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(71) Applicant: LEONARDO S.P.A. [IT/IT]; Piazza Monte Grappa, 4, 00195 Roma (IT).

(72) Inventor: CHIRICO, Davide; c/o LEONARDO S.P.A., Strada Provinciale, 83 - da Monteiasi a Grottaglie, 74023 Grottaglie (TA) (IT).

(74) Agent: STUDIO TORTA S.P.A.; Via Viotti, 9, 10121 Torino (IT).

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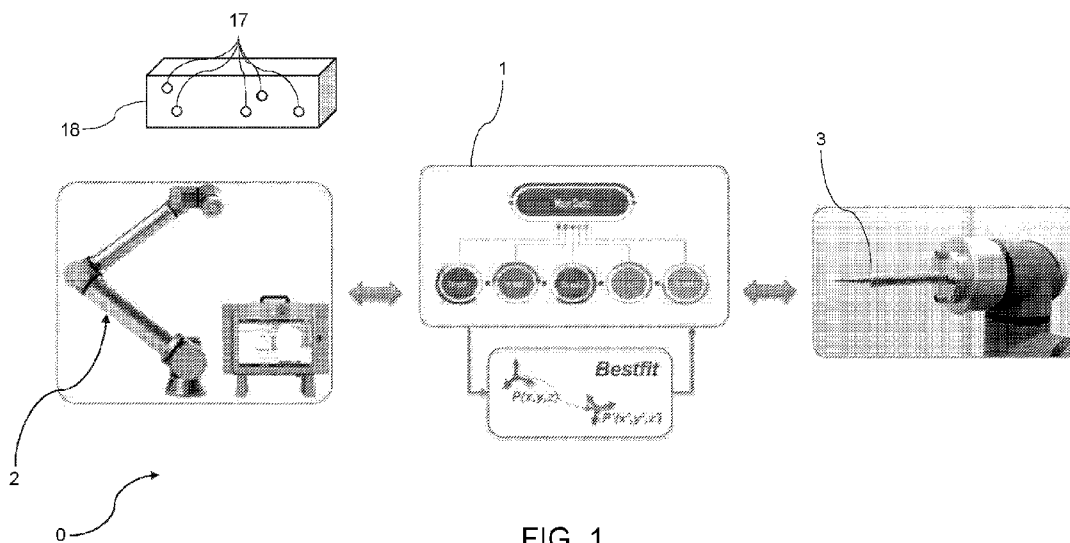


FIG. 1

(57) **Abstract:** Control software (1) of an industrial robot (2) loadable into, and executable by, computing resources of the industrial robot (2) so that, when executed, the industrial robot (2) becomes configured to carry out operations on real pieces in a work environment. The control software (1) is designed so that, when executed, the industrial robot (2) becomes configured to receive operation instructions to be carried out in the work environment and containing spatial coordinates, expressed in a virtual reference system, of a virtual environment modelling of the work environment and to carry out the operations instructed. In addition, the control software (1) is designed so that, when executed, the industrial robot (2) becomes configured to calculate a spatial transformation model (16) to align the virtual reference system of the work environment, in the virtual environment modelling, with a real reference system of the work environment in which the industrial robot (2) operates, in order to allow the latter to carry out the operations in the work area based on instructions received. In order to calculate (block 15) the spatial transformation model (16) between the virtual reference system and the real reference system, the control software (1) is also designed so that, when executed, the industrial robot (2) becomes configured

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to cause (block 4) a contact feeler (3) of the industrial robot (2) to interact with a real piece (18) in the work area to determine, in the real reference system, spatial coordinates of a number of contact points of surfaces of the real piece (18) at alignment holes made in the real piece (18) and determine (block 10) the spatial coordinates of at least one characteristic point, in particular the centre, of each alignment hole (17) based on the spatial coordinates of one or more of the contact points relative to the alignment hole (17). The control software (1) is also designed so that, when executed, the industrial robot (2) becomes configured to calculate (block 15) the spatial transformation model (16) between the virtual reference system and the real reference system based on the spatial coordinates of the at least one characteristic point of each alignment hole (17) and the spatial coordinates of the characteristic point of a corresponding alignment hole (17) in the virtual environment modelling of the real piece (18).

SPATIAL REFERENCING FOR INDUSTRIAL COLLABORATIVE ROBOTS

CROSS-REFERENCE TO RELATED APPLICATIONS

This Patent Application claims priority from Italian Patent Application No.
5 102023000010827 filed on May 29, 2023, the entire disclosure of which is incorporated herein by reference.

TECHNICAL FIELD OF THE INVENTION

The present invention relates in general to the field of industrial robots, and in
10 particular to the spatial referencing of collaborative industrial robots (Cobot, *Collaborative Robot*).

The present invention is advantageously usable on any robot provided with force
sensors so that the robot is adapted to determine spatial information of a work
environment in order to carry out operations with precision and to avoid collisions with
15 other objects or people present in the work environment.

The present invention is advantageously usable in industrial production, in
particular in the context of operations of picking and positioning (*pick&place*), palletizing
and machine tool automation, in particular when precision of the order of millimetres is
required; in scenarios envisaging the positioning of the robot in a work area and when the
20 repetition of predefined movements of the robot itself is required.

STATE OF THE ART

As is known, known solutions for the spatial referencing of the robots, in particular
a cobot, and numerical control machines (CNC, *Computer Numerical Control*), make
25 available systems that involve using external *target* devices. Typically, known solutions
are designed to cooperate with an external measurement system, the latter adapted to
detect the spatial position of external *target* devices in the real reference system of a
machining scheme; in particular, the external measurement system comprises a probe, a
laser, a camera, sensors and/or other types of detection devices. The external *target* devices
30 are placed near holes provided to accommodate such devices and are typically and
alternatively reflective type *target* devices, in particular comprising a reflective surface,
or physical type *target* devices, i.e. without a reflective surface.

In particular, the reflective type target devices are used in projection systems, in

particular comprising lasers to search the *target* devices to detect their position. On the other hand, the physical *target* devices, typically called *tooling balls*, are used in robots or CNC machines that adopt a *contact probe*, for example a Renishaw probe, as a measuring instrument.

5 Additional known solutions make available systems that involve using artificial vision systems configured to detect the *target* devices present in order to measure their geometric characteristics; in particular, the artificial vision system is adapted to determine the spatial coordinates as a function of the geometric characteristics of the *target* devices.

10 In the case of cobots, the development of applications in which robots operating on a workpiece or the same workpiece do not occupy predetermined positions and are inserted and removed from a work area based on the needs of the production cycle typically requires *off-line* programming with the aid of simulation *software* in order to implement and manage these applications. In these cases, in order to make the transition from the simulation environment to the real work area, it is typically required to adopt an
15 alignment system capable of guaranteeing the transformation of spatial coordinates from virtual to real, in particular with a degree of precision that is as high as possible. By way of example, an industrial robot such as the Universal Robot cobot, UR10e, makes available an elementary logic that generates a-reference characteristic (*feature*) based on the measurement of three alignment points; in order to obtain undistorted alignments, the
20 measurement must take place in the absence of measurement noise and with the alignment points arranged in their respective nominal positions.

It is further known that KR 101 438 657 B1 discloses a method comprising a step in which at least three inspection holes are selected and made in the same positions of 3D data in a base tool. The described method further provides a step in which at least three
25 different measurement units are arranged within the inspection holes; and a step in which calibration is performed while at least three robot movements are modified with respect to the ends of the measurement units such that each of the ends of the measurement units corresponds to the centre point of the robot tip. Furthermore, the method described provides for a step in which a teaching value measured in the calibration step is
30 transmitted to a computer, and compared with a value of the data modelled by a simulation software, and in which the size of the error is verified. Wherein, the measurement unit comprises a connecting bar having a lower surface with an insertion pin to be arranged in the hole and comprises a plurality of magnets arranged to be separated by a predetermined gap from the insertion pin; and a body, one end of which is

inserted into another insertion pin arranged on the upper surface of the connecting bar and the other end of which is provided with a removable measurement pin.

Further, WO 2022/104328 A1 describes a method for calibrating a robotic cell; wherein, the method comprises localizing the positions of one or more cameras and components with respect to a position of the robotic arm using a common coordinate system, moving the robotic arm according to a movement scheme, and using cameras and sensors to determine the position of the robotic arm at multiple times during the movement. The method further comprises identifying a discrepancy in the position of the robotic arm between an expected position and the position determined in real time, as well as calculating, by means of an auto-calibrator, a compensation for the identified discrepancy, the auto-calibrator resolving the elements in the robotic cell system as a system. The method provides for modifying the actions of the robotic arm in real time during the movement based on the compensation of this discrepancy.

OBJECT AND SUMMARY OF THE INVENTION

The Applicant was able to observe that the known solutions are amenable to improvement.

In particular, the aforementioned projection systems present problems of optical nature, in particular due to the reflectivity of the *target* device that makes it difficult for the projection system (in particular, by the laser thereof) to localize and/or due to the external brightness that negatively affects the localization of the target device and the goodness of the measurement made, as well as further problems such as for example problems with the housing of the *target* device inside the holes that negatively affects the measurement (in particular by altering or distorting it) and problems related to the need to position and remove the target devices from the work area at the beginning and at the end of a production cycle.

With regard to the machine vision systems, the accuracy of the measurement of the geometric characteristics depends on the system used; in particular, in the case of robots or CNC machines, the accuracy of the measurement of the geometric characteristics depends on the accuracy of the positioning of the robot or CNC machine with respect to the position of the *target* device to be measured. In addition, the accuracy of the measurement of the geometric characteristics is also significantly influenced by further types of errors, for example parallax errors, errors in the positioning of the robot or the

CNC machine and/or positioning errors with respect to the perpendicular to the *target* device.

In the case of contact probes, these solutions (including the solution described in KR 101 438 657 B1) have, for example, problems of housing the target device inside the holes that negatively affect the measurement (in particular by altering or distorting it), are expensive as high precision is required and are subjected to certification processes to validate the accuracy of the measurements made, have problems related to the need to position and remove the target devices from the work area at the beginning and at the end of a production cycle and, in the case of Renishaw probes (typically of the wireless and battery-powered type), are negatively affected by the battery charge status of the contact probes themselves. For example, the solution presented in KR 101 438 657 B1 does not provide for the calculation of the centre of the holes, but of the position of an external measuring unit, specially installed inside the hole; wherein, such a measuring unit could also be disengaged from the test holes and assume any position in space.

Furthermore, in relation to the UR10e cobot, taking into account the problems, it is required to develop robust alignment systems capable of solving situations in which the measurement of the alignment points can be affected, for example, by errors due to measurement noise or by spatial positions of the same that are not absolute, that is, different from the relative nominal values and often not falling within a permissible tolerance range.

Aim of the present invention is therefore to provide a control *software* for an industrial robot that solves at least in part the problems of the prior art. In addition, the aim of the present invention is therefore to make available a control *software* for an industrial robot that allows to determine spatial information of a hole without using further devices external to the robot. It is also an aim of the present invention to make available a control *software* for an industrial robot that allows to measure the centre of a hole, and not the position of external measuring units to be installed specifically in that hole.

According to the present invention a control *software* of an industrial robot is made available as claimed in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a block diagram of a spatial referencing system for robots implementing the control *software* of an industrial robot according to the present

invention.

Figure 2 shows a flowchart depicting a process implementable by the control *software* of an industrial robot according to an embodiment of the present invention.

Figure 3 illustrates a flowchart depicting a process implementable by the control *software* of an industrial robot according to another embodiment of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

The present invention will now be described in detail with reference to the accompanying figures to allow a skilled person to make and use it. Various modifications of the embodiment described will be immediately clear to the skilled person and the general principles disclosed can be applied to other embodiments and applications without departing from the protection scope of the present invention, as defined in the enclosed drawings. Therefore, the present invention shall not be limited to the shown and described embodiments, but it must be granted the widest protection scope in accordance with the features disclosed and claimed.

Unless otherwise defined, all the herein used technical and scientific terms have the same meaning commonly used by the ordinary skilled in the art of the present invention. In case of conflict, the present invention, including definitions provided, will be binding. Furthermore, the examples are provided for merely illustrative purposes and must not be regarded as limiting.

In particular, the block diagrams included in the enclosed figures and hereinafter described must not be considered as a representation of the structural features, i.e. construction limitations, but must be construed as a representation of functional features, namely inner properties of the devices and defined by the obtained effects i.e. functional limitations which can be implemented in different ways, so as to protect the functionality thereof (chance of functioning).

In order to ease the understanding of the herein described embodiments, reference will be made to some specific embodiments and a specific language will be used to describe them. The terminology used in the present document aims at describing only particular implementations, and is not intended to limit the scope of the present invention.

Figure 1 shows a block diagram of a spatial referencing system **20** for industrial robot **2**, also referred to as a smart alignment system (SAS). The spatial referencing system **20** comprises computer resources (i.e., electronic processing resources not illustrated here) and a control *software* **1** of the industrial robot **2**, in particular a *multi-thread*

software application. In particular, the spatial referencing system **20** is configured to cause a robot **2**, in particular a cobot, to be spatially referenced. According to a preferred embodiment, the industrial robot **2** comprises a contact feeler **3**, force sensors, in particular placed in one or more joints of the robot **2**, and computer resources, in particular an electronic control unit, designed to execute the control *software* **1** of an industrial robot **2**. In particular, the contact feeler **3** of the industrial robot **2** is a tip-shaped instrument. The industrial robot **2** is configured to carry the contact feeler **3** at a flange of the industrial robot **2** itself.

The control *software* **1** is loadable in, and executable by, computing resources of the industrial robot **2** to cause, when executed, the industrial robot **2** to become configured to carry out operations on real pieces in a work environment. In particular, the control *software* **1** is programmed to cause, when executed, the industrial robot **2** to become configured to execute multiple *software* modules, in particular *thread*, simultaneously. Each *thread* consists of several functional blocks, in particular *routines*.

The control *software* **1** is designed so that, when executed, the industrial robot **2** becomes configured to receive operation instructions, for example from a software module loaded into and executable from the robot's computational resources **2** or from an external device, for example from a mobile device (for example a *smartphone*, a *phablet*, a PC and the like) or from a fixed device (for example a desktop PC or other), adapted to transmit operation instructions to the robot **2**, to be carried out in the work environment and containing spatial coordinates, expressed in a virtual reference system, of a virtual environment modelling of the real work environment and to carry out the operations instructed.

In particular, the spatial coordinates expressed in the virtual reference system are three-dimensional (3D) coordinates.

According to one aspect of the present invention, the instructions of operations to be carried out on real pieces comprise at least one list of operations to be performed; in particular, each operation of the list comprises a series of states of the operation, each associated with a set of spatial coordinates expressed in the virtual reference system. In detail, the set of spatial coordinates comprises, for each state of the operation, at least the spatial coordinates of the industrial robot **2** and of components of the industrial robot **2**.

The control *software* **1** is designed to cause, when executed, the industrial robot **2** to become configured to calculate a spatial transformation model **16**, here a rototranslation matrix, to align the virtual reference system of the work environment in

the virtual environment modelling, with a real reference system of the work environment in which the industrial robot **2** operates, in order to allow the latter to carry out the operations in the work area based on instructions received.

The control *software* **1** of the robot **2**, with the aim of calculating a spatial transformation model **16** between the virtual reference system and the real reference system, is also designed so that, when executed, the industrial robot **2** becomes configured to:

- cause (block **4**) a contact feeler **3** of the industrial robot **2** to interact with a real piece **18** (that is, a workpiece or a piece on which it is wished to work) in the work area to determine, in the real reference system, spatial coordinates of a number of contact points of surfaces of the real piece **18**, in the vicinity of (in detail, at) alignment holes **17** made in the real piece **18**, with which the contact feeler **3** has come into contact; in which, the contact points are located on surfaces of the real piece **18** and the contact feeler **3** comes into contact directly (in detail, not by other means) with these surfaces;

- determine (block **10**) the spatial coordinates of at least one characteristic point, in particular the centre, of each alignment hole **17** based on the spatial coordinates of one or more of the contact points relative to, in particular located on a surface of the real piece **18** delimiting (in detail laterally) the alignment hole **17**; and

- calculate (block **15**) the spatial transformation model **16** between the virtual reference system and the real reference system based on the spatial coordinates of the at least one characteristic point, in particular of the centre, of each alignment hole **17** and spatial coordinates of the characteristic point of a corresponding alignment hole **17** in the virtual environment modelling of the real piece.

In detail, the holes **17** are already present on the real piece **18**, and the industrial robot **2** is configured to operate on the real piece **18**, in order to reference itself spatially, without requiring further new holes **17** to be made specifically on the real piece **18**. In more detail, the present invention allows the robot **2** to reference itself spatially without requiring a human operator to make further holes **17** on the real piece **18**.

In particular, the control *software* **1** is also programmed so that, when executed, the industrial robot **2** becomes configured to cause a contact feeler **3** of the industrial robot **2** to interact with the real piece **18** in the work area so as to determine the contact points located on the internal surface (i.e., a surface defined by the real piece **18** and defining the perimeter of the alignment hole **17**) or external (i.e., a surface of the real piece **18** different from the internal surface) to the alignment holes **17** made in the real piece **18** in

the work area in the real reference system.

The control *software 1* of an industrial robot **2** is therefore programmed so that, when executed, the industrial robot **2** becomes configured to carry out operations on real pieces in a work environment as a function of the operation instructions received and the spatial transformation model **16** calculated.

Figure 2 shows a flowchart representing a process implementable by the control *software 1* of an industrial robot **2** in order to determine (block **10**) the characteristic point of a hole **17**, in particular the centre of the hole **17**.

The control *software 1* of an industrial robot **2** is designed so that, when executed, the industrial robot **2** becomes configured to:

- communicate with force sensors of the industrial robot **2** adapted to provide an output indicative of the fact that the contact feeler **3** of the industrial robot **2** has come into contact with the real piece **18** of the work area; and

- determine the spatial coordinates of the contact points in which the contact feeler **3** has come into contact with surfaces of the real piece **18** of the alignment holes **17** made in the real piece **18** of the work area in the real reference system based on the output provided by the force sensors.

The control *software 1* is preferably designed so that, when executed, the industrial robot **2** becomes configured to move the contact feeler **3** based on the output of the force sensors; in particular, the industrial robot **2** becomes configured to determine direction and feed rate as a function of the output of the force sensors and control the contact feeler **3** to cause the latter to assume the determined feed rate and to assume the determined direction. In particular, the control *software 1* is also designed so that, when executed, the robot **2** determines the feed rate as a function of the output of the force sensors and as a function of a predefined speed value as a function of calibration tests of the alignment system, so that the determined speed follows the predefined speed value.

The control *software 1* is designed so that, when executed, the industrial robot **2** becomes configured to perform a series of actions and *routines* in order to determine the spatial coordinates of the characteristic point, in particular the centre, of an alignment hole **17**.

In particular, the contact feeler **3** is positioned, for example manually, in the vicinity of an alignment hole **17**, in particular of circular shape, (not illustrated here) of the real piece **18** of the work area (block **4**), in particular it is inserted in the alignment hole **17** with a random inclination; moreover, according to an aspect of the present invention, the

contact feeler **3** is inserted in the alignment hole **17** with a random tangent point on the perimeter of the alignment hole **17**.

The industrial robot **2** is therefore preferably configured to control the movement of the contact feeler **3** so that it comes into contact with contact points of the real piece **18**, in particular three points adjacent to the alignment hole **17**, on surfaces external to the hole **17** itself, in order to determine a plane in which the alignment hole lie **17** (block **5**). In particular, the control *software* **1** of an industrial robot **2** is designed so that, when executed, the industrial robot **2** becomes configured to determine the spatial coordinates of the contact points based on an output of the force sensors; in detail, the robot **2** becomes configured to determine the coordinates of a contact point when the output of the force sensors is indicative of the fact that the contact sensor **3** has come into contact with a contact point.

In particular, to determine the spatial coordinates of a characteristic point of an alignment hole **17**, in particular the centre of the hole **17**, the control *software* **1** of an industrial robot **2** is designed so that, when executed, the industrial robot **2** becomes configured to calculate the plane in which the alignment hole lies **17** based the spatial coordinates of the contact points with surfaces external to the hole itself **17**. In addition, the control *software* **1** of an industrial robot **2**, in particular the *routine* for calculating the lying plane described with reference to the block **5**, is designed so that, when executed, the industrial robot **2** becomes configured to determine a direction in which to position, or an orientation that must be assumed by, the contact feeler **3** in such a way that the determined direction is, also approximately, parallel to the axis of the hole **17**, therefore perpendicular to the plane in which the hole **17** itself lies, and control the contact feeler **3** to position it in the direction determined. In particular, the robot **2** is configured to determine the determined direction by calculating the normal to the plane in which the alignment hole lies **17** based on the contact points detected on the surface, in the vicinity of the hole **17** itself, and controls the contact feeler **3** to position it along the calculated normal. Subsequently, the robot **2** is configured to position the contact feeler **3** at an initial position inside the alignment hole **17**, in particular a position in which it was previously inserted (block **6**); in particular, the robot **2**, when positioning the contact feeler **3**, is configured to control the contact feeler **3** so that it assumes the previously determined direction.

To determine the spatial coordinates of a characteristic point of an alignment hole **17**, in particular the centre of the hole **17**, the control *software* **1** of an industrial robot **2**, in

particular the routine integrated in the control software **1** and referred to as a block with reference number **7** in Figure 2, is designed so that, when executed, the industrial robot **2** becomes configured to move the contact feeler **3** so that it comes into contact with contact points, in particular with two contact points, with surfaces inside the hole **17**, in order to determine spatial coordinates of first contact points.

The control software **1** is conveniently designed so that, when executed, the industrial robot **2** also becomes configured to determine a first segment as a function of the spatial coordinates of the first contact points in order to determine a first representative point, in particular the midpoint, of the first segment determined.

Subsequently, the robot **2** is configured to position the contact feeler **3** at the first determined representative point; moreover, the industrial robot **2** is configured to move (block 7) the contact feeler **3** so that it comes into contact with two other contact points with surfaces inside the hole **17**.

To this end, the control *software* **1** of an industrial robot **2**, in particular the routine described with reference to block **7**, is also designed so that, when executed, the industrial robot **2** becomes configured to determine a direction orthogonal to the first determined segment, move (block 7) the contact feeler **3** in the orthogonal direction so that it comes into contact with contact points with surfaces inside the hole **17** to determine spatial coordinates of second contact points of the hole **17**, in particular two second contact points of the hole **17**, and determine a second segment, based on the spatial coordinates of the second contact points of the hole **17**, in order to determine a second representative point, i.e. a potential characteristic point, in particular the midpoint of the second segment determined.

The control *software* **1** of an industrial robot **2** is further programmed so that, when executed, the industrial robot **2** becomes configured to determine (block **10**) the characteristic point of the hole **17**, in particular the centre, based on the determined potential characteristic point, i.e. the midpoint of the second segment.

The control *software* **1** of an industrial robot **2** is optionally programmed so that, when executed, the robot **2** also becomes configured to re-execute the routine described with reference to block **5**, in order to determine a new direction, in particular an axial direction to the hole **17** determined with greater accuracy than the previously determined direction, in which to position the contact feeler **3** and control the contact feeler **3** in order to position it in the new determined direction.

The control *software* **1** of an industrial robot **2** is conveniently programmed so that,

when executed, the industrial robot **2** becomes configured to execute the routine described with reference to block **7** several times, in particular iteratively, in order to determine different contact points and different potential characteristic points to determine (block **10**) the characteristic point of the hole **17**, in particular the centre.

5 The control *software 1* of an industrial robot **2**, in particular a routine **8**, is designed so that, when executed, the industrial robot **2** becomes configured to project the contact points on the plane in which the hole lies **17**, for example, by means of orthogonal projection techniques.

10 In order to determine the spatial coordinates of a characteristic point of an alignment hole **17**, in particular the centre, the control *software 1* of an industrial robot **2**, in particular a routine of the block **8** in Figure 2, is also preferably designed so that, when executed, the industrial robot **2** becomes configured to determine different sets of contact points of the hole **17** comprising one or more contact points, in particular three contact points, of the hole **17** in order to determine, for each set of contact points, a potential
15 characteristic point, in particular the centre, as a function of the spatial coordinates of the contact points of the set. In particular, the industrial robot **2** is configured to determine the sets of the contact points of the alignment hole **17** as a function of the possible permutations of the contact points taken in groups of three points in order to determine a potential characteristic point for each set.

20 The control *software 1* of an industrial robot **2**, in particular a routine represented by a block **8** in Figure 2, is designed so that, when executed, the industrial robot **2** becomes configured to determine (block **10**) the characteristic point of the hole **17** based on the potential characteristic points determined and a predetermined criterion for calculating characteristic points.

25 Furthermore, in order to determine the spatial coordinates of a characteristic point of an alignment hole **17**, in particular the centre, the control *software 1* is optionally programmed so that, when executed, the industrial robot **2** becomes configured to determine a reference system rotated as a function of the real reference system and by a predefined angle, for example by 45°, in order to determine (block **10**) the characteristic
30 point of the hole **17** as a function of the real reference system rotated (block **9**); in particular, the reference system rotated is determined by rotating the real reference system by the predefined angle.

Subsequently, the robot **2** is configured to execute again the routine described with reference to block **7** in order to determine a further potential characteristic point of the

hole **17** as a function of a new measurement of the coordinates of the contact points of the hole **17**. Subsequently, the robot **2** becomes configured to execute again the routine described with reference to block **8** in order to determine different potential characteristic points as a function of the different sets of contact points of the hole **17** comprising one or more contact points of the hole **17**; in particular, each set comprising three contact points.

Subsequently, the control *software 1* of an industrial robot **2** is designed so that, when executed, the industrial robot **2** becomes configured to determine the characteristic point (block **10**) of the hole **17**, in particular the centre of the hole **17**, as a function of the potential characteristic points determined (block **10**). In particular, the control *software 1* is programmed so that, when executed, the industrial robot **2** becomes configured to determine (block **10**) the characteristic point of the hole **17**, in particular the centre of the hole **17**, by averaging the coordinates of the previously determined potential characteristic points.

Figure 3 shows a flowchart representing a process implementable by the control *software 1* of an industrial robot **2**; in particular, the process, when executed, causes the industrial robot **2** to become configured to determine (block **15**) the spatial transformation model **16**.

In particular, in order to calculate the spatial transformation model **16** between the virtual reference system and the real reference system, the control *software 1* of an industrial robot **2** is designed so that, when executed, the industrial robot **2** becomes configured to form (block **12**) different sets of characteristic points of alignment holes **17** made in the real piece **18** of the work area (block **12**). In particular, the control *software 1* is designed so that, when executed, the industrial robot **2** becomes configured to determine, in particular receive from a mobile or fixed user terminal (not illustrated here), information indicative of the number of characteristic points of the alignment holes **17** to be considered in the subsequent steps (block **11**); by way of example, the information indicative of the number of characteristic points is a minimum number of characteristic points that each set must comprise.

Furthermore, the control *software 1* is designed so that, when executed, the industrial robot **2** becomes configured to determine the sets of characteristic points as a function of the information indicative of the number, in particular the minimum number, of characteristic points of the alignment holes **17** that each set must contain; in particular, the robot **2** is configured to determine the sets of characteristic points so that each set of

characteristic points comprises a number of characteristic points that is at least the minimum number of the characteristic points. By way of example, the robot **2** is configured to determine permutations of the characteristic points so that each permutation, therefore a set of characteristic points, comprises a number of characteristic points that is at least the minimum number of the characteristic points (block **13**).

Furthermore, according to one aspect of the present invention, the industrial robot **2** is configured to form (block **12**) each of the different sets of characteristic points of the alignment holes **17** by selecting (block **13**), from a plurality of different characteristic points, a number of characteristic points for that set that are determined to satisfy a coverage condition of, or distribution on, the surface of the real piece **18**.

In detail, the industrial robot **2** is configured to determine that a number (or a set) of characteristic points satisfy (in particular, when considered as a set) the surface coverage condition of the real piece **18** when they delimit a coverage region greater than, or equal to, a comparison coverage region. In particular, the industrial robot **2** is configured to compute a coverage region delimited by different characteristic points based on the spatial coordinates of those characteristic points; wherein, for example, said coverage region is the area delimited by the characteristic points.

Alternatively, the industrial robot **2** is configured to determine that a number (or a set) of characteristic points satisfy the surface coverage condition of the real piece **18** when it is determined that they are positioned, or distributed, in different predefined sub-regions of the surface of the real piece **18**; in particular, they are distributed so as to cover at least the different predefined sub-regions. In particular, the surface coverage condition of the real piece **18** is satisfied when at least one characteristic point of the characteristic points under analysis is found in each sub-region of the predefined sub-regions. Conveniently, the surface coverage condition of the real piece **18** is satisfied when the characteristic points are distributed over, or so as to cover, the entire surface of the real piece **18**; in this way, not only the optimal solution is defined, but the consistency between the calculated model **16** and the real extension of the real piece **18** is guaranteed.

Otherwise, if a set comprised characteristic points of a single portion of the surface of the real piece **18**, the error could be minimal, but would only be valid at the area affected, i.e. covered, by the characteristic points with which the set of characteristic points is defined; in this case, the transformation error could be high (and not acceptable) for the remaining part of the surface of the real piece **18**.

Subsequently, the control *software* **1** of an industrial robot **2** is preferably designed

so that, when executed, the industrial robot **2** becomes configured to:

- calculate (block **14**), for each set of characteristic points of alignment holes **17**, a spatial transformation model **16** based on the spatial coordinates of the characteristic points of the alignment holes **17** of the set and the spatial coordinates of characteristic points of corresponding alignment holes **17** in the virtual environment modelling of the real piece **18**;

- calculate, for each spatial transformation model **16**, an alignment error between the virtual reference system and the real reference system based on a predetermined evaluation metric of the alignment; in particular, a root mean square error (*RMS*); and

- calculate the spatial transformation model **16** between the virtual reference system and the real reference system based on the calculated spatial transformation models and the alignment errors calculated.

In particular, to calculate the spatial transformation model **16** between the virtual reference system and the real reference system based on the calculated spatial transformation models and the alignment errors calculated, the control *software 1* is also designed so that, when executed, the industrial robot **2** becomes configured to select one of the calculated spatial transformation models based on the alignment errors calculated and a predetermined selection criterion.

The control *software 1* is also optionally designed so that, when executed, the industrial robot **2** becomes configured to determine (block **14**) the spatial transformation model **16** by executing a *best-fit* algorithm.

In particular, the *best-fit* algorithm, when executed, is designed to cause the industrial robot **2** to become configured to determine a rototranslation matrix representing the spatial transformation model **16**. In particular, the control *software 1*, in particular the *best-fit* algorithm, is designed so that, when the industrial robot **2** is executed, it becomes configured to determine a covariance matrix of the alignment points as a function of the characteristic points of the alignment holes **17** and the characteristic points of corresponding alignment holes **17** in the virtual environment modelling.

In addition, the *best-fit* algorithm is designed so that, when the industrial robot **2** is executed, it becomes configured to determine a decomposition to the singular values (*Singular Value Decomposition*, SVD) of the covariance matrix of the alignment points in order to determine (block **15**) the spatial transformation model **16**, in particular characterized by the minimum possible alignment error of the determined alignment errors, as a function of the determined decomposition to the singular values. In particular,

the *best-fit* algorithm is designed so that, when executed, the industrial robot **2** becomes configured to determine the alignment error, calculated as a function of the decomposition to the singular values of the covariance matrix of the alignment points.

Furthermore, the control *software 1* is optionally programmed so that, when executed, the robot **2** becomes configured to calculate a *scaling* factor, i.e. an index of volume variation of the real piece **18**, in order to improve the robustness of the spatial transformation model **16**. In particular, the calculated *scaling* factor is used in order to obtain a spatial transformation consistent with the real reference system. The control *software 1* is programmed so that, when executed, the robot **2** becomes configured to calculate the spatial transformation model **16** via quaternions so that the spatial transformation model **16** is free of the *gimbal lock* problem.

The control *software 1* of an industrial robot **2** is designed so that, when executed, the industrial robot **2** also becomes configured to determine (block **15**) the spatial transformation model **16** as a function of the alignment errors calculated. In particular, the spatial transformation model **16** is determined so that the alignment error calculated thereon is not greater than the alignment error calculated on a different spatial transformation model **16** determined. Therefore, the control *software 1* is programmed so that, when executed, the industrial robot **2** becomes configured to exclude sets of characteristic points on which the calculated spatial transformation models are mostly affected by measurement noise; this is because it is likely that one or more contact points, from which the characteristic points of an excluded set derive, are affected by measurement error (block **15**).

Based on what has been previously described, the advantages which the present invention allows to obtain are clear.

In particular, the control *software 1* of an industrial robot **2** is programmed so that, when executed, the industrial robot **2** becomes configured to autonomously determine the set of characteristic points with which the robot **2** determines the spatial transformation model **16** so as to exclude the spatial transformation models mostly affected by alignment error.

Consequently, the control *software 1* is programmed so that, when executed, the industrial robot **2** becomes configured to exclude the characteristic points mostly affected by measurement error, which would worsen the performance of the transformation model **16** produced. In detail, the Applicant has also observed that the use of several alignment holes offers the possibility to identify different rototranslation models calculated on

subsets of holes **17** always different, therefore the present invention allows to converge to the solution with the least possible error.

Furthermore, the present invention allows to select the holes **17** automatically, without this operation, of selecting the holes **17**, having to be carried out by the operator.

5 In addition, the control software **1** is programmed so that, when executed, the industrial robot **2** becomes configured to determine characteristic points of holes **17** without the need to employ external devices, such as laser probes or external contact probes, to perform measurements and without the need to employ external target devices such as reflective targets, *tooling balls* and others.

10 Furthermore, a further advantage that the control *software 1* has is that, when executed, the industrial robot **2** becomes configured to autonomously calculate the *scaling* factor.

In addition, the control *software 1* makes it unnecessary to implement and integrate an interface software for integration with the controller of the industrial robot **2**.

15

CLAIMS

1. Control *software* (1) for an industrial robot (2);

the control *software* (1) is loadable in, and executable by, computing resources of
5 the industrial robot (2) so that, when executed, the industrial robot (2) becomes configured to carry out operations on real pieces in a work environment;

the control *software* (1) is designed so that, when executed, the industrial robot (2) becomes configured to receive operation instructions to be carried out in the work environment and containing spatial coordinates, expressed in a virtual reference system,
10 of a virtual environment modelling of the work environment and to carry out the operations instructed;

the control *software* (1) is also designed so that, when executed, the industrial robot (2) becomes configured to calculate a spatial transformation model (16) to align the virtual reference system of the work environment, in the virtual environment modelling,
15 with a real reference system of the work environment in which the industrial robot (2) operates, in order to allow the latter to carry out operations in a work area based on instructions received;

with the aim of calculating the spatial transformation model (16) between the virtual reference system and the real reference system, the control *software* (1) is also designed
20 so that, when executed, the industrial robot (2) becomes configured to:

- cause (block 4) a contact feeler (3) of the industrial robot (2) to interact with a real piece (18) in the work area to determine, in the real reference system, spatial coordinates of a number of contact points of surfaces of the real piece (18) at alignment holes (17) made in the real piece (18);

25 - determine (block 10) the spatial coordinates of at least one characteristic point, in particular the centre, of each alignment hole (17) based on the spatial coordinates of one or more of the contact points relative to the alignment hole (17); and

- calculate (block 15) the spatial transformation model (16) between the virtual reference system and the real reference system based on the spatial coordinates of the at least one characteristic point of each alignment hole (17) and spatial coordinates of the
30 characteristic point of a corresponding alignment hole (17) in the virtual environment modelling of the real piece (18).

2. The control *software* (1) of an industrial robot (2) according to claim 1, wherein, in order to calculate the spatial transformation model (16) between the virtual reference system and the real reference system, the control *software* (1) is further designed so that, when executed, the industrial robot (2) becomes configured to:

5 - form (block 12) different sets of characteristic points of the alignment holes (17);
 - calculate (block 14), for each set of characteristic points of alignment holes (17), a spatial transformation model (16) based on the spatial coordinates of the characteristic points of the alignment holes (17) of the set and the spatial coordinates of characteristic points of corresponding alignment holes (17) in the virtual environment modelling of the
10 real piece (18);

 - calculate, for each spatial transformation model (16), an alignment error between the virtual reference system and the real reference system based on a predetermined evaluation metric of the alignment; and

 - determine (block 15) the spatial transformation model (16) between the virtual
15 reference system and the real reference system based on the calculated spatial transformation models (16) and the alignment errors calculated.

3. The control *software* (1) of an industrial robot (2) according to claim 2, wherein, in order to calculate (block 15) the spatial transformation model (16) between the virtual
20 reference system and the real reference system based on the calculated spatial transformation models (16) and the alignment errors calculated, the control *software* (1) is also designed so that, when executed, the industrial robot (2) becomes configured to select (block 15) one of the calculated spatial transformation models (16) based on the alignment errors calculated and a predetermined selection criterion.

25 4. The control *software* (1) of an industrial robot (2) according to claim 2 or 3, and further designed to cause, when executed, the industrial robot (2) to become configured to form (block 12) each of the different sets of characteristic points of the alignment holes (17) by selecting (block 13), from a plurality of different characteristic points, a number
30 of characteristic points for that set that are determined to satisfy a surface coverage condition of the real piece (18).

5. The control *software* (1) of an industrial robot (2) according to any one of the preceding claims, wherein, in order to determine the spatial coordinates of a characteristic

point of an alignment hole (17), the control *software* (1) of an industrial robot (2) is designed so that, when executed, the industrial robot (2) becomes configured to:

- calculate a plane on which the alignment hole lies (17) as a function of the spatial coordinates of the points of contact with the surface external to the hole (17), in

5 the vicinity of the same alignment hole (17);

- determine (block 5) a direction in which to position the contact feeler (3) so that the determined direction is axial to the hole (17), therefore orthogonal to the plane on which the hole lies (17) and control the contact feeler (3) to position it in the direction determined.

10

6. The control *software* (1) of an industrial robot (2) according to any one of the preceding claims, wherein, in order to determine the spatial coordinates of a characteristic point of an alignment hole (17), the control *software* (1) of an industrial robot (2) is designed so that, when executed, the industrial robot (2) becomes configured to:

15 - move (block 7) the contact feeler (3) so that it comes into contact with contact points, in particular with two contact points, with surfaces inside the hole (17), in order to determine spatial coordinates of first contact points and determine a first segment as a function the spatial coordinates of the first contact points in order to determine a first representative point, in particular the midpoint, of the first segment determined;

20 - determine a direction orthogonal to the first segment determined, move (block 7) the contact feeler (3) in the direction determined so that it comes into contact with contact points with surfaces inside the hole (17) to determine spatial coordinates of second contact points of the hole (17), determine a second segment as a function of the spatial coordinates of the second contact points of the hole (17) in order to determine a potential characteristic point, in particular the midpoint of the second segment determined; and

25

- determine (block 10) the characteristic point of the hole (17), in particular the centre, as a function of the potential characteristic point determined.

7. The control *software* (1) of an industrial robot (2) according to claim 5, wherein, in order to determine the spatial coordinates of a characteristic point of an alignment hole (17), the control *software* (1) of an industrial robot (2) is designed so that, when executed, the industrial robot (2) becomes configured to:

30

- determine (block 8) different sets of the contact points of the alignment hole (17) comprising one or more contact points of the hole (17) in order to determine, for each set

of contact points, a potential characteristic point, as a function of the spatial coordinates of the contact points of the set; and

- determine (block **10**) the characteristic point of the hole (**17**) as a function of the potential characteristic points determined and a predetermined criterion for calculating

5 characteristic points.

8. The control *software* (**1**) of an industrial robot (**2**) according to any one of the preceding claims, wherein, in order to determine the spatial coordinates of a characteristic point of an alignment hole (**17**), the control *software* (**1**) of an industrial robot (**2**) is
10 designed so that, when executed, the industrial robot (**2**) becomes configured to determine a reference system rotated as a function of the real reference system and a predefined angle in order to determine (block **10**) the characteristic point of the hole (**17**) as a function of the real reference system rotated.

9. The control *software* (**1**) of an industrial robot (**2**) according to any one of the preceding claims, wherein the control software (**1**) of an industrial robot (**2**) is designed so that, when executed, the industrial robot (**2**) becomes configured to:

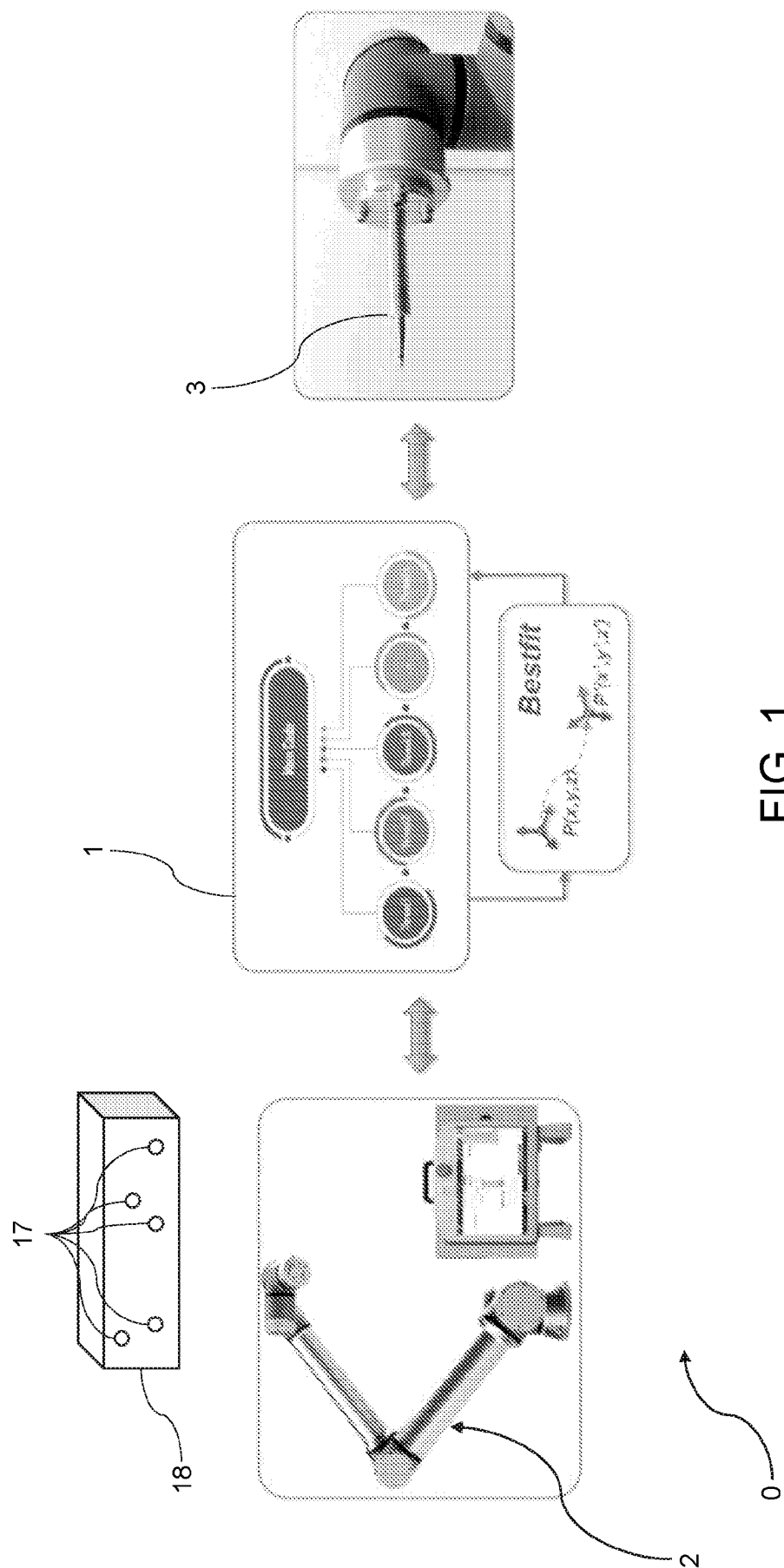
- communicate with force sensors of the industrial robot (**2**) adapted to provide an output indicative of the fact that the contact feeler (**3**) of the industrial robot (**2**) has come
20 into contact with the real piece (**18**) of the work area; and

- determine the spatial coordinates of the contact points in which the contact feeler (**3**) has come into contact with surfaces of the real piece (**18**) of the alignment holes (**17**) made in the real piece (**18**) of the work area in the real reference system as a function of the output provided by the force sensors.

25

10. The industrial robot (**2**) comprising a contact feeler (**3**), force sensors and computing resources designed to execute a control *software* (**1**) of an industrial robot (**2**) so that the industrial robot (**2**) becomes configured to operate according to any one of the claims **1-9**.

30



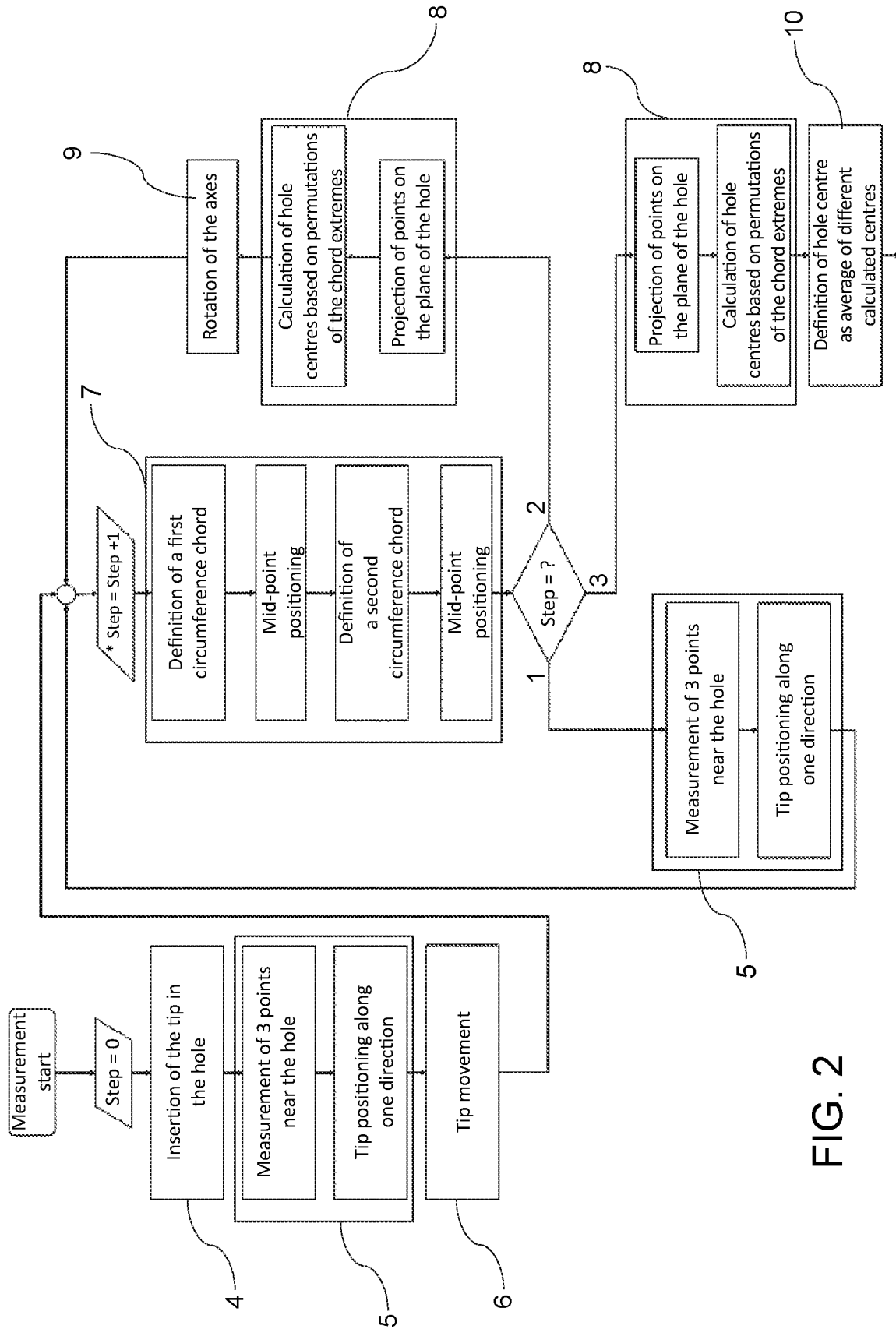
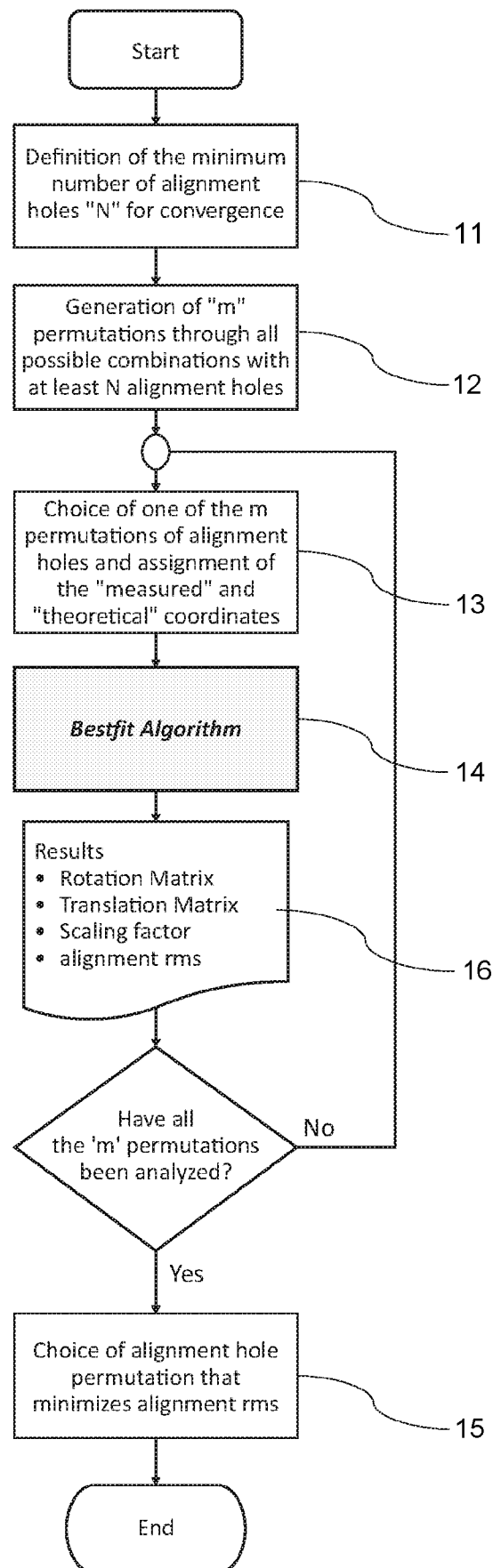


FIG. 2

FIG. 3



INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2024/055163

A. CLASSIFICATION OF SUBJECT MATTER INV. B25J9/16 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) B25J G05B		
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, COMPENDEX		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2022/104328 A1 (BRIGHT MACHINES INC [US]) 19 May 2022 (2022-05-19)	1,5 - 10
Y	paragraph [0023] - paragraph [0039] paragraph [0059] - paragraph [0065] paragraph [0119] - paragraph [0120] -----	2 - 4
X	KR 101 438 657 B1 (ILSHINTECH CO LTD [KR]) 12 September 2014 (2014-09-12)	1,5 - 10
Y	paragraph [0004] - paragraph [0034] ----- - / - -	2 - 4
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 18 September 2024		Date of mailing of the international search report 30/09/2024
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 De Santis, Agostino

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2024/055163

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ANCUTA PAUL-NICOLAE ET AL: "STUDY ON IMPROVING THE MEASUREMENT ACCURACY BY TOUCH PROBE WITH A COBOTIC MULTI-APPLICATION PLATFORM", INTERNATIONAL JOURNAL OF MECHATRONICS AND APPLIED MECHANICS, no. 11, 31 December 2022 (2022-12-31), pages 243-248, XP093111604, Bucharest ISSN: 2559-4397 the whole document -----	1 - 10
Y	TIAN WEI ET AL: "Determination of optimal samples for robot calibration based on error similarity", CHINESE JOURNAL OF AERONAUTICS, vol. 28, no. 3, 2 April 2015 (2015-04-02), pages 946-953, XP093206434, NL ISSN: 1000-9361, DOI: 10.1016/j.cja.2015.03.003 the whole document -----	2 - 4
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