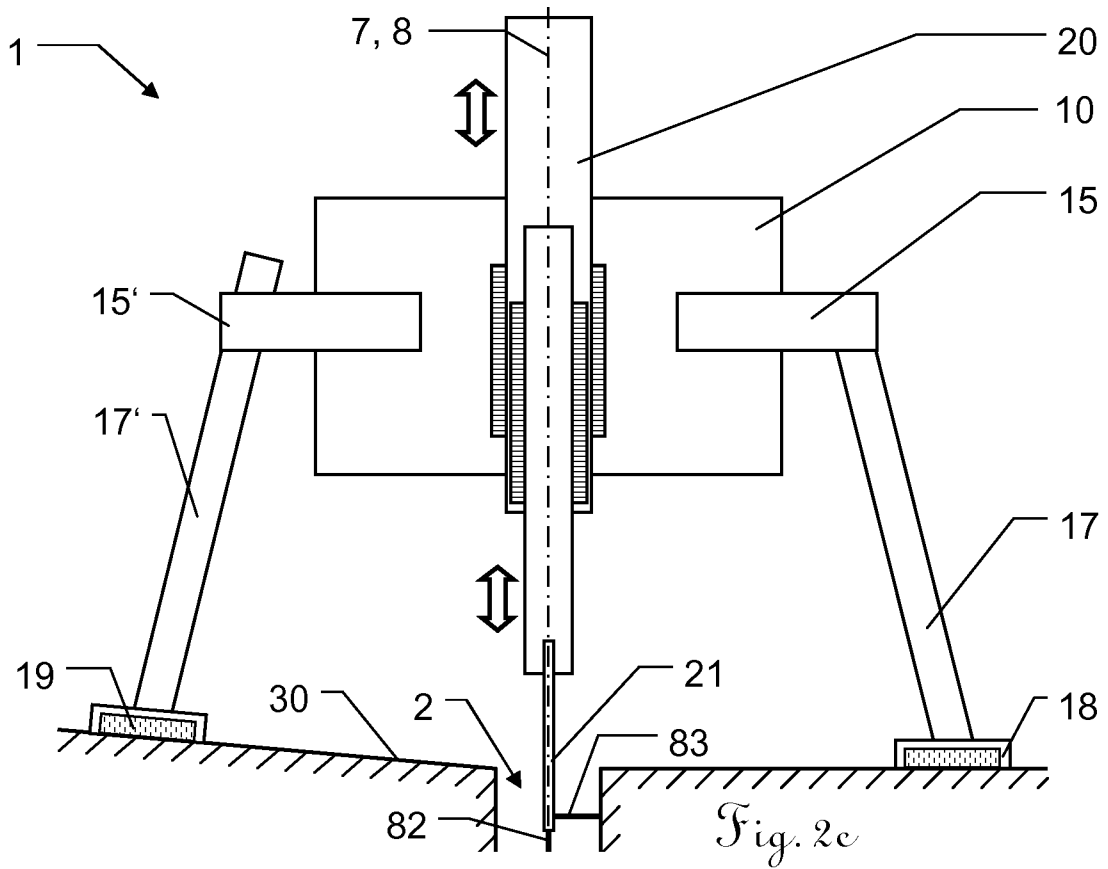
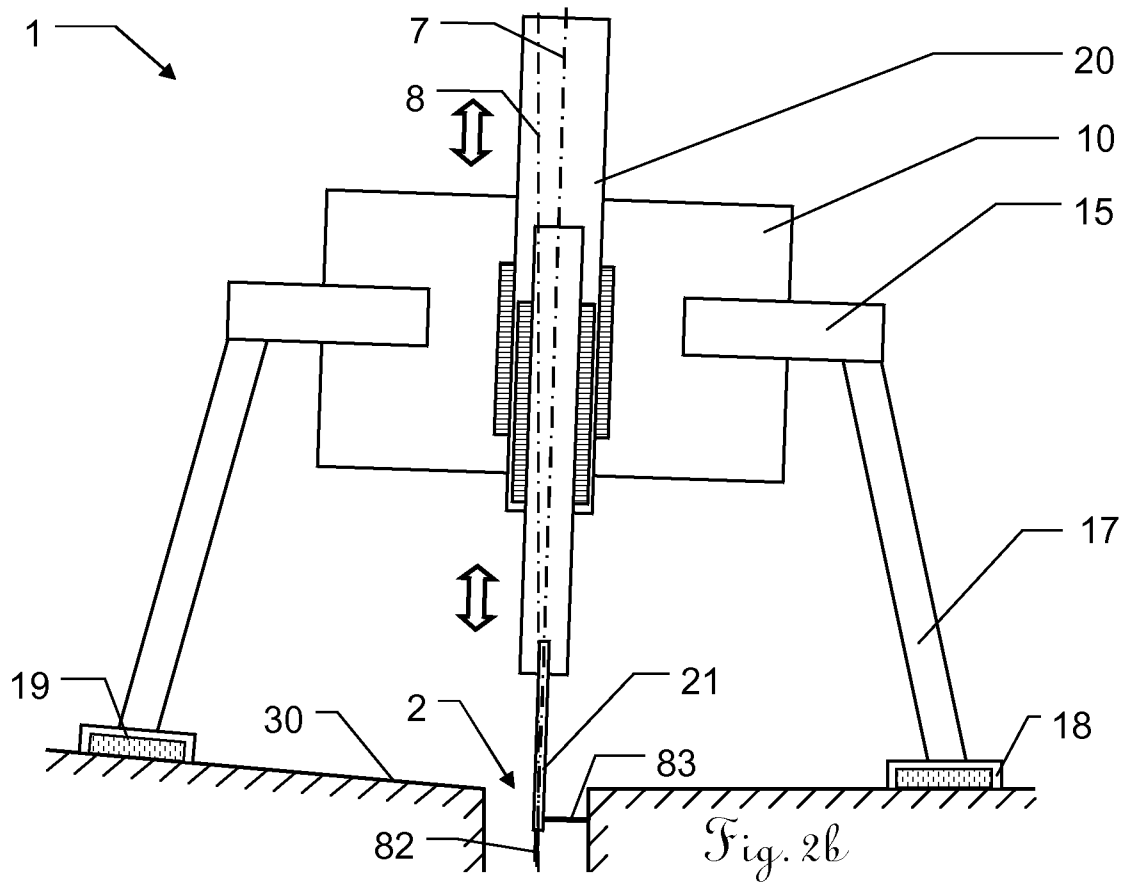


Fig. 16





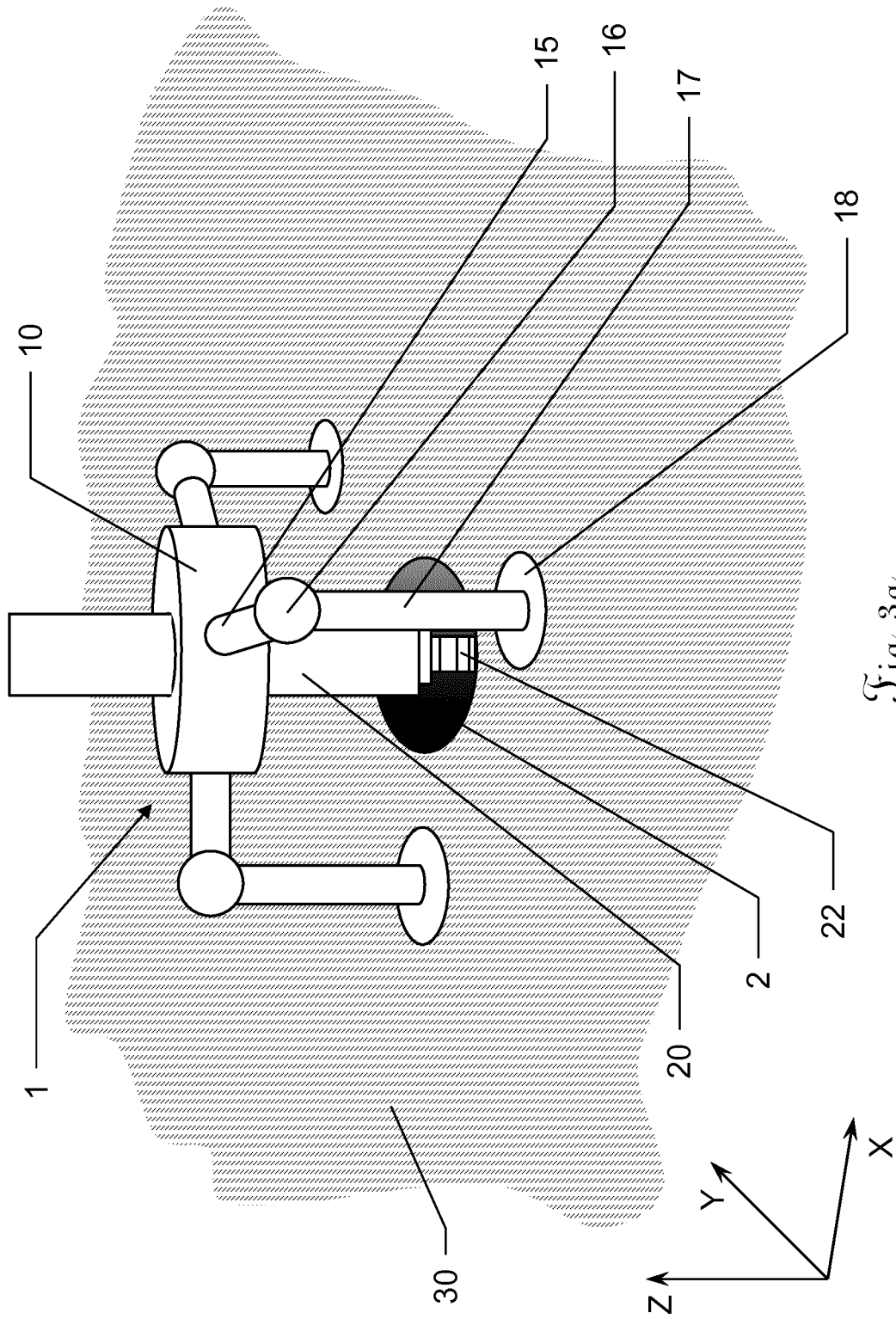


Fig. 3a

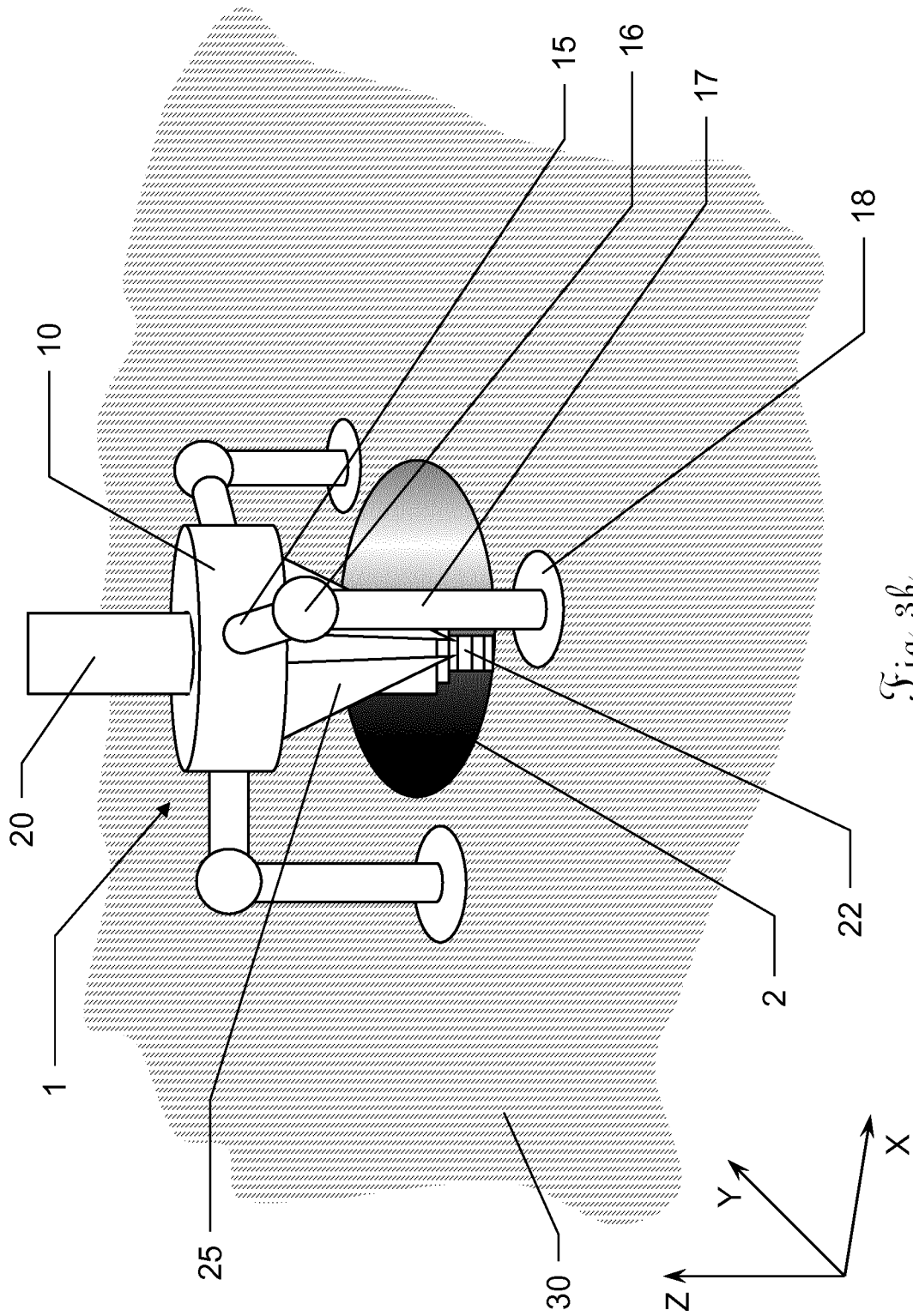


Fig. 3b

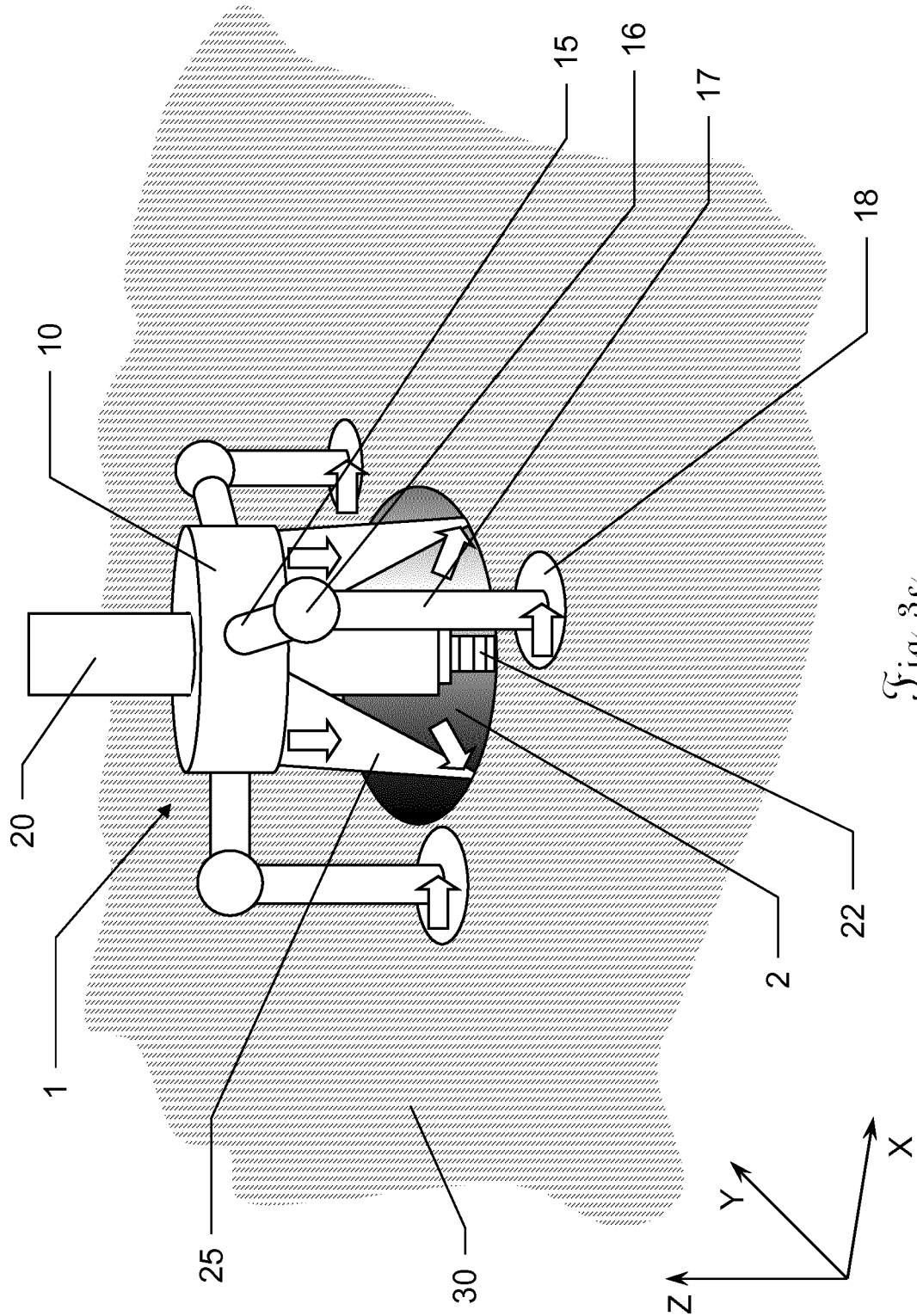


Fig. 3c

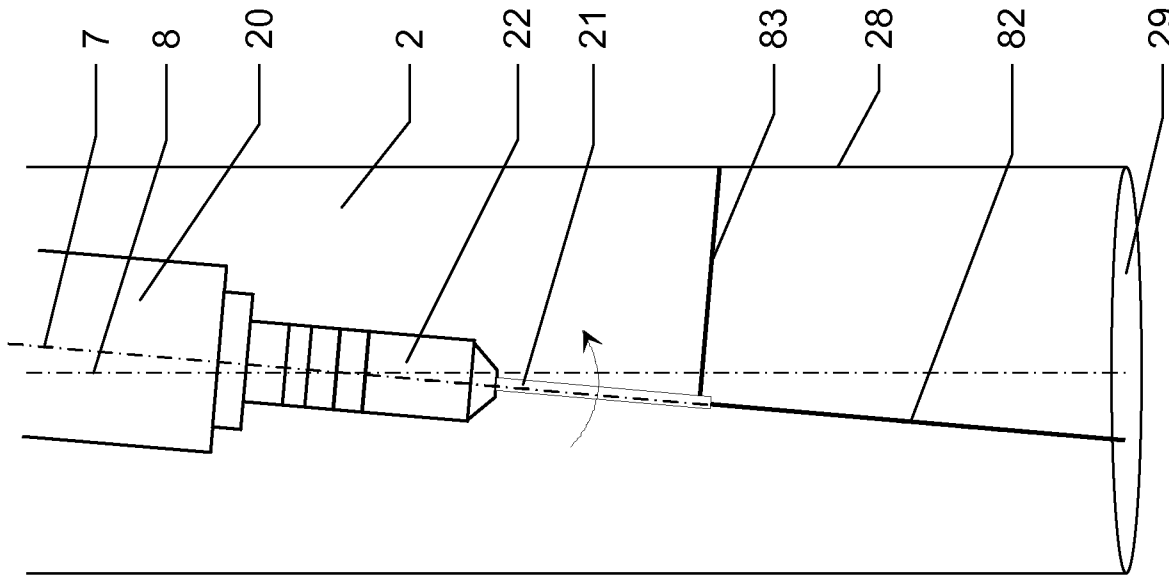


Fig. 4b

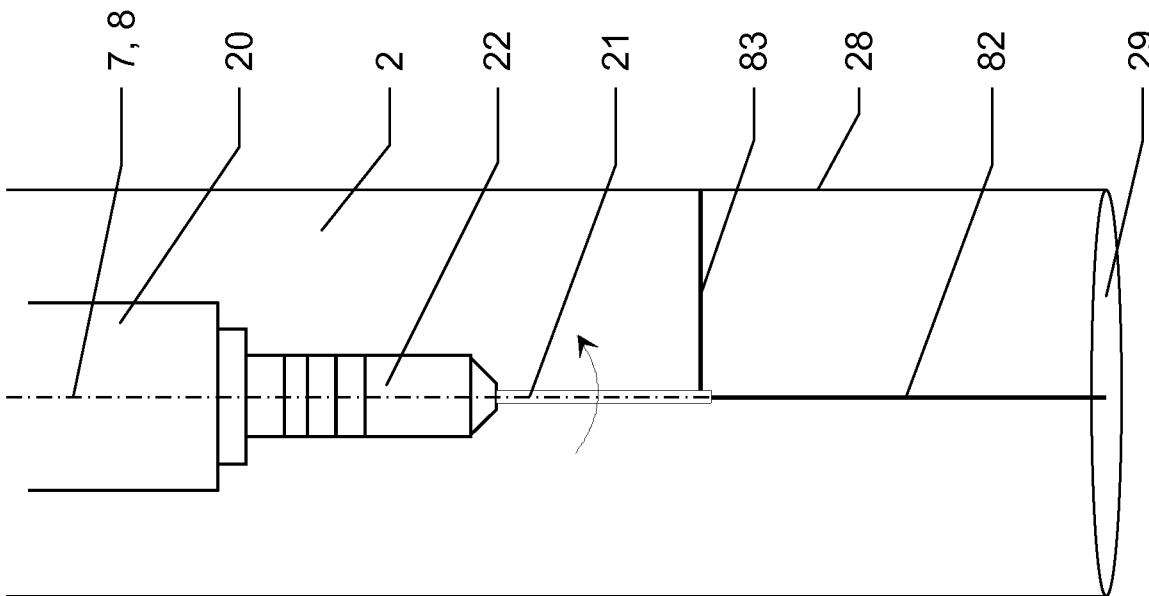


Fig. 4a

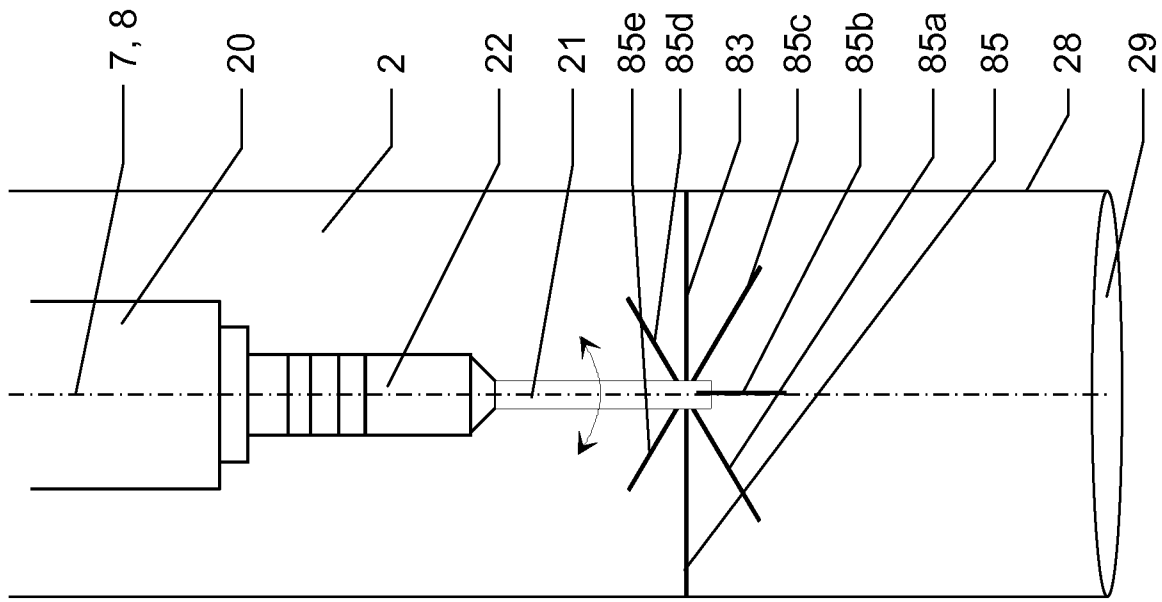


Fig. 5a

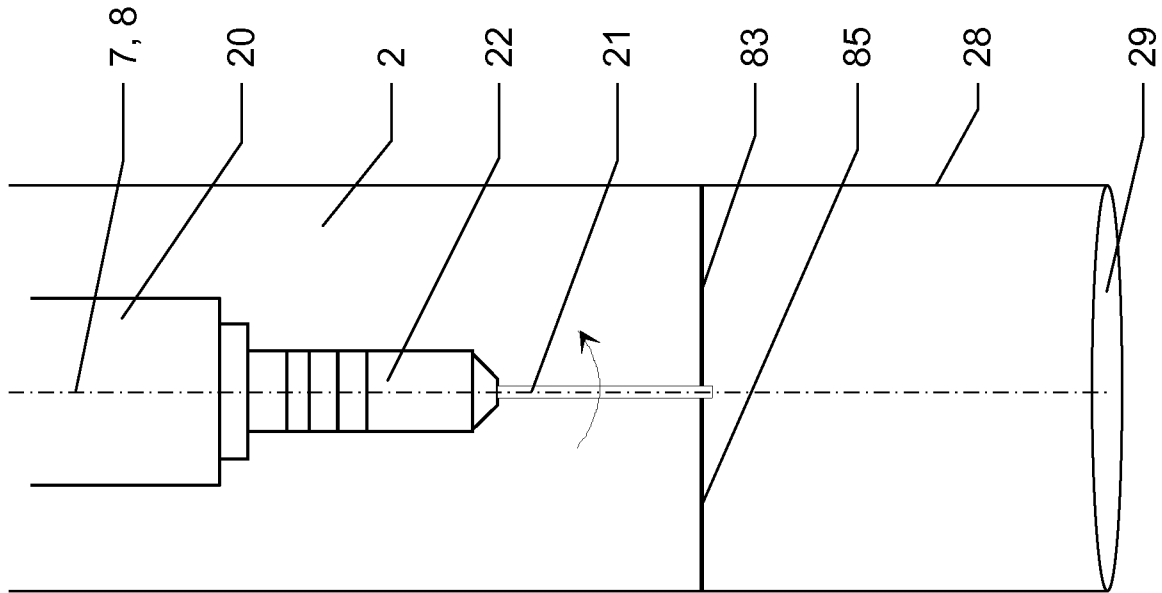


Fig. 5b

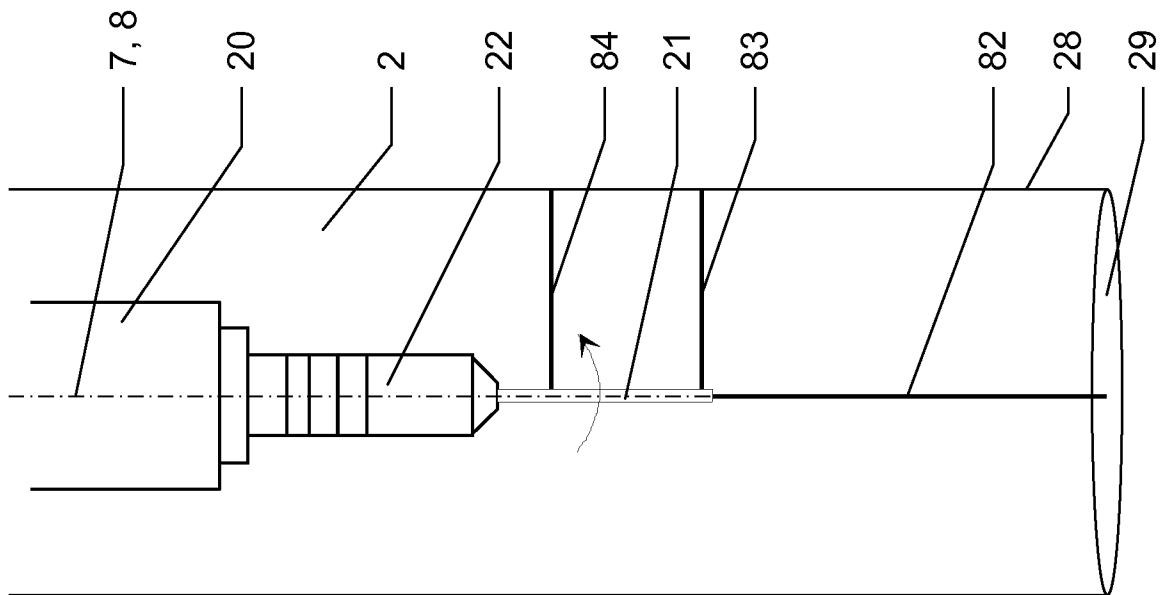


Fig. 5c

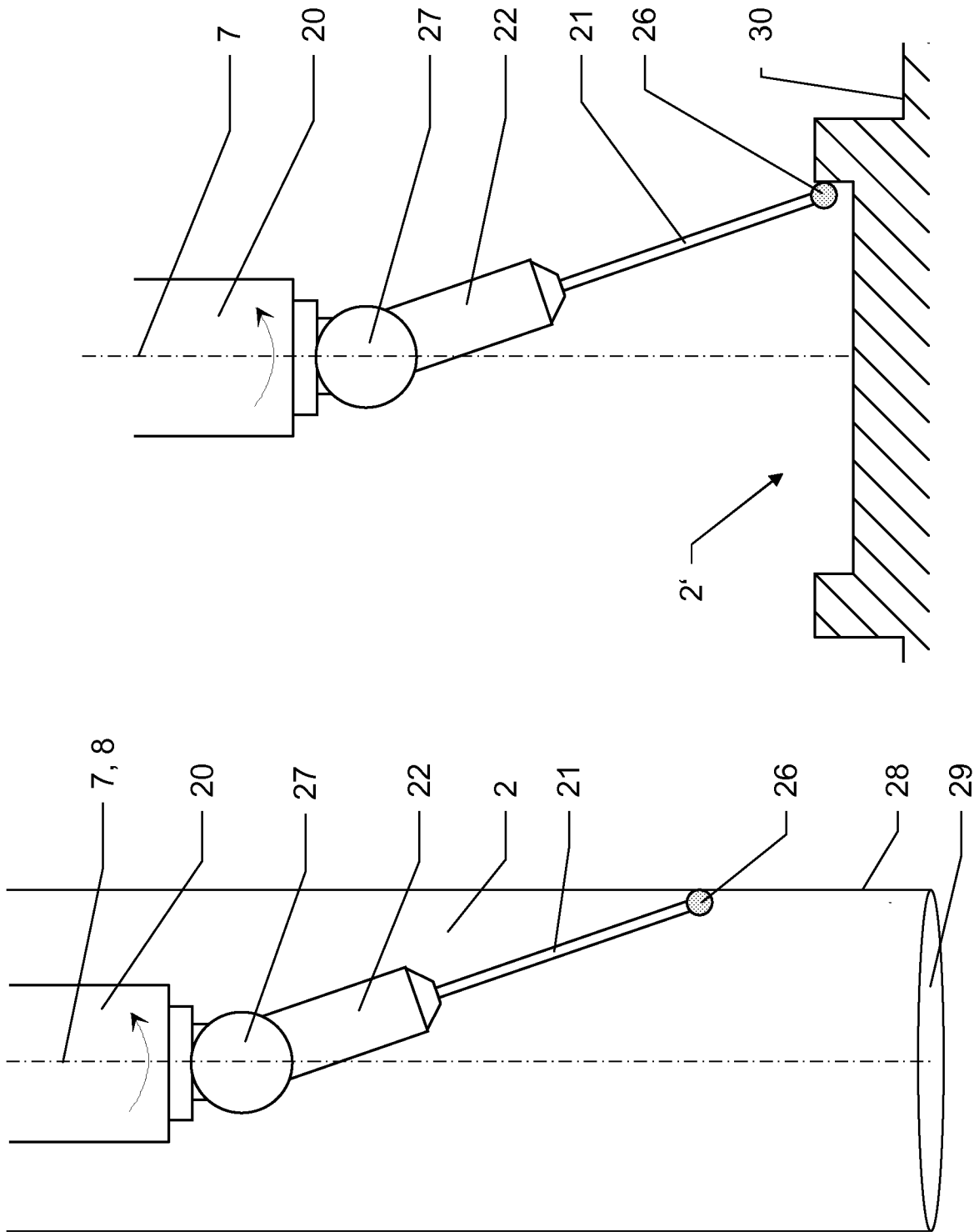


Fig. 6b

Fig. 6a

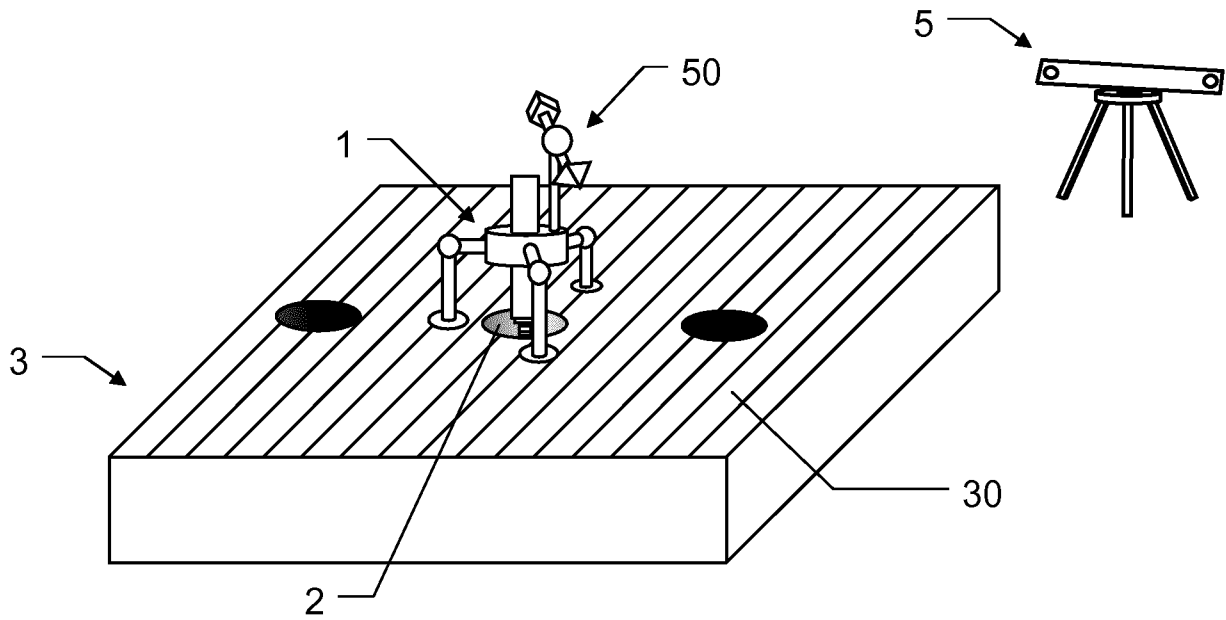


Fig. 7a

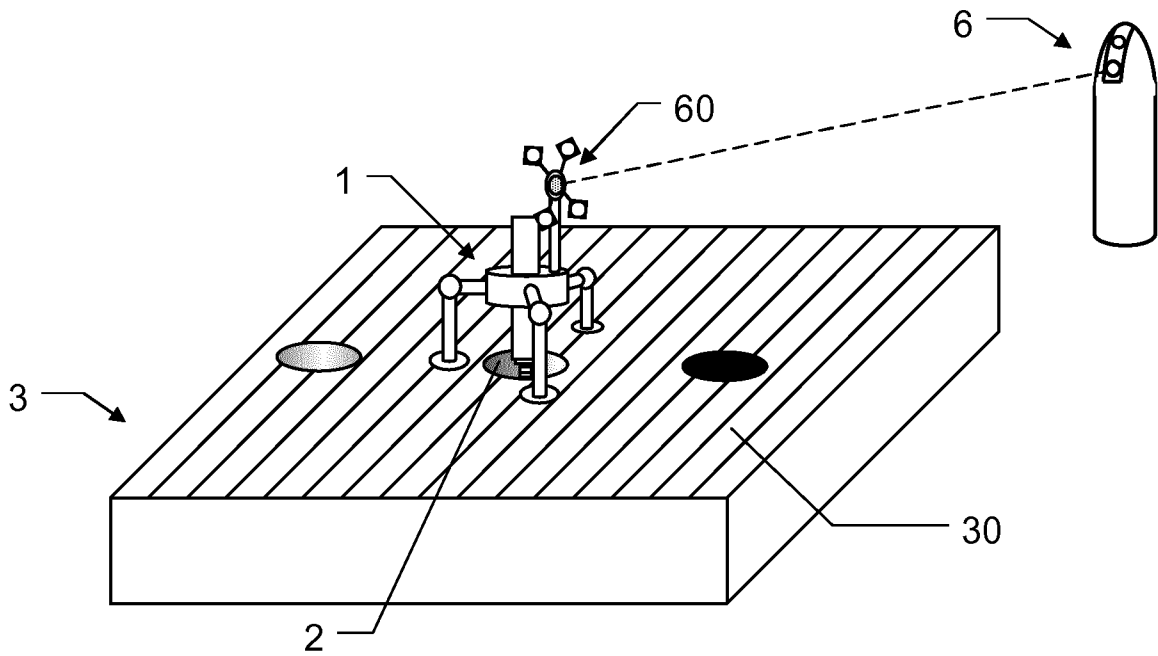


Fig. 7b

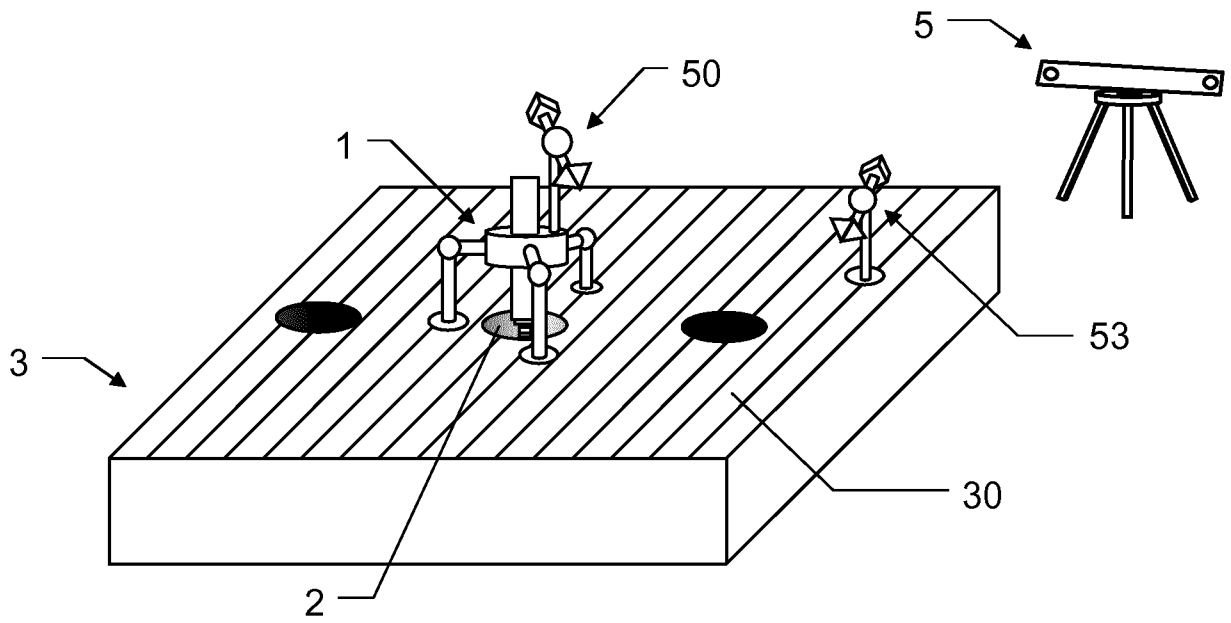


Fig. 8a

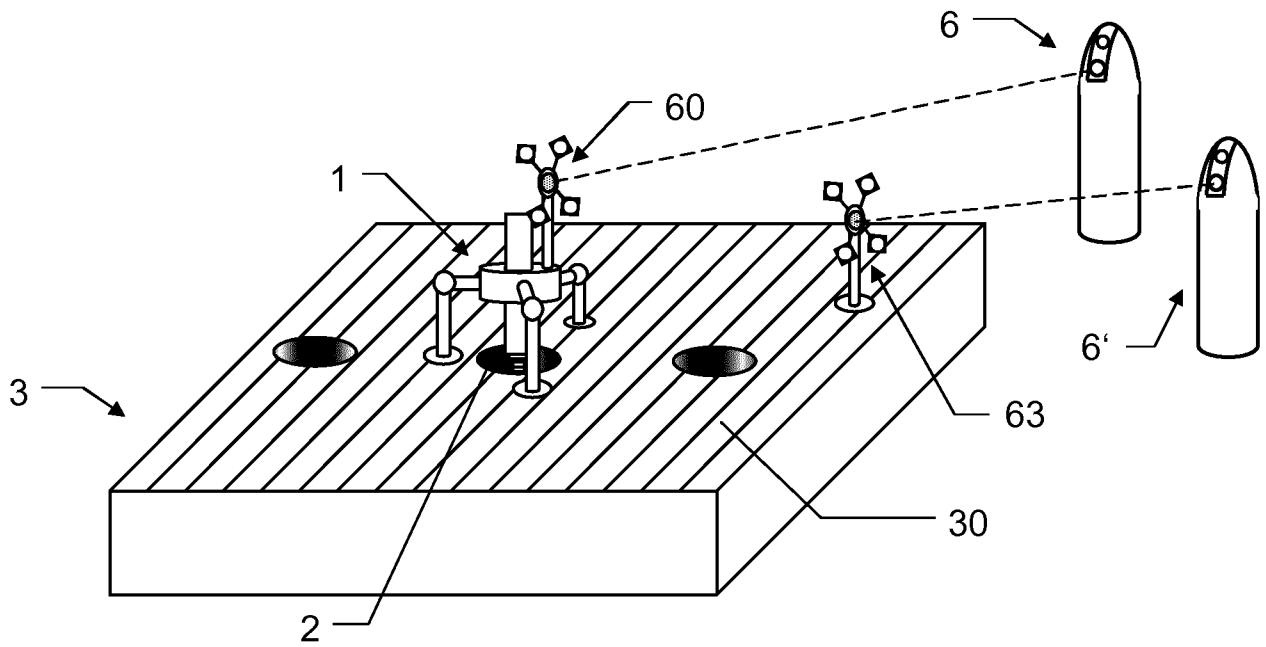


Fig. 8b

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/066912

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01B11/00 G01B21/04
ADD.
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
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)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 452 033 A (INTERNAT METROLOGY SYSTEMS LTD [GB]; IMS COMPANY LTD [KR]) 25 February 2009 (2009-02-25) the whole document	1,2,5-8, 13,18, 20-22
X	US 2008/084558 A1 (THOMPSON VINCENT [US] ET AL) 10 April 2008 (2008-04-10) the whole document	1-17, 19-22
X	EP 0 491 369 A2 (KOESTER GERHARD [DE] SCHEIBNER BERND DIPL ING [DE]) 24 June 1992 (1992-06-24) the whole document	1,2,5,7, 8,12,21
X	EP 2 244 052 A1 (XPRESS HOLDING B V [NL]) 27 October 2010 (2010-10-27) paragraph [0044] - paragraph [0063]; figures 1-2	1,2,5,7, 8,12,21
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Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents :

<p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier application or patent but published on or after the international filing date</p> <p>"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)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p>	<p>"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</p> <p>"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</p> <p>"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</p> <p>"&" document member of the same patent family</p>
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Date of the actual completion of the international search 21 October 2013	Date of mailing of the international search report 11/11/2013
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Rueda Gomez, Adriana
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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/066912

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

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