EVALUATION OF FEEDBACK AND FEEDFORWARD LINEARIZATION STRATEGIES FOR AN ARTICULATED ROBOT

Roland Riepl, Hubert Gattringer and Hartmut Bremer
Institute for Robotics, Johannes Kepler University, Altenbergerstr. 69, 4040 Linz, Austria

Keywords: Robotics, Nonlinear control, Decentralized control, Linearization, Multi-body dynamics, Identification.

Abstract: The increasing demand of high performance applications in industrial environments calls for improved control strategies for nonlinear mechanical systems. Common flatness based approaches, effectively linearizing a highly nonlinear system, are available and ready for deployment. This contribution focuses on evaluating these strategies in a modern and widely used industrial setup.

1 INTRODUCTION

The objective to reduce cycle times while increasing the tool center point precision and dynamics, especially in robotic applications, requires sophisticated motion control.

Robots with a high number of degrees of freedom, for example articulated robots, are complex machines. Their system dynamics may be described by the equations of motion, a set of highly nonlinear differential equations. In contrary to the common approach, using Lagrange equations of second kind, this contribution utilizes the projection equation in subsystem representation, well described in (Bremer, 2008). Next to commonly used decentralized proportional and derivative (PD) control schemes, different model-based linearization techniques exist, as (Isidori, 1985; Slotine and Li, 1990; Fliess et al., 1995; Khalil and Dombre, 2004) suggest. These methods effectively linearize and decouple the equations of motion by using the inverse dynamic model in the feedback loop.

State of the art hardware with high processing power and low reaction times allows implementing these methods, not only under laboratory conditions, but also in industrial setups. With these tools at hand, the suggested linearization strategies are used to control a Stäubli RX130 industrial robot. Due to the fact that the author is unaware of any works which compare and investigate these approaches, this contribution tries to evaluate their performance. Focusing on measurements, the occurring lag errors with different control approaches are the basis for a final interpretation and conclusion.

2 SYSTEM DYNAMICS

In order to present detailed information on the multi-body system under investigation,

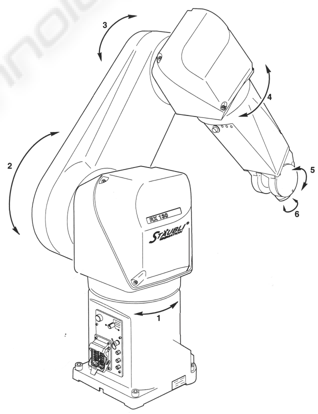

Figure 1: Sketch of the RX130L.

Figure 1 shows a sketch of the Stäubli industrial robot. It is a medium scale robot with six degrees of freedom, 1.6 m reach and a total mass of 235 kg.

Fundamentally, the basis for model based control approaches are the equations of motion

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{G}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{Q}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{Q}_m \in \mathbb{R}^n, \qquad (1)$$

where $\mathbf{q}$ denotes the vector of minimal coordinates, respectively the robots joint angles, $\mathbf{M}(\mathbf{q})$ is the configuration dependent, positive definite and symmetric mass matrix and $\mathbf{G}(\mathbf{q},\dot{\mathbf{q}})$ contains the velocity dependent nonlinearities as coriolis and centrifugal forces. The vector $\mathbf{Q}(\mathbf{q},\dot{\mathbf{q}})$ consists of all generalized forces,

Riepl R., Gattringer H. and Bremer H. (2010).
EVALUATION OF FEEDBACK AND FEEDFORWARD LINEARIZATION STRATEGIES FOR AN ARTICULATED ROBOT.
In *Proceedings of the 7th International Conference on Informatics in Control, Automation and Robotics*, pages 192-197
DOI: 10.5220/0002918301920197

e.g. forces resulting from gravity or friction. The actuating motor torques are separated on the right side of the equations of motion and found in the vector $\mathbf{Q}_m$. The variable n represents the number of degrees of freedom which equals the number of joints, assuming a rigid multi body system.

The equations of motion, as stated in (1), are commonly derived using analytical methods, e.g. with the Lagrange equations. However, an articulated robot consists of several joints and may be regarded as an assembly of n arm/motor units.

Introducing such a unit, also called subsystem, as sketched in Figure 2,

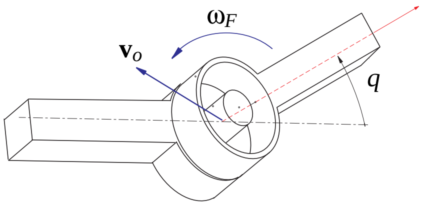

Figure 2: An arm/motor subsystem.

with the vector $\dot{\mathbf{y}}_k$

$$\dot{\mathbf{y}}_k = \begin{bmatrix} \mathbf{v}_0^T & \omega_F^T & q \end{bmatrix}_k^T \tag{2}$$

containing the translational and rotational velocities $\mathbf{v}_0$ and ω_F of the k-th subsystems reference frame and the corresponding joint angle q, leads with the projection equation

$$\sum_{k=1}^{N_{sub}} \left(\frac{\partial \dot{\mathbf{y}}_k}{\partial \dot{\mathbf{q}}}\right)^T [\mathbf{M}_k \ddot{\mathbf{y}}_k + \mathbf{G}_k \dot{\mathbf{y}}_k - \mathbf{Q}_k] = \mathbf{0} \tag{3}$$

in subsystem representation, see (Bremer, 2008), to the equations of motion. This synthetical method, based on projecting the linear and angular momentum in the free directions of movement, effectively makes use of the serial composition of several attached arm/motor units. The interested reader may find more information on the subsystems matrices and vectors, $\mathbf{M}_k$, $\mathbf{G}_k$ and $\mathbf{Q}_k$ and their detailed derivation in (Gattringer, 2006).

2.1 Model Verification

After an identification process as suggested in (Sciavicco and Siciliano, 2004; Khalil and Dombre, 2004), the model parameters are verified by comparing measured and simulated motor torques. The simulation is carried out by integrating the equations of motion. The reference trajectory for verification purposes strictly differs from the ones used during the identification process to assure the parameters' correctness in the whole task space.

Figure 3 presents the accordance of the first three joints. Joints four to six are of equivalent quality.

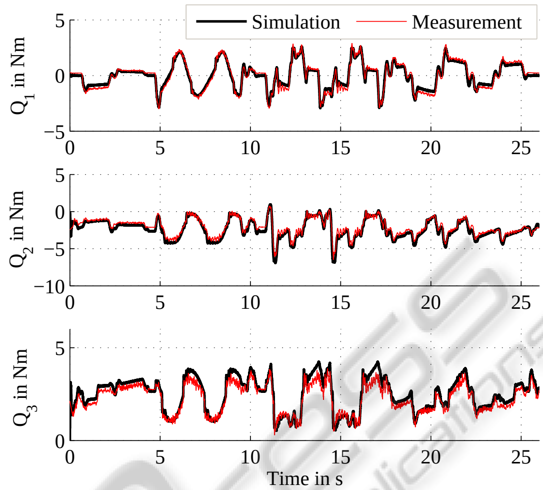

Figure 3: Measured versus simulated motor torques.

3 MOTION CONTROL

This section summarizes the control strategies for tracking the tool center point along a desired trajectory. All introduced methods are part of the evaluation process.

3.1 Decoupled PD-control

As the name suggests, the decoupled PD-control is a decentralized single joint control law. Each single axis compensates the nonlinearities, e.g. influences from the other joints, while tracking the desired reference trajectory in joint space. The control law is given by

$$\mathbf{Q}_m = \mathbf{K}_P(\mathbf{q}_d - \mathbf{q}) + \mathbf{K}_D(\dot{\mathbf{q}}_d - \dot{\mathbf{q}}), \tag{4}$$

where the lower right index d denotes the desired reference values for joint positions and velocities. The positive definite diagonal matrices $\mathbf{K}_P$ and $\mathbf{K}_D$ are the proportional and derivative gains.

The major disadvantage of this common and simple control law is the lack of knowledge about the system which is to be controlled.

Asymptotic stability can only be proven if the system remains in steady state with the classical stability theorems of mechanical systems, summarized in (Bremer, 1988).

3.2 Decoupled PD-control with Feedforward

To negate the major drawback of the decoupled PD-control an additional feedforward term is inserted into control law (4), yielding

$$\mathbf{Q}_m = \mathbf{K}_P(\mathbf{q}_d - \mathbf{q}) + \mathbf{K}_D(\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) + \mathbf{u}_{FF}. \quad (5)$$

Effectively exploiting the system knowledge, obtained through the dynamic modeling and identification, the necessary reference motor torques which guide the tool center point along a desired trajectory, are given with the equations of motion (1) and are so intuitively suitable for a feedforward control

$$\mathbf{u}_{FF} = \mathbf{M}(\mathbf{q}_d)\ddot{\mathbf{q}}_d + \mathbf{G}(\mathbf{q}_d, \dot{\mathbf{q}}_d)\dot{\mathbf{q}}_d + \mathbf{Q}(\mathbf{q}_d, \dot{\mathbf{q}}_d). \quad (6)$$

Obviously, if the reference trajectory is two times continuously differentiable with respect to time, the resulting feedforward torques will show a continuous progression. This set of feedforward control is also called exact feedforward linearization in literature, see (Hagenmeyer and Delaleau, 2003).

With this choice the PD-controller's task is reduced to compensate modeling inaccuracies, parameter variations and external or unknown disturbances.

Proving asymptotic stability, however, still leads to further challenges, because inserting the feedforward term and evaluating the equations of motion transforms the dynamics to a nonlinear time-variant system. The interested reader may find more information in (Kugi, 2008; Hagenmeyer and Delaleau, 2003).

3.3 Computed Torque

Introducing the computed torque control law

$$\mathbf{Q}_m = \mathbf{M}(\mathbf{q})\ddot{\mathbf{v}} + \mathbf{G}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{Q}(\mathbf{q}, \dot{\mathbf{q}}) \quad (7)$$

and inserting it into the equations of motion (1) yields the system

$$\ddot{\mathbf{q}} = \mathbf{v} \quad (8)$$

of n double integrators, resulting in a solely linear interrelation between the new system input $\mathbf{v}$ and the joint angles $\mathbf{q}$. A possible choice for the new system input $\mathbf{v}$ is

$$\mathbf{v} = \ddot{\mathbf{q}}_d + \mathbf{K}_D(\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) + \mathbf{K}_P(\mathbf{q}_d - \mathbf{q}) \quad (9)$$

with the positive definite diagonal matrices $\mathbf{K}_P$ and $\mathbf{K}_D$ as stabilizing gains.

By defining the joint tracking error $\mathbf{e} = \mathbf{q}_d - \mathbf{q}$ and inserting Equation (9) in (8) the system dynamics of the tracking error $\mathbf{e}$ for the closed loop system

$$\begin{aligned} \ddot{\mathbf{q}}_d - \ddot{\mathbf{q}} + \mathbf{K}_D(\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) + \mathbf{K}_P(\mathbf{q}_d - \mathbf{q}) &= \mathbf{0} \\ \ddot{\mathbf{e}} + \mathbf{K}_D\,\dot{\mathbf{e}} + \mathbf{K}_P\,\mathbf{e} &= \mathbf{0} \quad (10) \end{aligned}$$

is found. Equation (10) instantly allows to shape the error dynamics by choosing the gains $\mathbf{K}_P$ and $\mathbf{K}_D$, for example by pole placement.

Please note, in literature the computed torque method is also referred to as inverse dynamics, feedback linearization or flatness based control, as (Isidori, 1985; Slotine and Li, 1990; Fliess et al., 1995) describe.

3.4 Extended Linearization

Similar to Subsection 3.3, the nonlinearities in the equations of motion are eliminated with the control law

$$\begin{aligned} \mathbf{Q}_m \;=\; & \mathbf{M}(\mathbf{q})(\ddot{\mathbf{v}} + \mathbf{K}_0\,\mathbf{q} + \mathbf{K}_1\,\dot{\mathbf{q}}) \\ & + \mathbf{G}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{Q}(\mathbf{q}, \dot{\mathbf{q}}). \quad (11) \end{aligned}$$

Inserting the control law (11) into the equations of motion (1) yields

$$\ddot{\mathbf{q}} = \mathbf{v} - \mathbf{K}_0\,\mathbf{q} - \mathbf{K}_1\,\dot{\mathbf{q}} \quad (12)$$

or equivalent in state space representation

$$\frac{d}{dt}\begin{bmatrix} \mathbf{q} \\ \dot{\mathbf{q}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{E} \\ -\mathbf{K}_0 & -\mathbf{K}_1 \end{bmatrix} \begin{bmatrix} \mathbf{q} \\ \dot{\mathbf{q}} \end{bmatrix} + \begin{bmatrix} \mathbf{0}, \\ \mathbf{E} \end{bmatrix} \mathbf{v}, \quad (13)$$

which describes the dynamics of the closed loop system. Apparently, this MIMO-system is controllable with the whole repertory of tools available from linear system theory, for example linear quadratic regulators or pole placement, well summarized in (Chen, 1998).

Certainly, before designing a linear controller for system (13), the matrices $\mathbf{K}_0$ and $\mathbf{K}_1$ need to be chosen. It is suggested to pick them in a manner so that the closed loop system (13) resembles its physical counterpart. One suggestion is that the eigenvalues of the linearized equations of motion may be used as guideline for picking the eigenvalues of the closed loop system. However, due to stability issues positive eigenvalues in the closed loop system (13) need to be avoided.

Asymptotic stability of Equation (13) is derived with linear system theory.

3.5 Friction Feedback Issues

One common problem with feedback linearization methods occurs when friction models are part of the inverse dynamics. This is usually the case for any mechanical or robotic application. If the classical model for friction

$$Q_{fric} = d_v\,\dot{q} + d_c \text{signum}\,(\dot{q}) \quad (14)$$

is part of the feedback loop, then the noisy measurement of the velocity signal $\dot{q}$ will be amplified and fed

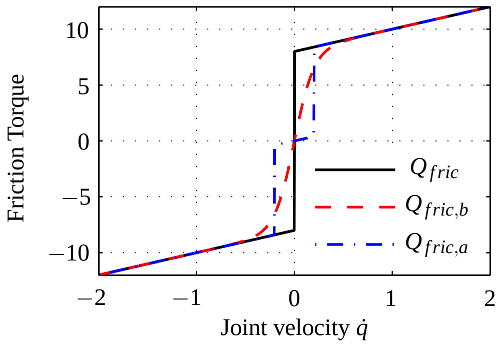

Figure 4: Friction models for feedback loop.

through to the actuators, directly resulting in a disturbing hum.

To counter this effect the friction characteristics in the feedback loop have to be adapted. Two simple solutions are given by

$$
\begin{aligned}
Q_{fric,a} &= d_v\,\dot{q} + d_c \text{ signum } (\dot{q}) \quad \text{for } \dot{q} \geq \varepsilon_1 \\
Q_{fric,a} &= 0 \quad \text{else} \\
&\text{or} \\
Q_{fric,b} &= d_v\,\dot{q} + d_c \tanh\,(\dot{q}/\varepsilon_2)
\end{aligned}
\tag{15}
$$

with suitable values for ε_1 and ε_2. Figure 4 shows the original and adapted friction models.

4 EXPERIMENTS

The introduced control strategies are evaluated in a series of experiments. Additionally, details on the laboratory setup and the recorded data are the dominating topics of this section.

4.1 Setup

In the laboratory, the Stäubli RX130 industrial robot is interfaced with state-of-the-art motion hardware. All mechanical and electrical parts of the robot itself, like motors and resolvers, remain untouched. The servo drives, powering the synchronous motors, and the digital processing unit are of industrial standard but still offer the necessary development tools for implementing the proposed methods.

Figure 5 shows the main components and their interrelation to each other. The central computing unit is connected to six servo drives via a high-speed Powerlink bus. Each servo drive acts as an amplifier for the AC motor, evaluates resolver signals and may use an internal linear cascaded controller for position and velocity control of the attached motors.

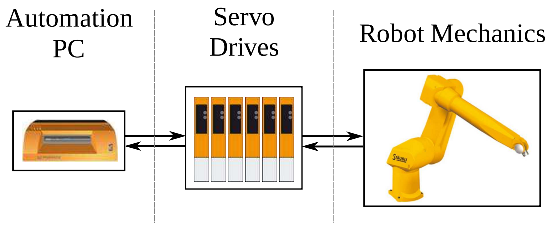

Figure 5: Setup.

4.2 Trajectory

A reference trajectory with significant characteristics is necessary for the process of evaluation. It needs to cover a reasonable workspace while containing high dynamics, even in disadvantageous poses and configurations.

A suitable choice, meeting this prerequisites, is found in (ISO NORM 9283, 1998) which originally defines a standardized trajectory for tool center point measurements and evaluations. By sharing a common objective, the proposed trajectory is also the reference in the following experiments.

The velocity and acceleration of the tool center point is given with 1 m/s and 5 m/s^2. These settings represent the highest values without exceeding the available actuating torques. The trajectory itself is a composition of straight lines, circles and squares in space.

The inverse kinematics is computed numerically, yielding the according joint values and their derivatives with respect to time. It is also guaranteed that all reference joint angles are two times continuously differentiable with respect to time.

4.3 Centralized / Decentralized Control

When realizing the introduced control structures on the industrial hardware, the feedforward and feedback approach show major differences. Basically, the model based control methods – feedforward as well as feedback – evaluate the equations of motion each sample step in order to linearize the mechanical system. Furthermore some stabilizing gains guarantee stability.

However, in the case of feedforward control, which is a decoupled and decentralized method, the stabilizing PD feedback loop may be implemented directly on the servo drives which profit from very short response times and a fast sampling rate. On the other hand, linearizing the system only by using reference values instead of actual ones, is not as exact as with feedback linearization.

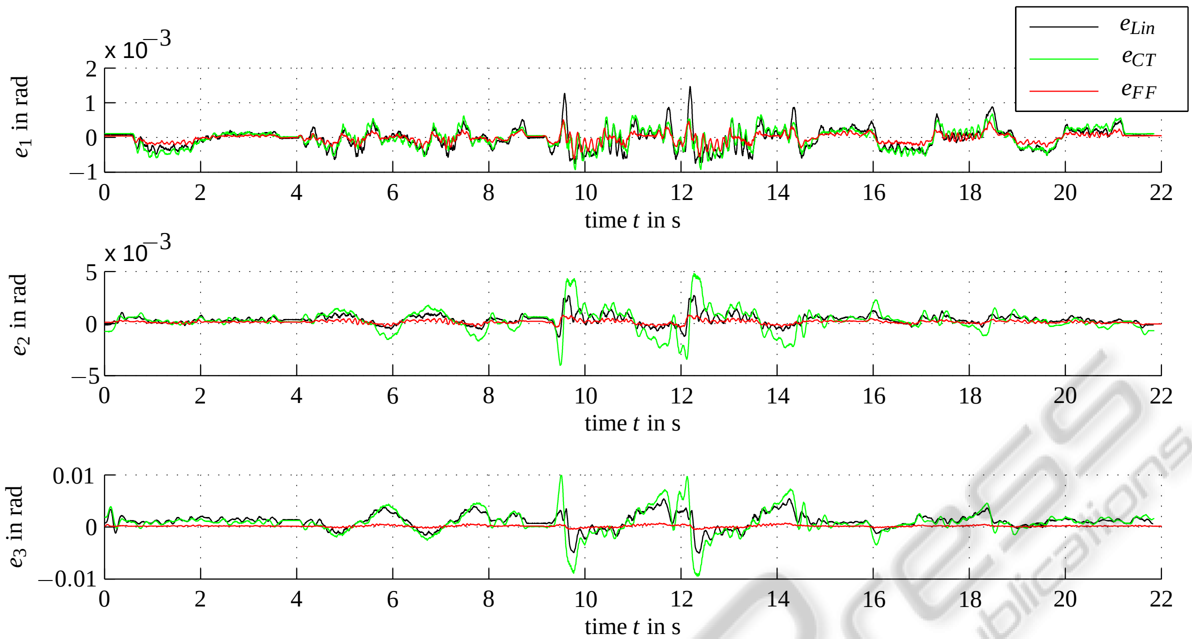

Figure 6: Lag errors with various control strategies.

4.4 Results

During a series of experiments the lag errors of the joints are recorded. Due to the rigid construction and the high stiffness of the gears, the joints' lag errors may be used to give estimations for the tool center accuracy. Also, all design parameters are chosen with highest possible gains which were evaluated in another set of preceding investigations.

In Figure 6, the lag errors for joint one, two and three are revealed. The lag errors resulting with extended linearization are denoted with e_{Lin}, respectively the ones with computed torque and feedforward with e_{CT} and e_{FF}.

While the performance of the control methods seems to be nearly equal for joint one, the joints two and three show different results. Especially axes with high loads resulting from gravity are benefiting from their reduced lag errors with the feedforward approach.

The axes four, five and six are of similar behavior and thus omitted. All values presented are joint angles, transformed to the gears' output sides.

5 INTERPRETATION

It is clearly not immediately evident that the feedforward linearization excels in performance in case of this robotic application. The reason lies in the structure of control. If the feedforward linearization is used in combination with the decoupled PD - control, the servo drives assume the task of decentralized controllers. These decentralized controllers profit from very short cycle times, still supported by the feedforward variables.

The centralized control methods, which linearize the system by feedback, are mathematically outstanding and superior. However, due to the delays which arise from closing the feedback loop to the central processing unit, the maximum gains are drastically reduced. Thus, deviations from the model and external disturbances are eliminated in a slower manner.

The effort for preparation – originating from obtaining the dynamic model with a valid and well identified set of parameters – is equal for all proposed model-based control strategies because they share a common origin, the equations of motion.

To sum up, the method of choice to control the motion of an articulated robot with six axes is the feedforward linearization approach. Model based system knowledge can effectively be exploited to support the servo drives internal, fast sampling controllers which are technically mature and professional products.

6 CONCLUSIONS

With the interpretation at hand, the feed forward linearization technique is investigated in more detail. From a practical viewpoint, the endeffector error along a given trajectory is a characteristic of interest. Assuming a rigid model and high gear stiffnesses, the forward kinematics is evaluated to compute the deviation between the desired trajectory and the actual trajectory.

To analyze the effects of the feedforward linearization, the experiment is conducted with and without superimposed feed forward loop. Figure 7 shows the tool center point (short TCP) error in inertial coordinates. The *x*- and *y*-axes are parallel to the robots mounting surface whereas the *z*-axis points in the same direction as the gravity vector.

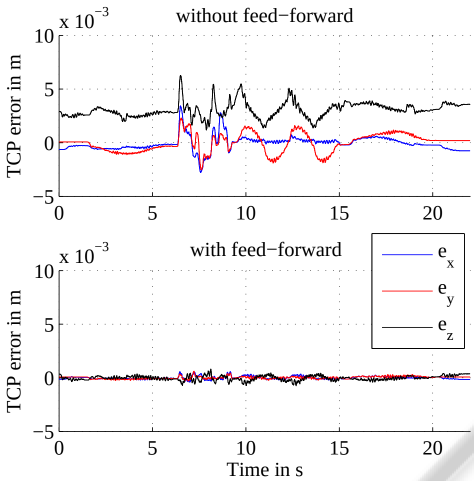

Figure 7: Evolution of TCP errors.

Interpreting the plot shows, that the robots manipulator has nearly an average of 4 mm deviation in direction of the *z*-axis. This static payload of the robot's own mass is instantly compensated with the feed forward approach. During the phases with high dynamics, the result with feed-forward control is also considerably improved.

ACKNOWLEDGEMENTS

The authors acknowledge the support and cooperation with Bernecker & Rainer, especially the group of Alois Holzleitner and Gernot Bachler. The motion control system provided allows quick implementation and offers technical perfection which made this research possible.

REFERENCES

Bremer, H. (1988). *Dynamik und Regelung mechanischer Systeme*. Teubner Studienbücher, Stuttgart.

Bremer, H. (2008). *Elastic Multibody Dynamics: A Direct Ritz Approach*, volume 35 of *Intelligent Systems, Control, and Automation: Science and Engineering*. Springer-Verlag GmbH.

Chen, C.-T. (1998). *Linear System Theory and Design (Oxford Series in Electrical and Computer Engineering)*. Oxford University Press, third. edition.

Fliess, M., Lévine, J., and Rouchon, P. (1995). Flatness and defect of nonlinear systems: Introductory theory and examples. *International Journal of Control*, 61:1327–1361.

Gattringer, H. (2006). *Realisierung, Modellbildung und Regelung einer zweibeinigen Laufmaschine*. PhD thesis, Johannes Kepler Universität Linz.

Hagenmeyer, V. and Delaleau, E. (2003). Robustness analysis of exact feedforward linearization based on differential flatness. *Automatica*, 39(11):1941 – 1946.

Isidori, A. (1985). *Nonlinear Control Systems*. Springer-Verlag.

ISO NORM 9283 (1998). Manipulating industrial robots - performance and criteria. Norm, EN ISO 9283.

Khalil, W. and Dombre, E. (2004). *Modeling, Identification and Control of Robots*. Kogan Page Science, London.

Kugi, A. (2008). Introduction to tracking control of finite- and infinite-dimensional systems. *Stability. Identification and Control in Nonlinear Structural Dynamics (SICON)*.

Sciavicco, L. and Siciliano, B. (2004). *Modelling and Control of Robot Manipulators*. Springer, United Kingdom.

Slotine, J.-J. and Li, W. (1990). *Applied Nonlinear Control*. Prentice Hall.