

# 52. IWK

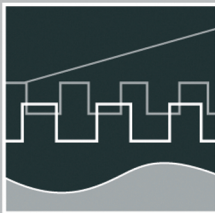
Internationales Wissenschaftliches Kolloquium  
International Scientific Colloquium



**PROCEEDINGS**

10 - 13 September 2007

## **FACULTY OF COMPUTER SCIENCE AND AUTOMATION**



## **COMPUTER SCIENCE MEETS AUTOMATION**

### **VOLUME I**

**Session 1 - Systems Engineering and Intelligent Systems**

**Session 2 - Advances in Control Theory and Control Engineering**

**Session 3 - Optimisation and Management of Complex  
Systems and Networked Systems**

**Session 4 - Intelligent Vehicles and Mobile Systems**

**Session 5 - Robotics and Motion Systems**



**Bibliografische Information der Deutschen Bibliothek**  
Die Deutsche Bibliothek verzeichnet diese Publikation in der deutschen  
Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über  
<http://dnb.ddb.de> abrufbar.

**ISBN 978-3-939473-17-6**

### Impressum

- Herausgeber: Der Rektor der Technischen Universität Ilmenau  
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff
- Redaktion: Referat Marketing und Studentische Angelegenheiten  
Kongressorganisation  
Andrea Schneider  
Tel.: +49 3677 69-2520  
Fax: +49 3677 69-1743  
e-mail: kongressorganisation@tu-ilmenau.de
- Redaktionsschluss: Juli 2007
- Verlag:   
Technische Universität Ilmenau/Universitätsbibliothek  
Universitätsverlag Ilmenau  
Postfach 10 05 65  
98684 Ilmenau  
[www.tu-ilmenau.de/universitaetsverlag](http://www.tu-ilmenau.de/universitaetsverlag)
- Herstellung und  
Auslieferung: Verlagshaus Monsenstein und Vannerdat OHG  
Am Hawerkamp 31  
48155 Münster  
[www.mv-verlag.de](http://www.mv-verlag.de)
- Layout Cover: [www.cey-x.de](http://www.cey-x.de)
- Bezugsmöglichkeiten: Universitätsbibliothek der TU Ilmenau  
Tel.: +49 3677 69-4615  
Fax: +49 3677 69-4602

© Technische Universität Ilmenau (Thür.) 2007

Diese Publikationen und alle in ihr enthaltenen Beiträge und Abbildungen sind urheberrechtlich geschützt. Mit Ausnahme der gesetzlich zugelassenen Fälle ist eine Verwertung ohne Einwilligung der Redaktion strafbar.

## Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52<sup>nd</sup> International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.

I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.



Professor Peter Scharff  
Rector, TU Ilmenau



Professor Christoph Ament  
Head of Organisation



## Table of Contents



## CONTENTS

	Page
<b>1 Systems Engineering and Intelligent Systems</b>	
A. Yu. Nedelina, W. Fengler DIPLAN: Distributed Planner for Decision Support Systems	3
O. Sokolov, M. Wagenknecht, U. Gocht Multiagent Intelligent Diagnostics of Arising Faults	9
V. Nissen Management Applications of Fuzzy Control	15
O. G. Rudenko, A. A. Bessonov, P. Otto A Method for Information Coding in CMAC Networks	21
Ye. Bodyanskiy, P. Otto, I. Pliss, N. Teslenko Nonlinear process identification and modeling using general regression neuro-fuzzy network	27
Ye. Bodyanskiy, Ye. Gorshkov, V. Kolodyazhniy, P. Otto Evolving Network Based on Double Neo-Fuzzy Neurons	35
Ch. Wachten, Ch. Ament, C. Müller, H. Reinecke Modeling of a Laser Tracker System with Galvanometer Scanner	41
K. Lüttkopf, M. Abel, B. Eylert Statistics of the truck activity on German Motorways	47
K. Meissner, H. Hensel A 3D process information display to visualize complex process conditions in the process industry	53
F.-F. Steege, C. Martin, H.-M. Groß Recent Advances in the Estimation of Pointing Poses on Monocular Images for Human-Robot Interaction	59
A. González, H. Fernlund, J. Ekblad After Action Review by Comparison – an Approach to Automatically Evaluating Trainee Performance in Training Exercise	65
R. Suzuki, N. Fujiki, Y. Taru, N. Kobayashi, E. P. Hofer Internal Model Control for Assistive Devices in Rehabilitation Technology	71
D. Sommer, M. Golz Feature Reduction for Microsleep Detection	77

F. Müller, A. Wenzel, J. Wernstedt A new strategy for on-line Monitoring and Competence Assignment to Driver and Vehicle	83
V. Borikov Linear Parameter-Oriented Model of Microplasma Process in Electrolyte Solutions	89
A. Avshalumov, G. Filaretov Detection and Analysis of Impulse Point Sequences on Correlated Disturbance Phone	95
H. Salzwedel Complex Systems Design Automation in the Presence of Bounded and Statistical Uncertainties	101
G. J. Nalepa, I. Wojnicki Filling the Semantic Gaps in Systems Engineering	107
R. Knauf Compiling Experience into Knowledge	113
R. Knauf, S. Tsuruta, Y. Sakurai Toward Knowledge Engineering with Didactic Knowledge	119
<b>2 Advances in Control Theory and Control Engineering</b>	
U. Konigorski, A. López Output Coupling by Dynamic Output Feedback	129
H. Toossian Shandiz, A. Hajipoor Chaos in the Fractional Order Chua System and its Control	135
O. Katernoga, V. Popov, A. Potapovich, G. Davydau Methods for Stability Analysis of Nonlinear Control Systems with Time Delay for Application in Automatic Devices	141
J. Zimmermann, O. Sawodny Modelling and Control of a X-Y-Fine-Positioning Table	145
A. Winkler, J. Suchý Position Based Force Control of an Industrial Manipulator	151
E. Arnold, J. Neupert, O. Sawodny, K. Schneider Trajectory Tracking for Boom Cranes Based on Nonlinear Control and Optimal Trajectory Generation	157



K. Shaposhnikov, V. Astakhov The method of ortogonal projections in problems of the stationary magnetic field computation	165
J. Naumenko The computing of sinusoidal magnetic fields in presence of the surface with bounded conductivity	167
K. Bayramkulov, V. Astakhov The method of the boundary equations in problems of computing static and stationary fields on the topological graph	169
T. Kochubey, V. Astakhov The computation of magnetic field in the presence of ideal conductors using the Integral-differential equation of the first kind	171
M. Schneider, U. Lehmann, J. Krone, P. Langbein, Ch. Ament, P. Otto, U. Stark, J. Schrickel Artificial neural network for product-accompanied analysis and control	173
I. Jawish The Improvement of Traveling Responses of a Subway Train using Fuzzy Logic Techniques	179
Y. Gu, H. Su, J. Chu An Approach for Transforming Nonlinear System Modeled by the Feedforward Neural Networks to Discrete Uncertain Linear System	185
<b>3      Optimisation and Management of Complex Systems and Networked Systems</b>	
R. Franke, J. Doppelhammer Advanced model based control in the Industrial IT System 800xA	193
H. Gerbracht, P. Li, W. Hong An efficient optimization approach to optimal control of large-scale processes	199
T. N. Pham, B. Wutke Modifying the Bellman's dynamic programming to the solution of the discrete multi-criteria optimization problem under fuzziness in long-term planning	205
S. Ritter, P. Bretschneider Optimale Planung und Betriebsführung der Energieversorgung im liberalisierten Energiemarkt	211
P. Bretschneider, D. Westermann Intelligente Energiesysteme: Chancen und Potentiale von IuK-Technologien	217

Z. Lu, Y. Zhong, Yu. Wu, J. Wu WSReMS: A Novel WSDM-based System Resource Management Scheme	223
M. Heit, E. Jennenchen, V. Kruglyak, D. Westermann Simulation des Strommarktes unter Verwendung von Petrinetzen	229
O. Sauer, M. Ebel Engineering of production monitoring & control systems	237
C. Behn, K. Zimmermann Biologically inspired Locomotion Systems and Adaptive Control	245
J. W. Vervoorst, T. Kopfstedt Mission Planning for UAV Swarms	251
M. Kaufmann, G. Bretthauer Development and composition of control logic networks for distributed mechatronic systems in a heterogeneous architecture	257
T. Kopfstedt, J. W. Vervoorst Formation Control for Groups of Mobile Robots Using a Hierarchical Controller Structure	263
M. Abel, Th. Lohfelder Simulation of the Communication Behaviour of the German Toll System	269
P. Hilgers, Ch. Ament Control in Digital Sensor-Actuator-Networks	275
C. Saul, A. Mitschele-Thiel, A. Diab, M. Abd rabou Kalil A Survey of MAC Protocols in Wireless Sensor Networks	281
T. Rossbach, M. Götze, A. Schreiber, M. Eifart, W. Kattanek Wireless Sensor Networks at their Limits – Design Considerations and Prototype Experiments	287
Y. Zhong, J. Ma Ring Domain-Based Key Management in Wireless Sensor Network	293
V. Nissen Automatic Forecast Model Selection in SAP Business Information Warehouse under Noise Conditions	299
M. Kühn, F. Richter, H. Salzwedel Process simulation for significant efficiency gains in clinical departments – practical example of a cancer clinic	305

D. Westermann, M. Kratz, St. Kümmerling, P. Meyer Architektur eines Simulators für Energie-, Informations- und Kommunikationstechnologien	311
P. Moreno, D. Westermann, P. Müller, F. Büchner Einsatzoptimierung von dezentralen netzgekoppelten Stromerzeugungsanlagen (DEA) in Verteilnetzen durch Erhöhung des Automatisierungsgrades	317
M. Heit, S. Rozhenko, M. Kryvenka, D. Westermann Mathematische Bewertung von Engpass-Situationen in Transportnetzen elektrischer Energie mittels lastflussbasierter Auktion	331
M. Lemmel, M. Schnatmeyer RFID-Technology in Warehouse Logistics	339
V. Krugljak, M. Heit, D. Westermann Approaches for modelling power market: A Comparison.	345
St. Kümmerling, N. Döring, A. Friedemann, M. Kratz, D. Westermann Demand-Side-Management in Privathaushalten – Der eBox-Ansatz	351
 <b>4      Intelligent Vehicles and Mobile Systems</b>	
A. P. Aguiar, R. Ghabchelloo, A. Pascoal, C. Silvestre , F. Vanni Coordinated Path following of Multiple Marine Vehicles: Theoretical Issues and Practical Constraints	359
R. Engel, J. Kalwa Robust Relative Positioning of Multiple Underwater Vehicles	365
M. Jacobi, T. Pfützenreuter, T. Glotzbach, M. Schneider A 3D Simulation and Visualisation Environment for Unmanned Vehicles in Underwater Scenarios	371
M. Schneider, M. Eichhorn, T. Glotzbach, P. Otto A High-Level Simulator for heterogeneous marine vehicle teams under real constraints	377
A. Zangrilli, A. Picini Unmanned Marine Vehicles working in cooperation: market trends and technological requirements	383
T. Glotzbach, P. Otto, M. Schneider, M. Marinov A Concept for Team-Orientated Mission Planning and Formal Language Verification for Heterogeneous Unmanned Vehicles	389

M. A. Arredondo, A. Cormack SeeTrack: Situation Awareness Tool for Heterogeneous Vehicles	395
J. C. Ferreira, P. B. Maia, A. Lucia, A. I. Zapaniotis Virtual Prototyping of an Innovative Urban Vehicle	401
A. Wenzel, A. Gehr, T. Glotzbach, F. Müller Superfour-in: An all-terrain wheelchair with monitoring possibilities to enhance the life quality of people with walking disability	407
Th. Krause, P. Protzel Verteiltes, dynamisches Antriebssystem zur Steuerung eines Luftschiffes	413
T. Behrmann, M. Lemmel Vehicle with pure electric hybrid energy storage system	419
Ch. Schröter, M. Höchemer, H.-M. Groß A Particle Filter for the Dynamic Window Approach to Mobile Robot Control	425
M. Schenderlein, K. Debes, A. Koenig, H.-M. Groß Appearance-based Visual Localisation in Outdoor Environments with an Omnidirectional Camera	431
G. Al Zeer, A. Nabout, B. Tibken Hindernsvermeidung für Mobile Roboter mittels Ausweichecken	437
<b>5      Robotics and Motion Systems</b>	
Ch. Schröter, H.-M. Groß Efficient Gridmaps for SLAM with Rao-Blackwellized Particle Filters	445
St. Müller, A. Scheidig, A. Ober, H.-M. Groß Making Mobile Robots Smarter by Probabilistic User Modeling and Tracking	451
A. Swerdlow, T. Machmer, K. Kroschel, A. Laubenheimer, S. Richter Opto-acoustical Scene Analysis for a Humanoid Robot	457
A. Ahranovich, S. Karpovich, K. Zimmermann Multicoordinate Positioning System Design and Simulation	463
A. Balkovoy, V. Cacenkin, G. Slivinskaia Statical and dynamical accuracy of direct drive servo systems	469
Y. Litvinov, S. Karpovich, A. Ahranovich The 6-DOF Spatial Parallel Mechanism Control System Computer Simulation	477

V. Lysenko, W. Mintchenya, K. Zimmermann 483  
Minimization of the number of actuators in legged robots using biological objects

J. Kroneis, T. Gastauer, S. Liu, B. Sauer 489  
Flexible modeling and vibration analysis of a parallel robot with numerical and analytical methods for the purpose of active vibration damping

A. Amthor, T. Hausotte, G. Jäger, P. Li 495  
Friction Modeling on Nanometerscale and Experimental Verification

**Paper submitted after copy deadline**

**2 Advances in Control Theory and Control Engineering**

V. Piwek, B. Kuhfuss, S. Allers 503  
Feed drivers – Synchronized Motion is leading to a process optimization



U. Konigorski / A. López

## Output Coupling by Dynamic Output Feedback

### INTRODUCTION

In this paper, the synchronization of predefined control variables of a linear, time invariant multivariable system by means of dynamic output feedback is considered.

Many control applications require the synchronization or coupling of two or more control variables. Examples for this kind of problem are the speed synchronization of different electrical drives within a production line also called 'electronic gear' or the slip prevention between the different wheels of a car. The classical approach to solve this problem is the use of additional PI compensators to correct the divergences between the coupled control variables. This simple approach is often sufficient to accomplish the goals of stability and asymptotic synchronization of the closed-loop. However, this approach does not result in an exact dynamic synchronization and asymptotic synchronization is only achieved for piecewise constant reference inputs or disturbances.

Previous works [1,2] offer two different ways to tackle the problem of the synchronization of multiple outputs in state space. These methods solve the problem of synchronizing a given set of control variables by assigning a suitable eigenstructure to the closed-loop by means of state feedback. Since generally not all states are available for measurement, the implementation of these approaches relies on the use of observers to supply the missing degrees of freedom.

For that purpose also dynamic output feedback of appropriate order can be used where the states of the compensator supply the missing degrees of freedom for the design. Moreover, dynamic output feedback establishes the possibility to design PI-like compensators or to account for additional constraints as to the structure of the compensator. However, the problem of eigenvalue assignment by structurally constraint controllers generally has no analytic solution and therefore demands numerical methods to solve the underlying non-linear system of equations [3]. What's more, the problem of synchronization leads to some special restrictions in the eigenstructure of the closed-loop that have to be taken into account. In the following a new approach for the design of structurally constraint dynamic output feedback controllers is presented which not only allows arbitrary eigenvalue assignment but also assures the synchronization of some predefined output variables.

### STATEMENT OF THE PROBLEM AND PRELIMINARY RESULTS

Consider a linear, time-invariant system of order  $n$  which is supposed to be completely controllable and observable.

$$\begin{aligned}\dot{x}_s(t) &= A_s \cdot x_s(t) + B_s \cdot u_s(t) \\ y_s(t) &= C_s \cdot x_s(t)\end{aligned}\quad (1)$$

The number of inputs and outputs is denoted by  $p$  and  $q$ , respectively. In what follows, for system (1) the dynamic output feedback

$$\begin{aligned}\dot{x}_d(t) &= A_d \cdot x_d(t) + B_d \cdot y_s(t) + F_1 \cdot w(t) \\ u_s(t) &= -C_d \cdot x_d(t) - D_d \cdot y_s(t) + F_2 \cdot w(t)\end{aligned}\quad (2)$$

of order  $r$  is used to place the  $n+r$  poles of the resulting closed loop system

$$\begin{bmatrix} \dot{x}_s(t) \\ \dot{x}_d(t) \end{bmatrix} = \dot{x}(t) = \begin{bmatrix} A_s - B_s D_d C_s & -B_s C_d \\ B_d C_s & A_d \end{bmatrix} x(t) + \begin{bmatrix} B_s F_2 \\ F_1 \end{bmatrix} w(t)\quad (3)$$

at a predefined set  $\Lambda = \{\lambda_1, \dots, \lambda_{n+r}\}$  of real or conjugate complex values. Simultaneously the solution  $x_s(t)$  of (3) must be such, that  $l < p$  linear coupling conditions

$$T_2^t \cdot y_s(t) = T_2^t \cdot C_s \cdot x_s(t) = 0\quad (4)$$

are met, where the superscript ‘ $t$ ’ denotes the transpose of a matrix. Obviously, we can always assume that the  $l$  coupling conditions are linear independent and thus the  $(l \times q)$  coupling matrix  $T_2^t$  has rank  $l$ .

Before proceeding further with the description of a new approach which numerically solves the aforementioned design problem, some useful results from the corresponding literature [3,4] are summarized shortly.

It is easy to verify that the closed loop system (3) can also be written in terms of a constant output feedback

$$\begin{aligned}\dot{x}(t) &= [A - BKC]x(t) + BF w(t) \\ y(t) &= Cx(t)\end{aligned}\quad (5)$$

with

$$A = \begin{bmatrix} A_s & 0 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} B_s & 0 \\ 0 & I \end{bmatrix}, \quad C = \begin{bmatrix} C_s & 0 \\ 0 & I \end{bmatrix}, \quad K = \begin{bmatrix} D_d & C_d \\ -B_d & -A_d \end{bmatrix}, \quad F = \begin{bmatrix} F_2 \\ F_1 \end{bmatrix}.\quad (6)$$

According to (6) the constant output feedback matrix  $K$  contains all free parameters of the original dynamic output feedback (2). Now from the eigenvalue/eigenvector equation of the closed loop system (5)

$$(\lambda_i I - A + BKC) \cdot v_i = 0$$

can be deduced the important relation

$$v_i = -(\lambda_i I - A)^{-1} B \cdot p_i\quad (7)$$



where  $v_i$  is the right eigenvector to the closed loop eigenvalue  $\lambda_i$  and

$$p_i = KC \cdot v_i \quad (8)$$

is a so called parameter vector (see [3,4]). In case of complete state feedback, e.g.  $C = I$ , this nonzero parameter vector  $p_i \neq 0$  can almost arbitrarily be chosen. Otherwise it is subject to non-obvious constraints. In any case, substituting (7) into (8) yields

$$\left[ I + KC(\lambda_i I - A)^{-1} B \right] \cdot p_i = [I + KG(\lambda_i)] \cdot p_i = H_i \cdot p_i = 0 \quad (9)$$

and for  $p_i \neq 0$  this results in the condition

$$\det(H_i) = 0. \quad (10)$$

If (10) is solved by a suitable choice of  $K$ ,  $\lambda_i$  is an eigenvalue of the closed loop system (5) and therefore minimizing the cost function

$$J(K) = \sum_{i=1}^{n+r} w_i \cdot \det(\bar{H}_i^t) \cdot \det(H_i) = \sum_{i=1}^{n+r} w_i \cdot \det(\bar{H}_i^t H_i), \quad w_i > 0 \quad (11)$$

with respect to  $K$  yields a solution  $K^*$  to the pole placement problem provided  $J(K^*) = 0$ . In (1)  $\bar{H}_i$  denotes the conjugate complex of  $H_i$ .

## OUTPUT COUPLING BY CONSTANT OUTPUT FEEDBACK

First of all, the coupling condition (4) needs to be adapted to the new output equation in (5), where according to (6) the new output matrix  $C$  has  $r$  additional columns due to the compensator states. Since these additional outputs are not involved in the coupling, the matrix  $T_2^t$  needs to be expanded with a zero matrix of dimension  $(l \times r)$

$$T_2^t \cdot y_s = \begin{bmatrix} T_2^t & 0 \end{bmatrix} \cdot y = \tilde{T}_2^t \cdot y = 0. \quad (12)$$

Now, substituting the Laplace transform of (5) in (12) leads to a new expression for the coupling conditions

$$\tilde{T}_2^t C (sI - A + BKC)^{-1} B \begin{bmatrix} \tilde{F}_1 & \tilde{F}_2 \end{bmatrix} w(s) = 0, \quad (13)$$

where  $F = \begin{bmatrix} \tilde{F}_1 & \tilde{F}_2 \end{bmatrix}$ . After applying a modal transformation to (13) (see [2]) it becomes

$$\sum_{i=1}^{n+r} \frac{\tilde{T}_2^t C v_i w_i^t B \begin{bmatrix} \tilde{F}_1 & \tilde{F}_2 \end{bmatrix}}{s - \lambda_i} \begin{bmatrix} w_1(s) \\ w_2(s) \end{bmatrix} = 0 \quad (14)$$

where  $v_i$  and  $w_i^t$  represent the right and left eigenvectors of the closed-loop system (5),

respectively. Obviously, with

$$w_2(s) = 0 \quad (15)$$

equation (14) can be split into two parts

$$\begin{aligned} \tilde{T}_2^t C \cdot v_i &= 0, \quad i = 1 \dots m \\ w_i^t B \cdot \tilde{F}_1 &= 0, \quad i = m + 1, \dots, n + r. \end{aligned} \quad (16)$$

The set of equations (16) represent the output- and input-coupling conditions for the constant output feedback system (5) and are formally equivalent to the coupling equations presented in [2] for the case of full state feedback, where it is shown that just the output-coupling conditions are relevant for the calculation of the controller  $K$ .

Therefore, substituting (7) into (16) the output-coupling condition reads

$$\tilde{T}_2^t C (\lambda_i I - A)^{-1} B \cdot p_i = \tilde{G}(\lambda_i) \cdot p_i = 0 \quad (17)$$

and thus the parameter vector  $p_i$  must be contained in the null space

$$\tilde{G}(\lambda_i) \cdot \tilde{N}_i = 0 \quad (18)$$

of  $\tilde{G}(\lambda_i)$  to generate via (7) an eigenvector  $v_i$  that is compliant with the output-coupling condition (16). According to [5], the eigenvectors  $v_i$  constructed in this way span the  $(A, B)$ -invariant subspace in the kernel of  $\tilde{T}_2^t C$  which in the sequel is assumed to have dimension  $m$ . So, any arbitrary  $\tilde{p}_i \neq 0, i = 1, \dots, m$  results in an admissible parameter vector

$$p_i = \tilde{N}_i \tilde{p}_i \neq 0, \quad i = 1, \dots, m \quad (19)$$

and the remaining  $n + r - m$  input-coupling conditions in (16) yield

$$[v_1, \dots, v_m, \quad B] \cdot \begin{bmatrix} M \\ \tilde{F}_1 \end{bmatrix} = 0 \quad (20)$$

from which a nonsingular prefilter  $\tilde{F}_1$  can be calculated [2]. This  $\tilde{F}_1$  makes the corresponding  $n + r - m$  eigenvalues of the closed loop system (5) uncontrollable from the input  $w_1$ . Therefore, what remains is the calculation of the constant output feedback matrix  $K$  in the feedback law

$$u = -Ky + \tilde{F}_1 w_1 \quad (21)$$

for the system  $(A, B, C)$  such that the closed loop has the  $n + r$  predefined eigenvalues from the set  $\Lambda$ . This can be achieved by numerical minimization of (11) where for the first  $m$  eigenvalues the additional constraints (19) must be taken into consideration. With

respect to (9) this results in

$$J(K) = \sum_{i=1}^m w_i \cdot \det(\tilde{N}_i^t \bar{H}_i^t H_i \tilde{N}_i) + \sum_{i=m+1}^{n+r} w_i \cdot \det(\bar{H}_i^t H_i), \quad w_i > 0. \quad (22)$$

### NUMERICAL EXAMPLE

The dynamics of a DC motor are described by the following equations

$$\begin{aligned} J \frac{d\ddot{\varphi}(t)}{dt} &= c_m i(t) - d\omega(t) \\ u(t) &= Ri(t) + c_m \omega(t) + L \frac{di(t)}{dt} \end{aligned} \quad (23)$$

where  $J$  represents the moment of inertia,  $c_m$  the motor constant,  $d$  the speed proportional damping,  $R$  the resistance,  $L$  the inductance,  $u$  the input voltage,  $i$  the motor current,  $\varphi$  the mechanical angle and  $\omega = \frac{d\varphi}{dt}$  the mechanical angular speed.

Consider two independent motors "A" and "B" with  $R_A = R_B = 1$ ,  $L_A = L_B = 0,05$ ,  $c_{mA} = c_{mB} = 1$ ,  $d_A = d_B = 0$  but different moments of inertia  $J_A = 0,1$  and  $J_B = 0,025$  [1] (units are ignored). Their state equations can be summarized as follows

$$\dot{x}_s(t) = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 40 & 0 & 0 & 0 \\ 0 & -20 & -20 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 0 & 0 & 0 & -20 & -20 \end{pmatrix} \cdot x_s(t) + \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 20 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 20 \end{pmatrix} \cdot u_s(t), \quad y_s(t) = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot x_s(t) \quad (24)$$

where  $x_s = [\varphi_A \quad \omega_A \quad i_A \quad \varphi_B \quad \omega_B \quad i_B]^t$  is the  $n$ -dimensional state vector and the measured variables are  $y_s = [\varphi_A \quad \omega_A \quad \varphi_B]^t$ . The two uncoupled drives have their eigenvalues at  $\Lambda_s = \{0 \quad 0 \quad -10 \pm 26,45i \quad -10 \pm 10i\}^t$  and they shall be shifted to

$$\Lambda = \{-4 \quad -20 \pm 25i \quad -15 \pm 6i \quad -8 \quad -10 \quad -12\}^t \quad (25)$$

by means of a dynamic output feedback of order 2. Simultaneously the angles  $\varphi_A$  and  $\varphi_B$  of the two motors must be synchronized. Thus the coupling matrix is set to  $T_2^t = [1 \quad 0 \quad -1]$ . Following the guidelines given in [5] for the calculation of the  $(A, B)$ -invariant subspace of  $T_2^t C_s$  it is found that the dimension of this subspace is  $m = 3$ . Hence three eigenvectors can be found which are compliant with the output-coupling conditions (16) and these eigenvectors have been chosen to be  $v_{\lambda=-4}$  and  $v_{\lambda=-20 \pm 25i}$ . Then from (18) the corresponding null spaces  $\tilde{N}_i$  can be easily calculated and after performing a minimization of the cost function (22) with the predefined set of closed-loop eigenvalues (25) the following constant output feedback matrix  $K$  is found

$$K = \begin{pmatrix} 2,525 & 0,513 & -0,513 & 0,390 & -0,167 \\ 2,660 & 3,428 & 0,599 & 1,368 & -0,452 \\ 156,35 & 14,41 & -2,772 & -6,753 & 11,637 \\ 343,65 & -158,17 & 147,64 & 119,42 & 70,753 \end{pmatrix} \quad (26)$$

from which the system matrices  $(A_d, B_d, C_d, D_d)$  of the dynamic controller (2) can be extracted according to (6). Finally, with the help of (20) the prefilter

$$\tilde{F}_1 = [-3,575 \quad -14,299 \quad -353,550 \quad -311,178]^t \cdot 10^{-3} \quad (27)$$

can be calculated and the transfer function of the closed-loop system then reads

$$G(s) = \begin{pmatrix} \frac{4100s^5 + 2,46 \cdot 10^5 s^4 + 5,974 \cdot 10^6 s^3 + 7,24 \cdot 10^7 s^2 + 4,348 \cdot 10^8 s + 1,027 \cdot 10^9}{s^8 + 104s^7 + 5282s^6 + 1,57 \cdot 10^5 s^5 + 2,86 \cdot 10^6 s^4 + 3,18 \cdot 10^7 s^3 + 2,09 \cdot 10^8 s^2 + 7,32 \cdot 10^8 s + 1,027 \cdot 10^9} \\ \frac{4100s^6 + 2,46 \cdot 10^5 s^5 + 5,974 \cdot 10^6 s^4 + 7,24 \cdot 10^7 s^3 + 4,348 \cdot 10^8 s^2 + 1,027 \cdot 10^9 s}{s^8 + 104s^7 + 5282s^6 + 1,57 \cdot 10^5 s^5 + 2,86 \cdot 10^6 s^4 + 3,18 \cdot 10^7 s^3 + 2,09 \cdot 10^8 s^2 + 7,32 \cdot 10^8 s + 1,027 \cdot 10^9} \\ \frac{4100s^5 + 2,46 \cdot 10^5 s^4 + 5,974 \cdot 10^6 s^3 + 7,24 \cdot 10^7 s^2 + 4,348 \cdot 10^8 s + 1,027 \cdot 10^9}{s^8 + 104s^7 + 5282s^6 + 1,57 \cdot 10^5 s^5 + 2,86 \cdot 10^6 s^4 + 3,18 \cdot 10^7 s^3 + 2,09 \cdot 10^8 s^2 + 7,32 \cdot 10^8 s + 1,027 \cdot 10^9} \end{pmatrix} \quad (28)$$

Obviously the outputs 1 and 3 or  $\varphi_A$  and  $\varphi_B$  share the same transfer function

$G_{\varphi_{A/B}}(s) = \frac{\varphi_{A/B}(s)}{w_1(s)}$  and thus are perfectly synchronized. Moreover, since  $\omega_A = \frac{d\varphi_A}{dt}$  or

$\omega_A(s) = s \cdot \varphi_A(s)$ , the second output  $\omega_A(s)$  has the transfer function

$$G_{\omega_A}(s) = \frac{s \cdot \varphi_A(s)}{w_1(s)} = s \cdot G_{\varphi_A}(s).$$

#### References:

- [1] Reglerentwurf für Mehrgrößensysteme unter der Nebenbedingung vorgegebener Ausgangsgrößenverkopplungen, A. Jochheim VDI Verlag, Reihe 8 Nr. 457
- [2] Ausgangsgrößenverkopplung bei linearen Mehrgrößensystemen, U. Konigorski, at 4/99 P. 165
- [3] Ein direktes Verfahren zum Entwurf strukturbeschränkter Zustandsrückführungen durch Polvorgabe, U. Konigorski, VDI Verlag, Reihe 8, Nr. 156
- [4] Vollständige modale Synthese linearer Systeme und ihre Anwendung zum Entwurf strukturbeschränkter Zustandsrückführungen, G. Roppenecker, VDI Verlag, Reihe 8, Nr. 59
- [5] Linear Multivariable Control: A Geometric Approach, W. M. Wonham, Springer-Verlag, 2<sup>nd</sup> Edition

#### Authors:

Prof. Dr.-Ing. Ulrich Konigorski  
Dipl.-Ing. Alejandro López Pamplona  
Institute für Automatisierungstechnik, TU Darmstadt, Landgraf-Georg Straße 4  
64283, Darmstadt  
Phone: +49 615116 3014  
Fax: +49 615116 6114  
E-mail: ukonigorski@iat.tu-darmstadt.de