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Accuracy and Calibration Issues of Industrial Manipulators

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1. Introduction

Since initial stages of the adoption of industrial robot, the reason for their development was to replace humans in repetitive tedious and hazardous manual work. However, due to rise of production and falling prices, the use of robots becomes an economically viable solution in more and more applications (Hefele & Brenner, 2001). Nowadays, industrial robot manipulators are an important component of most automated manufacturing systems, and especially in the automotive industry. They have been used for many years in industry efficiently in mass production applications, where simple sequences of movements are pre-recorded in the memory of the robot controller. Nevertheless, manipulators are still rarely used in industrial applications with frequently changing operations where continuous reprogramming is needed, since this requires teaching the points for each operation and specifying the trajectories for the new sequences of motion using robots teach-pendants. This problem can be overcome only if the programs and the points are designed off-line using manipulators' models and simulated work cells. The implementation of off-line programming (OLP) requires very good accuracy of manipulators, which can be achieved by a process of robot calibration to reduce the effects of the kinematic model errors due to the manufacturing tolerances of the robot elements and the assembly processes, in addition to changing working environment conditions and effects of tear and wear. This means that the model of the manipulator in the controller should be a precise representation of the mechanisms and allows the system to achieve the desired manipulator *pose* (position and orientation) with minimum offsets.

Calibration is therefore used to improve robot positioning accuracy, through software rather than changing the mechanical structure or design of the robot itself (Elatta et al., 2004). Since robots are mechanical devices, they can be affected by slight changes due to manufacturing tolerances, changes of working environment temperature, wear of parts and component replacement (Elatta et al. 2004). Calibration is therefore meant to minimise these effects and avoid having to modify operations' programs and allows the use of off-line programming and effective use of manipulators in more industrial and non industrial applications.

To achieve high accuracy, the kinematic model used in the controller, should be a faithful mathematical description of the relationship, which relates the end-effector pose to the individual joint values. Ideally, this model should account for geometrical and no

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geometrical parameters, which can affect this relationship. However, all industrial manipulator controllers in the market contain ***nominal*** kinematic representations which are common to all manipulators of the same model. It is for this reason that improving manipulator accuracy passes through improving the kinematic model, by generating the *real* kinematic parameters for each particular manipulator after its assembly.

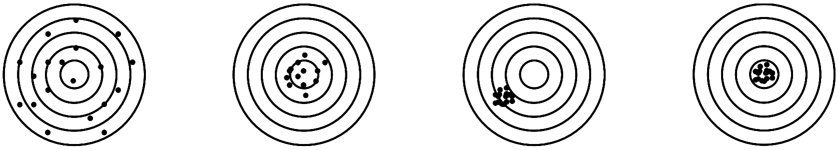
The work described in this chapter focuses on kinematic model improvement as a means of improving the accuracy of robots (Calibration) without having to impose stricter manufacturing tolerances, and presents an overview of the major research achievements in the field. The chapter discusses the issue of calibration in general and achieved research results, while it describes the procedure developed by the authors in previous work (Abderrahim & Whittaker, 2000) for the direct identification of the D-H kinematic model parameters. In addition the chapter describes the recent developments concerning the improvement of robot manipulators accuracy, which did make their way through to the market and made "*Absolute Accuracy*" of industrial robots a reality nowadays ((Renders, 2006) and (Fixel, 2006)).

The remainder of this chapter is organized as follows. The next section describes the repeatability and the accuracy as the most important values that determine the precision performance of an industrial manipulator. Error sources are also highlighted in this section. Section 3 gives an overview on industrial manipulators calibration followed by describing in details the calibration methods in section 4. Examples for the most commonly used robot simulation software are presented in section 5. In section 6, two examples for commercial calibration procedures are described and finally conclusions are summarized in section 7.

2. Accuracy and Error Sources

The important two values describing the precision performance of manipulator specified in the international standard ISO 9283, which sets the performance criteria of industrial manipulator are the *pose repeatability* and *pose accuracy*. Until recently and given that most of manipulator programming has been done on-line, where command points are acquired in teach mode, the most relevant performance specification was the repeatability. Pose repeatability is a measure of the ability of the robot to move back to the same position and orientation. Pose Accuracy, on the other hand, is defined as the ability of the robot to precisely move to a desired position in 3-D space. Fig. 1 illustrates the repeatability and accuracy graphically, by showing how close and scattered the achieved positions relative to the desired location at the centre of the circles.

The achievable repeatability of current industrial manipulators is very high and reaches values bellow 0.1 mm by most robots, while standard robot accuracy can range between 5 and 15 mm (Fixel, 2006) and can be higher depending on the make and model (Abderrahim & Whittaker, 2000). The repeatability errors are mainly caused by the inability of the controller to achieve exactly the same joint values at different runs, and the possible presence of backlash in the manipulator reduction gears. However, the latter effect is very unlikely due to the availability nowadays of zero-backlash gears. The pose accuracy errors are affected by numerous geometric and non-geometric parameters. The accuracy involves using the inverse kinematic model for the calculation of the joint values that correspond to the commanded 3D pose and therefore errors are caused by defects in this model. The main geometric parameters that affect this model are the dimensions of the manipulator links and orientation of the joints. During the manufacturing, the parts variation of dimensions is inevitable from one robot to the other due to tolerances. According to (Kevin et al., 2000), in revolute 6 DOF manipulators the length of first 3 links contribute to the position and joints 4, 5, and 6 (wrist) contribute primarily to the orientation of the tool frame. Other parameters that are not included in kinematic models and affect the accuracy include: Elasticity of joints and links, load proportion and joint deflection, actuator heating, sensors stability and drifts, gearbox flexibility and eccentricity and environment working temperature (Hefele & Brenner, 2001). In addition, end-effector fixing position and the determination of the world coordinate frame also affect the pose accuracy in the work environment.



Poor Accuracy
Poor Repeatability

Good Accuracy
Poor Repeatability

Poor Accuracy
Good Repeatability

Good Accuracy
Good Repeatability

Fig. 1. Achieved position according to repeatability and accuracy qualities.

3. Calibration Overview

There has been a lot of work on the subject of improving the positioning accuracy of industrial robot manipulators ((Hayati & Mirmirani, 1985), (Mooring & Pack, 1987), (Driels & Swaze, 1994) and (Roth et al., 1987) among many others). Most of the authors considered the main source of errors to be only geometric, with the exception of (Chen at al., 1987) and Whitney et al. (Whitney et al., 1986), who included explicitly non-geometric errors as well. Although some introduced their own models (Whitney et al., 1986), the majority used models that are universally valid and widely accepted, such as the Denavit-Hartenberg or modified versions of it ((Khalil et al., 1991), (Driels, 1993) and (Harb & Burdekin, 1994)). Much previous work is based only on computer simulations, but some validation work used real measurements ((Chen at al., 1987), (Whitney et al., 1986), (Stone, 1987) (Stanton & Parker, 1992) (Khalil et al., 1991),(Driels, 1993),(Driels & Pathre, 1994) and (Abderrahim & Whittaker, 2000)), and very recently there is even commercial application dedicated to robot calibration ((Renders, 2006) and (Fixel, 2006)). Stone (Stone, 1987) developed a model and also a novel general identification method to estimate his S-model parameters, based on the circle-point analysis (Mooring et al., 1991) which lead to what he designated as *joint features*. These joint features are the *plane of rotation, centre of rotation* and *radius of rotation*. If required, the D-H parameters can then be extracted from the S model. Stone's motivation for developing his model was because “the D-H Model is not amenable to direct identification” (Stone, 1987). However, with small modification, the D-H Model has been used successfully for calibration in several of the papers referred to above. Although the S-Model can be identified using the method proposed in (Stone, 1987), it still suffers the same disproportion as the D-H model when consecutive joint axes are parallel or near parallel. The real problem here is that the control software of existing industrial manipulator does not use the S-model parameters. The physically explicit significance of the D-H model and its widespread use in robot control software make it very desirable to develop identification methods that obtains the D-H parameters directly, whilst at the same time is able to deal with the case where consecutive joint axes are parallel. Our procedure proposed in (Abderrahim & Whittaker, 2000) makes use of the features introduced by Stone, but differs from Stone's work by making more use of the *radius of rotation* and also translating the *plane of rotation* along the *axis of rotation* to make it coincide with the D-H X-Y plane. Using the idea developed by (Hayati & Mirmirani, 1985), a new parameter was introduced to modify the model to be able to deal with the disproportion at parallel or near parallel joint axes. In this way the proposed method can be viewed as a combination of Stone's and Hayati's methodologies. In the method, the position of the end-effector caused by the movement of only one joint axis is measured, and the process is repeated for each joint in an inward sequence, starting from joint n and ending at joint 1. In a similar sequence the measured Cartesian positions of the end-effector are then used for the estimation of the features for each link (joint). These are in turn used for the estimation of link parameters.

4. Calibration Methods

Robot calibration is a process by which manipulator real parameters' values affecting its accuracy are established through direct or indirect measurement, and used to improve its accuracy by modifying the positioning software. The calibration procedure involves modelling, measurement, parameter identification and implementation of compensation. The first step is establishing a model to relate the 3D Cartesian position of the end-effector in terms of joint values and all other kinematic *parameters* that affect this function. The next step is to perform an external accurate measuring of the end-effector Cartesian pose corresponding to each set of joint values. The measurement should be performed in a number of positions sufficient for the process of identification. The identification method is chosen according to the model and how the measurements were taken. Using the set poses and the corresponding joint angles, the true kinematic values should be estimated through and identification process. These new parameters, which deviate from their nominal values, shall improve the manipulators accuracy when implemented in the controller. It has to be noted that in the case of establishing the non-geometric sources of errors and evaluating their effects a similar approach and steps have to be followed. Nowadays, calibration techniques and absolute accuracy are provided by major manipulator manufacturers such as ABB (Fixel, 2006) and KUKA robots. Access to modify the controller is not obvious, and may not be possible for third parties. In this case, the alternative method of compensation can be established off-line, where compensated end-effector Cartesian positions are calculated using the "real" estimated inverse kinematic model. The latter method is offered nowadays by calibration and metrology equipment manufacturers such as Metris (Metris, 2005). In the rest of this section we develop the mentioned steps covering the method described in our previous work and other new developments by others with emphasis on existing industrial solutions.

4.1. Modelling

Coordinate frame kinematic models are based upon the assignment of Cartesian coordinate frames fixed relative to each link of the robot arm. The Denavit-Hartenberg (D-H) model has been widely adopted in robotics due to its explicit physical interpretation of the mechanisms and the relatively easy implementation in the programming of robot manipulators. Other models are mentioned in the overview section above, where the mentioned references can be consulted for in-depth information. Since the D-H model was used in our work and due to its practical relevance it is the only one covered in this section. The D-H model is presented as 4X4 matrix that results from the following product:

$$T = A_1 \cdot A_2 \cdot \ldots \cdot A_n \ , \tag{1}$$

where T denotes the transformation of the link n coordinate frame into the base coordinate frame of the robot arm. A_i designates the D-H transformation matrix relating frame i to frame i-1. The nth link frame coincides with the end-effector's coordinate frame. Fig. 2 illustrates the spatial relative position of two consecutive links and their associated coordinate frames.

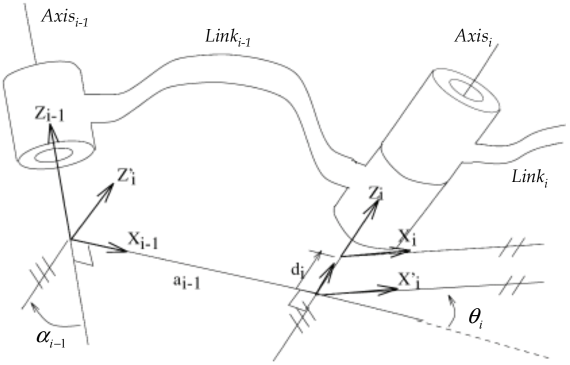


Fig. 2. The D-H parameters illustration in case of a revolute joint.

The spatial transformation between two consecutive links is a function of the joint type that connects them together. It is caused by a number of rotations and translations summarised by

$$A_i = A_i(q_i) \equiv Rot(z,\theta_i)\, Trans(0,0,d_i)\, Trans(a_{i-1},0,0)\, Rot(x,\alpha_{i-1}) \tag{2}$$

$$A = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_{i-1} & \sin\theta_i \sin\alpha_{i-1} & a_{i-1}\cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_{i-1} & -\cos\theta_i \sin\alpha_{i-1} & a_{i-1}\sin\theta_i \\ 0 & \sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

When this model is used as a basis for kinematic and inverse kinematic calculations the errors affecting the parameters, a_i, d_i, α_i and θ_i should be estimated during the calibration process. If non-geometric effects such as temperature and joint compliance are considered, then the model should account for them directly or indirectly.

4.2. Measurement

This section is dedicated to describe the systems that are capable of providing accurate measurements fit for application in the calibration process. The first system described is the system used in our previous work (Abderrahim & Whittaker, 2000), and the second is chosen because it represents one of the few existing industrial effective solution in the market.

During the mentioned work the instrument used to measure the Cartesian end-effector position of the Puma manipulator, relative to the robot base frame, was a laser tracking system called "*Optotrac*" designed and built at the University of Surrey (Mayer & Parker, 1988). The instrument consists of two tracking sub-systems that each directs a laser beam towards a retro-reflective target, attached to the end-effector of the robot arm, by using two orthogonally mounted optical scanner units. The resultant tracking errors from driving the scanners are used to calculate the 3-dimensional position of the target. The instrument has a repeatability of $0.1 mm (Stanton & Parker, 1992). Simultaneously with the target position measurements, the angular positions of the first three links were measured by extracting the relevant encoder signals from the robot controller, using hardware developed at Glasgow University (Abderrahim & Whittaker, 1996) fig. 3. Hand-shaking signals were established to synchronise the measurements taken by the two systems. The *optotrac* set up takes very long time, which makes using it for industrial applications much less effective than existing industrial solutions nowadays, such as the *Krypton K600* and *K400* (Renders, 2006) and the *Leica Lasertracker LTD 500* (Fixel, 2006). It is worth mentioning that, all these systems would have served well our measurement requirements.

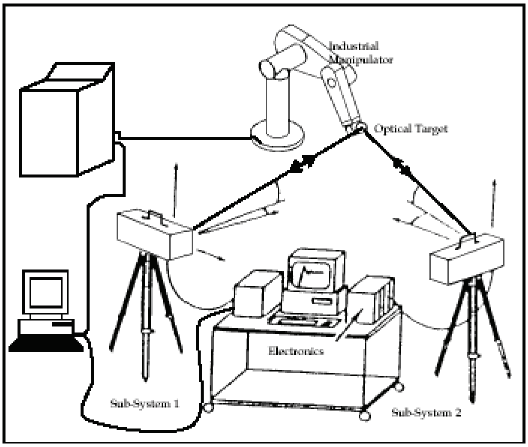


Fig. 3. The measurement system including the Optotrac & motor angles and currents acquisition hardware.

The second measurement system to describe here is the Krypton *K600* solution. The main piece of the *K series* measurement system is the camera system, consisting in three linear CCD cameras, shown in fig 4. The camera system relies on infra red light active LEDs, and therefore they cannot be seen by the human eye. When a LED is picked by the three linear cameras the computer calculates its exact position in the 3D space.

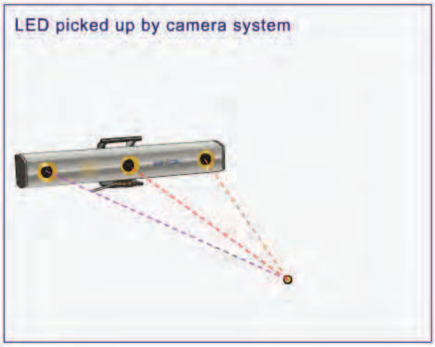


Fig. 4. The Krypton K600 Camera system (*Courtesy of Metris*).

The calculation is achieved by comparing the image of the 3 linear CCD cameras, from the effect of having 3 planes intersecting on the LED position, which is then calculated relative the pre-calibrated camera as illustrated in fig 5. According to the manufacturer the system is capable of tracking up to 256 LEDs simultaneously, through computer controlled strobing. This simultaneous multiple point tracking allows the measurement of the position and orientation of objects by attaching to them 3 or more LEDs and measuring their positions simultaneously. The system has a single point accuracy starting at 60 μ and is capable of measuring targets at 6 m distance from the camera.

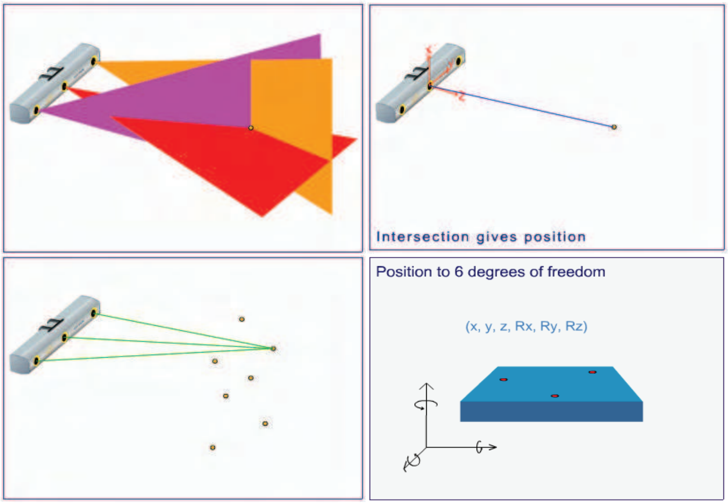


Fig. 5. Illustration of the measurement steps of the K600 (*Courtesy of Metris*).

This measurement system is a fundamental piece of metrology, which can be used for robot calibration and other application like motion analysis and 3D CMM inspection. This system is then valid for any calibration procedure that relies on measuring the pose of the end-effector of the manipulator. All is needed is fixing the LEDs precisely on the end-effector and start the measurement, which takes only minutes. Until recently the measurement step was often a lengthy and the main hurdle for achieving effective calibration.

4.3. Parameters Identification

Among the variety of methods of parameters identification, this section is limited to describing a method where the authors have done research and experimental tests (Abderrahim & Whittaker, 2000). In the current work, only robots with revolute joints have been considered. Prismatic joints have only one feature, the line of translation. Stone (Stone, 1987) gives a simple approach for the estimation of this feature. Concerning the required measurements, Stone (Stone, 1987) determines the model parameters through direct measurement of the joints' motions by attaching to the moving link a target whose position is measured. Stone allows free positioning of the target on the moving link while Stanton (Stanton & Parker, 1992), due to the nature of the measurement system, specifies a target fixed to the end-effector. The measurement of the target Cartesian position in the current work uses the same system used by Stanton.

The joint features are identified link by link. In a similar manner to Stone, we identify first the *plane of rotation*: the plane containing a circle described by a point on a rotating link, followed by the *centre of rotation*: the centre of that circle which will be situated on the joint axis. We also explicitly identify the *radius of rotation*. We next introduce a novel translation of the *plane of rotation* along the *axis of rotation* so that it coincides with the D-H X-Y plane. This translation, along with the three identified features, allows the D-H model parameters to be extracted.

4.3.1. Features Identification

Identifying the *plane-of-rotation* is a straightforward task. When joint *i* is made to rotate and the rest of the joints (1 to *i-1* and *i+1* to *n*) are locked, the target fixed relative to the end-effector then traces a circle in space. The coefficients of the plane of rotation can be estimated by fitting to a plane the *m* measured Cartesian positions of the target corresponding to *m* deferent positions of joint *i*. Several methods have been suggested to solve this problem, as stated in (Stone, 1987) and (Stanton & Parker, 1992). For reasons of simplicity, Stone's linear least square technique is used in our work. The method attempts to minimise the sum of the perpendicular distances between the measured points and the estimated plane of rotation. Though not essential, it aids visualisation, when measuring the target motion due to movement of joint *i*, all joints 1 to *i-1* and *i+1* to *n* are locked in their zero positions. Independently, each joint of the manipulator is made to move through the required *m* positions, maintaining a correct sense of rotation. It is assumed that the joint angles $q_{i,\,j}$ are ordered such that $q_{i,\,j} < q_{i,\,j+1}$ where *i* is the joint number and *j* is the order of the corresponding measured end-effector position $\vec{p}_j = \left[x_j y_j z_j\right]^T$.

The equation of a plane can be written as:

$$Ax + By + Cz + D = 0 \tag{4}$$

where *x*, *y* and *z* are the coordinates of the points of the plane and the coefficients A, B, C and D are to be identified. This equation can be rewritten as:

$$z = Ex + Fy + G = \phi^T \Theta \tag{5}$$

where the $\phi = [x, y, 1]^T$ and $\Theta = [E, F, G]^T$, which are defined as the information and parameters vectors. The *z* coordinate is defined to be the output of Eq. (4). A simple regression of *z* on *x*, *y* and 1 corresponds to the minimisation of the sum of the squared errors in the *z* coordinate.

$$\Xi = \sum_{j=1}^{m} (z - z_j)^2 = \sum_{j=1}^{m} (\phi^T \Theta - z_j)^2 \tag{6}$$

The minimisation of this expression by equating it to zero yields the linear least squares solution (Hsia, 1977), where it is assumed that the coordinates of the information vector are independent variables and measured without error. Three points of the measured target positions are used for the formation of the new coordinate frame. These three points uniquely form an initial approximation of x-y plane, hence the plane of rotation. The points are chosen to be mutually most distant from one another and are denoted by $\vec{p}_k$, $\vec{p}_l$ and with $k < l < m$ in order to preserve the sense of rotation. Fig. 6 assists in the understanding of the formation of the new coordinate frame where the plane of rotation is estimated.

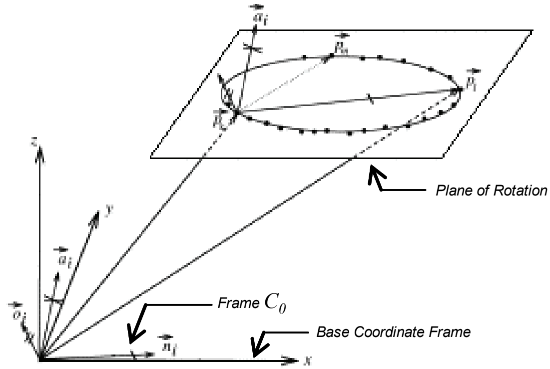


Fig. 6. The formation of new coordinate frame from the measured points.

The *x*-axis is chosen to be parallel to the line joining $\vec{p}_k$ to $\vec{p}_l$. The *z*-axis is perpendicular to this axis and to the line joining $\vec{p}_k$ to $\vec{p}_m$. The *y*-axis completes the orthogonal system. The origin of this initial coordinate frame is coincident with the origin of the frame in which the data are measured (presented), which in our case is the robot arm base coordinate frame. The homogeneous transformation matrix between the measurement frame and the new frame C_0 is given by:

$$R_i = \begin{bmatrix} \vec{n} & \vec{o} & \vec{a} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

where $\vec{n}$, $\vec{o}$ and $\vec{a}$ are he unit vectors of the newly formed coordinate frame, which forms a pure rotation *T*. The measured data can be transferred to the newly formed frame C_0 where a least square regression is executed to calculate the coefficients of the plane of rotation, which in turn are transferred back the measurement coordinate frame. The detailed procedure and justification are treated in (Abderrahim & Whittaker, 2000). In the procedure used in the current work, unless the target position is already on the nominal D-H X-Y plane, the plane of rotation for each link should now be translated to coincide with the D-H X-Y plane. This is first done by using the offsets between the *n*th axis and the target attached to the nth link. Consequently, accurate knowledge of the target location with reference to the last link is essential. In the case of other links, the previously estimated parameters are used. If for some reason this information is not available, nominal lengths could be used. The translation is along the z-axis of the C_i for each link.

By a similar least squares procedure, the coordinates of the *centre of rotation* $\vec{p}_i$ can be identified. The *radius of rotation* is then easily established.

The next step is the coordinate frames construction and the D-H parameters identification. This part makes use of the set of the estimated *n* normal vector to the *planes of rotations* $\vec{a}_i$ and *n* centre of rotations $\vec{p}_i$ to specify the locations and orientations of the D-H model link coordinate frames. First, partial D-H models are specified to define the location and orientation of the individual D-H coordinate frames in terms of the base frame of the robot arm. These are given by:

$$T_i = A_1 \cdot A_2 \cdot \ldots \cdot A_i \tag{8}$$

From above we deduce:

$$\begin{cases} T_i = T_{i-1} \cdot A_i \\ \text{and} \\ A_i = T_{i-1}^{-1} \cdot T_i \end{cases} \tag{9}$$

where the expression of the individual T_i are given by:

$$T_i = \begin{bmatrix} \vec{n}_i & \vec{o}_i & \vec{a}_i & \vec{p}_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

Using the result of expression (9) and (10) and equating them to the expression of A_i given in (3) the parameters forming the matrices can be calculated in a backward iteration from the last joint to the first. The errors affecting the kinematic model parameters can be extracted. This method was tested experimentally and results proved its effectiveness (Abderrahim & Whittaker, 2000).

4.4. Compensation Implementation

Compensation is the last important step in manipulator calibration, and consists of replacing the nominal kinematic model parameters by the new calculated "true" values in the robot's position control software. However this operation is neither easy nor always possible, and usually implemented by the robot manufacturer such as the case of ABB. The other option is the compensation off-line of all points of the programs using the established correct kinematic model. The 3D Cartesian positions are used with the inverse correct kinematic model to calculate the joint values for the real robot. These values are then used in the nominal forward kinematic model to calculate new 3D compensated end-effector positions. These compensated positions are then loaded in the robot controller, with the nominal kinematic model, and when executed achieve the real desired positions. In this process, the robot is commanded to an offset pose from the intended, and because of its model errors it reaches the correct pose. This solution is the easiest to implement, but attention should be paid to avoid *relative* 3D command positions, which include on-line calculations that involve the nominal kinematic model. This option is implemented in the calibration software, *ROCAL*, provided by Metris (Renders, 2006).

5. Robot Simulation Software and Off-Line Programming

With the rapid development of information and computer technology, recent years have seen an increase of computer simulation environments of complete manufacturing cells and Robotics Computer Simulation modules that are also offered by some robot manufacturers. Robot Simulation modules are provided for Off-Line Programming (OLP) systems which incorporate original path planning and interpolation algorithms of the robot controller (Beyer and Wulfsberg, 2004). Tremendous time saving can be achieved and costly programming mistakes can be spared if the tasks can be planed and simulated before implementation (Elatta et al., 2004). These simulation tools can also be used to quickly investigate robot applications using accurate 3D computer models and path planning algorithms. Off-Line prepared programs can then be loaded directly in the robot controller, but due to differences between the real robot and nominal model in the simulation software, position points have to be corrected. This process can be reduced or completed eliminated if the robot is calibrated and the "true" compensated model is transferred to the simulation environment. In this case the whole production line can be simulated and robot programs can be simply downloaded from the simulation environment to the actual robot on the shop floor with no "touch-up". This also means that a failing robot can be replaced by another "absolute accuracy" robot with minimum disruption to the production line (Hefele & Brenner, 2001).

As samples of these computer simulations software, a brief description of the three most known to the authors is given next:

- **IGRIP (Interactive Graphics Robot Instruction Program):** developed by the company Delmia, is a Robotic Simulation and Off-Line Programming Solution. According to the company, it permits the design and simulation and analysis of the complete manufacturing cell. IGRIP includes the most comprehensive library of robot models available, with more than 500 industrial robot models, including the latest from FANUC, ABB, Motoman and Nachi. Application-specific devices such as weld guns, work piece positioners, rails, gantries, and workpiece clamps are available in options such as Arc, Spot, and Paint (Delmia, 2003).
- **RobotStudio:** is a simulation software developed by ABB and reflects the group's great effort to produce such a mature product. RobotStudio is built on the ABB VirtualRobot, which is an exact copy of the real software that runs the robots in production, and can generate exact RAPID programs. It allows very realistic simulations to be performed, using real robot programs and configuration files identical to those used on the shop floor. It is therefore easy to transfer robot programs and configuration parameters between a robot and the computer. According to ABB, virtual robot technology concept makes the company the only supplier offering true off-line programming, with no translation or touch-up. In addition, the company's calibration software is built on the RobotStudio platform, and that is how it uses a virtual model identical to the real calibrated robots (see www.abb.com/ for more details). RobotStudio provides the tools to increase the robot systems profitability by allowing the users perform tasks such as training and optimization without disturbing production.
- **Festo COSIMIR Professional:** is a PC-based software package for 3D modelling (including fault finding and design optimization), programming and performance emulation of various industrial robot systems. Modelling with COSIMIR Professional is made simple by virtue of the libraries of robots, end effectors and automation components. The program also imports several CAD formats. The programming feature supported by COSIMIR Professional, permits off-line programming of most commonly used Robots, allowing syntax check and automatic integration of position lists, automatic creation of complex parameter assignment, and the up load and download to and from Kuka, ABB, and all Mitsubishi controllers. The simulation mode permits the testing of cell and tool designs. All motion sequences and handling processes can be instantly simulated in the modelled work cell to avoid collisions and optimise cycle times (see www.festo.com/ for more details). Compilers of more robot models can be integrated in the software at any time to produce realistic simulations and analysis of the designed process (Karras, 2003). According to recent consultation with *Festo GmbH,* the software has the capability of connecting the real robot controller to the simulation PC to produce precise cycle time to permit a *real* optimisation and analysis.

6. Existing Absolute Accuracy and Industrial Calibration examples

In both examples presented in this section, to the best knowledge of the authors, no mathematical theory behind the choice of the measurement point or identification algorithms has been published. Therefore the intention is to bring to the reader's intention some of the sample calibration tools available in the market and describe how they work.

The absolute calibration of ABB robots (**AbsAcc**) is implemented as a model based solution, highly integrated in the standard controller software. The solution is developed in-house by ABB and uses the standard kinematic description as a base. AbsAcc covers two parts, geometric compensation and deflection compensation. There is a set of parameters (approx 40) describing the individual properties for a calibrated robot. Once the parameters are loaded and activated, the operator can use the robot as normal. All compensations are done automatically without any further adjustments or special handling. The positioning accuracy of a calibrated robot depends on the robot size and variant and is in average between 0,25 mm and 0,55 mm for a robot handling between 5 and 500 kg.

The calibration is performed for each individual manipulator that requires AbsAcc and normally this is done in the factory. The calibration software ***CalibWare*** and the procedure require the robot to be measured and for this purpose a 3D measuring station is needed. ABB uses the Leica Lasertracker (LTD 500) in order to have a measuring accuracy that supports the calibration and verification. The process compensates for geometric and no geometric errors as shown in fig. 7.

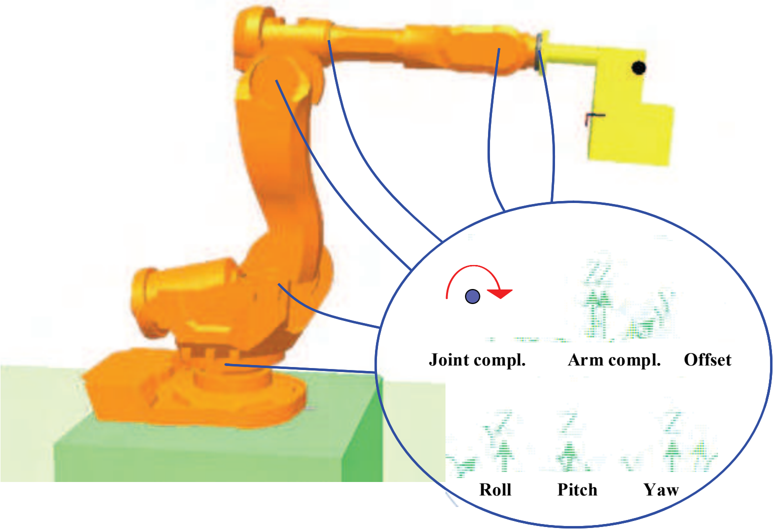


Fig. 7. Geometry deviations and joint deflection due to load *(Courtesy of ABB).*

The calibration itself contains 100 positions randomly distributed within the robot working area and giving excitation to all robot axes. From the result a set of parameters that best minimizes the error between the model and real robot are calculated. The robot positioning accuracy is then verified by running 50 more positions and calculating the difference between the ordered position and the measured, according to the set up shown in fig. 8.

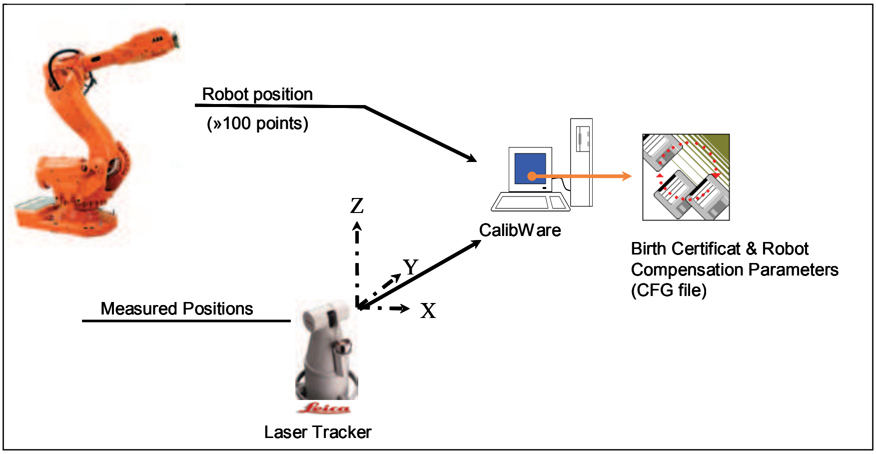


Fig. 8. ABB calibration process set up. *(Courtesy of ABB).*

On the other hand, the calibration procedure provided by **Metris** employs the Krypton K600 camera to measure between 25 to 100 calibration poses. These poses are automatically generated in the field of view of the camera and in the working volume of the robot. The ROCAL software will thus create a set of poses evenly spread. This set of poses is then converted into a robot program, which is loaded to the robot and executed. In each of the poses, at least 3 infrared LED's attached to the robot tool frame are measured fig. 9. Measuring three LED's, gives position and orientation of the robot tool frame, which is called "6D". With most other systems, only 3D or 1D position is acquired. Acquiring position and orientation during the measurement reduces the number of robot positions that are required to identify a higher number of robot parameters.

The set of estimated robot positions and the measured poses are used to calculate a new robot model. This robot model contains: the real link lengths and angles, deflection of links, joints deflection, base deflection, coupling errors and encoder offsets.

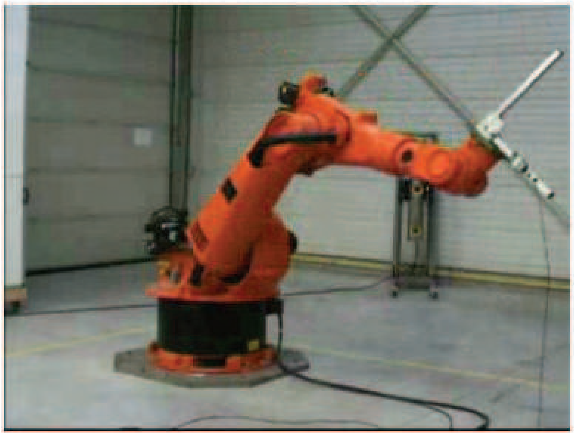


Fig. 9. Minimum of 3 LEDs are attached the tool frame during the calibration to obtain complete pose (6D). (*Courtesy of Metris*).

Since Metris is not a robot manufacturer, their system of measurement and calibration targets all robots makes and models. According to (Renders, 2006), it takes only about 1 hour of work to include a new robot model. All is needed is a description of all joint axes with respect to the base frame of the robot. As for the compensation of the errors, this is done on the target positions of the program (off line). The compensation on the controller level is more difficult and requires more effort. If this is required, another software module (***RETRAC***) and the new robot model are provided by Metris to be integrated in the controller path planner. Therefore any robot that connects to that controller can run the Absolute Accuracy version.
The combinations of ROCAL software and the *K series* measurements system are able to calibrate the entire cell and hence provide the link between simulations and the real world. The software provides three types of calibration routines, robot calibration, tool calibration and environment calibration. In the tool calibration LEDs are fixed to the tool and measurements are performed to establish the tool TCP frame, as illustrated in fig 10. In the case of the environment calibration, the CMM capabilities of the measurement system are used to register reference points of the environment relative to the robot and establish a fixture frame.

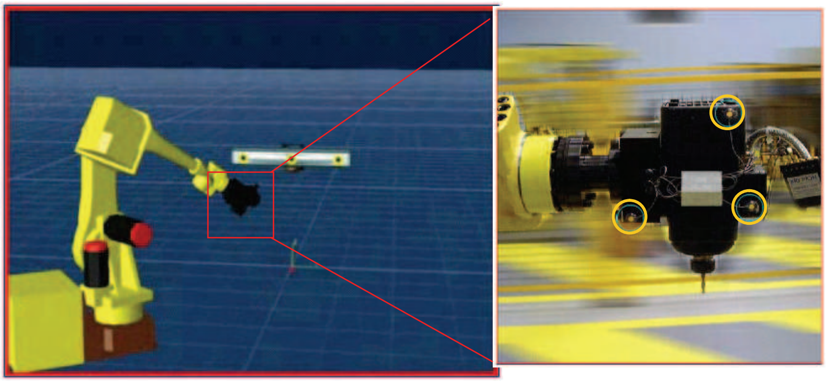


Fig. 10. During tool calibration LEDs are fixed to the tool (*Courtesy of Metris*).

For illustration a real example of the achieved accuracy after calibration of a 159 Kg payload industrial robot manipulator holding full load is presented next. The original pose accuracy before calibration was 3.25 mm and 5.43 mrad. After complete calibration these figures are brought down to 0.29 mm and 0.35 mrad.
If a subset of parameters is calculated in partial calibration the achieved accuracy is a little worse than the mentioned above, but still improve the Cartesian positioning of the robot a great deal. For the same manipulator mentioned above, encoder offset calibration achieves a complete pose accuracy of 1.44 mm and 3.87 mrad, while geometrical only calibration guarantees an accuracy of about 0.72 mm and 2.12 mrad.
The Rocal software and the *K600* system make a powerful tool, which makes it possible to move a 150kg robot load under 0.5 mm average error in its entire working volume.

7. Conclusion

This chapter discussed the accuracy issues of robot manipulators and the importance of searching for absolute accuracy for industrial manipulators. It shows how there is an increased need to use off-line programming and robotic and manufacturing simulation software to analyse and optimise the processes and trajectories of manipulators present in the process. Throughout the chapter it has been emphasised that without absolute accuracy there cannot be off-line programming of robots and without calibration there cannot be absolute accuracy. Therefore the combination of OLP and absolute accuracy, production line design and development in manufacturing can be done in record times through realistic simulations. Programs can be downloaded directly to the robots without touch-up and corrections, which can be interpreted in reduction of downtime, great efficiency, easy and rapid duplication of production lines or even complete cells.

The text presents therefore an overview of the work and methods of accuracy improvement and explains the main steps to be followed in this process. Existing commercial solutions have been described to give the reader an idea of the state of the art of the technology and where to find it. Obviously these are not the only commercial solutions but they have been chosen because, to the best knowledge of the authors, they are among the best solutions and they provided all information to make our evaluation.

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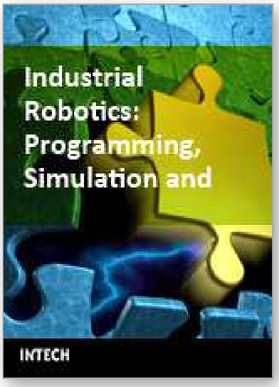

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This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

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