Robotica (2004) volume 22, pp. 505–512. © 2004 Cambridge University Press
DOI: 10.1017/S026357470400027X Printed in the United Kingdom

Practical robot calibration with ROSY

Lukas Beyer and Jens Wulfsberg

Laboratory for Production Engineering, University of the Federal Armed Forces, Holstenhofweg 85, D-22043 Hamburg (Germany)
E-mail: Lukas.Beyer@UniBw-Hamburg.de

(Received in Final Form: January 10, 2004)

SUMMARY

The accuracy of pose of industrial robots is often unsatisfactory for advanced applications. Particularly regarding off-line programming, exchangeability and high precision tasks problems may occur which can be very time-consuming and costly to solve.[1] Therefore a calibration system ROSY has been developed in order to increase the accuracy of standard robots and parallel-kinematic structures, like the Tricept robots.

1. INTRODUCTION

The number of industrial robots (IR) installed in Germany has reached 100,000 by the year 2000.[2] Thus a new milestone in the degree of automation in industrial production had been set, which was particularly promoted by a sharp decline in the manufacturing costs of the flexible assistants.

On the other hand, the international machine tool (MT) industry had a severe sales crisis, particularly during the years 1992–94, so that it was not until 1999 that Germany was able to achieve the same level of production as in 1990.[3] Apart from a market shakeout, this has led to the development of new machine concepts in close co-operation with scientific research: Parallel kinematics were expected to provide improved dynamics and accuracy, while also reducing system costs.[4]

In addition, IRs have improved continuously, particularly regarding payload, accuracy, speed and reliability, so that today they are no longer used only for fairly simple functions, such as spot welding and material handling, but have taken on many special tasks which were not regarded as robot applications before, e.g. laser welding, water jet cutting or robot-guided hemming.

The Laboratory for Production Engineering has played its part in extending the range of IR applications in the past, especially by increasing the working accuracy of standard robots. In recent times attempts have been made, by combining the specific advantages of both the developments mentioned above, to extend the possible types of application for industrial robots – in particular, for those with parallel kinematics – so that they can cover highly accurate and flexible applications which have so far mainly been reserved for machine tools or special machines. The core of these efforts is the development of the measurement and calibration system ROSY (Robot Optimization System).

2. OBJECTIVES

New solutions can only achieve long-term success in industrial production if they promise an increase in efficiency, and hence an increase in productivity or a reduction in unit costs with consistent or improved quality when compared with the methods used so far. Therefore the new equipment must either incur lower manufacturing costs or have a correspondingly higher performance. Consequently, the starting point of this research project was the search for a suitable *type of machine* that was able to fulfil these prerequisites within certain niches.

Current prices for parallel machine tools focused attention on parallel kinematics of a more simple, robot-oriented design at an early stage. Since the manufacturing tolerances of the individual components are not a major goal here, these machines can be manufactured at relatively low costs on the one hand, and on the other hand they offer much room for an increase in accuracy. For this reason and because of the main fields of research at the laboratory, in the past parallel-kinematic industrial robots (PIR) have proven to be an interesting research topic. They can be used profitably for certain special applications in the gap which exists between conventional robots and machine tools in terms of tolerance and cost, and they have the chance to open up new applications based on this approach (Fig. 1).[5]

Furthermore, it was necessary to find out which *kinematic structure* appeared most promising in order to fulfil particular tasks faster, more accurately or more cheaply than before. Since these applications mostly demand high flexibility of the production equipment, it was essential that the machine should have six degrees of freedom in order to be able to reach any pose within its workspace. Therefore, the option remaining was the choice between two basic structures: either a fully parallel hexapod or a hybrid kinematic which consists of a tripod and a conventional serial wrist.

Now hexapods usually have the disadvantage of a limited workspace and a restricted range of possible orientations, which often makes a real five-sided machining of a workpiece difficult. The hybrid structure avoids these restrictions by means of a parallel section that is mainly responsible for setting the spatial position, whereas the freely swivelling hand covers a wide orientation range. In this way, for instance, a hemispherical workpiece can be processed everywhere perpendicularly to its surface. On these criteria the preferred test object was the Tricept parallel-kinematic robot.[6] The final aim is to have a "universal" machine that is

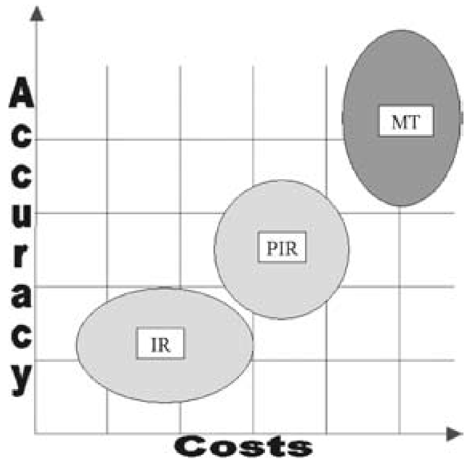

Fig. 1. Classification of conventional industrial robots, parallel-kinematic robots and machine tools in terms of accuracy and cost[5].

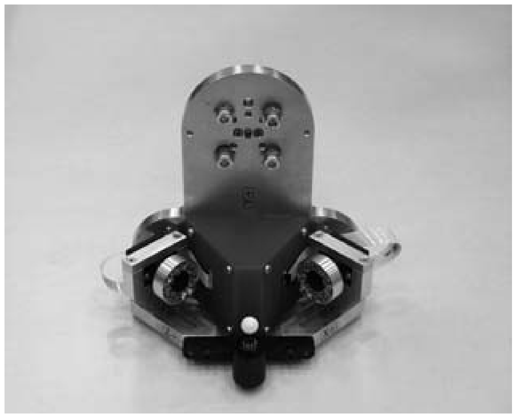

Fig. 2. Measurement tool with two CCD cameras and reference sphere.

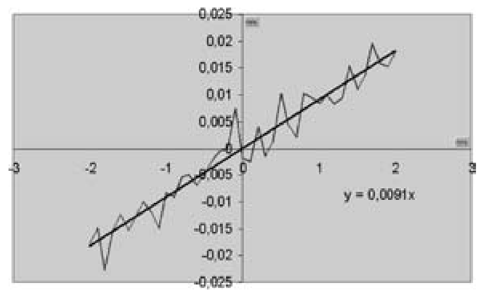

Fig. 3. Absolute accuracy of the measurement tool with regression line.

flexible, fast, strong and accurate enough to perform specific tasks better than before, i.e. with an accuracy of pose (AP) of 0.1 mm or better.

3. SYSTEM DEVELOPMENT

3.1. Measurement strategy

The first objective was to find a way of determining the machine's current accuracy quickly and without large equipment. Therefore a time-consuming "all-round calibration" with interpolated error matrices for different orientations in space, as described by Kreidler, was ruled out from the beginning.[7] Further methods with external measuring devices or large reference parts did not meet the requirements either.

Otherwise, if one follows a system theory approach to find out the kinematic errors of a structure, it is not necessary to cover the whole workspace during a measurement; one only has got to ensure that the single axes are moved within a representative range. This led to the conclusion that it is enough to measure a single position in space from a sufficient number of different orientations. This strategy was confirmed by numerous calibrations of standard robots with six joints where an improvement of up to 92% on original accuracy was achieved, in best cases tending towards a minimum of 150 μm (see section 4).

3.2. Sensor development

The requirements for the sensors were fast data acquisition, touchless function, high resolution, low weight and cost. Accordingly, the best choice was a measuring tool based on a videometric principle with two digital CCD cameras. As there was nothing similar available on the market, we had to develop this ourselves (Fig. 2). The tool is attached to the mounting plate of the robot, and with a special measurement program the deviations at 40 different poses around a white ceramic sphere are recorded in three dimensions (X, Y and Z component).

Although common devices were used, a highly precise measurement with low noise was achieved due to the very good optical quality of the lenses and several camera calibration methods. Finally, the resulting standard deviation is 1.5 μm and the absolute accuracy over the measurement range is greater than 99% without any further measures, but can still be improved by simple linear regression (Fig. 3). This enables a good condition and convergence of the numerical algorithms used for parameter identification to be guaranteed.[8]

By means of a special adapter the tool can be attached to any industrial robot from 1 kg to 500 kg payload with a standard mounting plate – regarding parallel structures e.g. to the Tricept type SRT60. The measurement process itself can be performed within five minutes as the robot program is generated by the calibration system automatically.

3.3. Kinematic modelling

For serial kinematics a six-dimensional model with RPY-angles in frame notation is used to perform the direct transformations because the standard Denavit-Hartenberg model used in robots controllers has certain disadvantages in terms of unsteadiness during optimization. The inverse algorithms are solved numerically to avoid multiple solutions dependent on varying angle and configuration definitions in different controller types.

As it is commonly known, unlike serial structures, where the direct kinematic problem (DKP) is easier to solve than the inverse (IKP), with parallel structures the problem is

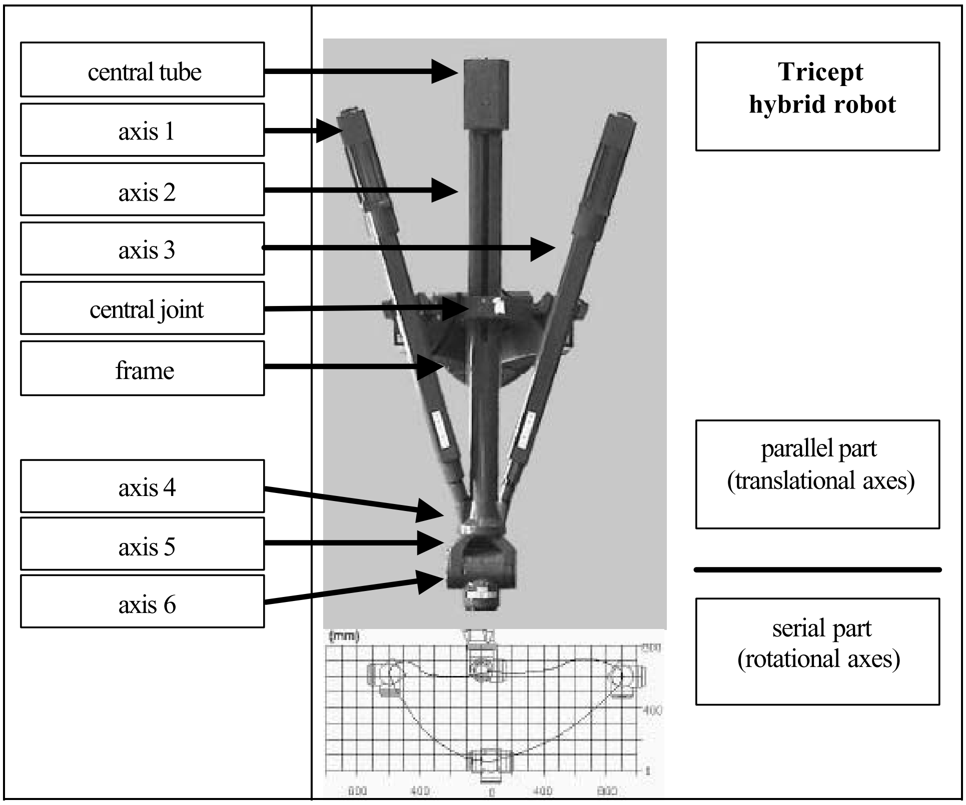

Fig. 4. Kinematical linkage of the Tricept.

contrary: The DKP usually cannot be calculated analytically, but has to be solved by iteration.[9]

Particularly with the hybrid Tricept robot (Fig. 4) further problem arose:

- *Combination of serial and parallel part for DKP and IKP*
  Due to the restrictions mentioned above, the direct transformation consists of a numerical part for the parallel structure and an analytical one for the hand, whereas the inverse problem is solved numerically for the wrist (with respect to the hand's configuration and parameters) and analytically for the rest.

- *Calculation of the influence of the screws*
  When the Tricept is moved in direction Y, the lower parts of the struts are turned against the upper ones, which leads to a deviation in length. This effect has to be taken into account and described mathematically for DKP, IKP and parameter identification. It makes transformation significantly more complicated than in normal tripod algorithms.

- *Lack of parameters*
  In the different robot controllers the Tricept linkage is described with only a few constants (5) and variables (6) which differs greatly from the parameter set necessary for a calibration. To ensure a complete kinematic description of the mechanism, at least 39 parameters are recommended. Further parameters might be added for a more detailed description of the cardanic joints.

According to these requirements, a new and complete kinematic model of the Tricept had to be developed for the purpose of calibration. This fact directly led to the question of how to implement the calculated correction values, which will be discussed in the following paragraphs.

3.4. Parameter identification

The core problem of calibration is the calculation of *real* kinematic parameters that can replace the *ideal* lengths and angles that were determined during the design process and are used to control the machine regardless of manufacturing and assembly errors which can never be eliminated completely. The input for this algorithm is the 3D measurement data from a certain amount of different poses. So the goal is the solution of a multidimensional, non-linear, unrestricted optimization problem.[10]

For this purpose, first the output of the real system $\vec{y}_R$ is measured and compared with the results from the ideal model $\vec{y}_M$. With several given input vectors $\vec{x}$ the parameter vector $\vec{p}$ is modified until the residuum r of the target function has reached a minimum. Finally, model and reality are aligned by using the determined parameter vector of the model function for describing the real system.

The problem of parameter identification for any kinematic structure can be described in compact form as follows:

$$\vec{p} = (p_1 \ldots p_d)^T;\ \vec{p} \in \mathbb{R}^d,$$
$$\vec{x} = (\vec{x}_1 \ldots \vec{x}_k)^T;\ \vec{x}_i \in \mathbb{R}^n;\ i \in [1, 2, \ldots, k];\ \vec{x} \in \mathbb{R}^{kPn},$$
$$\vec{y}_M = (\vec{y}_{M\_1} \ldots \vec{y}_{M\_k})^T;\ \vec{y}_{M\_1} \in \mathbb{R}^m;\ i \in [1, 2, \ldots, k];\ \vec{y}_M \in \mathbb{R}^{kPm},$$
$$\vec{y}_R = (\vec{y}_{R\_1} \ldots \vec{y}_{R\_k})^T;\ \vec{y}_{R\_1} \in \mathbb{R}^m;\ i \in [1, 2, \ldots, k];\ \vec{y}_R \in \mathbb{R}^{kPm}$$

https://doi.org/10.1017/S026357470400027X Published online by Cambridge University Press

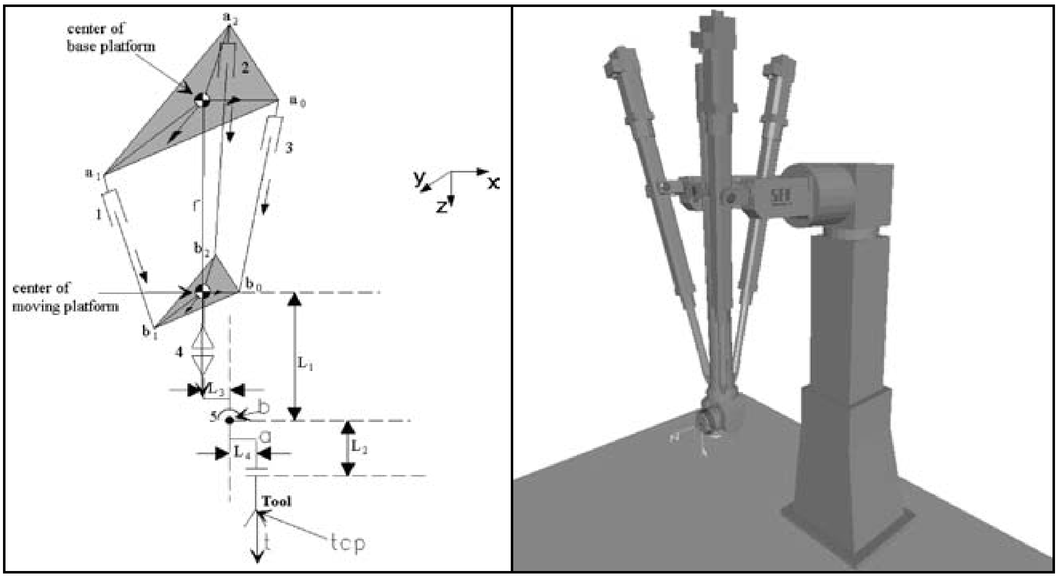

Fig. 5. Fully parametric simulation model of Tricept SRT60.

Thus the system behaviour can be determined by the model function $\vec{f}^*$:

$$\vec{y}_M = \vec{f}^*(\vec{x}, \vec{p}); \quad \vec{f}^* \in \mathbb{R}^{kPm}$$

The minimization of r in order to identify an optimum $\vec{p}$ follows from the Euclidean norm of the output vectors:

$$\min_{\vec{p}\in R} O(\vec{p}) = \frac{1}{2} \cdot \sqrt{(\vec{y}_M - \vec{y}_R)^T \cdot (\vec{y}_M - \vec{y}_R)} = \frac{1}{2} \cdot \sqrt{\sum_{i=1}^{m} r_i(\vec{p})^2}$$

The numerical calculations are performed using a gradient-descent method with a linear estimation of the Jacobian and appropriate step size control. Many investigations proved that with the Levenberg-Marquardt method the best compromise between convergence and robustness could be achieved.

3.5. Kinematic calibration

There are basically two methods available to compensate for the kinematic errors of industrial robots: either the correction of the machine data in the robot controller or the correction of the robot program.[11] In the case of controller correction some knowledge of the system variables describing the kinematic structure in the robot controller and different manual changes are necessary to implement the calculated kinematic parameters. Problems will occur when – as mentioned above – the number of parameters of the controller model is not sufficient to achieve the desired accuracy.[12]

In the case of the Tricept robot, this inconvenience has led to a new approach which allows accuracy to be enhanced without affecting the machine control: For a particular application, the previously calculated robot signature and the off-line robot program generated on CAD basis are merged into a new path taking into account the machine's errors. This commands "wrong" cartesian positions that guide the "wrong" robot to the "right" place, again not by just adding interpolated error matrix elements or correction vectors, but by systematic calculation of the occuring cartesian errors at each pose of the path. This process is also called "fake target method" and is valid for the whole work area, not only for the measured region.

The practical implementation is quite simple: The user program is provided on floppy disk, and after specification of robot language and serial number the poses are uploaded, changed and saved back within a few seconds. This way improvements in accuracy of up to 90% have been achieved for Tricept robots (see section 4).

3.6. Graphic visualisation

Another goal of the project was to provide an inexpensive method for operatives to generate robot programs by the use of given workpiece data. Generally there are many different off-line programming (OLP) systems on the market, but most of them are workstation-based and exceed the costs of a parallel robot. There are also PC-based programs available, but not all of them support parallel kinematics.

After some investigations, an affordable Windows-based system could be found which provides the necessary kinematic structures and the desired features. After the geometric models of the Tricept robots with variable parameters had been designed jointly with the developers (Fig. 5), the complete kinematic algorithms were implemented. This way a machine model was created that can easily be adjusted to the real mechanism; so the robot signature can be stored in the simulation model, which makes controller or program modifications unnecessary.

4. RESULTS

4.1. Standard robots

The system was first tested with standard robots to optimise measurement technique, data transfer and parameter identification before the kinematically more complicate case of Tricept robots was investigated. One example was a

https://doi.org/10.1017/S026357470400027X Published online by Cambridge University Press

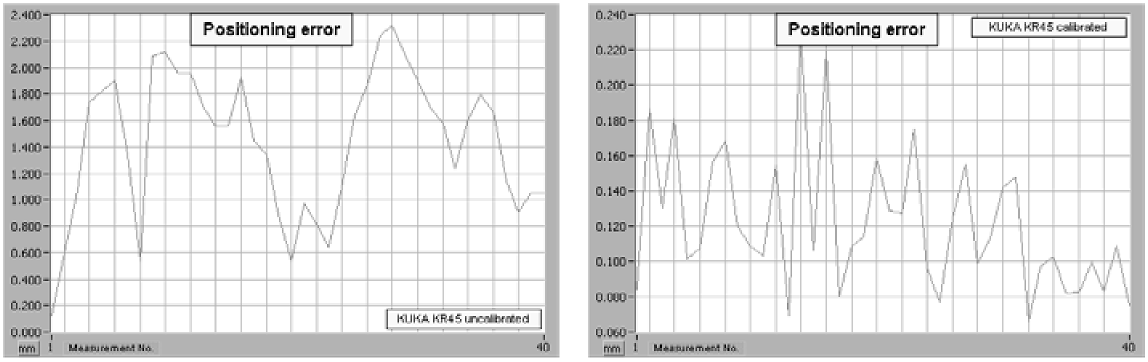

Fig. 6. Calibration Results for standard robot KUKA KR45 (before/after).

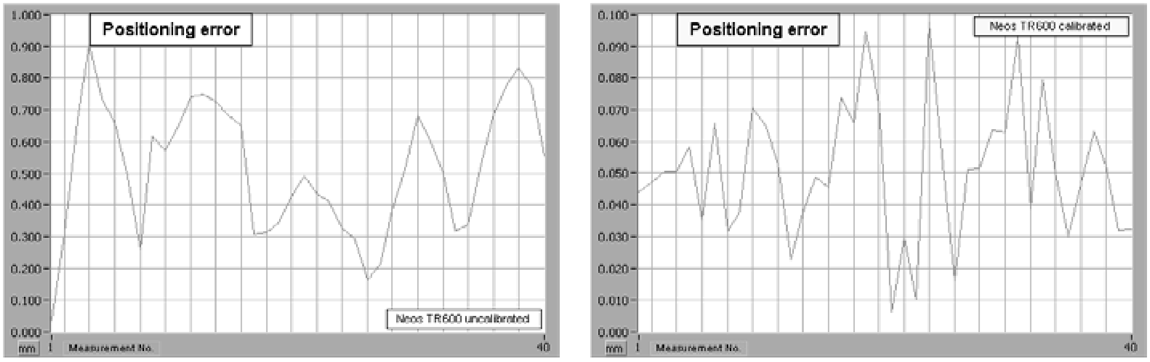

Fig. 7. Calibration results for Tricept robot Neos TR600 (before/after).

KUKA KR45 standard robot with six axes and 45 kg payload. This machine was considered to be quite accurate as it was a new one, but nonetheless during the measurement of 40 poses deviations up to 2.4 mm arose. The average error was 1.44 mm (Fig. 6a). After the calculation of the parameter errors, the robot was calibrated in two ways, first by controller correction, i.e. adjustment of the relevant kinematic system variables, and second by program correction, that means by calculation of the expected error for each pose of the user program. Both methods led to similar results, where the program adaptation was slightly better because there more parameters are available to be modified. The final medium error was 0.12 mm, which means an improvement of 92% (Fig. 6b).

4.2. Tricept robots

When applied to a Tricept robot, the system showed better initial deviations, as could be expected. Nevertheless, there occurred an average error of 0.52 mm – the reason was probably that the tested robot was an older one and might have been affected by wear or crash. Because a controller correction is not possible with the Tricept, as mentioned above, a program correction was executed directly after parameter identification. The new measurement delivered deviations below 0.1 mm throughout with an average of 50 µm, which again represents an error reduction by over 90% (Fig. 7). The value of 50 µm was also met when a standard measurement of accuracy of pose according to ISO 9283 was performed. Accordingly, with kinematic calibration the small Tricept's accuracy can be improved up to the range of the larger Tricept machines (TM805 etc.) with five axes and direct measurement system (DMS).

These procedures have been carried out for other Tricept types, also new machines, e.g. the SRT60 Tricept from SEF. Its initial error was 0.2 mm up to 0.5 mm, which could be reduced to below 0.1 mm by calibration in every case.

4.3. Path accuracy

After the desired results for AP had been achieved, the focus of interest was attracted by the possible improvement of path accuracy. It could be expected that the error reduction was not as significant as with static measurements because dynamic effects would cause additional deviations.

The experiment was conducted as a circularity test with a ballbar measurement system. The circle was programmed with 600 mm diameter and 50% override. The first measurement showed a circularity error of 440 µm according to ISO 230. After accounting the waypoints of the path with the expected cartesian errors, the deviation could be reduced to 210 µm, which still is an improvement of more than 50% (Fig. 8). In spite of these good results, some research was made on the topic of dynamic effects. These considerations are outlined in section 6.

5. INDUSTRIAL APPLICATIONS

5.1. Laser hard soldering

In the automotive industry Tricept robots are used to perform laser hard soldering of e.g. car boot panels. In the standard

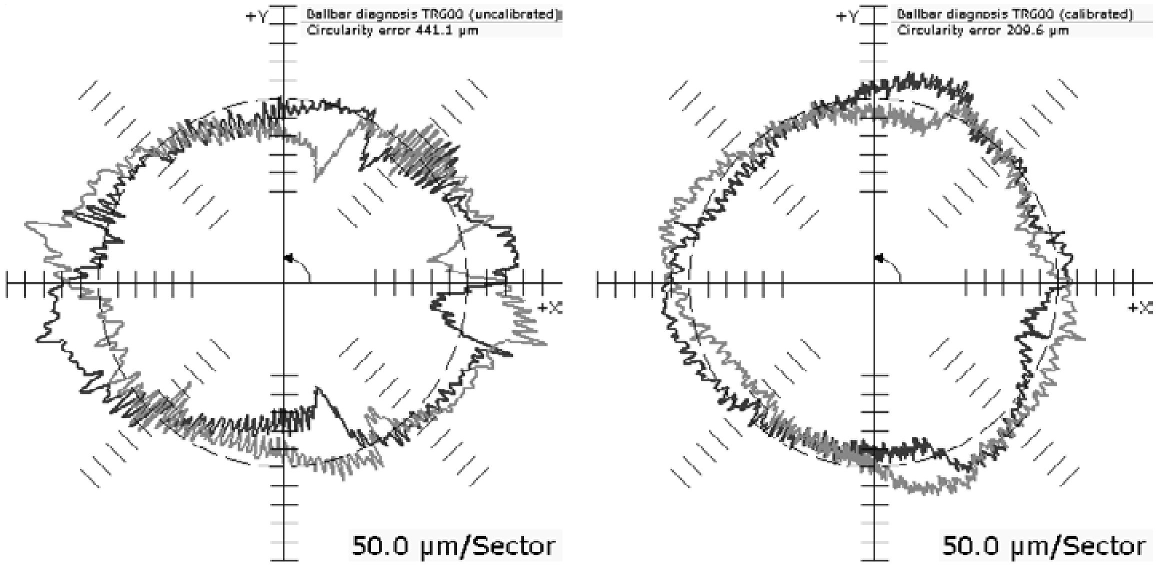

Fig. 8. Circularity test results for Tricept robot Neos TR600 (before/after).

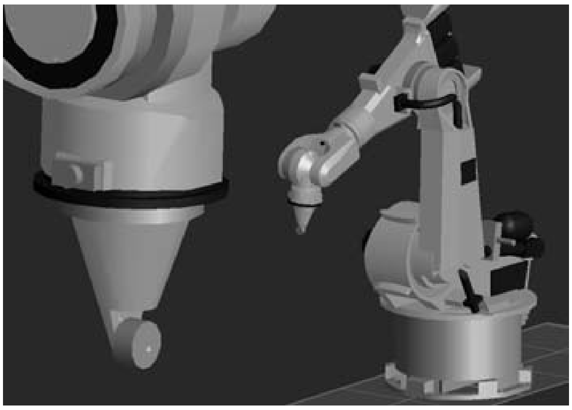

Fig. 9. Sample application: robot-guided hemming of automotive parts.

application, the robot is guided by a teach sensor searching for the exact location of the seam before executing the process. Obviously, this increases cycle time, so attempts are being made to save the sensor by using accurate (i.e. calibrated) robots. This would result in an increase of output of nearly 100% for the installation.

Nevertheless, one has to take into account the event of robot failure. In this case robot calibration can save time, too: If only calibrated robots are used in the line, then the damaged machine can quickly be exchanged with another one without the need of costly manual program adaption (by teach-in).

5.2. Robot-guided hemming

Another possible application is the use of heavy load standard robots to perform robot-guided hemming of automotive parts, e.g. car doors (Fig. 9). These parts are normally hemmed with hydraulic machines which are quite expensive and specially designed for the current type of car. So hemming with robots is an interesting alternative, at least for models with a low quantity, because the cell can easily be adapted to a new type.

The problem is that the robot has to apply a constant force onto the part to be hemmed, so robot deviations cause bad hemming results. Therefore either 6D force and momentum sensors can be attached to the robot tool or – which is the less expensive method – calibrated robots can be used. This way process reliability can be guaranteed for this high precision application.

6. FURTHER ASSIGNMENTS

6.1. Minimal models

One problem with parameter identification is that some parameters are dependent on others which sometimes leads to mathematically correct, but physically senseless results.[13] So currently a method is developed to automatically eliminate dependent parameters from the optimization process. For this purpose, first a single value decomposition (SVD) of the Jacobian is performed to find out the number of independent variables (rank of J). Afterwards, a Gauss algorithm is applied to determine these independent parameters, sorted by relevance. With this minimal set of parameters, the optimization procedure is executed as described above.

6.2. Thermal compensation

Because a mechanism with variable struts is warming up significantly when it is in use (Fig. 10), particularly if high forces or velocities are recommended, it is important to consider the spatial expansion of the machine's single components.

The conventional way to compensate for these effects would be to apply thermal sensors and to combine their output with a thermal model from which possible position deviations can be derived.[14] Another possibility is to measure deviations with laser sensors.[15] But this method is rather costly and its time constant is too long for real-time adjustment. Consequently, as a quicker way of compensation, it is proposed that subsequent quick reference measurements are performed at one certain position, e.g. one during each cycle of a

https://doi.org/10.1017/S026357470400027X Published online by Cambridge University Press

Fig. 10. Thermographic image of Tricept SRT60 after three hours in use.

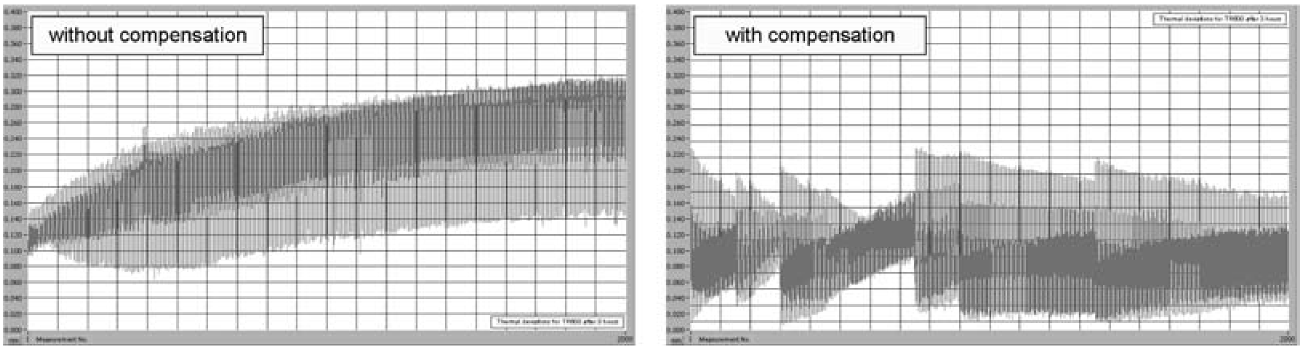

Fig. 11. Three hour measurement of TR600 accuracy (uncalibrated).

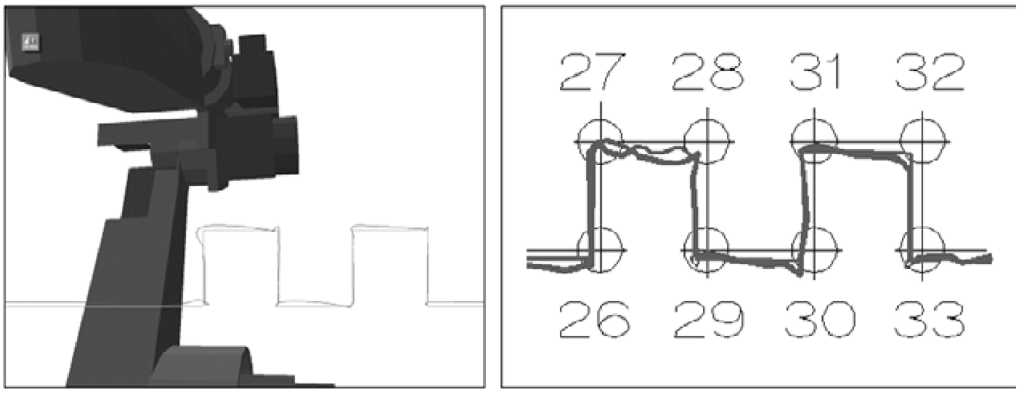

Fig. 12. Simulated and real path behaviour of a KUKA KR15 standard robot.

production line. To be able to feed-back the calculated changes to the controller, again a shift of the cartesian positions is necessary. The results obtained by application of this method are demonstrated in Fig. 11.

6.3. Dynamic modelling

As kinematic calibration does not take into account dynamic effects, path deviations can occur during production processes, especially with high velocities and heavy payloads. A possible solution to achieve a better path accuracy is to attempt a kinetic approach to the problem.[16] The trajectories produced by common simulation systems during off-line programming of an application usually differ significantly from the paths that the real arm will follow. The reason is not only the assumption of ideal kinematics, but also the lack of realistic path-planning algorithms, dynamic models and suitable control loops.

In recent years so-called RCS-modules became available for OLP systems which simulate the original path planning and interpolation algorithms of the robot controller. This had a remarkably positive effect on the trajectories, but there is still some work left: To be able to show a path behaviour close to reality, it is essential to model the machine's dynamic qualities by implementing masses, inertia, springs, clearance and friction into the simulation system. This data is considerably difficult to obtain, but even an imperfect modelling yields noticeable improvements (Fig. 12). To complete the model, it is necessary to copy the original control loops

https://doi.org/10.1017/S026357470400027X Published online by Cambridge University Press

into the simulation, e.g. as cascadic P/PI position and speed control with the appropriate gain factors.[17]

Realistic dynamic simulation (RDS) could help programmers to analyse the planned application with more information on the robot's abilities and thus to avoid downtime and additional work due to unforeseen path deviations.

6.4. Hexapod calibration

When the work related to tripod calibration is completed, it would be interesting to transfer the principle to a hexapod structure to find out if it produces comparable results. Here again the focus is not directed towards high precision machine tools, but more to robot-like structures with a less complicated design. A possible test object could be the Fanuc F200i hexapod robot or a mechanism specially designed at other research institutes.

7. CONCLUSION

The robot calibration system ROSY enables the accuracy of pose to be improved for conventional arms and parallel kinematics like the Tricept robot, up to the range of their repeatability of pose. For this purpose the robot is first measured using a calibration sphere and CCD cameras, then its kinematic errors and the resulting correction values are calculated. Finally the corresponding parameters of the control software or the user program are changed appropriately. The whole process can be accomplished easily and is usually finished in less than an hour. Additionally different methods for tool and base correction are implemented. On the one hand, this method enhances the exchangeability of industrial robots in the event of damage or crash, while on the other hand making it possible to perform highly accurate machining tasks which require off-line programming on the basis of CAD data. Examples of those processes are robot-guided hemming, friction stir welding, laser cutting, laser welding and laser soldering. Even high speed cutting of light metal alloys should be possible with close tolerances.

References

1. R. Bernhardt, "Deviation of Simulation and Reality in Robotics. Causes and Counter-Measures", *Proc. of the 28th Intern. Symp. on Automotive Technology and Automation*, Stuttgart (1995) pp. 139–144.
2. Sales statistics of the *Verband deutscher Maschinen- und Anlagenbauer* (VDMA) (2002) Homepage at www.vdma.de.
3. Statistics of the *European Committee for the Co-Operation of the Machine Tool Industries* (CECIMO) (2002) Homepage at www.cecimo.be.
4. J.-P. Merlet, *Parallel Robots* (Kluwer Academic Publishers, Dordrecht, 2000).
5. K. Großmann, "Zielstellungen und Anwendungsbereiche für Parallelkinematiken einfacher Bauart", *Proc. 3rd Machine Tool Seminar*, Dresden (2001) pp. 2–28.
6. B. Siciliano, "The Tricept robot: Inverse kinematics, manipulability analysis and closed-loop direct kinematics algorithm", *Robotica* **17**, Part 4, 437–445 (1999).
7. V. Kreidler, "Development and Software Methods for Parallel Kinematic Machine Accuracy", *Proc. 2nd Parallel Kinematics Seminar*, Chemnitz (2000) pp. 241–256.
8. L. Beyer and J. Wulfsberg, "Calibration of Parallel Robots with ROSY", *Proc. 3rd Parallel Kinematics Seminar*, Chemnitz (2002) pp. 493–505.
9. J. Hesselbach and H. Kerle, "Structurally Adapted Kinematic Algorithms for Parallel Robots up to Six Degrees of Freedom", *Proc. IFToMM "Theory of Machines and Mechanisms"*, Milano (1995) pp. 1930–1935.
10. L. J. Everett and T.-W. Hsu, "The Theory of Kinematic Parameter Identification for Industrial Robots", *Trans. ASME, Journal of Dynamic Systems, Measurement and Control* **110**, 96–100 (1988).
11. R. Alizade and N. Tagiyev, "A Forward and Reverse Displacement Analysis for a 6-DOF In-Parallel Manipulator", *Proc. IFToMM "Theory of Machines and Mechanisms"*, London (1994) pp. 115–124.
12. J. Wang and O. Masory, "On the accuracy of a Stewart platform. Part I: The effect of manufacturing tolerances", *Proc. of IEEE Int. Conf. on Robotics and Automation*, Atlanta (1993) pp. 114–120.
13. Ph. Drouet *et al.*, "Compensation of geometric and elastic errors in large manipulators with an application to a high accuracy medical system", *Robotica* **20**, Part 3, 341–352 (2002).
14. U. Heisel *et al.*, "Thermal Behaviour of Industrial Robots and Possibilities for Error Compensation", *Annals of the CIRP* **46**, 283–286 (1997).
15. K.-S. Chai, "A practical calibration process using partial information for a commercial Stewart platform", *Robotica* **20**, (Part) 315–322 (2002).
16. M. Spong and M. Vidyasagar, *Robot Dynamics and Control* (Wiley, New York, 1989).
17. L. Beyer, E. Roos and J. Wulfsberg, "Realistic Dynamic Simulation of Industrial Robots", *Proc. 4th International Symposium of Volkswagen Stiftung "Investigations of Non-Linear Dynamic Effects in Production Systems"*, Chemnitz (2003).

https://doi.org/10.1017/S026357470400027X Published online by Cambridge University Press