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A new calibration method for industrial robots

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SUMMARY

This paper presents a new calibration method for industrial robots. The calibration method is based on a combination of inclinometer and LVDT measurements and is very simple to use. The inclinometers measure the deviation from the gravity direction of a measurement rod and the LVDT sensor measures the length of the rod. The inclinometers can be used without any pre-calibration and the whole equipment is inexpensive, portable and robust.

KEYWORDS: Robot calibration; Kinematics, Robot accuracy, Off-line programming; Position measurements; Inclinometer; LVDT

1. INTRODUCTION

High kinematic accuracy is a prerequisite for general off-line programming of industrial robots. Kinematic accuracy means that different robots reach the same position with sufficient precision when running the same robot program. For most applications the kinematic accuracy of industrial robots is not good enough and there is a big need to improve robot accuracy. However, it is not economically feasible to produce mechanics with a sufficiently high precision because this will imply too expensive mechanical components and too complicated robot manufacturing. Instead the kinematic errors for every robot must be measured, identified and compensated. To make these compensations possible, a high precision measurement system is needed. The high precision measurement systems used today for robots are based on techniques with laser interferometers or theodolites. These instruments are expensive, take up a lot of space and are not suitable for the industrial environment where robots are used.

The aim of this work is to build and analyze a new robot calibration method, which may be manufactured at a much lower price than laser based systems but still having a sufficient measurement accuracy for the identification of robot kinematic errors. The calibration method is based on a combination of inclinometer and LVDT measurements and is very simple to use. The inclinometers measure the deviation from the gravity direction of a measurement rod and the LVDT sensor measures the length of the rod. The inclinometers can be used without any pre-calibration, and the whole equipment is inexpensive, portable and robust.

2. ROBOT STRUCTURE

An industrial robot may be viewed as a chain consisting of stiff links. Two links are joined to each other in such a way that they are rotatable in relation to each other around an axis of rotation, or displaceable in relation to each other along a linear movement path. An industrial robot usually has six axes of rotation. The last link in the chain may consist of a tool which, depending on the field of application, may be a gripper, a glue gun or a welding gun. In the following, the links in a robot will be referred to as arms, and their lengths will be referred to as arm's lengths.

For of the above axes of rotation or linear movement, a servo equipment with a driving motor and a position transducer is provided. The transducer delivers a signal, which is a measure of the angle of rotation of the actual axis in relation to a reference position. The servo system of each axis is supplied with a reference value of the angle of rotation or linear movement of the axis. The driving motor of the axis causes the robot to move until the axis position indicated by the position transducer of the axis corresponds to the reference value supplied to the servo system. In order for the position and orientation of the tool to correspond to the desired values, the mechanical structure of the robot and the parameters, so-called kinematic parameters, which describes it must be known with a high accuracy. Since the kinematic parameters are not exactly the same for each robot, the kinematic error parameters of each robot must be known if a high accuracy is to be attained.

Examples of kinematic error parameters are variations in the lengths of the arms, so-called arm's length errors, obliquities in the axes of rotation in relation to each other, so-called axis-attitude errors, and lateral displacements of the axes in relation to each other, so-called axis-offset errors. These deviations arise during the manufacturing of the different mechanical components and during the assembly thereof. Furthermore, the angle indicated by the position transducer of an axis must with great accuracy correspond to the actual angle of corresponding robot arm.

3. ROBOT CALIBRATION METHODS

To determine the deviation of an individual robot from an ideal robot, various forms of calibration methods are known.[1] The methods which are not based on interferometers or theodolites are not accurate enough to make a complete calibration, that is, determine both arm's length errors, axis-attitude errors, axis-offset errors, synchronizing errors, transmission errors and deflections errors for all of the axes of the robot. On the other hand, methods using interferometers or theodolites, which do manage to make a complete calibration, require expensive and delicate calibration equipment[2] and are not suitable for an industrial environment.

The objectives of this work is to provide a method[3] which

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- Makes it possible to calibrate all the axes of a six axis robot, as well as the mounting of the tool and the mounting of the robot foot.
- Manages to calibrate arm's length errors, axis-attitude errors, axis-offset errors, transmission errors, gravity induced compliance errors, robot mounting errors and tool mounting errors.
- Does not require expensive equipment.
- Can be used under active-service conditions, for example, in a production line for cars.
- Can be used without the robot-carried tool having to be dismantled.
- Can be used for fully-automatic calibration, for example during final testing of robots.
- Is fast and can be performed without complicated adjustments of robot positions.

The work also aims to provide calibration equipment to be used with the above mentioned calibration method, wherein the equipment

- Is inexpensive.
- Is robust enough to endure a workshop environment.
- ls portable and hence easy to transport
- Is very easy to calibrate.

4. THE MEASUREMENT TOOL.

Figure 1 shows a simplified version of the calibration tool. The measuring tool comprises a measuring rod with balls in the ends. One end of the rod is connected to a reference point (x_0, y_0, z_0) in a precision hole in the robot foot or in the floor. The other end of the measuring rod comprises a resilient part for connection to a predetermined measuring point on the robot (x_r, y_r, z_r) in a second precision hole, which is arranged on a robot arm or on a robot-carried calibration tool. The resilient measuring part includes a LVDT for distance measurement in the z-direction. The measuring rod has an axis of rotation, which intersects the reference point (x_0, y_0, z_0) and the measuring point (x_r, y_r, z_r. The measuring device further comprises an inclinometer arranged on a sensor shelf, which is arranged perpendicular to the measuring rod. The inclinometer measures the angle between the gravity vector and the rotation axis of the measuring rod.

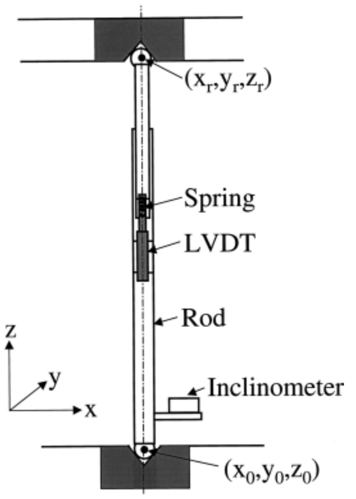

Fig. 1. A simplified version of the calibration equipment.

5. THE MEASUREMENT APPROACH

Figure 2 shows the principle of how an axis of rotation is determined with high precision by means of an inclinometer. In the left drawing of Figure 2 the rod is in its first orientation and in the right figure the rod has been turned 180 degrees around its axis of rotation. The angle α to be determined is the average direction of the axis of rotation in relation to the direction of the gravity field g. That means that the axis of rotation in the left part of Figure 2 has the direction $\alpha - \xi/2$, where $\xi/2$ is the spin amplitude when the sensor is rotated around the axis of rotation. In the right part of Figure 2 the axis of rotation has the direction $\alpha + \xi/2$. An inclinometer, with an offset error ∂ and with a mounting error β, is mounted such that the axis of the inclinometer, which is its zero direction, is substantially parallel to the axis of rotation. Angles are indicated relative to the gravity vector with a positive angle in the clockwise direction.

The output signal of the sensor in the left part of Figure 2 is given by the difference between the direction of deflection and the axis of the inclinometer

$$u_{s1} = K_s(-\alpha + \xi/2 - \beta - \partial) \qquad (1)$$

Where $K_s$is the sensitivity of the sensor.

In the right part of Figure 2 the sensor is rotated 180 degrees around the axis of rotation. The output signal of the sensor is then

$$u_{s2} = K_s(\alpha + \xi/2 - \beta - \partial) \qquad (2)$$

If these two relations are combined we get

$$(u_{s2} - u_{s1})/2 = K_s \cdot \alpha \qquad (3)$$

The difference between the deflections of the sensor for the two measurements is thus proportional to the average direction α of the axis of rotation in relation to the direction of the gravity field. Thus, neither the mounting error β nor the offset error ∂ of the sensor will influence the measurement result. Therefore the sensor may be mounted in a simple way and a sensor without absolute calibration can be used.In addition, any centering errors ξ, which give rise to spin of the axis of rotation, will be compensated away.

To determine a point (x_r, y_r, z_r) with this measurement, it is possible to use an equipment with either one inclinometer or two inclinometers.

5.1 Measurement with one inclinometer

In the one inclinometer case an equipment of the type shown in Figure 1 is used to determine the coordinates for the measuring point (x_r, y_r, z_r) relative the reference point (x_0, y_0, z_0). The measuring device is connected to the two precision holes (the one on the floor and one on the robot arm or tool) and is then rotated three times, one-fourth of a revolution each time, whereby the inclinometer is read at the angles 0, $\pi/2$, π and $3\pi/2$. The corresponding sensor deflections are u_{s0}, $u_{s\pi/2}$, $u_{s\pi}$ and $u_{s3\pi/2}$, and with the aid of these values the inclination of the measuring rod in the x- and y- directions can be calculated according to

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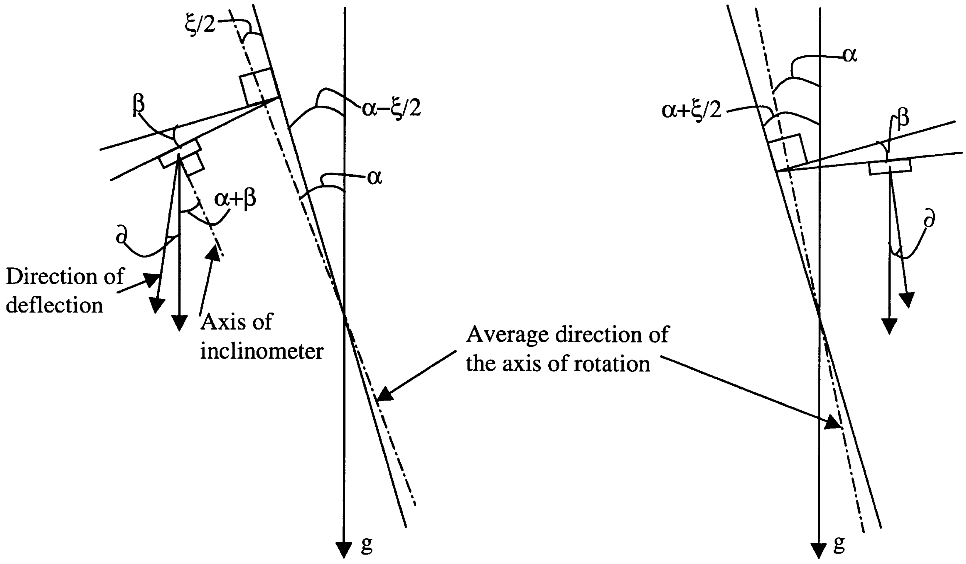

Fig. 2. High precision determination of the axis of rotation by an inclinometer.

$$a_x = (u_{s0} - u_{s\pi})/2K_s \tag{4}$$

$$a_y = (u_{s\pi/2} - u_{s3\pi/2})/2K_s \tag{5}$$

If the length of the measuring probe is L_s the coordinates of the measuring point (x_r, y_r, z_r) can be calculated according to

$$x_r = x_0 + L_s \cdot \sin(\alpha_x) \tag{6}$$

$$y_r = y_0 + L_s \cdot \sin(\alpha_y) \tag{7}$$

$$z_r = z_0 + \sqrt{L_s^2 - \left((x_0 - x_r)^2 + (y_0 - y_r)^2\right)} \tag{8}$$

5.2 Calibration in the two inclinometer case

In the two inclinometer case, two inclinometers are placed orthogonal to each other, one in the x-direction and the other one in the y-direction. To determine the coordinates for the measuring point (x_r, y_r, z_r), the measuring device is connected to the two precision holes and is then rotated one time one-half of a revolution. The x-inclinometer is read at the angles 0 and π whereas the y-inclinometer is read at the angles $\pi/2$ and $3\pi/2$. The corresponding sensor deflections are $u_{s1,0}$, $u_{s2\pi/2}$, $u_{s1,\pi}$ and $us_{2,3\pi/2}$, and with the aid of these values the inclination of the measuring rod in the x- and y-directions can be calculated according to

$$\alpha_x = (u_{s1,0} - u_{s1,\pi})/2K_{s1} \tag{9}$$

$$\alpha_y = (u_{s2,\pi/2} - u_{s2,3\pi/2})/2K_{s2} \tag{10}$$

If the length of the measuring probe is L_s, the coordinates of the measuring point (x_r, y_r, z_r) can be calculated according to (6) – (8) above.

6. CONCLUSIONS

In this article a new calibration method for industrial robots based on a combination of inclinometer and LVDT measurements has been presented. The inclinometers measure the deviation from the gravity direction of a measurement rod and the LVDT sensor measures the length of the rod. The inclinometers can be used without any pre-calibration and the whole equipment is inexpensive, portable and robust.

The calibration equipment can be manufactured at a much lower price than laser based systems and it still has a sufficient measurement accuracy for the identification of robot kinematic errors. In a forthcoming article measurement results will be present.

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REFERENCES

1. ISO/TC 184/SC 2 N 293 (ISO/TC 184/SC 2/WG 2 N291) (March, 1994).
2. K. Schröer, “Calibration Applied to Quality Control and Maintenance in Robot Production”, *Report on Project Results* (Frauenhofer-Institut für Productionsanlagen und Konstruktionstechnik, Berlin, Germany, 1994).
3. T. Brogårdh and J-E Snell, “Anordning och förfarande för kalibrering av en fieraxlig industrirobot”, *Swedish Patent* C2 508 176 (1997).

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