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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

52^{nd} Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
September 10 – 13, 2007

A. Balkovoy, V. Cacenkin, G. Slivinskaia

Statical and dynamical accuracy of direct drive servo systems

ROBOTICS AND MOTION SYSTEMS

The modern direct drive servo systems based on brushless AC motors (BLACM) have been gaining popularity owing to their high torque to current ratio, high efficiency and robustness. The high stiffness of mechanical coupling and high resolution of digital control and measuring systems, allow the considering of BLACM direct drive servo systems as continuous systems. In these systems, the BLACM may be considered as double integrator. The position closed loop with this actuator may be designed with proportional-integral-differential (PID) controller or with a state-space controller. So, the comparison of various control structures with PID control and state-space control render the interest.

From the example of the drive system with PID controller, it may be shown that direct drive servo system with BLACM has the astaticism of the third order and brings the acceptable transients. The structure of such system is in Fig. 1 represented.

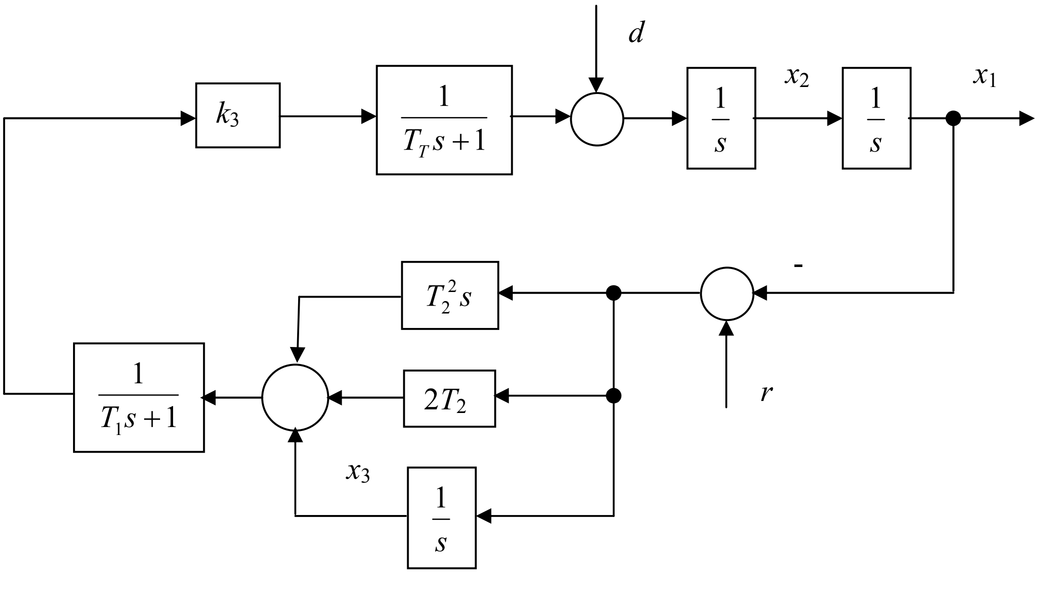

Fig. 1. The drive system with PID controller

The first-order link with time-constant T_T represents the non-ideal conversion of BLACM currents in the current stiff inverter (CSI) into the motor torque and the first-order link with time-constant T_1 represents the lag-effect in digital controller [1]. The transfer function of the "ideal" controller is designed with "critical" damping in numerator that makes the design of controller parameters sufficient easier [2]:

$$G_C(s) = k_3\left(\frac{1}{s} + 2T_2 + T_2^2 s\right) = \frac{k_3(1 + 2T_2 s + T_2^2 s^2)}{s} \tag{1}$$

The closed loop transfer functions from command and from disturbance of the system in Fig. 1 are:

$$G_{CLr}(s) = \frac{k_3(1 + 2T_2 s + T_2^2 s^2)}{T_1 T_T s^5 + (T_1 + T_T)s^4 + s^3 + k_3 T_2^2 s^2 + 2k_3 T_2 s + k_3} \tag{2}$$

$$G_{CLd}(s) = \frac{s(1 + (T_1 + T_T)s + T_1 T_T s^2)}{T_1 T_T s^5 + (T_1 + T_T)s^4 + s^3 + k_3 T_2^2 s^2 + 2k_3 T_2 s + k_3} \tag{3}$$

The error of the system is:

$$e(s) = (1 - G_{CLr}(s))r(s) - G_{CLd}(s)d(s)\,. \tag{4}$$

Now, the errors coefficients from command and from disturbance may be calculated [1]:

$$C_r(k) = \frac{\mathrm{d}^k}{\mathrm{d}s^k}(1 - G_{CLr}(s))\,|_{s=0};\, C_d(k) = -\frac{\mathrm{d}^k}{\mathrm{d}s^k}G_{CLd}(s)\,|_{s=0};\, k = 0,1,2,... \tag{5}$$

As a result, the errors coefficients are:

$$C_r(0) = 0;\; C_r(1) = 0;\; C_r(2) = 0;\; C_r(3) = \frac{6}{k_3};\, C_d(0) = 0;\; C_d(1) = -\frac{1}{k_3}. \tag{6}$$

So, in the servo system with BLACM and PID-controller, the astaticism from command of the third order may be achieved.

The controller parameters are selected with "critical" damping in numerator. In this case, the time constant T_2 of the controller may be calculated from the index of oscillation and base frequency $\omega_0 = \sqrt[3]{k_3}$:

$$T_2 = \frac{2}{\omega_0}\sqrt{\frac{M^2 - M\sqrt{M^2 - 1}}{M^2 - 1}}\,. \tag{7}$$

Usually, index of oscillation is M=1,2…1,5 in dependence of stability of system parameters [3].

The simplest structure of system with state-space control is in Fig. 2 represented. The closed loop transfer functions of the system in Fig. 2 are:

$$G_{CLr}(s) = \frac{x_1(s)}{r(s)} = \frac{l_1}{s^2 + l_2 s + l_1};\;\; G_{CLd}(s) = \frac{x_1(s)}{r(s)} = \frac{1}{s^2 + l_2 s + l_1}; \tag{8}$$

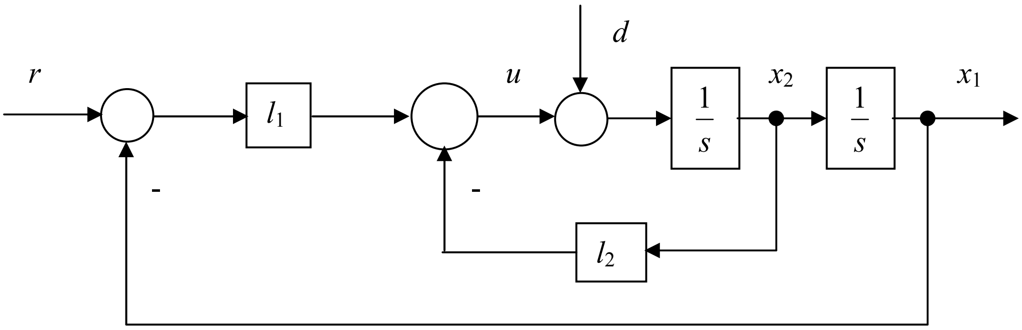

Fig. 2. The drive system with state-space controller

the error of the system is:

$$e_r(s) = \frac{s^2 + l_2 s}{s^2 + l_2 s + l_1}. \tag{9}$$

In accordance with (5), in the servo system Fig 2, the astaticism from command of the first order may be achieved:

$$C_r(0) = 0;\ C_r(1) = \frac{1}{l_1 l_2};\ C_d(0) = -\frac{1}{l_1}. \tag{10}$$

The further development of the system with state-space control is the structure where the full-order observer is added (Fig. 3).

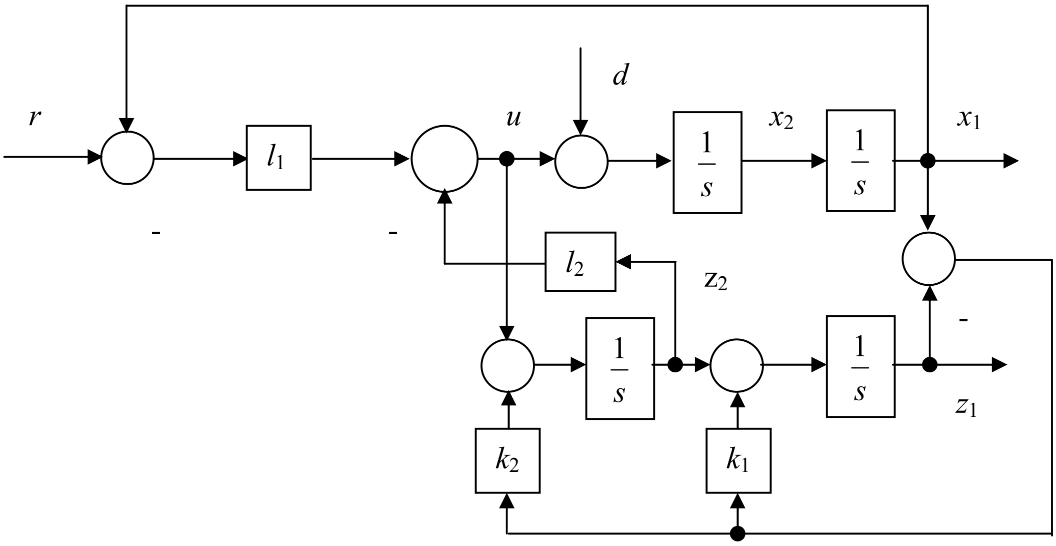

Fig. 3. The drive system with full-order observer

For the state-space control, the velocity from observer is used. The closed loop transfer functions of the system in Fig. 3 are:

$$G_{CLr}(s) = \frac{(s^2 + k_1 s + k_2) l_1}{s^4 + (k_1 + l_2)s^3 + (k_1 l_2 + k_2 + l_1)s^2 + (k_1 l_1 + k_2 l_2)s + k_2 l_1};$$
$$G_{CLd}(s) = \frac{s^2 + (k_1 + l_2)s + k_1 l_2 + k_2}{s^4 + (k_1 + l_2)s^3 + (k_1 l_2 + k_2 + l_1)s^2 + (k_1 l_1 + k_2 l_2)s + k_2 l_1}. \tag{11}$$

Using (4) and (5), the errors coefficients may be calculated:

$$C_r(0) = 0;\ C_r(1) = \frac{1}{l_1 l_2};\ C_d(0) = -\frac{1}{l_1} - \frac{k_1 l_2}{k_2 l_1}. \tag{12}$$

So, the steady-state errors of the system in Fig 3 are approximately the same as in system from Fig. 2.

It is expected that similar to PID controller, the definite advantages may be obtained from the system with state-space controller and state-space errors observer. The structure of such a system is in Fig. 4 depicted. The state-space errors are from the outputs of observer acquired.

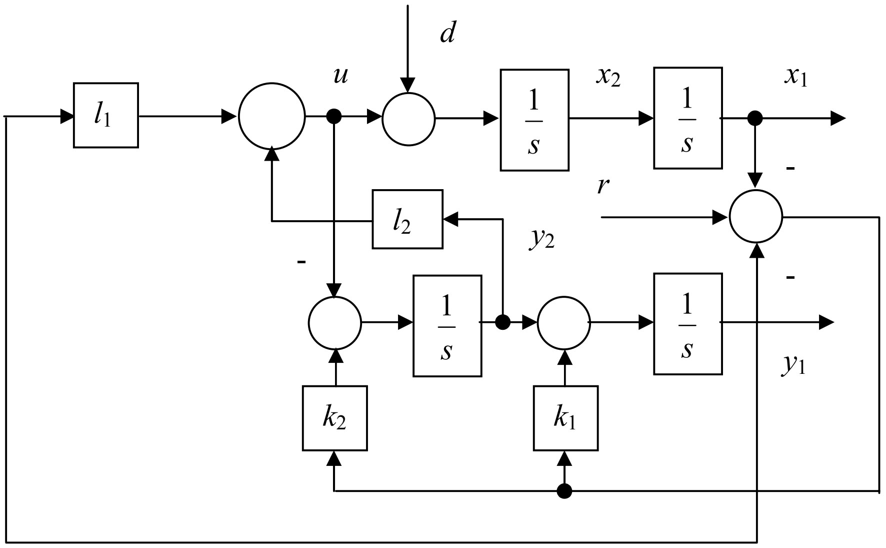

Fig. 4. The system with state-space controller and state-space errors observer

The closed loop transfer functions of the system in Fig. 4 are:

$$G_{CLr}(s) = \frac{(k_1 l_1 + k_2 l_2)s + k_2 l_1}{s^4 + (k_1 + l_2)s^3 + (k_1 l_2 + k_2 + l_1)s^2 + (k_1 l_1 + k_2 l_2)s + k_2 l_1};$$
$$G_{CLd}(s) = \frac{s^2 + (k_1 + l_2)s + k_1 l_2 + k_2 + l_1}{s^4 + (k_1 + l_2)s^3 + (k_1 l_2 + k_2 + l_1)s^2 + (k_1 l_1 + k_2 l_2)s + k_2 l_1}. \tag{13}$$

The errors coefficients are:

$$C_r(0) = 0;\ C_r(1) = 0;\ C_r(2) = \frac{2}{k_2} + \frac{2(k_2 + k_1 l_2)}{k_2 l_1};\ C_d(0) = -\frac{1}{k_2} - \frac{k_2 + k_1 l_2}{k_2 l_1}. \tag{14}$$

So, in the servo system from Fig 4, the astaticism from command is the second order but the steady state errors due to acceleration or load are remaining.

The further development of the system properties is the compensation of the constant disturbance. The simplest model of the constant disturbance is the "slow" disturbance in compare to system and observer transients. The model of such "constant" value is the output of integrator with zero random initial condition [4]:

$$\begin{aligned}&\frac{\mathrm{d}d}{\mathrm{d}t}=0;\\&d(0)=d_0,\end{aligned}\tag{15}$$

where d is the disturbance; d_0 is the scalar random disturbance.

The equations for system variables are:

$$\begin{bmatrix}\dot{x}_1\\\dot{x}_2\\\dot{x}_3\end{bmatrix}=\begin{bmatrix}0&1&0\\0&0&1\\0&0&0\end{bmatrix}\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}+\begin{bmatrix}0\\1\\0\end{bmatrix}u;\ x_1=C=\begin{bmatrix}1&0&0\end{bmatrix}\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}.\tag{16}$$

In equations (15), the controlled states are x_1 and x_2. The disturbance x_3 is uncontrolled. All the parameters are observable. So, the closed loop controller and observer may be designed. The structure of the system with state-space controller, state-space errors observer and disturbance model is in Fig. 5 depicted.

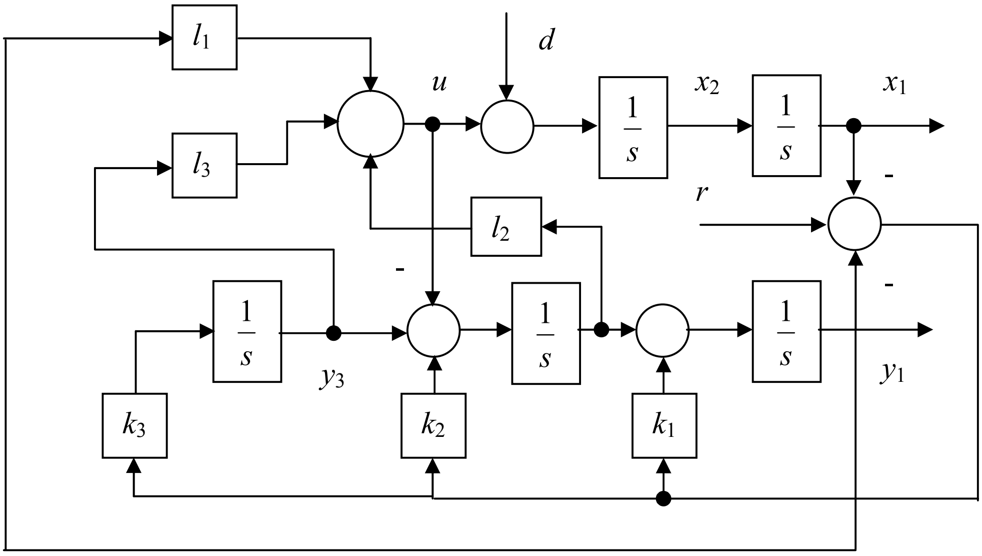

Fig. 5. The system with state-space controller, state-space errors observer and disturbance model

The disturbance compensation means l_3 = 1. The closed loop transfer functions of the system in Fig. 5 are:

$$G_{CLr}(s) = \\ = \frac{(k_1 l_1 + k_2 l_2 + k_3)s^2 + (k_2 l_1 + k_3 l_2)s + k_3 l_1}{s^5 + (k_1 + l_2)s^4 + (k_1 l_2 + k_2 + l_1)s^3 + (k_1 l_1 + k_2 l_2 + k_3)s^2 + (k_2 l_1 + k_3 l_2)s + k_3 l_1};$$
$$G_{CLd}(s) = \\ = \frac{s(s^2 + (k_1 + l_2)s + k_1 l_2 + k_2 + l_1)}{s^5 + (k_1 + l_2)s^4 + (k_1 l_2 + k_2 + l_1)s^3 + (k_1 l_1 + k_2 l_2 + k_3)s^2 + (k_2 l_1 + k_3 l_2)s + k_3 l_1}. \tag{17}$$

The errors coefficients are:

$$C_r(0) = 0;\ C_r(1) = 0;\ C_r(2) = 0;\ C_r(3) = \frac{6}{k_3} + \frac{6(k_2 + k_1 l_2)}{k_3 l_1};$$
$$C_d(0) = 0;\ C_d(1) = -\frac{1}{k_3} - \frac{k_2 + k_1 l_2}{k_3 l_1}. \tag{18}$$

The astaticism of the system has third order from reference and first order from disturbance.

The analysis of steady-state errors has shown the advantage of two structures: with PID controller and with state-space controller, state-space errors observer and disturbance model. The PID controller needs the digital differentiation that usually has noise due to discretisation. Also, the precision of the system depends from sampling period. In the drive system with observer, there is no differentiation and the precision of integration has weak dependence from sampling period. But the sampling period has to be small because of observer has to be "faster" as observed system.

The another criterion of the servo system selection is the quality of transients. The parameters of system with PID controller may be first evaluated using (7) for selected base frequency and index of oscillation. In the servo system with observer, the synthesis of controller parameters may be done independent.

For the structure in Fig. 5, the simple method of controller parameters selection is the use of modal control method [4]. The characteristic polynomial of controller is:

$$D_r(s) = s(s^2 + l_2 s + l_1) = 0. \tag{19}$$

Here, the zero root is the result of non-controlled disturbance x_3. Let the desirable characteristic polynomial of the plant as:

$$s(s^2 + 2\zeta_p \omega_p s + \omega_p^2). \tag{20}$$

From (19), (20) and the gain $l_3 = 1$ (selected to give perfect disturbance cancellation) following the equations:

$$l_1 = \omega_p^2;\ l_2 = 2\zeta_p \omega_p. \tag{21}$$

The characteristic polynomial of observer is:

$$D_{ob}(s) = s^3 + k_1 s^2 + k_2 s + k_3, \tag{22}$$

The method of observer parameters selection is again the use of modal control method. The desired characteristic polynomial is:

$$(s + a_o)(s^2 + 2\zeta_o \omega_o s + \omega_o^2) = s^3 + (2\zeta_o \omega_o + a_o)s^2 + (2\zeta_o \omega_o a_o + \omega_o^2)s + \omega_o^2 a_o. \tag{23}$$

The coefficients of observer are calculated as:

$$k_1 = 2\zeta_o \omega_o + a_o; k_2 = 2\zeta_o \omega_o a_o + \omega_o^2; k_3 = \omega_o^2 a_o. \tag{24}$$

The frequencies ω_p, ω_o depend of bandwidth of drive system and observer. The self-oscillation frequency of observer ω_o has to be higher as self-oscillation frequency of plant ω_p. The coefficients ζ_p, ζ_o determine the oscillations of transients. The coefficient a_o assign the speed of transients.

The further comparison of statical and dynamical errors of direct drive servo systems with BLACM demonstrates the advantages of system with PID controller and system with error state space observer. The PID controller is more sensitive to sampling frequency and error state space observer inserts the additional lag effect. The analytical research and simulation of the servo systems dynamical errors show the negative action of "small" time constants of PID-control and relative slow dynamics of system observer on servo system transients. For dynamics improvement of such systems, the "small" time constants of PID-control have to be reduced and the processing speed of the error state observer has to be enhanced. Some simulations and real systems dynamics validating these resume. The further research of control structures and controller and observer parameters has to be done in accordance with obtained here conclusions. The final choice has to be done after research of real systems.

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