Dynamic Photogrammetric Calibration of Industrial Robots

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Abstract:

Today's developments in industrial robots focus on aims like gain of flexibility, improvement of the interaction between robots and reduction of down-times. A very important method to achieve these goals are off-line programming techniques. In contrast to conventional teach-in robot programming techniques, where sequences of actions are defined step-by-step via remote control on the real object, off-line programming techniques design complete robot (inter-)action programs in a CAD/CAM environment. This poses high requirements to the geometric accuracy of a robot. While the repeatability of robot poses in the teach-in mode is often better than 0.1mm, the absolute pose accuracy potential of industrial robots is usually much worse due to tolerances, eccentricities, elasticities, play, wear-out, load, temperature and insufficient knowledge of model parameters for the transformation from poses into robot axis angles. This fact necessitates robot calibration techniques, including the formulation of a robot model describing kinematics and dynamics of the robot, and a measurement technique to provide reference data. Digital photogrammetry as an accurate, economic technique with realtime potential offers itself for this purpose.

The paper analyzes the requirements posed to a measurement technique by industrial robot calibration tasks. After an overview on measurement techniques used for robot calibration purposes in the past, a photogrammetric robot calibration system based on off-the-shelf lowcost hardware components will be shown and results of pilot studies will be discussed. Besides aspects of accuracy, reliability and self-calibration in a fully automatic dynamic photogrammetric system, realtime capabilities are discussed. In the pilot studies, standard deviations of 0.05-0.25mm in the three coordinate directions could be achieved over a robot work range of 1.7 x 1.5 x 1.0 m^3. The realtime capabilities of the technique allow to go beyond kinematic robot calibration and perform dynamic robot calibration as well as photogrammetric on-line control of a robot in action.

Keywords: Robotics, dynamic 3-D measurements, calibration, realtime

1. Introduction

Since the first utilization of a robot in the US car industry in 1955, robots play an continuously increasing role in industrial manufacturing processes. It is estimated that today about 700'000 industrial robots are being used. While the use of robots was restricted to simple tasks like spot welding and painting in the beginning, today's tasks include complicated actions like arc welding and assembly. Recent trends are the improvement of flexibility in less deterministic environments, the optimization of the interaction of multiple robots, the design of man-machine interfaces and the reduction of down-times. Therein, off-line programming techniques are gaining importance over conventional teach-in procedures. While with teach-in techniques a new work program is designed step by step in contact with the real work piece, the use of off-line programming techniques enables the complete design of complex work programs in a CAD/CAM environment, which is then downloaded to the robot. This enables to

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minimize down-times of productionlines when changing work programs and a much higher degree of integration of the robot programming into the industrial design process.

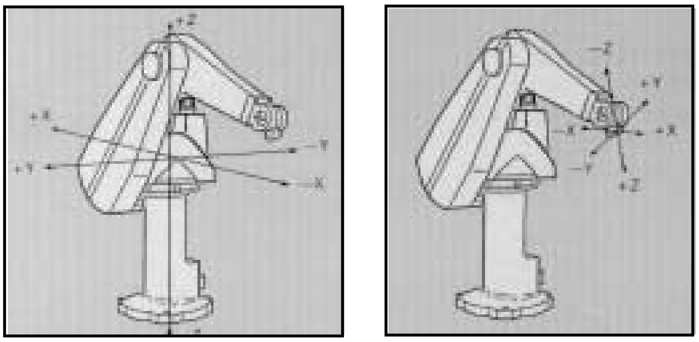

Fig. 1: Robot coordinate systems

A severe restriction for the use of off-line programming techniques is the limited geometric accuracy of industrial robots: although the repeatability of end effector positioning in the teach-in mode is in the order of 0.1 mm or less today, much higher errors may occur when absolute positions defined in an off-line designed work program have to be hit. Depending on the type of robot and the type of motion these errors may amount to up to 10 mm, thus requiring expensive post-teaching measures and relativating the efficiency of off-line programming techniques. Reasons for pose errors (pose = six parameters describing position and orientation) of a robots end effector are effects like tolerances, elasticities, wear-out, load, temperature and insufficient knowledge on the robots model parameters which are required for the transformations between real world coordinates, pose parameters and axis angles (Fig. 1). Therefore there is a need for robot calibration techniques, including models to describe the geometry of a robot and measurement techniques for the determination of boundary values. Most of these techniques determine end effector coordinates or (preferrably) complete pose parameter sets at a number of locations and orientations over a robots work range and derive robot model parameters from these measurements. This publication is limited to the discussion of measurement techniques for the determination of pose parameters via signalized points on a robots end effector. For mathematical models for the determination of robot model parameters the reader is referred to the references, e.g. (Nitschke et al., 1992) for the determination of all or single parameters of the kinematic structure of a robot following Denavit-Hartenberg methods or (Diewald, 1995) for the description of pose errors by polynomials.

2. Robot calibration measurement techniques

According to the variety of tasks of industrial robots, there is a wide range of requirements posed to calibration techniques. These requirements include:

- An accuracy potential of 0.1mm or better.
- In most cases the measurement of full poses (6-D) is preferred.
- The cost/performance ratio should not put a high burden on the economical benefit of the use of the robot.
- Ease of use of the technique, which should not require special skills.
- The measurement system must be brought to the robot, not vice-versa.
- The measurement system should work under factory floor conditions and should not pose special requirements to the environment.

To fulfil these requirements, a wide variety of measurement techniques has been applied to robot calibration tasks in the past. These measurement techniques include:

- Polar measurement techniques with geodetic total stations or interferometric laser trackers (Kyle 1993, Filz et al. 1995).
- Triangulation with theodolite systems (Kyle, 1993).
- Photogrammetry with film-based systems (Peipe, 1991) and high resolution digital systems (Diewald et al., 1993).
- Trilateration using wires, laserinterferometers or acoustic techniques.

- Tactile techniques using gauges or coordinate measurement machines.
- Inertial navigation systems, magnetic field systems.

A detailed overview can be found in (Diewald, 1995) and in (Tanner, 1990). Some of the above mentioned measurement techniques involve rather expensive measurement instrumentation, others are extremely slow. Single point tracking techniques are usually not suited for full pose determination (for an exception see Filz et al. 1995). For these reasons a pilot study on the applicability of a digital photogrammetric system based on lowcost vision hardware components to industrial robot calibration tasks was conducted, focusing especially to aspects of accuracy and realtime processing potential.

3. Photogrammetric point determination

Fig. 2: Signalized robot (Stäubli Puma 500), three camera photogrammetric system

For the determination of pose parameters the end effector of the robot was signalized with a plate marked with 13 circular targets (Fig. 2). The weight of the plate was adapted to medium load of the robot. For the study a two-dimensional signalization was used; to improve the accuracy of the end effector orientation parameters a three-dimensional signalization is recommended for future applications. The signalized end effector was moved to 200 poses distributed over a 1.7 x 1.5 x 1.0 m^3 sector of the robots work range, following a scheme designed after the requirements of model parameter determination. At each pose the 3-D coordinates of the marked points were determined from an image triplet acquired by three CCD cameras. From these coordinates the pose parameters were determined in a cartesian robot coordinate system, taking advantage from the redundancy provided by 13 points which yields a gain in precision and reliability.

3.1 System setup

CCD cameras	Sony XC77ce
sensor	2/3” interline transfer CCD sensor, black-white, interlaced
number of pixels	756 x 576 pixel
pixel size	11 x 11 μm^2
sensor size	8.8 x 6.6 mm^2
camera signal	analog
focal length	9 mm
framegrabber	Datacell S2200
signal type	analog video signal, no pixel clock
number of inputs	3 (RGB)
bus	S-Bus (SUN SparcStation)
sequence storage capabilities	1.6 triplets/sec -> host RAM 1.0 triplets/sec -> system disk

Table 1: Technical data of the imaging system

As aspects of automation, realtime processing and cost optimization were of prime importance in the pilot study, the imaging system was based on standard off-the-shelf lowcost hardware components. Images were acquired with three synchronized CCD cameras (Sony XC77ce, European CCIR videonorm) connected to a Datacell S2200 RGB framegrabber in a SUN SparcStation computer workstation. The connection of three synchronized monochrome cameras to one RGB framegrabber with three A/D converters allows for simultaneous image acquisition and transfer, which is crucial for dynamic applications. One image triplet was acquired at each pose. Due to the character of a pilot study and a non-optimized dataflow, online data processing was waived; instead, the calibration was conducted in a kinematic mode, and sequences of image triplets were stored and subsequently processed automatically. Fig. 2 shows the camera arrangement during data acquisition, Table 1 lists the technical data of the components.

The use of non-metric cameras requires a thorough calibration of the photogrammetric system itself to warrant a satisfactory accuracy potential. The determination of the orientation and camera model parameters of the three-camera system was performed simultaneously with the determination of the 3-D coordinates of the marked targets by self-calibrating bundle adjustment. In many applications of self-calibration a stationary point field is imaged by a single camera from different viewing directions and under different roll angles, thus reducing correlations between parameters to be determined. This strategy, however, is of limited practicability in the discussed application, as there is no stationary point field. A repetition of the robot poses under two or three different roll angles of the three cameras is restricted by the repeatability of end effector positioning; moreover, such a procedure would make data acquisition inconvenient. Instead, the robot pose sequence was driven only once, and one image sequence was acquired with each camera under constant orientation. To reduce correlations between subsets of parameters in the bundle adjustment and to define the scale, the robot was signalized with a reference bar of well known length (Fig. 3) after the actual robot calibration program of 200 poses and moved to another 27 poses at different locations and orientations. The reference bar was signalized with two targets at a distance of approximately 1.0 m and had been calibrated interferometrically to a standard deviation of 1 µm. This procedure of simultaneous calibration with additional geodetic information depicts an interesting alternative in tracking applications with a stationary multi-camera system and no stationary target field. A more detailed analysis of a similar procedure can be found in (Heikkilä, 1990).

Fig. 3: Reference bar for scale definition in the automatic self calibration of the photogrammetric system

3.2 Data processing

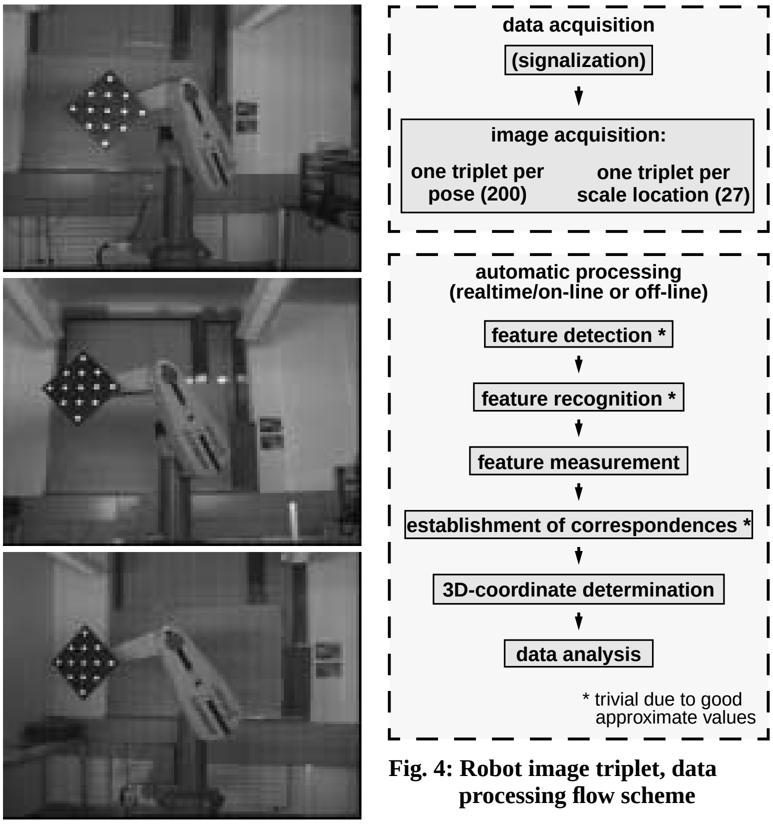

Fig. 4: Robot image triplet, data processing flow scheme

A typical image triplet and the dataflow in the automatic image data processing are shown in Fig. 4. The first two processing steps (detection and recognition of marked targets) are trivial due to possibility of image coordinate prediction via the pre-defined poses of the end effector and the given accuracy potential of the uncalibrated robot. After a rough pre-orientation of the system by interactive measurement of a few points, the locations of all other points can be predicted within a tolerance of a few pixels, thus providing sufficiently good approximate values for subsequent image coordinate measurement with subpixel accuracy using a centroid operator or least squares template matching. This means a significant simplification of the dataflow in automatic photogrammetric data processing, as also the correspondence problem is solved implicitly. The 3-D coordinates of the measured targets can be determined directly by spatial intersection or self-calibrating bundle adjustment.

Even the interactive step of the pre-orientation of the system by manual measurement of a few points can easily be automated, e.g. by the use of coded targets (van den Heuvel et al., 1992). Thus photogrammetric robot calibration can be fully automated.

3.3 Results

The standard deviations of the image coordinates obtained from least squares template matching were in the order of $^1/_{50}$ ... $^1/_{40}$ pixel; related to the image format of 756 x 576 pixel, this corresponds to a relative precision of approximately 1 : 30’000. In the subsequent self-calibrating bundle adjustment the object coordinates of all 13 marked targets at all 200 poses and of the two markers on the reference bar at 27 poses were determined simultaneously with camera orientation and calibration parameters. Eight camera model parameters per camera were introduced as unknowns: The camera constant, the principle point coordinates, two parameters modeling radial lens distortion, two parameters modeling decentering lens distortion and one horizontal scale factor compensating for different clock rates of cameras and framegrabber. By including the distance information of the 27 scale poses into the adjustment, determinability of all parameters could be achieved. The results of the bundle adjustment are summarized in the following table:

standard deviation of unit weight	$\hat{\sigma}_0 = 0.25\ \mu m$
standard deviation of object point coordinates	$\hat{\sigma}_X = 0.088$ mm $\hat{\sigma}_Y = 0.057$ mm $\hat{\sigma}_Z = 0.240$ mm

To get an indication the repeatability of coordinate determination some poses were measured twice without moving the robot in between. The RMS of these double measurements was:

repeatability (stationary robot, average over 8 poses)	$\sigma_X = 0.092$ mm $\sigma_Y = 0.037$ mm $\sigma_Z = 0.232$ mm

The precision parameters achieved in the pilot study do correspond to the expectations and could also be confirmed in another pilot study using a Robix educational robot (Favey/Schlatter, 1996).

No external reference measurements were available in the pilot studies. However, at least a partial external verification can obtained from known distances between the marked targets, assuming stability of the signalization plate. An examination of 800 horizontal and vertical check distances, derived from the photogrammetrically determined coordinates of the four corner points of the plate at all 200 poses, yielded the following results:

	standard deviation of distances [mm]	theoretical value from $\hat{\sigma}_{XYZ}$ [mm]
horizontal distances	0.241	0.140
vertical distances	0.085	0.100

Herein, the standard deviation of the horizontal distances is by a factor of 1.7 larger than the value obtained from the standard deviations of the object point coordinates without consideration of correlations, while the value for the vertical check distances is about consistent. Check distances in depth direction were not available due to the orientation of the plate towards the cameras. The reason for the discrepancy in the horizontal check distances was found after a thorough examination of the images, which showed line jitter effects in the order of $^{1}/_{10}$ pixel. Linejitter is a known effect degrading the accuracy in horizontal direction in image space when grabbing images from cameras with analog image data transfer; in most cases, however, the effect is smaller than $^{1}/_{20}$ pixel and shows stochastic behaviour, thus hardly influencing the accuracy potential of photogrammetric systems measuring targets with an extension of several pixels in image space. In the present application, linejitter was obviously enlarged by camera synchronization problems which were possibly caused by electromagnetic fields of the robot. With the chosen three-camera configuration, the horizontal image coordinate errors could not be detected by the network geometry. Using CCD cameras with internal A/D conversion and digital data transfer, this problem should not occur anymore.

The same data was processed a second time using a fast centroid operator instead of least-squares template matching. No significant difference could be found comparing the accuracy figures obtained with centroid operator with the results obtained from least-squares template matching. Only in cases of partly occulded targets a higher reliability can be expected from least-squares template matching.

A significant improvement of precision can be expected when using high resolution cameras: Standard deviations $\hat{\sigma}_{XYZ}$ = 0.035mm/0.035mm/0.05mm over a range of 2.1m x 1.3m x 0.6m were obtained by (Diewald et al., 1993) using Rollei réseauscanning-cameras; (Peipe, 1991) achieved standard deviations of 0.05-0.1mm over a work range with a largest extension of 1.7m with a hybrid system with medium format film-based cameras and a réseauscanner for image coordinate measurement.

3.4 Realtime processing potential

Besides the bundle adjustment, which is being performed off-line, the computational effort in photogrammetric robot calibration is mainly influenced by the image coordinate determination. The average computation time per target, related to the performance of a SUN SparcStation20, are listed in the following table:

prediction of location (in 3 images)	0.0002 sec
image coordinate determination by jeast squares template matching	0.0440 sec
image coordinate determination by centroid operator (per target)	0.0013 sec
spatial intersection	0.0005 sec

If the simultaneous bundle adjustment of the whole dataset is replaced by a system calibration using a smaller number of poses before the actual experiment, 3-D coordinates can be determined by spatial intersection. Using the fast centroid operator and spatial intersections, the determination of the coordinates of the marked points can be performed in video realtime ($^{1}/_{25}$ second) when the number of points is limited to 8-10. With further optimization of the software and slightly smaller targets the task can also be performed in video realtime on a high-end PC.

4. Conclusion

The pilot study has shown that a digital photogrammetric system based on lowcost standard vision hardware components can be a very powerful tool for industrial robot calibration tasks with moderate accuracy requirements. Standard deviations of 0.05-0.25 mm in the three coordinate directions could be obtained over a robots work range of 1.7 x 1.5 x 1.0 m^3; a further improvement can be expected when using solid state cameras with digital data transfer or high resolution cameras. Besides lowcost system components (a realtime system consisting of three CCD cameras, an RGB framegrabber and a PC can be compiled for ~5000 US$ hardware cost), a photogrammetric robot calibration system offers the advantages of full pose determination, fully automatic data processing and the potential of video realtime data processing. The latter is of special importance under the aspect of dynamic robot calibration, going beyond kinematic calibration by also determining inertial parameters and elasticities of a robot, which is of importance for fast robot actions and the exact motion along planned paths. Finally this may allow for the construction of light-weight robots with lower system cost and lower energy consumption, which do still offer a good accuracy potential after kinematic and dynamic calibration. The low cost of the components of a digital photogrammetric system as compared to the cost of an industrial robot does even enable the permanent photogrammetric surveillance of a sensor controlled industrial robot in certain applications.

Besides these aspects of accuracy, automation and realtime potential, future tasks in the field of industrial robot calibration will have to concentrate onto the geometric relation between robot and workpiece. The inclusion of the workpiece into modeling and measurement is a crucial prerequisite for the conversion of the accuracy potential of a calibrated robot into practical applications.

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References:

- Diewald, B., Godding, R., Henrich, A., 1993: Robot calibration with a photogrammetric on-line system using reseau-scanning-cameras. Optical 3-D Measurement Techniques II (Eds. Grün/Kahmen), Wichmann Verlag, Karlsruhe
- Diewald, B., 1995: Über-alles-Kalibrierung von Industrierobotern zur lokalen Minimierung der Posefehler. Ph.D. thesis, University of Saarbrücken
- Favey, E., Schlatter, A., 1996: Photogrammetrische Kalibrierung eines Roboters. Internal Publication Institute of Geodesy and Photogrammetry, ETH Zürich
- Filz, K., Vincze, M., Krautgartner, P., Spiess, S., 1995: The design of a concise beam deflection unit for external 6D robot measurements. Optical 3-D Measurement Techniques III (Eds. Grün/Kahmen), Wichmann Verlag, Karlsruhe
- Heikkilä, J., 1990: Update calibration of a photogrammetric station. International Archives of Photogrammetry and Remote Sesnsing, Vol. 28, Part 5/2, pp. 1234-1241
- van den Heuvel, F., Kroon, R., Le Poole, R., 1992: Digital close range photogrammetry using artificial targets. International Archives of Photogrammetry and Remote Sesnsing, Vol. 29, Part B5, pp. 222-229
- Kyle, S., 1993: Dimensional reference for robot calibration. Optical 3-D Measurement Techniques II (Eds. Grün/Kahmen), Wichmann Verlag, Karlsruhe
- Nitschke, H., Schirmer, W., Schnädelbach, K., 1992: Bestimmung geometrischer Parameter von Industrierobotern. Ingenieurvermessung 92 (Eds. Matthias/Grün), Dümmler Verlag, Karlsruhe
- Peipe, J., 1991: Photogrammetrische Verfahren zur Vermessung von Roboterbewegungen. Schriftenreihe DVW ‘Geodätische Verfahren im Maschinenbau’ (Eds. Welsch, Schlemmer, Lang), Verlag Konrad Wittwer
- Tanner, Ch., 1990: Das Masskörperverfahren zur Vermessung von Robotern. Ph.D. thesis No. 9261, ETH Zurich