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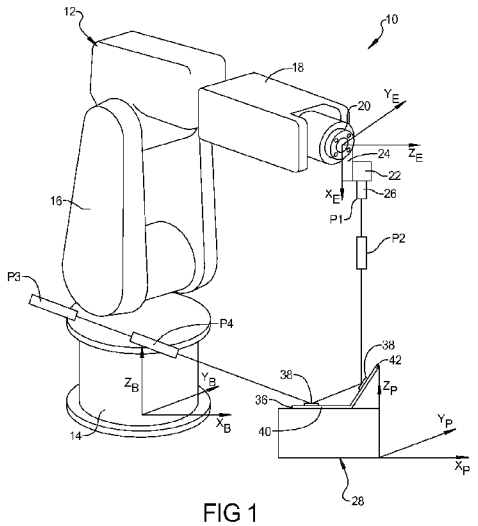


FIG 1

(57) Abstract: A calibration system (10) and method for calibrating an industrial robot (12) includes a focusable laser (22) for providing a laser beam and being mounted to the industrial robot (12) and a position sensitive calibration device (28) including at least one position sensitive device (38) for receiving position information from the laser beam and recording position and orientation of a pose of the industrial robot (12) and joint angles for that particular pose of the industrial robot (12) based on the position information, and a controller (72) communicating with the position sensitive calibration device (28) for providing a kinematics error model of the industrial robot (12), using a non- linear iterative optimization on the kinematics error model to identify robot external parameters and joint offset parameters from the recorded joint angles, and calibrating the robot external parameters and joint offset parameters of the industrial robot (12) to make the industrial robot (12) more precise and accurate.

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CALIBRATION SYSTEM AND METHOD FOR CALIBRATING INDUSTRIAL ROBOT

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] The present invention claims the priority date of co-pending United States Provisional Patent Application Serial Number 61/901,684, filed November 8, 2013.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0002] The present invention relates generally to industrial robots and, more particularly, to a calibration system and method for calibrating an industrial robot.

2. Description of the Related Art

[0003] In our modern era, the complexity of industrialization has played an important role in developing a strong economy, typically related to technological innovation in manufacturing. Manufacturing, in general, involves the development of large-scale productions utilizing industrial robots to create assembly lines. Generally, industrial robots reach high repeatability levels and for repetitive applications, they are able to perform such tasks successfully. Certainly repeatability demonstrates the quality of a modern industrial robot and their precise positioning capabilities.

[0004] However, it is also well known in the robot industry that while industrial robots have high repeatability, they also have low accuracy. Nevertheless, the recent demand of high accuracy applications such as welding tasks, micro assembly operations and surgery, etc., have increased the importance and interests of robot calibration among researchers over the last decades. Although there have been

significant improvements in terms of accuracy on the newly designed industrial robots, for such high accuracy applications, the accuracy of the robot alone is not enough. While there are several sources of inaccuracies (e.g. thermal expansions, gear errors, structural deformations, or even incorrect knowledge of link and joint parameters), the main source of inaccuracy lies in kinematic model parameter errors. The majority of the kinematic model parameters, (e.g. arm length, link offset, and link twist angles) are related to the structural mechanics of the robot manipulator. Typically, those parameters will not change by much once the industrial robot is sent from the factory and installed in manufacturing areas. However, some kinematic model parameters (e.g. joint offset) might be affected by the assembly or the replacement of motors and encoders.

[0005] According to researchers, around 90% of the inaccuracy in robot positioning is mostly due to errors in miscalculations on assumed initial positions of joint offset values of the industrial robot. Without an appropriate robot calibration, any robotic system will experience accuracy degradation over time. Due to this fact, robot calibration has been used to improve position and orientation accuracy of industrial robots by identifying inaccuracies in the kinematic model parameters in order to create a more accurate kinematics model that better fits to the real industrial robot.

[0006] Because industrial robots have high repeatability, but low accuracy, often, wrong assumptions on real links parameters or even small offsets exist in the individual robot joints that lead to errors in the internal kinematic model equations and as a consequence, affecting the accuracy of the robotic system. There are several robot calibration systems and approaches developed in the industry as well as in the academia. However, most of them are expensive or their procedures are time

consuming and, therefore, they are difficult to use extensively in the manufacturing plants. Therefore, there is a need in the art for a new calibration method for industrial robots that improves the accuracy of the robots significantly by using a new fast, low cost, and automated robot calibration system.

SUMMARY OF THE INVENTION

[0007] Accordingly, the present invention is a calibration system for calibrating an industrial robot. The calibration system includes a focusable laser for providing a laser beam and mounted to the industrial robot and a position sensitive calibration device including at least one position sensitive device for receiving position information from the laser beam and recording position and orientation of a pose of the industrial robot and joint angles for that particular pose of the industrial robot based on the position information. The calibration system also includes a controller communicating with the position sensitive calibration device for providing a kinematics error model of the industrial robot, using a non-linear iterative optimization on the kinematics error model to identify robot external parameters and joint offset parameters from the recorded joint angles, and calibrating the robot external parameters and the joint offset parameters of the industrial robot to make the industrial robot more precise and accurate.

[0008] In addition, the present invention is a method for calibrating an industrial robot including the steps of providing a focusable laser mounted to the industrial robot and providing a position sensitive calibration device having at least one position sensitive device (PSD). The method also includes the steps of aiming a laser beam from the focusable laser at a center of the at lease one PSD to find a beam position of a pose of the industrial robot and recording joint angles for that particular

pose of the industrial robot by a controller based on the beam position. The method further includes the steps of providing a kinematics error model of the industrial robot for the controller, using a non-linear iterative optimization on the kinematics error model by the controller to identify robot external parameters and joint offset parameters from the recorded joint angles, and calibrating the robot external parameters and joint offset parameters of the industrial robot to make the industrial robot more precise and accurate.

[0009] One advantage of the present invention is that a new calibration system and method are provided for automatically calibrating industrial robots. Another advantage of the present invention is that the calibration method is not only able to compute joint offset parameters of the industrial robot, but is also capable of simultaneously calibrating the robot's frame relationship. Yet another advantage of the present invention is that the calibration system includes a new portable and wireless position sensitive calibration device. Still another advantage of the present invention is that, during the whole calibration method, the procedure of aiming a laser beam at the center of each position sensitive device (PSD) of the position sensitive calibration device only repeats twice, so the approach is simpler and less time consuming than any other previous methods. A further advantage of the present invention is that the calibration system is a simple low-cost design easy to operate by the user. Yet a further advantage of the present invention is that the calibration system is robust to external disturbances commonly found in production lines. Still a further advantage of the present invention is that the calibration system is able to be used by any industrial robot manipulator. Another advantage of the present invention is that the calibration system is a fast automatic robot calibration system compared to existing calibration systems.

[0010] Other features and advantages of the present invention will be readily appreciated, as the same becomes better understood, after reading the subsequent description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a perspective view of one embodiment of a calibration system, according to the present invention, illustrated in operational relationship with an industrial robot.

[0012] FIG. 2 is an enlarged view of a portion of the calibration system and industrial robot of FIG. 2.

[0013] FIG. 3 is a perspective view of a position sensitive device of the calibration system of FIG. 1.

[0014] FIG. 4 is a schematic view of a circuit board used for the position sensitive calibration device of FIG. 3.

[0015] FIG. 5 is a schematic view of the calibration system, including internal components of the position sensitive calibration device of FIG. 3 with networking details, and industrial robot of FIG. 1.

[0016] FIG. 6 is a screen view of a graphical user interface for the calibration system of FIGS. 2 through 5.

[0017] FIG. 7 is a schematic view of a triangulation technique using a laser and camera for the calibration system of FIGS. 2 through 5.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

[0018] Referring to the drawings and in particular FIGS. 1 and 2, one embodiment of a calibration system 10, according to the present invention, is shown

in operational relationship with an industrial robot, generally indicated at 12. The industrial robot 12 is of an AAB industrial robot type having a six degree of freedom (6-DOF) robot manipulator (IRB 120) as known in the art of industrial robots. The industrial robot 12 has a base 14, a moveable body 16 mounted on the base 14, a moveable robot manipulator or arm 18 mounted on the body 16, and tool center point (TCP) 20 mounted on the arm 18. It should be appreciated that the industrial robot 12 may be any suitable type of industrial robot. It should also be appreciated that the calibration system 10 can be used not only to calibrate a frame relationship, but also a joint offset of the industrial robot 12 simultaneously, thus improving speed during the whole calibration process.

[0019] Referring to FIGS. 1 through 3, the calibration system 10 includes a focusable laser 22, an adapter fixture 24, a camera 26, and a position sensitive calibration device (PSCD), generally indicated at 28. The focusable laser 22 is of a laser pointer type. The camera 26 is of a digital type. The adapter fixture 24 has a generally "L" shape. The focusable laser 22 is mounted on the adapter fixture 24, as well as the camera 26 via a servo motor 29. The adapter fixture 24 is rigidly attached to the tool center point (TCP) 20 of the industrial robot 12 by a suitable mechanism such as fasteners 30 such that the laser beam is tuned to align its orientation toward the X-axis of the frame of the TCP 20. The focusable laser 22, camera 26, and servo motor 29 are connected by cables 32 to a source of power (not shown). It should be appreciated that the focusable laser 22 produces a laser beam that is directed to the PSCD 28.

[0020] Referring to FIGS. 1 and 3, the PSCD 28 is shown. The PSCD 28 is portable and disposed on a support surface below the TCP 20 of the industrial robot 12. The PSCD 28 includes a frame 34, a mounting fixture 36 mounted on the

frame 34, and at least one position sensitive device (PSD) 38, preferably a plurality of PSDs 38 to perform both calibration methods to be described. In the embodiment illustrated, the PSCD 28 includes two PSDs 38 fixed with an angle between them. The mounting fixture 36 includes a base portion 40 and a side portion 42 extending outwardly at an angle to the base portion 40. The base portion 40 is generally rectangular in shape, but may be any suitable shape. The base portion 40 is mounted to the top of the frame 34 by a suitable mechanism such as fasteners 44. The base portion 40 has an aperture 46 extending therethrough to receive one PSD 38. The side portion 42 has a generally triangular shape, but may be any suitable shape. The side portion 42 includes an aperture 48 extending therethrough to receive one PSD 38. The PSDs 38 are secured to the base portion 40 and side portion 42 by a suitable mechanism such as fasteners 50. As illustrated in FIG. 3, the angle between the PSDs 38 is approximately 120 degrees. The PSCD 29 may also include a transparent cover 52 disposed over the mounting fixture 36. It should be appreciated that the PSCD 28 is a wireless device to be described in connection with FIG. 5.

[0021] For the PSCD 28, the PSDs 38 are of a segmented type used for high precision feedback. The segmented PSDs 38 have a higher resolution than 0.1μm in theory. Even under the experimental condition, the resolution of the segmented PSD 38 may reach approximately 2μm. It should be appreciated that the calibration system 10 requires a laser beam to shoot into one PSD 38 in a way that the reflection lands into the other PSD 38. It should also be appreciated that more than one hundred twenty (120) degrees will make it difficult to find a good reflection from one PSD 38 to the other, and less than one hundred twenty (120) degrees will make the calibration system 10 less accurate. It should be appreciated that the location of the fixture 36 of the PSCD 28 is known with respect to the workpiece frame 34 of the

PSCD 28 while its location with respect to the base 14 of the industrail robot (12) is unknown.

[0022] Referring to FIG. 4, a schematic of a circuit, generally indicated at 52, used for the PSCD 28 is shown. Before the actual calibration task, a signal processing was designed and set up in order to test the properties of the PSDs 38. Since the active chip area of the PSDs 38 is comparatively small, the measurements had to be performed applying high precision tools to position the laser beam over the surface of the PSDs 38. Therefore, a Signatone CAP-945 high precision probe was used to acquire sufficient accuracy to calibrate the chip of the PSDs 38. The purpose of this circuit 52 is to process the PSDs 38 chip raw output to be able to determine the relative 2D position of the laser beam on the surface of the PSDs 38. The design can be structured into three functional stages. In the first stage the output signal of the four PSD electrodes 53 is amplified using operational amplifiers 54. The second and third stages are used to perform the computations needed to be able to determine the spot position. In the second stage, summing amplifiers 56 and differential amplifiers 58 are occupied to generate the input signals for the divider ICs 60 (third stage). It should be appreciated that the PSDs 38 and circuit 52 form a data acquisition system (DAS) to gather the feedback information needed for a robot controller 72 (FIG. 5) of the industrial robot 12 to ensure system accuracy and reliability. It should be appreciated that the circuit 52 is mounted on a circuit board and disposed within the frame 34 of the PSCD 28.

[0023] As illustrated in FIG. 5, the PSCD 28 must be able to carry the signal information from the PSDs 38 to the robot controller 72 in order to control the industrial robot 12 to the desired state. Figure 5 illustrates the basic internal components of the PSCD 28 as well as the interaction between the PSCD 28 and the

robot controller 72. Within the frame 34, the PSCD 28 includes the circuit 52 electrically connected to the PSDs 38, a universal serial bus (USB) analog to digital (A/D) converter 62 electrically connected to the circuit 52, and a USB wireless hub 64 electrically connected to the USB A/D 62. After the circuit 52 receives the raw data from the two PSDs 38, the signals are taken by the wireless USB hub 64 from the USB A/D 62. The feedback produced by the PSCD 28 has around 47ms of delay. The signals are received by a USB wireless transceiver 66 and communicated to a PC-based controller 68. Once the data reaches the PC-based controller 68, a graphical user interface (GUI) 74 (FIG. 6) to be described on the controller 68 is used by the operator so that the TCP 20 of the industrial robot 12 is moved to the desired position relative to the PSDs 38. The operator uses the GUI 74 to communicate from the controller 68 through a local area network (LAN) 70 to a robot controller 72 communicating with the industrial robot 12 to move the TCP 20. The robot controller 72 is an ABB robot controller (IRC5 Compact) known in the art. It should be appreciated that the robot controller 72 is conventional and known in the art to control the industrial robot 12.

[0024] Referring to FIG. 6, the calibration system 10 includes a graphical user interface (GUI) 74 on the controller 68 to provide for a user-friendly representation of the calibration process. The GUI 74 shows user option buttons 76 and real time process of PSD-based localization servo. The GUI 74 is embedded in the computer-based controller 68, as well as the calibration solution and algorithms. It should be appreciated that FIG. 6 also illustrates an experiment made moving a laser beam in square patterns 78 on the surface of the PSDs 38 for mapping and performance purposes.

[0025] A method, according to one embodiment of the present invention, for calibrating the industrial robot 12 is disclosed. The calibration process is completed by locating the TCP 20 and the focusable laser 22 at four different positions (position (P) 1 – 4) as illustrated in FIG. 1. During the calibration process, a laser beam from the focusable laser 22 is aimed to the center of the first PSD 38 in the side portion 42 of the mounting fixture 36 of the PSCD 28, i.e. PSD1, with a reflection orientation towards the second PSD 38 in the base portion 40 of the mounting fixture 36 of the PSCD 28, i.e. PSD2. Once an operator finds those two centers, the operator can also find a line that passes between them. At that time, the operator has found position one (P1), and the process is then repeated using the same orientation to find position two (P2). Then, the same process is used to find position three (P3) and position four (P4). The reflected line is a virtual linear constraint, meaning that the TCP 20 and the laser beam are constrained to move along that reflected line to calibrate the robot's external parameters. The PSCD 28 is located in an unknown position with respect to the industrial robot 12. During the whole calibration process, the procedure of aiming the laser beam at the center of each PSD 38 only repeats twice, so the approach is simpler and less time consuming than previous methods. Once the aiming procedure is done, the joint angles for that particular pose of the industrial robot 12 are recorded. Hence, four sets of robot joint angles can be recorded by the robot controller 72. Based on this recorded data along with the kinematic error model of the industrial robot 12, a calibration method is employed by the robot controller 72. Based on the recorded joint angles and robot forward kinematics, mathematically, the method of the present invention uses a non-linear iterative optimization technique to identify the robot parameters and joint offset parameters from the data recorded. Using different positions, poses and orientations,

errors in the kinematic parameters are minimized. As a final step for the calibration system 10, after all robot parameter errors are found, the controller 72 calibrates the robot external parameters and joint offset parameters of the industrial robot 12 and the industrial robot 12 is then compensated internally by the controller 72 based on the calibrated robot external parameters and joint offset parameters to make the industrial robot 12 more precise and accurate. It should be appreciated that the calibration method is not only able to compute the joint offset parameters of the industrial robot 12, but is also capable of simultaneously calibrating the robot's workpiece relationship by using the PSCD 28.

Analysis of Kinematics Error Model

[0026] For the industrial robot 12 with n (n=6) joints illustrated in Figure 1, a forward kinematics error model can be represented by the following equation,

[0027] $$^{B}T_{E} = \prod_{i=1}^{n} A_i \qquad (1)$$

[0028] where $^{B}T_{E}$ is a transformation matrix that expresses the position and orientation of the TCP 20 frame {E} of the arm 18 with respect to the robot base 14 frame {B}; A_i is a homogeneous transformation matrix associated with link i and joint i. By Denavit-Hartenberg (DH) model, which is widely used to represent the robot forward kinematics error model, each homogeneous transformation matrix A_i can be written as,

[0029] $$A_i = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

[0030] where the four quantities θ_i , a_i, d_i and α_i, denotes the joint angle, link length, link offset and link twist respectively. They are all parameters associated with link i and joint i. $c\theta_i$ denotes $cos(\theta_i)$ while $s\theta_i$ denotes $sin(\theta_i)$.

[0031] The same forward kinematics error model can be used to include the joint offset of each link as follows; let δ_i denote the offset value of the joint i, then each homogeneous transformation can be rewritten as,

[0032]
$$\tilde{A}_i = \begin{bmatrix} c\tilde{\theta}_i & -s\tilde{\theta}_i c\alpha_i & s\tilde{\theta}_i s\alpha_i & a_i c\tilde{\theta}_i \\ s\tilde{\theta}_i & c\tilde{\theta}_i c\alpha_i & -c\tilde{\theta}_i s\alpha_i & a_i s\tilde{\theta}_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

[0033] where $c\tilde{\theta}_i$ denotes $cos(\theta_i + \delta_i)$ and $s\tilde{\theta}_i$ denotes $sin(\theta_i + \delta_i)$. Combining the joint offset and substituting (3) into (1), forward kinematics ${}^{B}T_{E}$ with the offset is written as,

[0034]
$${}^{B}T_{E} = \prod_{i=1}^{6} \tilde{A}_i = \tilde{A}_1\tilde{A}_2\tilde{A}_3\tilde{A}_4\tilde{A}_5\tilde{A}_6 = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

[0035] It should be appreciated that joint 1 depends on the base 14 of the industrial robot 12 so in equation (4) there are five unknown parameters, which are the last five offsets δ_i ($i = 2,3,4,5,6$).

General PSD's Servo Control Strategy

[0036] The geometry of the PSCD 28 is known and therefore a fixed orientation is guaranteed. Once the laser beam is moved into the active area of the first PSD 38, the reflection will approximately also hit the second PSD 38. In other words, an orientation can be found such that the laser beam will hit very close to the center of both PSDs 38, and such orientation will be the same for P3 and P4 (FIG. 1). This can also be done for P1 and P2. The only requirement is that orientation in the

PSDs 38 will have to be fixed, e.g., it will have to be in a Z plane (completely flat) surface and X and Y orientation of the mounting fixture 36 has to approximately align with the X and Y orientation of the base 14 of the industrial robot 12. Once the orientation is fixed, the position control can be focused. Using servo control (using camera 26 only) of the servo motor 29, first ensure that the laser beam from the laser 22 will hit in the active area of the PSD 38 (moving parallel to the Z axis) and at the same time obtain depth information needed for the next steps as shown in the Figure 7.

[0037] The laser beam from the laser 22 is used to partition the axes easily and the depth information is obtained online. The camera 26 is mounted at an angle to the laser beam forming a triangle. The depth of the image features can be computed accurately using the triangular relationship. Furthermore, the height information between the focusable laser 22 and the object surface is computed to control the z-axis with respect to the arm 20 separately. After the servo control is done, the PSD servo control is used for fine localization. It should be appreciated that position control only is being used because the orientation found at the beginning will remain constant during this process and are moving parallel to a z plane.

[0038] The controller 74 is assumed to control the laser 22 making movements on a plane parallel to the surface of the PSD 38. Therefore any change in position of the end-effector equals the change in position on the surface of the PSD 38.

[0039] Let ${}^{P}T_{B}$ be the homogeneous transformation matrix of the base frame "{B}" of the base 14 with respect to the PSD frame "{P}" of the PSCD 28 as illustrated in FIG. 1;

[0040] $${}^{P}T_{B}=\begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix}$$

[0041] To obtain the relationship between the velocity on the end effector and the point projected in the surface of the PSD 38, lets define;

[0042] $$\xi = [v \quad w]^{T}$$

[0043] Where ξ represent the velocity, v is the translational velocity vector component and w is the angular velocity vector componet.

[0044] Since the PSD 38 is fixed and "R" is constant, the equation is:

[0045] $$\xi_{P} = \begin{bmatrix} R & 0_{3x3} \\ 0_{3x3} & R \end{bmatrix} \xi_{B}$$

[0046] Where ξ_{P} is the velocity of the end effector or TCP 20 with respect to the frame 34 of the PSCD 28 and ξ_{B} is the velocity of the end effector or TCP 20 with respect to the base 14 of the industrial robot 12.

[0047] Then;

[0048] $$\xi_{B} = \begin{bmatrix} R^{T} & 0_{3x3} \\ 0_{3x3} & R^{T} \end{bmatrix} \xi_{P}$$

[0049] Now let $s(t)$ denote the vector of feature values that can be obtain by the PSD 38 feedback. Let also $\dot{s}(t)$ be the corresponding velocity as follows;

[0050] $$\dot{s}(t) = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

[0051] Given that there is no moving or rotating along the Z axis (since it's a planar movement), that is; $v_{z} = 0$ and $w = 0$

[0052] Then the above can be combined, resulting in the following:

[0053] $$\dot{s}(t) = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = R v_{B}$$

[0054] Where $v_b=[v_x \ v_y \ \omega]^T$ denotes the three components of the translational velocity with respect to the base 14 of the industrial robot 12.

[0055] Now the error function can be defined as;

[0056] $$e(t) = s_d - s(t)$$

[0057] $$\dot{e}(t) = \dot{s}_d - \dot{s}(t)$$

[0058] Where s_d is the desired position on the surface of the PSD 38.

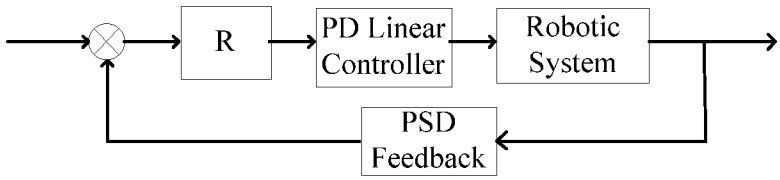
[0059] By inverting the previous equation, a desired end effector or TCP 20 velocity v_E can be obtained with respect to the base 14;

[0060] $$v_E = \begin{bmatrix} v_x \\ v_y \end{bmatrix} = R^{-1}\dot{s}(t)$$

[0061] The following controller can be used:

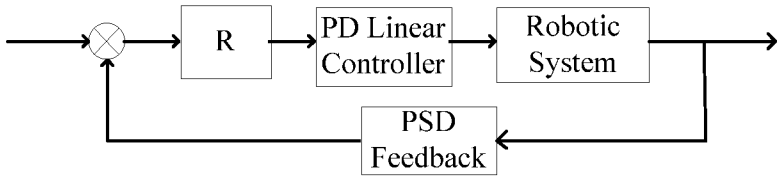
[0062] $$u = \ddot{y}^d + k_v\dot{e} + k_p e$$

[0063]



[0064] Because the orientation previously is set once the center of the PSD 38 is hit, the reflection should be somewhere in the active area of the second PSD 38, very close to the origin as well. At this point, the distance of the laser line ("h" information) should be given originally by the servo control, therefore, it can be used to modify the kinematics error model so that the point can be fixed since the center of the first PSD 38 has already been found as the new end effector or TCP 20 position and orientation.

[0065] This will allow use of a third separate control method that focuses only on the orientation along that point, as shown below;

[0066] 

[0067] lets now define again;

[0068] $\xi = [v \quad w]^T$

[0069] Where ξ represent the velocity, v is the translational velocity vector component and w is the angular velocity vector componet.

[0070] Since the second PSD 38 (PSD2) is fixed and "R" is still constant, the following equation can be written as:

[0071] $$\xi_P = \begin{bmatrix} R_1 & 0_{3x3} \\ 0_{3x3} & R_2 \end{bmatrix} \xi_B$$

[0072] Were ξ_P is the velocity of the TCP 20 with respect to the frame 34 of the PSCD 28 and ξ_B is the velocity of the end effector or TCP 20 with respect to the base 14 of the industrial robot 12.

[0073] Then;

[0074] $$\xi_B = \begin{bmatrix} R_1^T & 0_{3x3} \\ 0_{3x3} & R_2^T \end{bmatrix} \xi_P$$

[0075] Now $s(t)$ denotes the vector of feature values that can be obtain by the PSD2 feedback and $\dot{s}(t)$ be the corresponding velocity as follows:

[0076] $$\dot{s}(t) = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

[0077] Given that the orientation is only moved along the point found in step 2 (center of the first PSD 38) and moreover the distance between the first PSD (38) (PSD1) and PSD2 is known, the above can be combined, resulting in the following;

[0078] $$\dot{s}(t) = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = R_2 w_B$$

[0079] Where $w_{b=[w_x \quad w_y \quad 0]^T}$ denotes the three components of the angular velocity of the point found by PSD1 with respect to the base 14 of the industrial robot 12. It should be apprecited that only need to control Yaw and Pitch because Roll will have no effect on the position of the laser 22 in PSD2.

[0080] Now the error function can be defined as;

[0081] $$e(t) = s_d - s(t)$$

[0082] $$\dot{e}(t) = \dot{s}_d - \dot{s}(t)$$

[0083] Where s_d is the desired position on the surface of the PSD 38 (again (0,0))

[0084] By inverting the previous equation, a desired end effector or TCP 20 (position found by PSD1) angular velocity w_B with respect to the base 14 can be obtained;

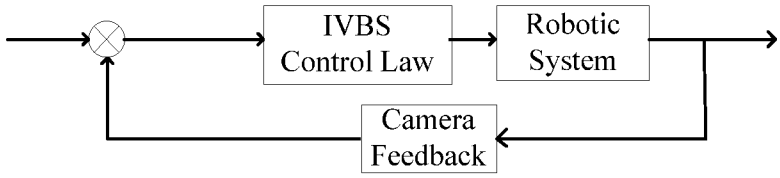
[0085] $$w_B = \begin{bmatrix} w_x \\ w_y \end{bmatrix} = R_2^{-1} \dot{s}(t)$$

[0086] The following controller can be used once again:

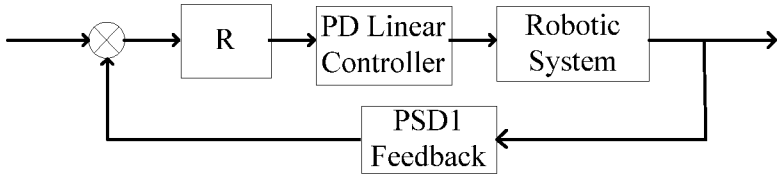
[0087] $$u = \ddot{y}^d + k_v \dot{e} + k_p e$$

[0088] Depending on how accurate, the distance of the laser line on step 2 can be determined. It can be chosen to go back and check for PSD1 to see if the laser beam is still in the center of the PSD1 or not and perform the control again (position control) and recheck in PSD2 and so on. Therefore, it is important to get h accurately the first time to save time. Finally, the system will switch between 3 different controllers as follows:

[0089]

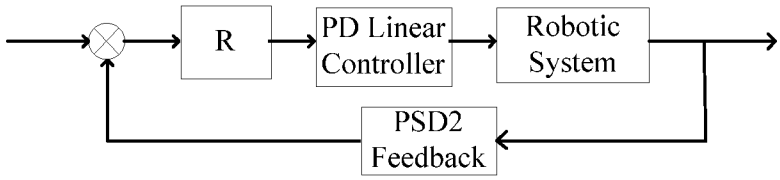


[0090]



[0091] Modify Kinematics Error Model with h information:

[0092]



[0093] Using this control strategy the problems of dependance between position and orientation of the laser 22 at both PSDs 38 is overcome by decoupling the problem into two control strategies. Therefore, it is not necessary to have both PSDs 38 feedback signals at the same time. Once the position and orientation in P1 (see FIG. 1) is found, the orientation of P2 can become constant and move along the laser beam line only changing position. This will guarantee that the laser 22 will roughly align in center of both PSDs 38 again so only the last two (2) control strategies are used for fine positioning if needed (it should be appreciated that fine positioning may not be needed again). It should be appreciated that the same can be applied to P3 and P4 in FIG. 1.

Joint Offset Calibration

[0094] The calibration process, shown in FIG. 1, is performed by locating the TCP 20 and the focused laser 22 several times at different locations. Because the focused laser 22 is rigidly fixed on the TCP 20, the jth position of the focused laser 22 is denoted as $P_j = \begin{bmatrix} P_{xj} & P_{yj} & P_{zj} \end{bmatrix}^T$ ($j = 1,2,3,4$) and the unit directional vector of the laser beam line as, $\begin{bmatrix} m_j & n_j & p_j \end{bmatrix}^T$. Replacing the recorded joint angles into the forward kinematics error equation (4), they can be decomposed as follows,

[0095]
$$\begin{bmatrix} m_j \\ n_j \\ p_j \\ 0 \end{bmatrix} = ({}^{B}T_{E})_j \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} T_{11} \\ T_{21} \\ T_{31} \\ 0 \end{bmatrix}_j, j = 1,2,3,4 \qquad (5)$$

[0096]
$$\begin{bmatrix} P_{xj} \\ P_{yj} \\ P_{zj} \\ 0 \end{bmatrix} = ({}^{B}T_{E})_j \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} T_{14} \\ T_{24} \\ T_{34} \\ 1 \end{bmatrix}_j, j = 1,2,3,4 \qquad (6)$$

[0097] Because P_1 and P_2 are in the same laser beam line 1, they have following relationships,

[0098]
$$\begin{aligned} m_1 &= m_2 \\ n_1 &= n_2 \\ p_1 &= p_2 \end{aligned} \qquad (7)$$

[0099] and,

[00100]
$$\frac{P_{x1} - P_{x2}}{m_1} = \frac{P_{y1} - P_{y2}}{n_1} = \frac{P_{z1} - P_{z2}}{p_1} \qquad (8)$$

[00101] Hence, for these two positions of the focused laser 22, the error is squared.

[00102]
$$\psi_1 = \psi_{11}^2 + \psi_{12}^2 + \psi_{13}^2 + \psi_{14}^2 \qquad (9)$$

[00103] Where

[00104]
$$\psi_{11} = (T_{11})_2 - (T_{11})_1 \qquad (10)$$

[00105] $$\psi_{12} = (T_{21})_2 - (T_{21})_1 \quad (11)$$

[00106] $$\psi_{13} = \frac{(T_{11})_1}{(T_{21})_1} - \frac{(T_{14})_2 - (T_{14})_1}{(T_{24})_2 - (T_{24})_1} \quad (12)$$

[00107] $$\psi_{14} = \frac{(T_{21})_1}{(T_{31})_1} - \frac{(T_{24})_2 - (T_{24})_1}{(T_{34})_2 - (T_{34})_1} \quad (13)$$

[00108] Similarly, consider P_3 and P_4 are in the same laser beam line 2, they have the same relations. Then another squared error is obtained.

[00109] $$\psi_2 = \psi_{21}^2 + \psi_{22}^2 + \psi_{23}^2 + \psi_{24}^2 \quad (14)$$

[00110] Where

[00111] $$\psi_{21} = (T_{11})_4 - (T_{11})_3 \quad (15)$$

[00112] $$\psi_{22} = (T_{21})_4 - (T_{21})_3 \quad (16)$$

[00113] $$\psi_{23} = \frac{(T_{11})_3}{(T_{21})_3} - \frac{(T_{14})_4 - (T_{14})_3}{(T_{24})_4 - (T_{24})_3} \quad (17)$$

[00114] $$\psi_{24} = \frac{(T_{21})_3}{(T_{31})_3} - \frac{(T_{24})_4 - (T_{24})_3}{(T_{34})_4 - (T_{34})_3} \quad (18)$$

[00115] Hence the unknown parameters, i.e. the last offsets δ_i ($i = 2,3,4,5,6$), are found by minimizing the total sum of the squared errors.

[00116] $$\Psi = argmin \sum_{k=1}^{2} \psi_k \quad (19)$$

[00117] Because of the complexity of the optimization problem with 5 parameters, the well-known Levenberg-Marquardt algorithm (LMA) is used to minimize the sum of squared errors.

Robot Frame Calibration

[00118] With the joint offset calculations ahead, the $({}^{B}T_{E})_j$ ($j = 1,2,3,4$) can also be found. Let R and t be the rotation matrix and the translation vector of ${}^{B}T_{D}$, respectively. Denote L_D and L_B as direction vectors of the laser beam from the

focused laser 22 with respect to the PSCD 28 {D} and the base 14 {B} frames, respectively. Considering the relationship between L_D and L_B, the following equation can be found,

[00119] $$L_B = RL_D = qL_Dq^* \quad (20)$$

[00120] Where

[00121] $$q = cos\left(\frac{\theta}{2}\right) + sin\left(\frac{\theta}{2}\right)\vec{k} \quad (21)$$

[00122] Substituting (21) into (20), the following results:

[00123] $$L_D - L_B = tan\left(\frac{\theta}{2}\right)(L_D + L_B)\times\vec{k} \quad (22)$$

[00124] Let $\Omega(v)$ denote a skew symmetric matrix, thus equation (22) can be written as;

[00125] $$\Omega(v)\vec{g} = b \quad (23)$$

[00126] where $L_D + L_B = a$, $L_D - L_B = b$ and $\vec{g} = tan(\theta/2)\vec{k}$. It should be appreciated that a minimum of two laser beams are needed.

[00127] Let $C = [\Omega(a_1) \quad \Omega(a_2)]^T$ and $D = [b_1 \quad b_2]^T$, then equation (23) can be expressed as:

[00128] $$C\vec{g} = D \quad (24)$$

[00129] From equation (24), $\vec{g}$ can be solved by using least squared method. $\vec{k}$ and θ can be computed by;

[00130] $$\vec{k} = \frac{\vec{g}}{\|\vec{g}\|} \quad (25)$$

[00131] $$\theta = 2\times atan\left(\frac{\vec{g}_{max}}{\vec{k}_{max}}\right) \quad (26)$$

[00132] Hence the rotation matrix R can be computed as follows:

[00133] $$R=\begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \quad (27)$$

[00134] where,

[00135]
$$\begin{aligned} R_{11} &= k_x^2(1-\cos(\theta))+\cos(\theta) \\ R_{12} &= k_x k_y(1-\cos(\theta))-k_z\sin(\theta) \\ R_{13} &= k_z k_x(1-\cos(\theta))+k_y\sin(\theta) \\ R_{21} &= k_x k_y(1-\cos(\theta))+k_z\sin(\theta) \\ R_{22} &= k_y^2(1-\cos(\theta))+\cos(\theta) \\ R_{23} &= k_y k_z(1-\cos(\theta))-k_x\sin(\theta) \\ R_{31} &= k_z k_x(1-\cos(\theta))-k_y\sin(\theta) \\ R_{32} &= k_y k_z(1-\cos(\theta))+k_x\sin(\theta) \\ R_{33} &= k_z^2(1-\cos(\theta))+\cos(\theta) \end{aligned}$$

[00136] For each laser beam, the following results:

[00137] $$\begin{bmatrix} x_{1Bk} \\ y_{1Bk} \\ z_{1Bk} \end{bmatrix}=\begin{bmatrix} x_{0Bk} \\ y_{0Bk} \\ z_{0Bk} \end{bmatrix}+\lambda_k\begin{bmatrix} m_{Bk} \\ n_{Bk} \\ p_{Bk} \end{bmatrix}, k=1,2 \quad (28)$$

[00138] then;

[00139] $$\begin{bmatrix} x_{1Bk} \\ y_{1Bk} \\ z_{1Bk} \end{bmatrix}=R\begin{bmatrix} x_{0Dk} \\ y_{0Dk} \\ z_{0Dk} \end{bmatrix}+\begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}+\lambda_k\begin{bmatrix} m_{Bk} \\ n_{Bk} \\ p_{Bk} \end{bmatrix}, k=1,2 \quad (29)$$

[00140] where $[x_{0Dk} \quad y_{0Dk} \quad z_{0Dk}]^T$ denotes the center point of k^{th} PSD 38 with respect to PSCD 28 {D}; $[x_{0Bk} \quad y_{0Bk} \quad z_{0Bk}]^T$ denotes the center point of k^{th} PSD 38 with respect to base 14 {B}; $[x_{1Bk} \quad y_{1Bk} \quad z_{1Bk}]^T$ denotes the k^{th} TCP 20 position with respect to the base 14 {B}, which can be obtained by the robot controller 72.

[00141] Let $[a_{xk} \quad a_{yk} \quad a_{zk}]^T = R[x_{0Dk} \quad y_{0Dk} \quad z_{0Dk}]^T$, then the following relations can be obtained,

[00142] $$\frac{x_{1Bk}-a_{xk}-t_x}{M_{Bk}}=\frac{y_{1Bk}-a_{yk}-t_y}{N_{Bk}}=\frac{z_{1Bk}-a_{zk}-t_z}{p_{Bk}} \quad (30)$$

[00143] In these relationships, the values of $\begin{bmatrix} t_x & t_y & t_z \end{bmatrix}^T$ are unknown and can be computed by:

[00144]
$$\begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} = \begin{bmatrix} \dfrac{(z_{1B2} - z_{1B1}) - (a_{z2} - a_{z1}) - \dfrac{P_{B2}}{M_{B2}}(x_{1B2} - a_{x2}) + \dfrac{P_{B1}}{M_{B1}}(x_{1B1} - a_{x1})}{\dfrac{P_{B1}}{M_{B1}} - \dfrac{P_{B2}}{M_{B2}}} \\ \dfrac{(x_{1B2} - x_{1B1}) - (a_{x2} - a_{x1}) - \dfrac{M_{B2}}{N_{B2}}(y_{1B2} - a_{y2}) + \dfrac{M_{B1}}{N_{B1}}(y_{1B1} - a_{y1})}{\dfrac{M_{B1}}{N_{B1}} - \dfrac{M_{B2}}{N_{B2}}} \\ \dfrac{(y_{1B2} - y_{1B1}) - (a_{y2} - a_{y1}) - \dfrac{N_{B2}}{P_{B2}}(z_{1B2} - a_{z2}) + \dfrac{N_{B1}}{p_{B1}}(z_{1B1} - a_{z1})}{\dfrac{N_{B1}}{P_{B1}} - \dfrac{N_{B2}}{P_{B2}}} \end{bmatrix} \quad (31)$$

[00145] Therefore, the calibration matrix will be given by:

[00146]
$${}^{B}T_{D} = \begin{bmatrix} R_{3\times3} & t_{3\times1} \\ 0_{1\times3} & 1 \end{bmatrix} \quad (32)$$

SIMULATION AND EXPERIMENTAL RESULTS

[00147] A 3-D computer model of the robot manipulator (IRB120) having the TCP 20 was built in the computer using Matlab. The DH parameters of the robot manipulator were derived as shown in Table I. In the simulations, the laser 22 was attached on the TCP 20 to align the laser beam line with the X-axis of the frame of the TCP 20. A virtual PSCD 28 was also built and fixed, so that the algorithm could find the robot configuration needed to align the laser beam line to hit the center of both PSDs 38 at 4 different positions. Experimental data was also collected, analyzed, and compared for robot calibration.

TABLE I. DH PARAMETERS OF THE ABB IRB 120 MANIPULATOR

Joints	α (mm)	α (deg)	d (mm)	θ (deg)
1	0	-90	290	0
2	270	0	0	-90
3	0	90	0	180
4	70	-90	302	0
5	0	90	0	0
6	0	0	72	0

A. Simulation of Joint Offset Calibration

[00148] Simulations of the joint offset calibration were performed using initial joint offset parameters, such that they can be identified using the method of the present invention. In other words, offset values were introduced for each joint in the kinematic model and compared with the values the method of the present invention was able to compute. The results of the calibration simulations are shown in Table II. The first column holds the joint offset number while column two holds the actual offset parameters used to initialize the simulations. In the third column, the initial parameters used by the optimization algorithm (LMA) are shown. In the fourth column, the solution of the algorithm is shown while the fifth column shows the error between them. The results shows perfect results, therefore they confirmed the efficiency of the method of the present invention.

TABLE II. SIMULATION RESULTS ON JOINT OFFSET CALIBRATION

Parameter (deg)	Actual Value	Initial Value	Simulation Result	Error
δ_2	1.20	0.0	1.2000	0.0000
δ_3	0.80	0.0	0.8000	0.0000
δ_4	-1.40	0.0	-1.4000	0.0000
δ_5	-0.60	0.0	-0.6000	0.0000
δ_6	-1.00	0.0	-1.0000	0.0000

B. Robot Workpiece Frame Calibration

[00149] Similarly, simulations of the workpiece frame calibration were performed. This time the relationship between the base 14 and the workpiece frame 34 of the PSCD 28 was initialized, such that each parameter can be identified by the method of the present invention. The results are shown in Table III. In the second column, the actual parameter values used to initialize the simulation are presented while in the third column the initial parameters for the algorithm (LMA) are

shown. The fourth column shows the solution of the algorithm and in the fifth column the error between them were presented. Again, perfect results were obtained and therefore confirmed the efficiency of the method of the present invention.

TABLE III. SIMULATION RESULTS ON JOINT OFFSET CALIBRATION

Parameter	Actual Value	Initial Value	Simulation Result	Error
R_{11}	0.4293	0.0	0.4293	0.0000
R_{12}	-0.8779	0.0	-0.8779	0.0000
R_{13}	-0.2120	0.0	-0.2120	0.0000
R_{21}	0.8738	0.0	0.8738	0.0000
R_{22}	0.4632	0.0	0.4632	0.0000
R_{23}	-0.1485	0.0	-0.1485	0.0000
R_{31}	0.2285	0.0	0.2285	0.0000
R_{32}	-0.1215	0.0	-0.1215	0.0000
R_{33}	0.9659	0.0	0.9659	0.0000
t_x	240.0000	0.0	240.0000	0.0000
t_y	160.0000	0.0	160.0000	0.0000
t_z	180.0000	0.0	180.0000	0.0000

C. Experimental Analysis

[00150] To prove that the method of the present invention works, real experiments were performed on the industrial robot 12. Experiments were performed moving the TCP 20 and laser 22 manually such that it aligns the laser beam line to both PSDs 38 centers at P1 and P2. Similarly, experiments were performed moving the TCP 20 and laser 22 for positions P3 and P4. Once the desired positions were achieved, the joint parameters of the industrial robot 12 were recorded from the robot controller 72 and eventually processed into the calibration method of the present invention. The experimental results are presented in Table IV for the joint offset and were compared with previous robot calibration. The first column shows the joint offset number while the second column shows the actual offset parameters which are unknown in the experiments. The third column shows the initial parameters of the LMA for both experiments. The fourth column shows the results of the optimization

for our previous calibration method and in the fifth column the results are shown for the present method of the present invention. The results show similar values in both methods and therefore the method of the present invention can achieve a similar level of accuracy of joint offset calibration.

TABLE IV EXPERIMENTAL RESULTS ON JOINT OFFSET CALIBRATION

Parameter	Actual Value	Initial Values	Previous Method	Present Method
δ_2	unknown	0.0	1.9240	2.2163
δ_3	unknown	0.0	0.5800	0.8722
δ_4	unknown	0.0	-0.1831	-0.1596
δ_5	unknown	0.0	0.0973	-0.2107
δ_6	unknown	0.0	-0.2453	-0.6281

[00151] Table IV essentially proves not only that both methods have similar level of accuracy of joint offset calibration, but also that they are feasible. Among the advantages of the new method of the present invention is the ability to perform the whole process using only 4 sets of position data instead of 7 needed for the previous method. Therefore the new approach is simpler and faster.

[00152] Accordingly, the calibration system 10 of the present invention is a simple low-cost design easy to operate by the user. The calibration system 10 of the present invention is robust to external disturbances commonly found in production lines. The calibration system 10 of the present invention includes a convenient wireless portable calibration device. The calibration system 10 of the present invention is able to be used by any industrial robot. The calibration system 10 of the present invention is a fast automatic robot calibration system compared to existing calibration systems. The calibration system 10 of the present invention is a portable, low-cost, and faster yet simpler than any other existing calibration system.

[00153] The present invention has been described in an illustrative manner. It is to be understood that the terminology, which has been used, is intended to be in the nature of words of description rather than of limitation.

[00154] Many modifications and variations of the present invention are possible in light of the above teachings. Therefore, the present invention may be practiced other than as specifically described.

WHAT IS CLAIMED IS:

1. A calibration system (10) for calibrating an industrial robot (12), said calibration system (10) comprising:

a focusable laser (22) for providing a laser beam and mounted to the industrial robot (12);

a position sensitive calibration device (28) including at least one position sensitive device (38) for receiving position information from the laser beam and recording position and orientation of a pose of the industrial robot (12) and joint angles for that particular pose of the industrial robot (12) based on the position information; and

a controller (72) communicating with said position sensitive calibration device (28) for providing a kinematics error model of the industrial robot (12), using a non-linear iterative optimization on the kinematics error model to identify robot external parameters and joint offset from the recorded joint angles, and calibrating the robot external parameters and joint offset of the industrial robot (12) to make the industrial robot (12) more precise and accurate.

2. A calibration system (10) as set forth in claim 1 wherein said at least one position sensitive device (38) comprises a pair of position sensitive devices (38) spaced and orientated at an angle relative to each other.

3. A calibration system (10) as set forth in claim 2 wherein said at least one position sensitive device (38) includes a mounting fixture (36) to support said position sensitive devices (38) at a fixed angle therebetween.

4. A calibration system (10) as set forth in claim 3 wherein said fixed angle is approximately one hundred twenty degrees.

5. A calibration system (10) as set forth in claim 1 wherein said position sensitive calibration device (28) includes a circuit (52) for recording data of the position and the joint angles.

6. A calibration system (10) as set forth in claim 5 wherein said position sensitive calibration device (28) includes a wireless hub (64) to transmit the data.

7. A calibration system (10) as set forth in claim 6 wherein said position sensitive calibration device (28) includes an analog to digital (A/D) converter (62) connected to said circuit (52) and said wireless hub (64).

8. A calibration system (10) as set forth in claim 7 wherein said wherein said position sensitive calibration device (28) includes a frame (34) to enclose said circuit (52), said A/D converter (62), and said wireless hub (64).

9. A calibration system (10) as set forth in claim 1 including an adapter fixture (24) attached to the industrial robot (12) and said focusable laser (22) being mounted to said adapter fixture (24).

10. A calibration system (10) as set forth in claim 1 including a camera (26) mounted to the industrial robot (12) at an angle to the laser beam to form a triangle.

11. A calibration system (10) as set forth in claim 3 wherein said at least one position sensitive device (38) is of a segmented type.

12. A method for calibrating an industrial robot (12) comprising the steps of:

providing a focusable laser (22) mounted to the industrial robot (12);

providing a position sensitive calibration device (28) having at least one position sensitive device (PSD) (38);

aiming a laser beam from the focusable laser (22) at a center of the at least one PSD (38) to find a beam position of a pose of the industrial robot (12);

recording joint angles for that particular pose of the industrial robot (12) by a controller (72) based on the beam position;

providing a kinematics error model of the industrial robot (12) for the controller (72);

using a non-linear iterative optimization on the kinematics error model by the controller (72) to identify robot external parameters and joint offset from the recorded joint angles; and

calibrating the robot external parameters and the joint offset of the industrial robot (12) by the controller (72) to make the industrial robot (12) more precise and accurate.

13. A method as set forth in claim 12 including the step of providing a pair of position sensitive devices (38) spaced at an angle relative to each other.

14. A method as set forth in claim 12 including the step of providing a mounting fixture (36) and supporting the PSDs (38) at a fixed angle therebetween with said mounting fixture (36).

15. A method as set forth in claim 12 including the step of providing a circuit (52) for recording data of the position and the joint angles.

16. A method as set forth in claim 12 wherein said step of calibrating comprises calibrating the robot external parameters and joint offset of the industrial robot (12) simultaneously.

17. A method as set forth in claim 12 including the step of completing the calibration by locating a top center position (20) of the industrial robot (12) at four different positions.

18. A method as set forth in claim 12 including the step of providing a camera (26) and mounting the camera (26) on the industrial robot (12) at an angle to the laser beam to form a triangle.

19. A method as set forth in claim 18 including the steps of using a triangular relationship between the camera (26) and the laser (22) to compute depth and height information between the laser (22) and the at least one PSD (38).

20. A method as set forth in claim 12 wherein said step of using a non-linear iterative optimization comprises using a Levenberg-Marquardt algorithm (LMA) to minimize a sum of squared errors.

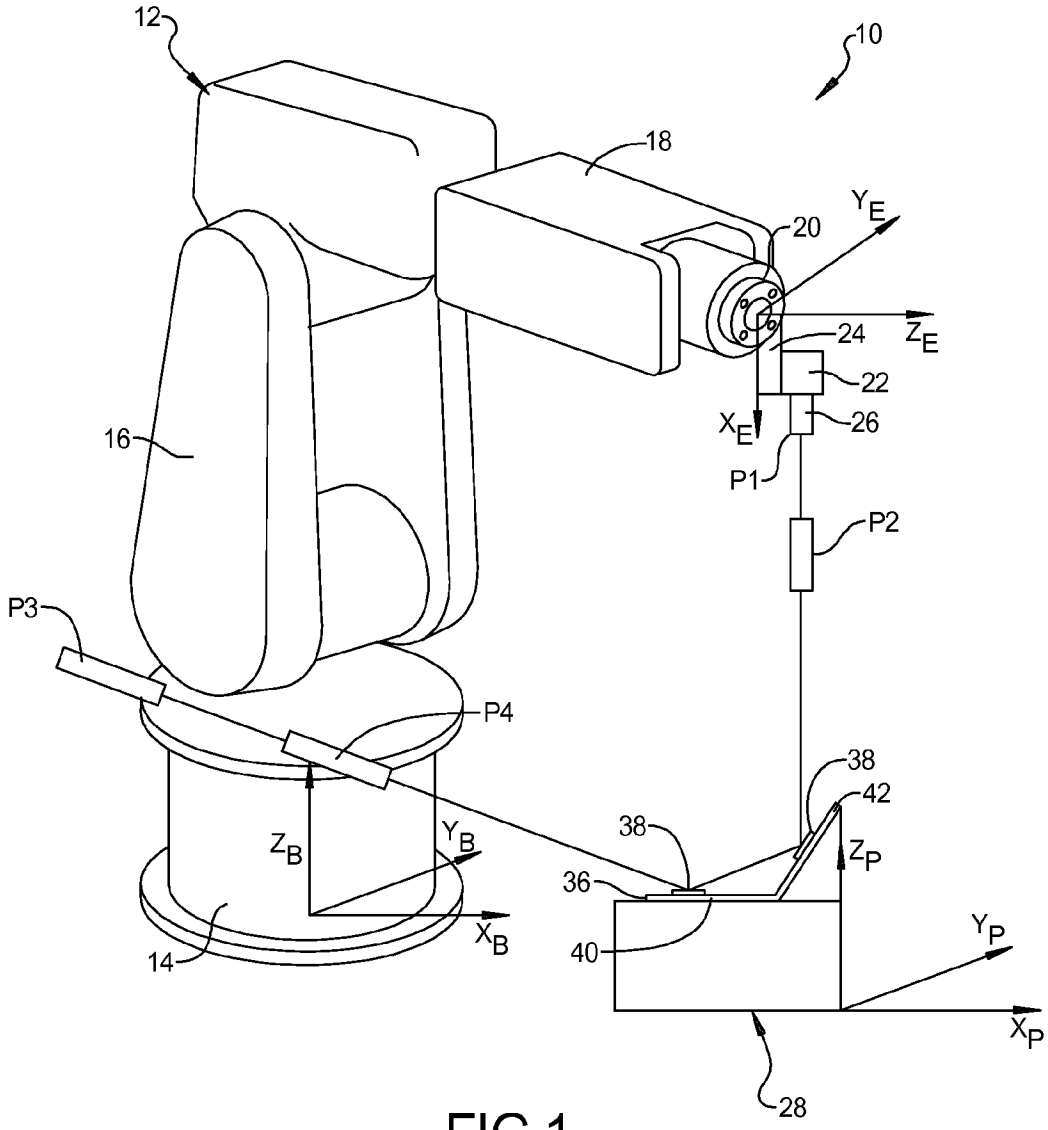

12
10
18
20
Y_E
Z_E
24
22
26
X_E
P1
P2
16
P3
P4
38
42
38
Z_P
36
Z_B
Y_B
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14
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Y_P
X_P
28

FIG 1

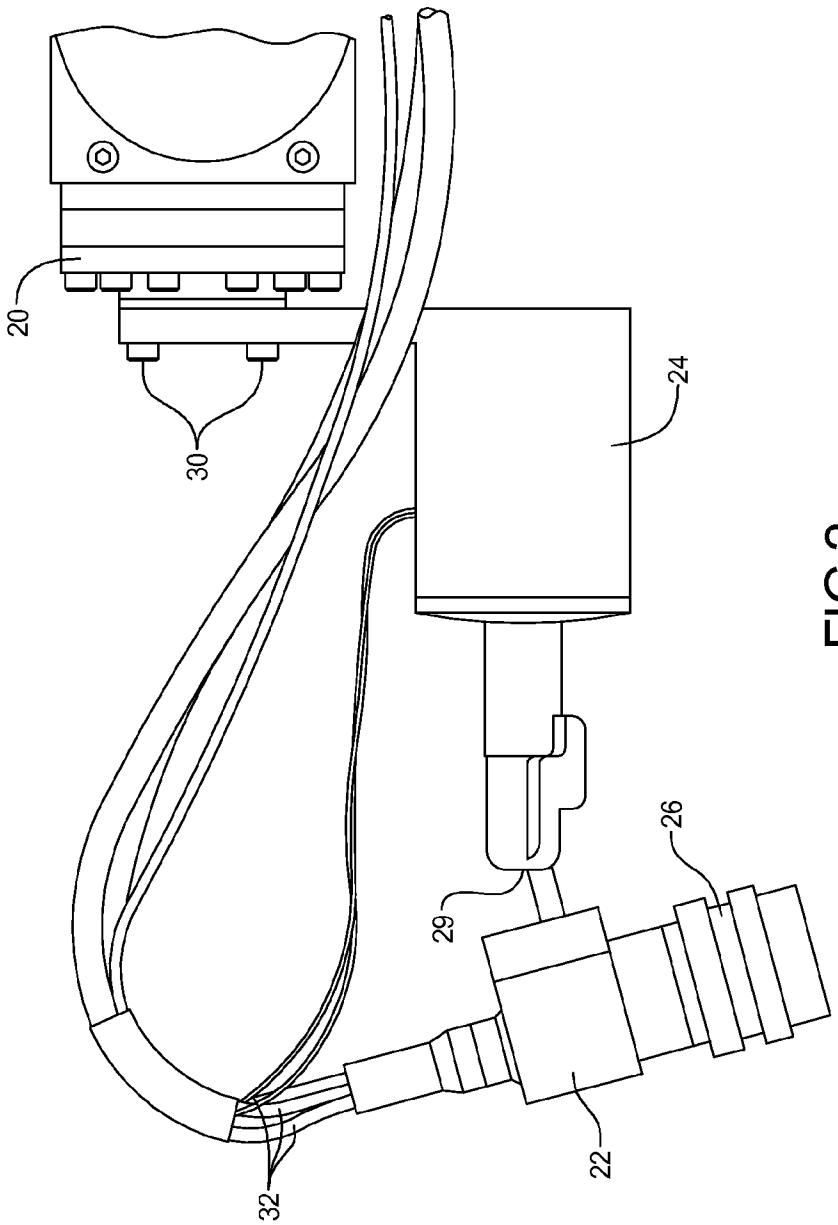


FIG 2

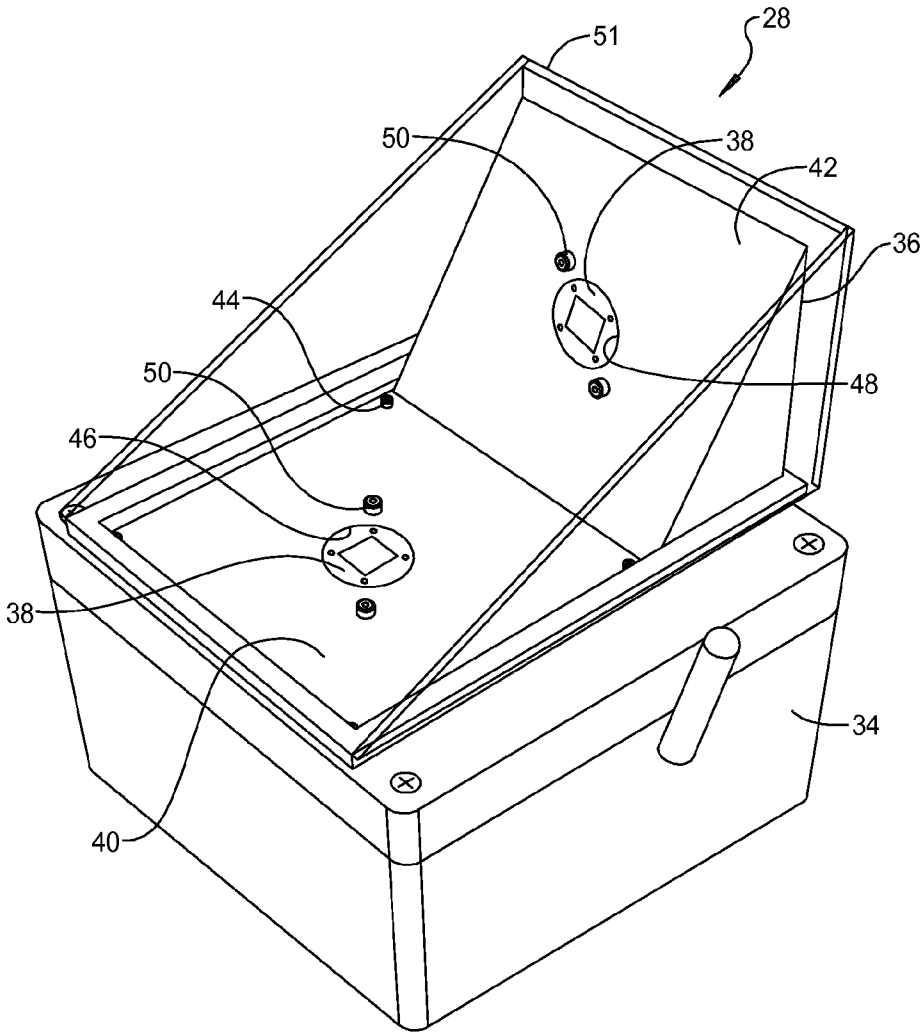


FIG 3

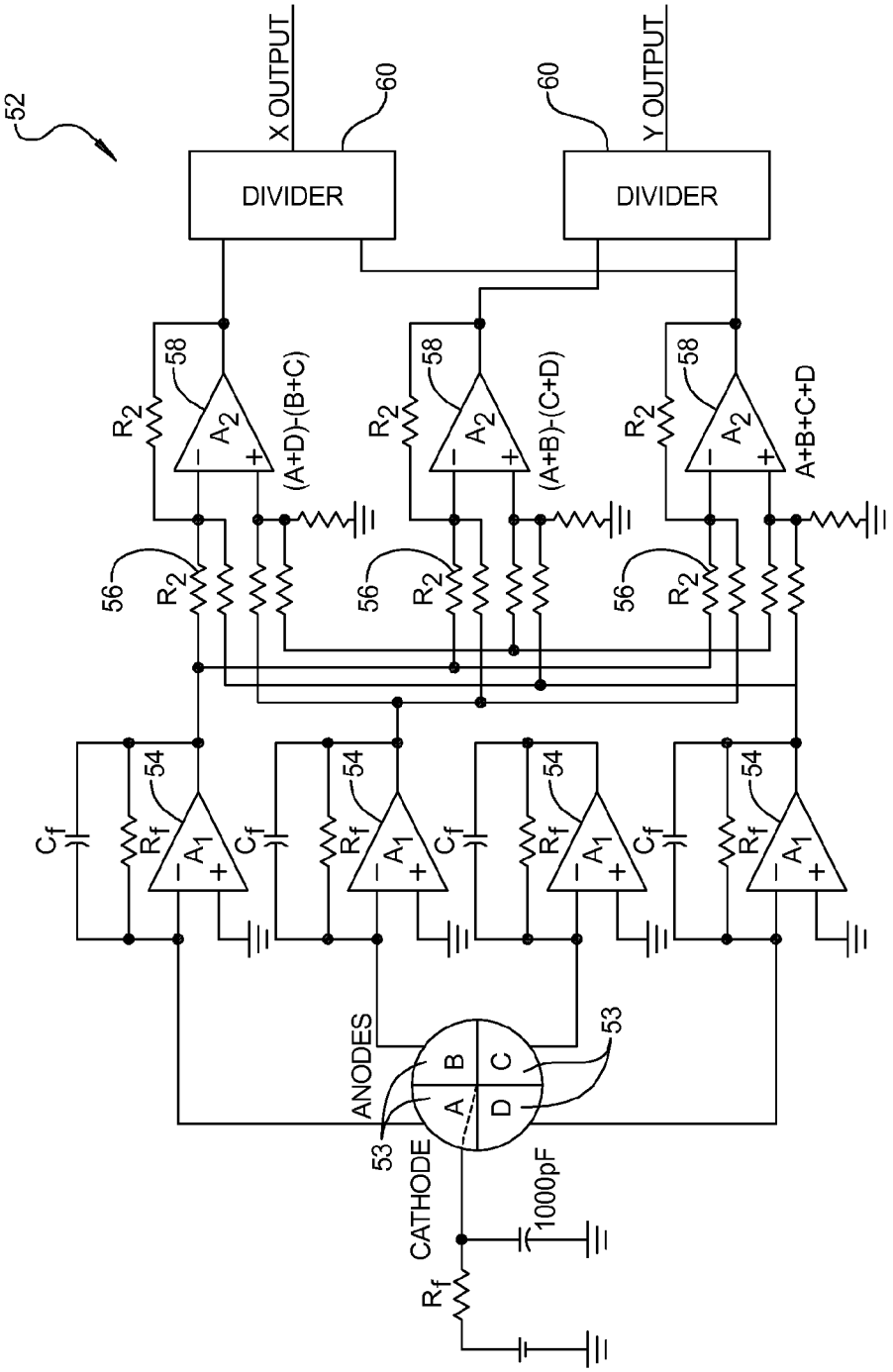

52
X OUTPUT
Y OUTPUT
60
60
DIVIDER
DIVIDER
58
58
58
R2
R2
R2
A2
A2
A2
(A+D)-(B+C)
(A+B)-(C+D)
A+B+C+D
56
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R2
R2
R2
54
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54
54
Cf
Cf
Cf
Cf
Rf
Rf
Rf
Rf
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A1
ANODES
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53
B
C
A
D
CATHODE
1000pF
Rf

FIG 4

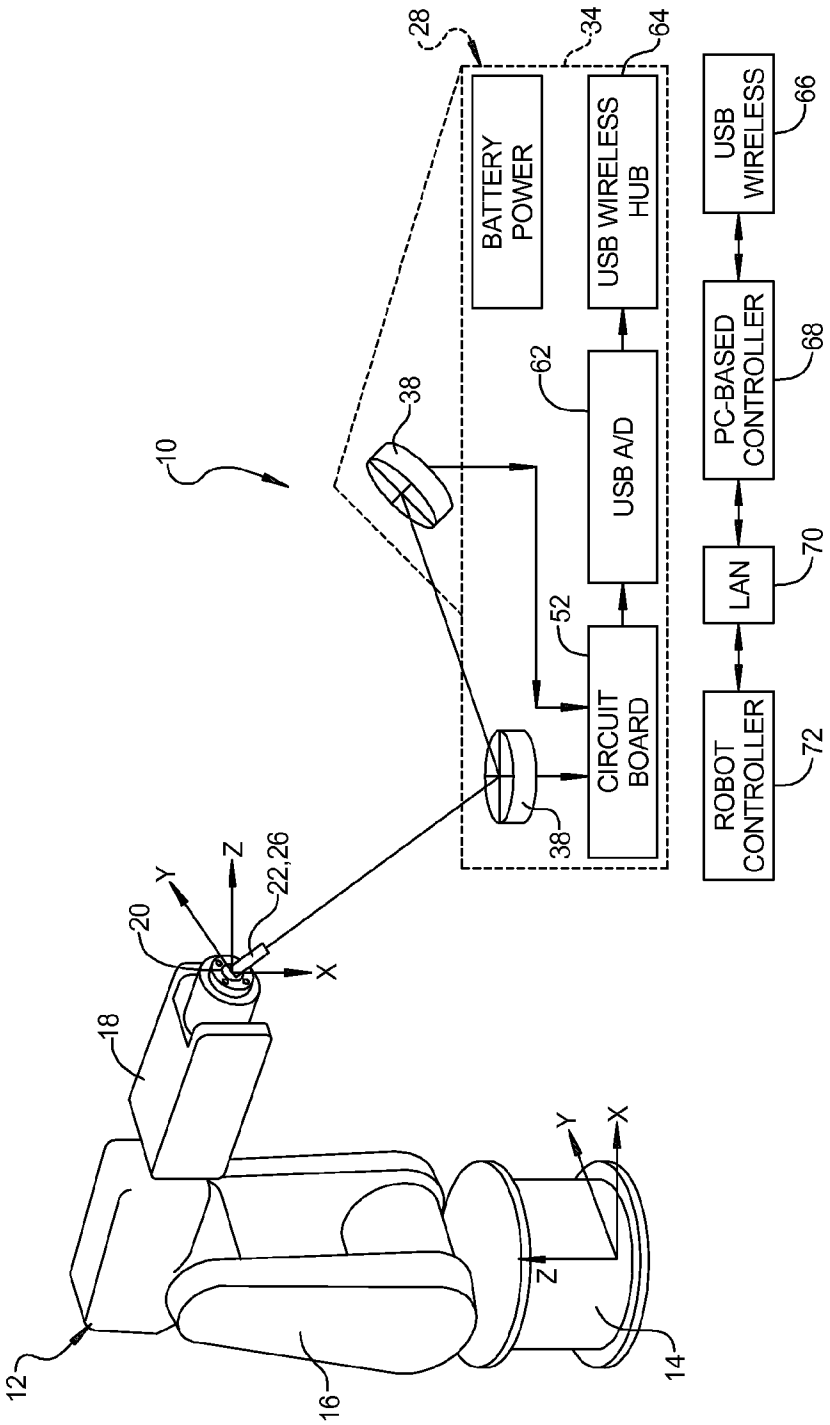

28
34
64
BATTERY POWER
USB WIRELESS HUB
USB WIRELESS
66
62
USB A/D
PC-BASED CONTROLLER
68
38
10
52
LAN
70
CIRCUIT BOARD
38
ROBOT CONTROLLER
72
Z
Y
22,26
20
X
18
Y
X
Z
12
16
14

FIG 5

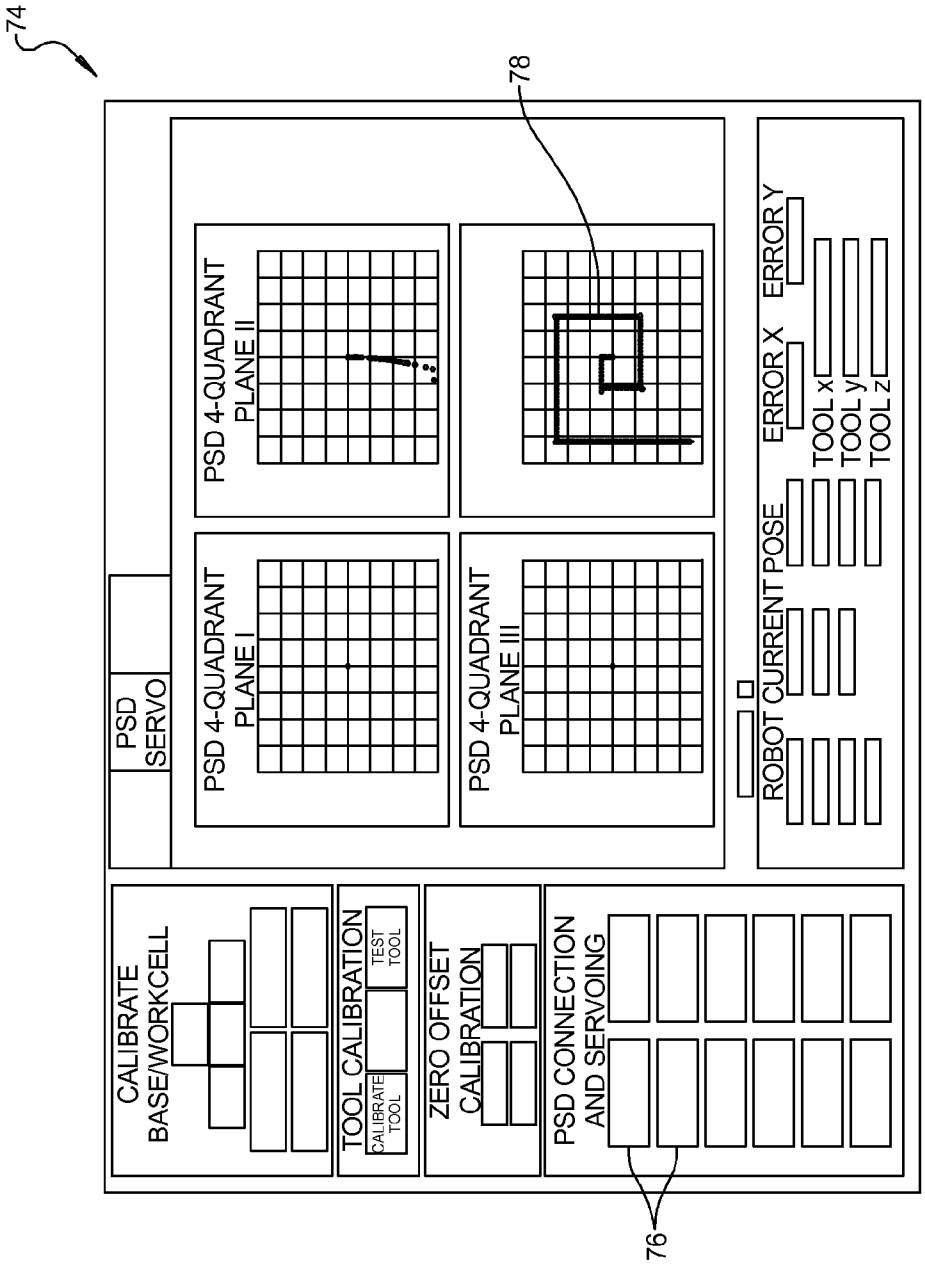

74
78
PSD SERVO
PSD 4-QUADRANT PLANE II
PSD 4-QUADRANT PLANE I
PSD 4-QUADRANT PLANE III
ROBOT CURRENT POSE
ERROR X
ERROR Y
TOOL x
TOOL y
TOOL z
CALIBRATE BASE/WORKCELL
TOOL CALIBRATION
CALIBRATE TOOL
TEST TOOL
ZERO OFFSET CALIBRATION
PSD CONNECTION AND SERVOING
76

FIG 6

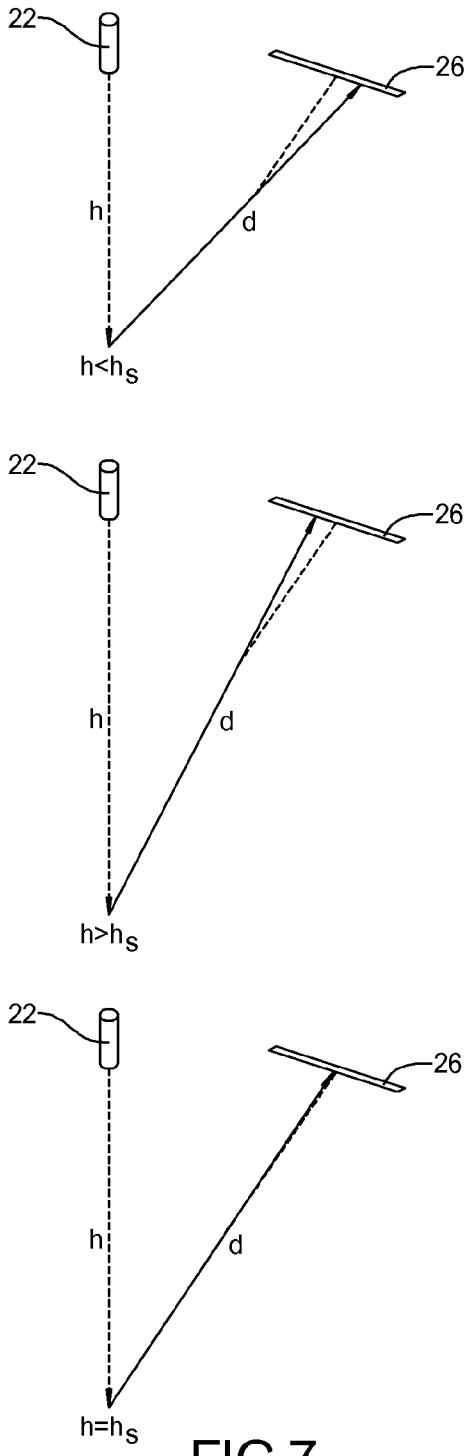


FIG 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/064535

A. CLASSIFICATION OF SUBJECT MATTER

B25J 13/08(2006.01)i, B25J 19/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B25J 13/08; G12B 13/00; G06F 19/00; G05B 15/02; G05B 19/04; B25J 19/00

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: robot, arm, manipulator, calibration, laser, position, sensor, and kinematic error model

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009-0157226 A1 (DE SMET, PIERRE) 18 June 2009 See paragraphs [0037]-[0045],[0055] and figures 1-4.	1-9,11-17
Y		10,18-20
Y	US 6044308 A (HUISSOON, JAN PAUL) 28 March 2000 See column 5, lines 29-36, column 6, line 53 - column 7, line 27 and figures 1,6a.	10,18,19
Y	WO 2013-023130 A1 (SIEMENS HEALTHCARE DIAGNOSTICS INC.) 14 February 2013 See abstract and figure 1.	20
A	US 6430472 B1 (BOILLOT et al.) 06 August 2002 See column 5, line 41 - column 7, line 10 and figures 1,3.	1-20
A	US 2005-0273202 A1 (BISCHOFF, RAINER) 08 December 2005 See paragraphs [0034]-[0037] and figures 1a,1b.	1-20

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

☒ See patent family annex.

* Special categories of cited documents:
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"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
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 March 2015 (13.03.2015)	**13 March 2015 (13.03.2015)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2014/064535

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		EP 1604789 A3	02/11/2006
		JP 2005-346718 A	15/12/2005