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Vincenzo Parenti-Castelli
Werner Schiehlen
Editors

ROMANSY 18 Robot Design, Dynamics and Control

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INTERNATIONAL CENTRE FOR MECHANICAL SCIENCES

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ROMANSY 18 ROBOT DESIGN, DYNAMICS AND CONTROL

PROCEEDINGS OF THE EIGHTEENTH
CISM-IFT_oMM SYMPOSIUM

EDITED BY

VINCENZO PARENTI CASTELLI
UNIVERSITY OF BOLOGNA, ITALY

WERNER SCHIEHLEN
UNIVERSITY OF STUTTGART, GERMANY

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PREFACE

The First CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators was held on September 5-8, 1973, in Udine, Italy, not long after IFToMM had been founded in 1969. The first ROMANSY, or Ro.Man.Sy., as the Symposium used to be referred to, marks the beginning of a long-lasting partnership between two international institutions, CISM, the Centre International des Sciences Mécaniques and IFToMM, the International Federation for the Promotion of Mechanism and Machine Science.

As the 18th Symposium returned to Udine, Ro.Man.Sy 2010 continued to preserve this tradition, by encouraging papers that are of a broad interest to the participants and by providing an environment and setting for meaningful technical and personal interactions among the delegates. In particular, the conference solicited papers providing a vision of the evolution of the robotics disciplines and indicating new directions in which these disciplines are foreseen to develop. Paper topics include, but are not limited to:

- 1. robot design and robot modules/components;*
- 2. service, education, medical, space, welfare and rescue robots;*
- 3. humanoid robots, bio-robotics, multi-robot, embodied multi-agent systems;*
- 4. challenges in control, modeling, kinematical and dynamical analysis of robotic systems;*
- 5. innovations in sensor systems for robots and perception;*
- 6. recent advances in robotics.*

The 18th ROMANSY took place July 5-8, 2010 in Udine, Italy and was enriched with three keynote lectures presented by Makoto Kaneko from Japan, Jorge Angeles from Canada and Andrés Kecskeméthy from Germany, who discussed new trends in applications and methodology. During the conference banquet a ceremony was arranged for the two recipients of the IFToMM Award of Merit 2010, Alberto Rovetta from Italy and Atsuo Takanishi from Japan, with a speech about IFToMM honors and awards, the presentation of each recipient by their nominators, the delivery of IFToMM honors and awards to recipients, and a short speech by each recipient.

Kinematic Calibration of Small Robotic Work Spaces Using Fringe Projection

Dipl.-Ing. Klaus Haskamp ^{*‡} and Prof. Dr.-Ing. E. Reithmeier ^{†‡}

^{*} Research Associate in the work group Production Measurement and Technology

[†] Head of the Institute and head of the working group Control Engineering

[‡] Institute of Measurement and Control Engineering, Leibniz Universität Hannover, Hannover, Germany

Abstract In recent years a number of medical therapy concepts have taken hold in the field of microsurgery. These concepts require measurement accuracies below 0.3 mm. The positioning accuracy needed in surgical applications is higher than what surgeons usually are able to achieve. In this case robot manipulators can be employed to support surgical skills. The robotic movement has to be sufficiently reliable and has to incorporate safety procedures like fast collision detection and avoidance. Furthermore, important premisses to the technical system were given by the absolute and the relative accuracy.

In industrial applications the absolute accuracy is enhanced by calibrating the kinematic parameters and compensating manufacturing errors. The achieved accuracies are less than 0.7 mm and do not comply with the actual medical standard. In this article a new method for modeling and calibrating the kinematics of robots with the aim of achieving precisions less than 0.1 mm respectively 0.1° in a 1000 mm³ work space is presented. The used mathematical description of the kinematics and the calibration strategy is explained in detail.

1 Introduction

Robots are applied in industrial applications as manipulator systems for tasks like pick and place, path-welding, bonding or milling. Medical engineering is a new application field. For example a robot can be equipped with a milling cutter or a burr and be used in the precision engineering from hard tissue like bones or tooth enamel. Thereby, new problems that refer to positioning- and the motion-behavior have to be solved. For example, a very high absolute positioning accuracy and an excellent tracking accuracy

have to be realized to remove only material, which is planned to carry off. Furthermore, the whole system has to be insensitive with respect to exterior disturbances, which are induced through the material removal.

Recent research works deal with the calibration of industrial robots, which is described in Wiest (2001), Atkinson (1996), Everett (1988). The kinematics is usually described using the modified Denavit-Hartenberg-Parameters to consider geometric errors like home position errors. Thereby, absolute accuracies of less than 1 mm were achieved. Medical applications have higher requirements relating to the absolute positioning accuracy and due to this the kinematic model have to be extended to include additional parameters. The problem is that the parameters are correlated and therefore cannot be identified separately.

In this work, a new calibration strategy for identifying the whole kinematics is presented. The kinematic is described using polynomial functions and due to this each geometrical and non-geometrical error, like offset angles and elasticities, are regarded. Additionally to the description of the kinematics the measurement procedure of the pose of the endeffector is explained in detail. The paper is concluded presenting a validation of the determined forward and inverse kinematic functions.

2 Methods for the Modeling of the Kinematics

2.1 Conventional Modeling

Generally, the forward kinematics ${}^0\mathbf{x} = \mathbf{f}(\mathbf{q})$ is described using the Denavit-Hartenberg-Notation or the modified Denavit-Hartenberg-Notation, as specified in Wiest (2001). ${}^0\mathbf{x}$ denotes the pose of the robot endeffector (TCP) with respect to an inertial world coordinate system CS_0 and \mathbf{q} represents the joint angles of the robot.

The inverse kinematics can be obtained from the solution $\mathbf{q} = \mathbf{f}^{-1}(\mathbf{x})$. Usually, this cannot be done analytically due to the fact that \mathbf{f} has a nonlinear character. Normally, nonlinear optimization algorithms like the Nelder-Mead-Method or the Rosenbrock-Method have to be implemented in order to calculate the joint angles \mathbf{q} for a given pose \mathbf{x} , as written in Logt (1998).

This modeling method implicates some advantages and disadvantages. The main benefit is given by the fast setup of the forward kinematic functions through easy geometrical relationships. On the other hand, the description is not clear if consecutive axis are parallel. Furthermore, singularities appear if the robot is in an inappropriate angle configuration. Another disadvantage is that mechanical components like elasticity and friction cannot be considered in this model so that an error remains between the virtual and the real kinematics.

2.2 Kinematic Modeling with respect to Polynomial Functions

In our application a 6-axis-robot as shown in figure 1 is moved in a small work space of about 1000 mm³. Due to the assumption that the joint movements are small the behavior of the forward and the inverse kinematics is approximately linear and both can be described using polygons:

$$x_i = \sum_{k=0}^{N_1-1} a_{1ik} \cdot q_1^k + \sum_{k=0}^{N_2-1} a_{2ik} \cdot q_2^k + \dots + \sum_{k=0}^{N_6-1} a_{6ik} \cdot q_6^k \quad (1)$$

$$q_i = \sum_{k=0}^{M_1-1} b_{1ik} \cdot x_1^k + \sum_{k=0}^{M_2-1} b_{2ik} \cdot x_2^k + \dots + \sum_{k=0}^{M_6-1} b_{6ik} \cdot x_6^k \quad (2)$$

$$1 \leq i \leq 6 \quad (3)$$

with a_{jik} and b_{jik} as the polynomial coefficients. The polynomial functions present a black-box-method. Because of this, each physical effect like deflection of the axis or home position errors are considered which is an advantage compared to the conventional model. However, the dimension of the working area restricts the applicability from describing the kinematics through polynomials. In the case that the work space is too large the kinematics and the polynomials become nonlinear and the functions g_i and h_i oscillate in the boundary area.

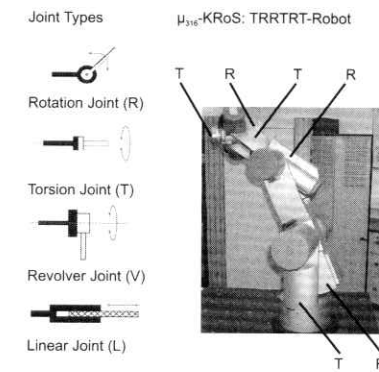


Figure 1. μ_{316} -KRoS-Robot

3 Identification of the Kinematics

3.1 Calibration Functional

The mathematical model of the kinematics deviates from the real kinematic structure of the robot with the consequence that positioning errors appear when a pose is approached. The errors can be divided in pure geometrical errors and non-geometrical errors. Examples for geometrical errors are home position errors or deviations from the orthogonality of the axis. Gear elasticities, friction or temperature influence are examples for non-geometrical errors. In order to enhance the absolute accuracy the geometric and non-geometric effects have to be taken into account within the model and to be identified through a calibration process.

In Wiest (2001) null position errors for example can be considered in the Denavit Hartenberg Matrix as an offset $\Delta\theta_i$ to the joint angle q_i . In order to identify the model parameter, a functional ε has to be defined which combines a set of measured poses $\mathbf{x}_{measure}$ with the modeled poses \mathbf{x}_{model} , as written in Wiest (2001):

$$\varepsilon = \sum_{i=1}^N \|\mathbf{x}_{measure,i} - \mathbf{x}_{model,i}\|^2 = f(\mathbf{p}) \quad (4)$$

with \mathbf{p} as the parameter vector. Usually, \mathbf{x}_{model} is expressed through the forward kinematics and the joint angles \mathbf{q} are given by the angle encoders. In this case we use the polynomial functions described in chapter 2.2. To estimate capable values for the parameters, the minimum of ε has to be determined using numerical methods.

Wiest (2001) points out that the measured pose should have 6 dimensions to get a high information content. Using laser tracker, a 3D-position can be captured with a very high accuracy of about $5\mu m \pm 10\frac{\mu m}{m}$, as described in Illemann (2007). By measuring different targets, which are fixed at the robot endeffector, a 6D-position measurement can be realized. Another opportunity for 6D-position measurement is given by fringe projection systems. This will be explained in detail in chapter 3.2.

3.2 Experimental Setup

Figure 2 shows the experimental setup. The measurement is accomplished by three spheres which are fixed at the endeffector and positioned in the working area.

As the result of the measurement using fringe projection, data points are fitted to spheres and the center points \mathbf{x}_{M1} , \mathbf{x}_{M2} and \mathbf{x}_{M3} are available for further analysis. A fringe projection system, as shown in figure 2, consists

of a beamer and one or more cameras. Common fringe projection systems use straight fringe patterns which are projected from the beamer onto an object, as specified in Valkenburg, Mc Ivor (1998). Afterwards the deformed patterns on the surface of the measurement object are recorded by the camera. The relationship between a camera pixel and the beamer phase is calculated using image processing and is used to reconstruct the object surface with triangulation. Furthermore, in figure 2 the principle of the construction of the endeffector coordinate system is illustrated. To start with the analysis the distances between the center points of the three spheres l_1 , l_2 and l_3 have to be calculated, whereas all lengths are different. The center of the coordinate system is given by the center point \mathbf{x}_{M1} . The z -axis is created from the difference vector of \mathbf{x}_{M1} and \mathbf{x}_{M3} : The x -axis is

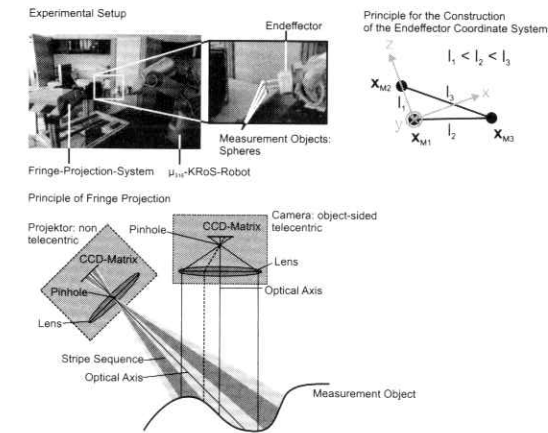


Figure 2. Experimental Rig and Principle for the Construction of the Endeffector Coordinate System

perpendicular to the z -axis and the normal vector of the plane, build up from \mathbf{x}_{M1} , \mathbf{x}_{M2} and \mathbf{x}_{M3} , and points in the direction of \mathbf{x}_{M3} . The y -axis can be constructed assuming that the coordinate system is a right hand system. Each coordinate system CS can be fully described using a position vector \mathbf{r} and the x -, y - and z -axis, which were combined in the matrix \mathbf{X} :

$$\mathbf{X} = [\mathbf{x} \quad \mathbf{y} \quad \mathbf{z}] \wedge CS = \{ \mathbf{r} \quad \mathbf{X} \} \quad (5)$$

Furthermore, the coordinate system is defined in the coordinate system of the fringe projection system. To get the measured pose $\mathbf{x}_{measure,i}$ a basis

coordinate system CS_{Basis} has to be determined:

$$CS_{Basis} = \{ \mathbf{r}_{Basis} \quad \mathbf{X}_{Basis} \} \quad (6)$$

This coordinate system is the new inertial coordinate system and is given by the joint angle configuration \mathbf{q}^* , which is absolute with respect to the home position of the robot. Through a movement of the robot endeffector the coordinate system, represented by the spheres, is displaced and tilted with respect to the coordinate system of the fringe projection system and CS_{Basis} . This coordinate system is named CS_{New} :

$$CS_{New} = \{ \mathbf{r}_{New} \quad \mathbf{X}_{New} \} \quad (7)$$

The displacement and the tilting of CS_{New} with respect to CS_{Basis} result in the pose $\mathbf{x}_{measure,i}$. Thereby, the difference vector \mathbf{r}_{diff}

$$\mathbf{r}_{diff} = \mathbf{r}_{New} - \mathbf{r}_{Basis} \quad (8)$$

is the positioning part of the pose. The rotation part can be estimated using the following equation:

$$\mathbf{X}_{Basis} = \mathbf{R} \cdot \mathbf{X}_{New} \quad (9)$$

$$\mathbf{R} = \mathbf{X}_{Basis} \cdot \mathbf{X}_{New}^{-1} \quad (10)$$

$$(11)$$

whereas \mathbf{R} is the 3x3 rotation matrix defined by the roll-pitch-yaw-angles (RPY).

4 Determination of the Kinematics

For the calculation of the polynomial coefficients the relative positioning accuracy from the movement to the joint angle configuration \mathbf{q}^* has to be estimated. Therefore, multiple measurements of the basis coordinate system have to be accomplished whereas the following standard deviations could be specified:

Table 1. Standard deviation of the pose

Position	[μm]	Rotation	[$^\circ$]
s_x	8	s_θ	0.01
s_y	8	s_ψ	0.009
s_z	11	s_ϕ	0.007

To determine the polynomial coefficients a_{jik} and b_{jik} , 500 measurements were done to get a high resolution of the work space. Each measurement consists of the measurement of the joint angles through the angle encoders and the measurement of the spheres with the fringe projection system. After that the coordinate systems $\{ \mathbf{r}_i \quad \mathbf{X}_i \}$ and the measured pose $\mathbf{x}_{measure,i}$ were calculated whereby corresponding pairs of values are available for the estimation of a_{jik} and b_{jik} . Finally, a_{jik} and b_{jik} were calculated using non-linear optimization algorithms. For convenience the values of the calculated polynomial coefficients are not shown.

5 Validation of the Determined Kinematic Functions

To specify the quality of the estimated kinematic polynoms the forward and the inverse kinematics have to be tested. To test the forward kinematics the robot was moved to a position and the pose $\mathbf{x}_{estimate}$ was calculated with the forward kinematic functions and the joint angles from the angle encoders. Furthermore, the three spheres, which are fixed at the robot endeffector, were measured through the method described in chapter 3.2 with the result $\mathbf{x}_{measure}$. Comparing $\mathbf{x}_{estimate}$ and $\mathbf{x}_{measure}$ shows that the deviation is quite small:

$$\Delta \mathbf{x} = \|\mathbf{x}_{estimate} - \mathbf{x}_{measure}\| \quad (12)$$

The values showed above are the maximum measured values from 20 dif-

Table 2. Deviation between $\mathbf{x}_{estimate}$ and $\mathbf{x}_{measure}$

Position	[μm]	Rotation	[$^\circ$]
Δx	87	$\Delta \theta$	0.08
Δy	40	$\Delta \psi$	0.05
Δz	56	$\Delta \phi$	0.09

ferent poses in the new working room of the robot.

This implies that the forward kinematic functions coincide with the real kinematics of the robot.

To test the inverse kinematics the joint angles \mathbf{q}_{demand} for a given pose \mathbf{x}_{demand} were calculated and the robot was moved to the configuration \mathbf{q}_{demand} . After that, the fringe projection system was used to measure the pose of the endeffector $\mathbf{x}_{measure}$. The comparison of \mathbf{x}_{demand} and $\mathbf{x}_{measure}$ shows that there is just a small difference:

$$\Delta \mathbf{x} = \|\mathbf{x}_{demand} - \mathbf{x}_{measure}\| \quad (13)$$

Table 3. Deviation between $\mathbf{x}_{\text{demand}}$ and $\mathbf{x}_{\text{measure}}$

Position	[μm]	Rotation	[$^{\circ}$]
Δx	87	$\Delta\theta$	0.06
Δy	39	$\Delta\psi$	0.08
Δz	55	$\Delta\phi$	0.06

The values shown above are the maximum measured values from 20 different poses in the new working room of the robot.

This implies that the inverse kinematic functions projects the real kinematics of the robot.

6 Conclusion

In this paper a new method for the identification of the kinematics was described. Beside the description of the kinematic functions the measurement procedure was explained in detail. To verify the forward and inverse kinematic functions the deviation for given poses were determined and the maximum occurred deviation is less than 0.1 mm respectively 0.1 $^{\circ}$.

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Forward Dynamics of 3-DOF Parallel Robots: a Comparison Among Different Models

Miguel Díaz Rodríguez ^{*}, Vicente Mata [†], Ángel Valera [‡], Álvaro Page [§]

^{*}Departamento de Tecnología y Diseño, Facultad de Ingeniería, Universidad de Los Andes, Mérida, Venezuela, dmiguel@ula.ve

[†]Centro de Investigación de Tecnología de Vehículos, Universidad Politécnica de Valencia, Spain, vmata@mcm.upv.es

[‡]Departamento de Ingeniería de Sistemas y Automática, Universidad Politécnica de Valencia, Valencia, Spain

[§]Departamento de Física Aplicada, Universidad Politécnica de Valencia, Valencia, Spain

Abstract In this paper, an approach for solving the forward dynamic problem by using identified parameters is presented. A comparison between the identified models; the so-called reduced model and the complete model, and a model with dynamic parameters obtained by a CAD approach is carried out. The results show that the reduced model, obtained based on a set of so-called relevant parameters, is closely related to the actual system response when compared with the other two models.

1 Introduction

Parallel robots perform better in terms of high accuracy, high-load capacity, high rigidity and speed compared to serial robots. Therefore, it is an object of study in academic circles and nowadays their application is being transferred into industry (Pierrot et al., 2009). Thus, the improvement and the development of accurate dynamic models for this class of robots, particularly for those with less than 6-DOF, are of current interest.

Realistic dynamic simulations of mechanical systems require an accurate knowledge of the underlying dynamic parameters. The dynamic parameters are usually determined by parameter identification techniques (Khalil and Dombre, 2002). However, when dynamic parameter identification is applied, only a subset of so-called base parameters can be identified. These parameters are a linear combination of the link inertial parameters which