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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

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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 52nd 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

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2 Advances in Control Theory and Control Engineering

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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.

$$\begin{aligned}\dot{x}_s(t) &= A_s \cdot x_s(t) + B_s \cdot u_s(t)\\ y_s(t) &= C_{s.} \cdot x_s(t)\end{aligned} \tag{1}$$

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

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

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

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

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

$$T_2^t \cdot y_s(t) = T_2^t \cdot C_s \cdot x_s(t) = 0 \tag{4}$$

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

$$\begin{aligned}\dot{x}(t) &= \left[A - BKC\right] x(t) + BF\, w(t)\\ y(t) &= C x(t)\end{aligned} \tag{5}$$

with

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

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)

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

can be deduced the important relation

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

where v_i is the right eigenvector to the closed loop eigenvalue λ_i and

$$p_i = KC \cdot v_i \tag{8}$$

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

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

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

$$\det(H_i) = 0\,. \tag{10}$$

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

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

with respect to K yields a solution K^* to the pole placement problem provided $J(K^*) = 0$. In (1) $\overline{H}_i$ 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 $(l \times r)$

$$T_2^t \cdot y_s = \left[T_2^t \quad 0 \right] \cdot y = \tilde{T}_2^t \cdot y = 0\,. \tag{12}$$

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

$$\tilde{T}_2^t C \left(sI - A + BKC \right)^{-1} B \left[\tilde{F}_1 \ \tilde{F}_2 \right] w(s) = 0\,, \tag{13}$$

where $F = \left[\tilde{F}_1 \quad \tilde{F}_2 \right]$. After applying a modal transformation to (13) (see [2]) it becomes

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

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

$$w_2(s) = 0 \tag{15}$$

equation (14) can be split into two parts

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

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

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

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

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

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 $\tilde{p}_i \neq 0, i = 1, \ldots, m$ results in an admissible parameter vector

$$p_i = \tilde{N}_i \tilde{p}_i \neq 0, \quad i = 1, \ldots, m \tag{19}$$

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

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

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

$$u = -Ky + \tilde{F}_1 w_1 \tag{21}$$

for the system (A, B, C) such that the closed loop has the $n + r$ predefined eigenvalues from the set Λ. 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

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

NUMERICAL EXAMPLE

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

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

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, φ 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

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

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

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

by means of a dynamic output feedback of order 2. Simultaneously the angles φ_A and φ_B of the two motors must be synchronized. Thus the coupling matrix is set to $T_2^t=\begin{bmatrix}1 & 0 & -1\end{bmatrix}$. 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 $v_{\lambda=-20\pm 25\mathrm{i}}$. 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

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

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

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

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

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

Obviously the outputs 1 and 3 or φ_A and φ_B share the same transfer function $G_{\varphi_{A/B}}(s)=\dfrac{\varphi_{A/B}(s)}{w_1(s)}$ and thus are perfectly synchronized. Moreover, since $\omega_A=\dfrac{d\varphi_A}{dt}$ or $\omega_A(s)=s\cdot\varphi_A(s)$, the second output $\omega_A(s)$ has the transfer function $G_{\omega_A}(s)=\dfrac{s\cdot\varphi_A(s)}{w_1(s)}=s\cdot G_{\varphi_A}(s)$.

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