# Automated calibration of a lightweight robot using machine vision

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**Abstract.** Calibration of industrial robots can greatly reduce commissioning time by avoiding expensive online programming. This article presents an approach to automating the measurement and compensation of kinematic errors, applied to a lightweight robot arm. A measurement station is designed to automate this calibration process. The measurement is based on the detection of a chequerboard pattern in camera images of the end-effector. An electronic description of the robot including its individual compensation parameters is then provided in the standardised format AutomationML and transmitted via OPC UA. The approach requires only minimal manual input and is shown to significantly improve the positioning accuracy of the robot.

## Introduction

Significant gains in efficiency can be expected in the commissioning of production equipment thanks to digitalisation. Commissioning time in production systems is often prolonged due to missing component information. This information has to be either entered manually based on a data sheet, or determined through measurements with the component in its application environment. One approach to reducing these costs is to provide the component with an electronic description including calibration data, based on measurements of the specific component instance at the manufacturer's plant. This is demonstrated in [1] for ball screws. Thus a component can become a cyber-physical system with plug-and-work capability [2].

In a typical industrial robot, the position repeatability is sufficient to allow a task to be reliably fulfilled once it has been programmed accordingly. However the absolute positioning accuracy is much lower, which means that the predefined trajectory has to be adjusted to each individual robot in order to compensate systematic errors. This is often achieved through online programming: the robot is physically "taught" the desired positions within the production system. Online programming leads to increased downtime when commissioning robots and reduces the potential for reusing a program when replacing a robot or using several robots to perform the same task [3].

Positioning errors can be divided into geometric (or kinematic) and non-geometric errors such as compliance [4]. Static geometric errors are systematic and can be determined without knowledge about the environment and task the robot is to be used for. This allows the measurement to be performed by the robot manufacturer before delivery and commissioning for example. The positioning errors can then be reduced through calibration and compensation. Robot calibration can be divided into four steps: kinematic modelling, pose measurement, kinematic identification and kinematic compensation [3].

Various types of measurement systems have been shown to be suitable for measuring positioning errors in order to calibrate robots [5]: telescopic ballbars, a laser tracker or an optical CMM. It is also possible to determine the position of a robot using a multi-camera system or a single camera [6]. Camera systems can either observe the robot from a fixed position or use moving cameras attached to the robot hand [7].

To increase productivity, the calibration process must require little manual effort and calibration time. A cost-efficient method combining an automatic calibration in the robot manufacturer's factory and electronic transmission to a control system in the field was not found in the available literature.

**Approach.** This paper aims to develop a low cost automatic calibration station that can be integrated in a robot manufacturer's production. The proposed concept is shown in Fig. 1. A single fixed camera is used for the position measurement to allow greater flexibility while keeping the physical structure of the calibration station simple. When considering the cost of calibrating a robot, the integration of this process into the component lifecycle must also be taken into account. For this reason the results of the calibration are integrated into a digital representation of the component in AutomationML. This description is subsequently combined with live information from the component's sensors and control electronics and made available via OPC UA. The approach is demonstrated using the lightweight robot LWA 4P manufactured by SCHUNK.

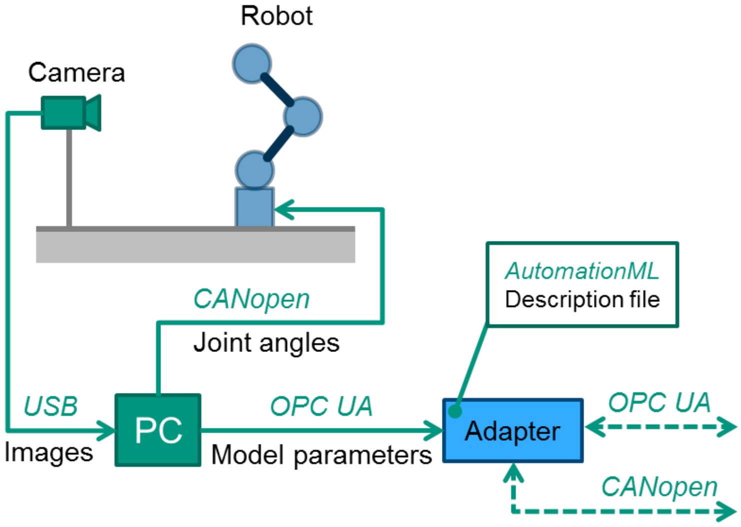


Figure 1: Concept for the measurement station

## Kinematic modelling

The LWA 4P is a serial link manipulator with 6 degrees of freedom. It consists of three spherical units each containing two perpendicular revolute joints, connected by two arms. Before designing the calibration station, the errors of an LWA 4P are analysed in order to evaluate the potential for improving the accuracy through calibration. To this end a measurement arm is fixed at a predefined distance from the base of the robot. The robot is fed a desired pose in the form of a set of joint angles and the Cartesian coordinates of defined points on the robot flange are measured. This is repeated once for each of 29 poses and the measured positions are compared to the positions predicted by an ideal kinematic model. The distance between measured and predicted positions is on average 5 mm. The measured positions are used to fit two different error models:

- A reduced 6-parameter model considering only an offset in the angle of each joint,
- A more detailed model that additionally considers errors in the orientation of joint axes and the distance in between joints.

The reduced model exhibits an average deviation of 1.5 mm from the measured poses, whereas the detailed model reduces the deviation to an average of 1.1 mm. Both models allow a significant accuracy improvement compared with the ideal kinematic model.

Based on this preliminary study, the simpler offset-angle model is chosen. The axes of the second and third joints are parallel. In the classic Denavit Hartenberg model, would mean small errors in the alignment of the axes lead to large errors in the model parameters. To avoid this difficulty, the kinematic model used in this project is based on the model formulated by Hayati and Mirmirani [8]. The positioning errors are modelled as an offset $\varphi_i$ in each of the 6 joint angles $\theta_i$ ($\theta_i^*$ designates the desired joint angle set by the control unit):

$$\theta_i = \theta_i^* + \varphi_i \tag{1}$$

## Design of a measurement station

The measurement station is designed to fulfil the following requirements:

- Fast and easy mounting and dismounting of the robot;
- Well-defined and repeatable positioning of the robot;
- Insignificant deformation of the structure for all relevant positions of the robot;
- Manually adjustable distance in between robot and camera;
- Minimal restrictions to the robot's movement.

These properties depend on the mechanical structure, the camera system and the selected target.

**Interfaces.** The first joint of the LWA 4P is attached to a base that provides electrical energy (24V DC) and field bus connectivity (CANopen). The mechanical interface of the measurement station consists of an aluminium plate with threaded holes to accommodate bolts for fixing the robot and two pins to ensure a well-defined position. The bolts can be inserted and tightened from above. Thus the robot can be mounted and dismounted quickly. The electric interface can also be connected easily by plugging one signal cable and one energy cable into the robot base.

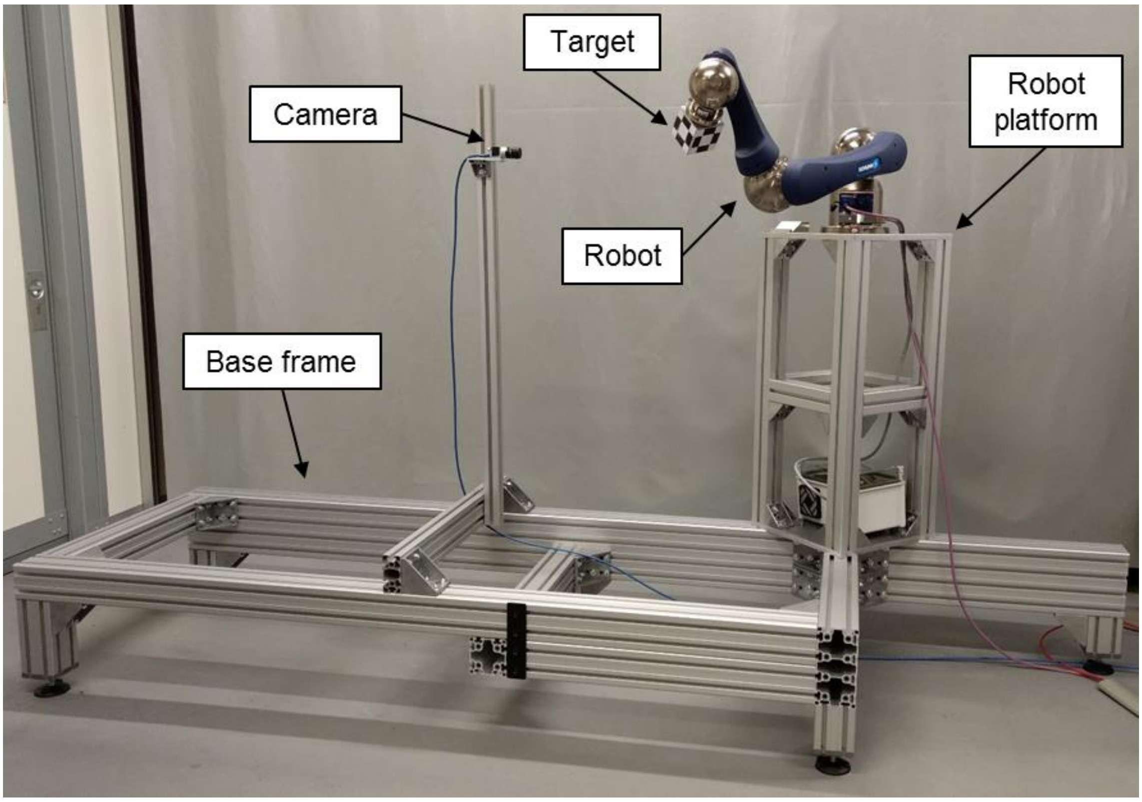


Figure 2: Measurement station for automated calibration

**Mechanical structure.** The mechanical structure consists of a base frame, a robot platform and a camera support, as shown in Fig. 2. The base frame is built out of aluminium profiles designed to be especially stiff with respect to bending loads. The robot platform consists of aluminium profiles and aluminium plates. It is designed to withstand loads due to overhanging robots with no significant deformation, while intruding as little as possible in the robot's workspace. The camera support is adjustable in three directions to allow for experimentation with different distances and positions relative to the robot.

**Image acquisition.** The camera Basler ace2500-14u is used to acquire the images needed for the position measurement. This camera has a CMOS sensor with a resolution of 2590 x 1942 pixels and a pixel size of 2.2 µm x 2.2 µm. In choosing the lens, the trade-off in between a wider field of view at lower focal lengths and lower distortion at higher focal lengths must be considered, in order to ensure sufficient precision of each measurement while allowing to measure many different robot positions. The Basler lens C125-0618-5M with a focal length f = 6 mm is chosen, leading to a horizontal angle of view of 52.4° to 53.1° and a vertical angle of 39.6° to 40.1°.

**Target.** In order to measure the position of the robot, features need to be recognised and localised within the camera images. These can either be pre-existing features on the robot or part of an end-effector that is mounted on the robot for measurement purposes. In this project a specially designed end-effector is used as a target. The target is an aluminium cube with an edge length of 80 mm, of which 5 faces are covered with a black and white 3x3 chequerboard pattern (Fig. 3). The 6th face is provided with a mechanical interface that can easily be centred and fixed to the robot flange. The central square in each pattern is larger in order to increase the distance between the corner points while maintaining a sufficient distance from the corners on the adjacent faces of the cube. Thus each face carries 4 points that can be used as features for position measurement. Depending on the orientation of the cube relative to the camera, up to 3 faces of the cube and 12 corner points can be visible in one image.

Figure 3: End-effector with chequerboard target

## Pose measurement

The target features corners where two white fields and two black fields meet, also known as X-corners. First the image is rectified based on a previous camera calibration in order to compensate lens distortion. The end-effector position predicted by the non-compensated forward kinematics is used to determine a disc-shaped region of interest in the image for each point on the cube. The X-corners in these regions of interest are detected using the subpixel algorithm described in [9]:

- The image is smoothed using a Gauss operator (with $\sigma_G = 10$);
- Saddle points in the intensity are located using the second directional derivatives (Fig. 4);
- Sub-pixel accuracy in the position of the corners is achieved by applying a Taylor polynomial to the local intensity around each saddle point.

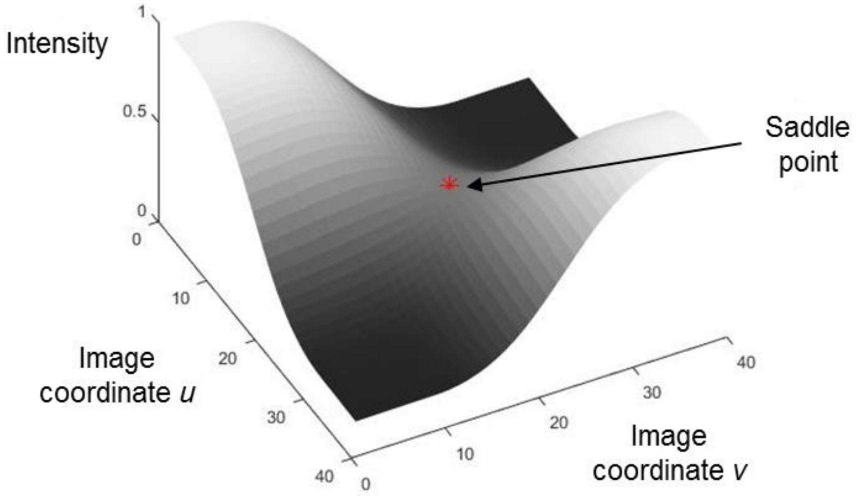


Figure 4: Corner detection based on saddle points in the intensity function

The pose of the target cube then needs to be reconstructed from the image points by taking into account the projection from a 3 dimensional world onto a 2 dimensional image. This can be expressed as a perspective-three-point problem (P3P). Following an approach presented in [10], the known distance in between three points on the surface of the cube is used to determine up to four possible solutions for the position of the cube. An arbitrary fourth point can then be used to select the most plausible cube position.

Given that there are up to 12 points in each image and the computing time is not subject to any strong constraints in this application, the P3P problem is solved for all possible combinations of three visible points. Out of the computed positions (up to 220 alternatives), the solution that fits the image points best in terms of mean square errors is selected.

The measurement algorithm is tested by placing the target directly on the platform in known positions. The results show an average Euclidian distance of 0.51 mm in between the exact position and that measured using the image processing algorithm. The standard deviation of the calculated Euclidian distances is 0.32 mm.

## Identification and compensation

Using the measurement method described above, 15 different poses are each measured once for a given robot. The measurements are compared with the expected poses based on the ideal kinematic model (Fig. 5). Based on the results of this measurement, the average bias or offset $\varphi_i$ of each joint $i$ is estimated. These are combined to form a model for error compensation.

The process is validated by measuring 35 poses not used for determining the error model. Each of these poses is measured first without error compensation and then using the offsets $\varphi_i$. The errors are compared using the Euclidian distance in between the position calculated using the kinematic model and that measured using the camera.

Before calibration the 50 poses show an average absolute error of 5.05 mm, as measured by the Euclidian distance, with a standard deviation of 1.96 mm. After calibration, there remains an average error of 3.62 mm (standard deviation 0.98 mm) among the poses used for calibration. The test poses not used for calibration also improve, achieving an average error of 3.34 mm with a standard deviation of 1.46 mm.

The results show that a significant improvement in accuracy can be achieved using the described approach for compensation of geometric errors. The calibration of the same robot using a measurement arm, as described above, led to a higher accuracy than when using a camera. This suggests that an improvement in the measurement setup and image processing could lead to a better accuracy after calibration.

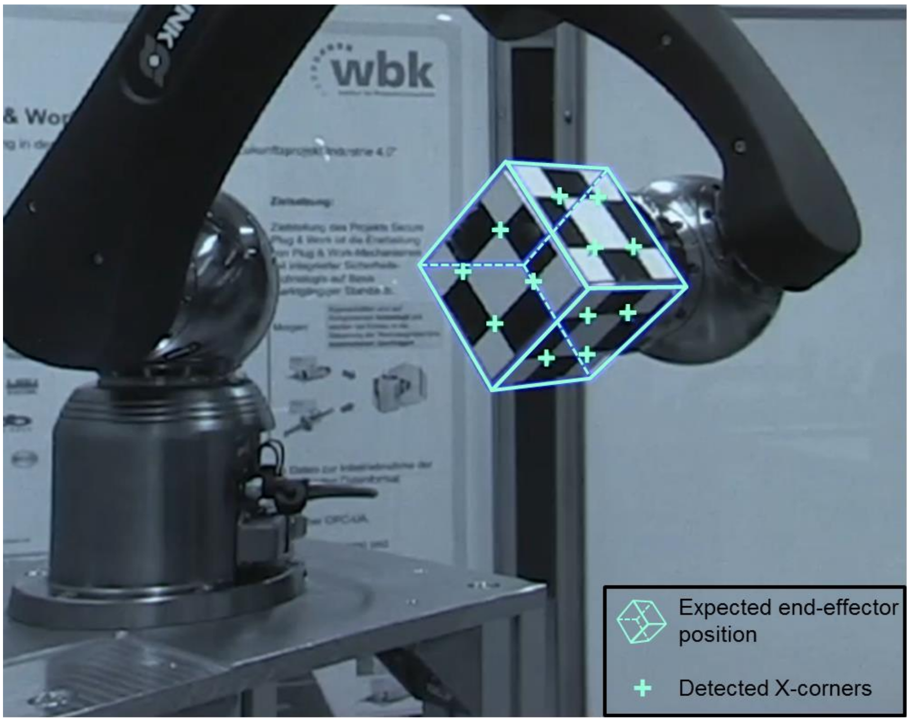
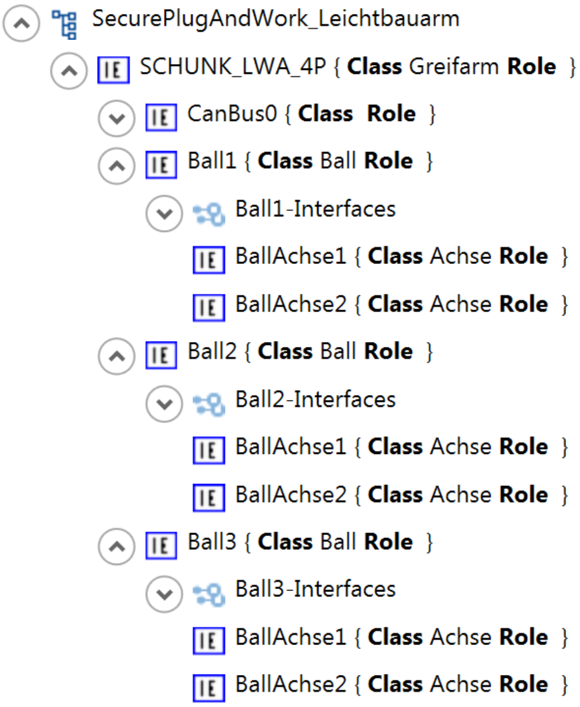


Figure 5: Image after processing

### Digital representation and integration in component lifecycle

In order to further reduce manual effort when commissioning the robot, the communication of the calibration information into the control system must also be automated. This can be achieved using a plug-and-work approach. The component is provided with a digital representation in the form of a description file in the standardised format AutomationML. The description has a hierarchical structure, as shown in Fig. 6. Each joint is represented by an *internal element* that is described by *attributes*. Attributes include type data as well as instance-specific data (i.e. calibration parameters).

The digital representation can be hosted on a single-board computer, serving as a plug-and-work adapter. This device is equipped with an SD card to save the static information and a CANopen interface to exchange live information with the component. In order to make the component description available to control units and other systems, the adapter provides an OPC UA server via TCP/IP. The OPC UA server combines the information from the AutomationML file with live data from the component's control electronics and sensors. Thus an up-to-date digital representation of the robot is available within the local network.



- SecurePlugAndWork_Leichtbauarm
  - SCHUNK_LWA_4P { **Class** Greifarm **Role** }
    - CanBus0 { **Class** **Role** }
    - Ball1 { **Class** Ball **Role** }
      - Ball1-Interfaces
      - BallAchse1 { **Class** Achse **Role** }
      - BallAchse2 { **Class** Achse **Role** }
    - Ball2 { **Class** Ball **Role** }
      - Ball2-Interfaces
      - BallAchse1 { **Class** Achse **Role** }
      - BallAchse2 { **Class** Achse **Role** }
    - Ball3 { **Class** Ball **Role** }
      - Ball3-Interfaces
      - BallAchse1 { **Class** Achse **Role** }
      - BallAchse2 { **Class** Achse **Role** }

Figure 6: Digital representation of a robot in AutomationML, as shown in *AML Editor*

## Summary and conclusion

Expensive online programming during the commissioning of robots can be avoided by calibrating the kinematic model beforehand. This paper presents a method for automating the calibration of a lightweight robot and an appropriate measurement station design. In order to calibrate the robot, its geometric positioning errors must be measured before delivery to the end-user. A camera-based measurement station is designed and the corresponding software is developed. Corners in a chequerboard pattern on a specially designed end-effector are used to determine the robot’s pose. Thus the geometric errors can be estimated and integrated in a digital representation of the robot, so that they can be compensated by the control system. The calibration method is shown to significantly reduce positioning errors. Further work should focus on increasing the accuracy, for example by improving the measurement setup and the image processing.

## Acknowledgements

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