NEW DECENTRALIZED CONTROL IN PROCESSING MACHINES WITH CONTINUOUS MOVING WEBS

by

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Abstract

Web-products are manufactured in sections of rollers which transport the web according to specific technological demands. To achieve the required final product, the transport of the web has to be successful without material defects and losses. To fulfil these demands, the tension in the web during transport must be kept on a desired value within close limits. Therefore, electrical and mechanical quantities of the drives have to be controlled by closed loop control systems.

The rollers in such processing machines are coupled by the web and are driven usually by electrical motors. So the processing machines are *multi-motor drives* and from the view of control a multi input - multi output system.

To improve the dynamic behaviour of the controlled system, new concepts with decoupling state space control are considered in this paper. The goal of the control are non-interacting, decentralized control-loops. Two decentralized control methods were developed and are discribed.

The first method is called *DECENTRALIZED DECOUPLING*. The state space controller of low order for each subsystem makes the controlled subsystems approximately unobservable and uncontrollable from the neighbouring subsystems. The second method is *FUZZY-CONTROL* which is in examination just now.

The new control methods are applicable for both, DC- and AC-drives. The identification of the process variables and the calculation of the control algorithm is performed by a microcomputer system.

NOMENCLATURE

Unnormalized quantities are written in capital letters whereas normalized quantities are written in small print.

$\underline{A}$	System matrix of the state space control
A_0	Area of the web
$\underline{B}$	Input matrix of the state space control
$\underline{B}_{Ki}$	Input matrix of the quantities of coupling
$\underline{C}$	Output matrix of the state space control
$\underline{C}_{Ki}$	Output matrix of the quantities of coupling
E	Modulus of elasticity
f_{ij}	Web force between the rollers No. i and j
f_{ij}^*	Reference web force between the rollers No. i and j
J_K	Criterion function
$\underline{K}$	Optimal regulator gain vector
L_N	Reference lenght of the web
l_{ij}	Lenght of the web between the rollers No. i and j
m_i	Torque of the motor shaft No. i
n_i	Speed of the motor shaft No. i
T_i	Time constant of the reduced closed loop current control
T_{ij}	Time constant of the web between the rollers No. i and j
T_{int}	Time constant of the integrator in the reference path
T_N	Reference time constant of the web ($T_N = L_N/V_N$)
$T_{\Theta N}$	Time constant of inertia
$\underline{u}$	Input vector of the state space control
$\underline{V}$	Transforming matrix
V_i	Gain of the closed loop current control
v_i	Velocity of the web in the section No. i
v_0	Average velocity of the web
V_N	Reference velocity of the web
$\underline{x}$	State vector
$\underline{y}$	Output vector of the state space control
ϵ_{ij}	Strain in the web between the rollers No. i and j
ϵ_N	Normalized strain
$\underline{\Lambda}$	Diagonal matrix of the eigenvalues

INTRODUCTION

In many industrial plants of processing machines with continuous moving webs – for example in the paper, textile, plastic, printing and metal industries – the web has to pass several processing stations. All sections of the continuous process are coupled by the web. At the beginning and at the end of the plant there are often winders installed.

In the system – schematically shown in Figure 1 – the web will be processed in different stations. In these stations, called nip sections, there are driven and undriven rollers to transport and process the web. In the nip sections the rollers transfer forces depending on the technological process. These forces must be kept on a desired value within close limits.

The rollers are driven by electrical motors and are controlled in current, speed and sometimes in force. A superimposed guidance system controls the total process.

If we assume that the web is pure elastic and only small changes from steady state occurs, we get the linear signal–flow graph of the mechanical system as shown in figure 1 and described in [1].

It is to point out that in this paper *normalized quantities* are used and that the variables have been transformed to the motor shaft. The normalization and the reference quantities are shown in Table 1.

All nip sections, the winders and rollers are coupled by the web because of the forces acting on the left and right side of a roller. This fact forms a multidimensional system. The input quantities of this system are the motor torques and the output quantities to be controlled are the speed and the forces.

The dynamic behaviour of the uncontrolled system is similar to a spring and mass system with multiple resonant peaks in the frequency characteristic as shown in figure 2.

CONVENTIONAL CONTROL OF THE SYSTEM

State Of The Art

Though linear multivariable control theory is wellknown since years, the state of the art of the control is the cascade control with simple decentralized P, PI or PID controller which are optimized according to linear single variable theory. In doing so the dynamic influence of the web forces is neglected. Therefore for several unfavourable dimensions of the mechanical parts, poor dynamic behaviour is observed in the plant, especially if the damping in the system is low and the resonance width is wide. Such oscillations cannot be compensated by cascade control.

To improve the dynamic behaviour of a cascade control, decentralized observers were used to decouple the system [2].

State Space Control Of The Total System

The optimal control for such multidimensional systems is a multivariable state space control with a matrix–PI–controller to decouple the system as described in [3], [4], [5].

The general state equations of a total system are

$$\begin{aligned} \underline{\dot{x}} &= \underline{A} \cdot \underline{x} + \underline{B} \cdot \underline{u} \\ \underline{y} &= \underline{C} \cdot \underline{x} \end{aligned} \tag{1}$$

The optimal control is the linear constant feedback law

$$\underline{u} = -\underline{K} \cdot \underline{x} \tag{2}$$

where $\underline{K}$ are the steady–state quadratic optimal regulator gains for continuous linear time–invariant multivariable systems. $\underline{K}$ is usually calculated with the *Quadratic Criterion Funktion* and the *Matrix Algebraic Riccati Equation.*

The principle schema and the result of such a controlled sytem is shown in figure 3. A non–oscillating and fast step response is obtained. On the other hand, the web forces are decoupled. The disadvantage of this control is the complex controller of high order. In the case of threading the web or the web is torn, the system is disintegrated in separate subsystems and the central control do not work properly. Nevertheless we use the result of the central control as the goal for the decentralized control.

Subsystem

To design a decentralized control we have to separate the total system into subsystems. As shown in figure 1 the subsystem exists of the roller, the electrical drive and the websection on the left side of the roller. If doing so, the total system exists of a lot of similar subsystems. The separation in this manner has two advantages. On the one hand it comes close to the technological system which exists of drives, rollers and websections. On the other hand it comes close to the mathematical description of the total system.

Figure 4 shows such a third order subsystem. The closed loop current control is reduced to a first order system, where V_i is the gain and T_i the time constant of the closed loop current control. The output is the torque on the motor shaft. The torque of acceleration is formed by the torque m_3 and the difference of the web forces f_{23} and f_{34} acting on the left and right side of the roller. The velocity v_3 is proportional to the speed n_3 and is the output of the integrator which represents the combined inertia of the roller and motor. A variation in v_3 produces variations in the strain ϵ_{23} via the time constant T_{23} of the web. T_{23} is dependent of the average transport velocity v_0 of the web.

$$T_{23} = \frac{l_{23}}{v_0} \cdot T_N \tag{3}$$

The force f_{23} is produced by ϵ_{23} according to Hooke's law, expressed through the normalized strain ϵ_N which describes the stiffness of the web.

$$\epsilon_N = \frac{F_N}{EA_0} \tag{4}$$

The speed v_2, the strain ϵ_{12} and the force f_{34} are the input quantities of coupling whereas the velocity v_3 and the strain ϵ_{23} are the output quantities of coupling.

Mathematical describing. To design a decentralized control it is useful to describe the subsystem in the *coupling orientated* description [6].
The state equations of the subsystem No. i are

$$\begin{aligned} \dot{\underline{x}}_i &= \underline{A}_{ii} \cdot \underline{x}_{ii} + \underline{B}_{Si} \cdot \underline{u}_{Si} + \underline{B}_{Ki} \cdot \underline{u}_{Ki} \\ \underline{y}_{Mi} &= \underline{C}_{Mi} \cdot \underline{x}_i \\ \underline{y}_{Ki} &= \underline{C}_{Ki} \cdot \underline{x}_i \end{aligned} \tag{5}$$

If we consider the subsystem No. 3 we get the following equations in the state space

$$\underline{x}_3 = [\, i_3 \quad v_3 \quad \epsilon_{23} \,]^T \tag{6}$$

$$u_{S3} = i_3^* \tag{7}$$

$$\underline{u}_{K3} = [\, v_2 \quad \epsilon_{12} \quad f_{34} \,]^T \tag{8}$$

$$\underline{y}_{K3} = [\, -v_3 \quad v_0\epsilon_{23} \quad f_{23} \,]^T \tag{9}$$

$$\underline{y}_{M3} = [\, i_3 \quad v_3 \quad f_{23} \,]^T \tag{10}$$

$$\underline{A}_{33} = \begin{pmatrix} -1/T_i & 0 & 0 \\ 1/T_{\Theta N} & 0 & -1/\epsilon_N T_{\Theta N} \\ 0 & 1/l_{23}T_N & -v_0/l_{23}T_N \end{pmatrix} \tag{11}$$

$$\underline{B}_{K3} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1/T_{\Theta N} \\ -1/l_{23}T_N & v_0/l_{23}T_N & 0 \end{pmatrix} \tag{12}$$

$$\underline{B}_{S3} = [\, V_i/T_i \quad 0 \quad 0 \,]^T \tag{13}$$

$$\underline{C}_{K3} = \begin{pmatrix} 0 & -1 & 0 \\ 0 & 0 & v_0 \\ 0 & 0 & 1/\epsilon_N \end{pmatrix} \tag{14}$$

$$\underline{C}_{M3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1/\epsilon_N \end{pmatrix} \tag{15}$$

NEW DECENTRALIZED CONTROL

Single Subsystem

If we neglect the quantities of coupling we get a separate subsystem. To compare the results we used the data of our experimental plant, shown in table 2.

The step response of the web force f_{23} due to the motor current i_3^* of the uncontrolled subsystem of third order is shown in figure 5. We recongnize an oscillation not well damped. The frequency is about 5 Hz and the damping factor 0,034. Such a system cannot be controlled by simple PI–cascade controller.

Therefore a state space control was designed with the linear quadratic criterion function and the Riccati equation. The data of the obtained regulator gains are shown in table 2. To avoid a closed loop error of the controlled system, an integrator in the reference path was added.

The step response of the web force f_{23} due to the reference force f_{23}^* is shown in figure 6a. We get a very fast non–oscillating step response equal to figure 3.

But if we couple two of such decentralized controlled systems to a total system (figure 6b), we get a significant deterioration of the dynamic behaviour as shown in figure 6c. Because of the influence of the coupling quantities, oscillations occur and the force f_{34} of the neighbouring subsystem has large dynamic changes. This is the consequence of the neglect of the quantities of coupling during the design of the control.

To get a proper dynamic behaviour the quantities of coupling must be taken into account.
To do this, there are two possibilities

- design of decoupling networks
- decentralized decoupling.

The first possibility requires the design of a special decoupling network and presupposes the measurement of the quantities of coupling. As this requirements are not always possible, the second possibility is considered and explained.

Decentralized Decoupling

Theoretical basis. The decentralized decoupling is a method for state space control. The method is based on the single subsystem and the remaining system, which is coupled with the considered subsystem. The connections between both systems are the quantities of coupling. Figure 7 shows this facts.

It can be seen that the subsystem is in principle controllabel from the input vectors $\underline{u}_{Si}$ and $\underline{u}_{Ki}$ and observable from the output vectors $\underline{y}_{Mi}$ and $\underline{y}_{Ki}$. Thus the dynamic behaviour of the subsystem depends on the controller *and* the remaining system. The goal of the method is to design a controller which minimize the influence of the remaining system. In doing so, the subsystem is extensively decoupled from the remaining system.

The state space controller has two functions

- to guarantee the desired dynamic and stability of the total system and
- to minimize the influence of the remaining system.

The consequence for the design of the decentralized controller is

- the eigenvalues of the controlled subsystem have to be in the required area and
- the sensitivity of the eigenvalues concerning the vectors $\underline{y}_{Ki}$ and $\underline{u}_{Ki}$ have to be as less as possible.

The solution to design such a controller is to consider the sensitivity of the eigenvalues.

Sensitivity of the eigenvalues. To use the sensitivity of the eigenvalues it is recommended to transform the subsystem which is described in equation 5 into a system like following

$$\underline{x} = \underline{V} \cdot \underline{z} \tag{16}$$

$$\dot{\underline{z}} = \underline{\Lambda} \cdot \underline{z} + \underline{B}_K^* \cdot \underline{u}_K \tag{17}$$

$$\underline{y}_K = \underline{C}_K^* \cdot \underline{z} \tag{18}$$

where

$$\underline{\Lambda} = \text{diag}\,(\lambda_1, \ldots, \lambda_n) \tag{19}$$

$\underline{\Lambda}$ is the diagonal matrix of the eigenvalues of the subsystem.
The transformed matrices $\underline{B}_K^*$ and $\underline{C}_K^*$ are obtained from the equations

$$\underline{B}_K^* = \underline{V}^{-1} \cdot \underline{B}_K \tag{20}$$

$$\underline{C}_K^* = \underline{C}_K \cdot \underline{V} \tag{21}$$

Litz [6] has defined the general sensitivity of the eigenvalues

$$\frac{\partial \lambda_m}{\partial k_{ij}} = S_{ij}^m = -c_{Km}^* \cdot b_{Km}^* \tag{22}$$

Equation 22 had been revised for the use of our problem. We got the following quadratic criterion function to design the controller

$$J_K = \sum_{m=1}^{n} \sum_{j=1}^{p_k} \sum_{i=1}^{q_k} \left| \frac{c^*_{im} \cdot b^*_{ij}}{\lambda_m} \right|^2 \tag{23}$$

where n is the order of the system, p_k are the numbers of the input quantities of coupling and q_k are the numbers of the output quantities of coupling.

To calculate the gain vector $\underline{K}$ of the state space controller, the criterion function is to minimize concerning of the gain elements k

$$\frac{\partial J_K}{\partial k} \rightarrow min \tag{24}$$

Unfortunately it is not possible to find an explicit mathematical solution. So an algorithm was used to find the solution.

Algorithm. To minimize the criterion function, a gradient–free method is used [7]. In the first step the designer of the controller has to choose the area within the eigenvalues are supposed to be, dependent of stability, dynamic and damping. The algorithm starts with estimated values of the gain $\underline{K}$. We suggest to use the gain values obtained from the design of the single subsystem. The only condition is that the estimated eigenvalues are within the area chosen in step one.

The algorithm is described in [8] and is written compatible to the software Ctrl–C. After each step a simulation is made with a graphic output of the controlled values.

The advantage of this method is that no measurements of the quantities of coupling is required. It is only necessary to know where the quantities of coupling are active in the subsystem (values b^*_{ij} and c^*_{im}).

Examples. With the data of our experimental plant some examples of the design were made.

First, the chosen area of eigenvalues was

$$|\Im\{\lambda_i\}| \leq 5 \cdot |\Re\{\lambda_i\}| \tag{25}$$

$$\Re\{\lambda_i\} \leq -10 \tag{26}$$

We started the algorithm with the gain values listed in table 2. This values led to a value of the criterion function $J_{K1} = 185$. After some steps we have got a value $J_{Kopt} = 25,7$ and practicable gain values. As shown in figure 8 the dynamic behaviour is good as well as the decoupling.

If we change the area of eigenvalues to

$$|\Im\{\lambda_i\}| \leq 5 \cdot |\Re\{\lambda_i\}| \tag{27}$$

$$\Re\{\lambda_i\} \leq -5 \tag{28}$$

we are able to minimize more and get a value of $J_K = 2,3$. This leads to the results in figure 9. The decoupling is nearly perfect, but the transient response time is bigger than in figure 8. It is to remark, that the high gain values may cause problems in real plants, especially the gains of the speed K_n and the force K_f.

If the state space quantities are not well measurable, decentralized observers can be used [6], [8], [10].

Robustness. In all processing machines with continuous moving webs there is one parameter which is not well–known or varies during processing. It is the elasticity of the web, normalized the factor ϵ_N. Examples of this fact are a coater or printer, where the web gets wet and dry during processing.

To test the robustness of the decentralized control, the factor ϵ_N was changed in a range of $0,4\epsilon_N$ to $1,6\epsilon_N$. Figure 10 shows that a bigger ϵ_N than the chosen value during designing the controller, i.e. the web becomes wet or more elastic like rubber, causes no problems.

If the web gets more stiff a change of about 50 % is allowed. Only if the change is greater then 60 % instability is caused. Further investigations were made concerning other parameters, for example the lenghts of the web between two rollers or the inertia of the rollers. We got the same results as above. Even at standstill of the machine no problems occured [8]. So it is to notice that the designed control is robust against changes of the parameters in a wide range.

EXPERIMENTAL RESULTS

Experimental investigations were made with the experimental plant of our institute to verify the theoretical results. The plant exists of two winders and three nip sections, driven by electrical motors.

Hardware Concept

To put into practice the new designed control, an advanced microcomputer system was installed. It is the system *SIMICRO–AMS* from *Siemens* with the operating system *RMOS2*.

It is to remark that the *sampling time has to be less then 5 ms* for a proper working of the decentralized control.

Results

Figure 11 shows a comparison of the measured step responses of the web forces. Figure 11a shows a system, where only the current and speed is controlled. The forces are in an open loop control. Figure 11b shows a closed loop control of the forces with a cascade control of current, speed and force with PI–controllers. Both control systems are state of the art in real plants. Figure 11c shows a state space control without decoupling. This system is discribed in figure 6. As shown in figure 11d the quality of the control is improved by the decentralized decoupling control. Nearly no changes occur in the neighbouring subsystem (force F_{34}). The measured results confirmes the theoretical investigations very well (compare figure 8). Another advantage of the new control is the fact that no new investigations or changes in the mechanical systems are necessary. Only a new control is to design.

FUZZY CONTROL

General Survey

The new designed decentralized control has one disadvantage. If we compare figure 8 and figure 9 we can say the better the decoupling, the bigger is the transient response time of the controlled system. In figure 8 after about 400 ms the reference value of the force is reached whereas in figure 9 with the optimal decoupling about 800 ms are necessary. So we can say, the better the decoupling, the more bad the dynamic. To avoid this fact we looked at new possibilities. Therefore in the last months we made investigations with *Fuzzy Control* [9].

Design Of The Control

The signal–flow graph of the Fuzzy Control for two subsystems is shown in figure 12. It is to point out that the design of the Fuzzy controllers were made only with the *single subsystem* without knowledge of the quantities of coupling. If we double the single Fuzzy controlled subsystem, we get two systems as shown in figure 12.

The Fuzzy controllers have two inputs and one output. One input is the error df_i of the forces $f_{ij}^* - f_{ij}$. The other input $d\epsilon_i$ is the difference of the velocities $v_j - v_i$ of the rollers and the steady–state reference value of the velocity error ϵ_i^*, which is given from the reference value of the force f_{ij}^*. As it can be seen in figure 12, the second input $d\epsilon_i$ is approximately the derivation of the force f_{ij}.

The design of the Fuzzy controller was made with trapezoidal membership–functions of the errors df_i and $d\epsilon_i$ whereas the membership–functions of the output are singletons [10].

Results Of Simulation

To compare the Fuzzy Control, we did the same as in the previous investigations. The step responses of the forces f_{23} and f_{34} due to the reference forces f_{23}^* resp. f_{34}^* are shown in figure 13. If we compare these results with that of figure 8, we realize that the decoupling is equal, but the dynamic behaviour is more better as that of the decentralized control in figure 8.

It can be noticed that the results of the Fuzzy Control are closer on those of the optimal state space control with a matrix–PI–controller according to figure 3. The Fuzzy Control is not yet realized in our experimental plant.

But there are also some disadvantages in Fuzzy Control, for example the change of the dynamic behaviour due to the value of the reference force.

Nevertheless we continue our investigations in Fuzzy Control to solve the problems because of the success of our first investigations.

CONCLUSION

In this report, two decentralized control methods were developed. The first method is called *DECENTRALIZED DECOUPLING.* The state space controller of low order makes the controlled subsystems approximately unobservable and uncontrollable from the neighbouring subsystems. The *DECENTRALIZED DECOUPLING* is realized as a state space control. The controlled

Unnormalized Quant.	Normalized Quant.	Reference Value
Current I	$i = I/I_{AN}$	Rated current I_{AN}
Torque M	$m = M/M_{iN}$	Rated torque M_{iN}
Speed N	$n = N/N_{0N}$	Rated speed N_{0N}
Velocity V	$v = V/V_N$	Rated velocity V_N
Length L_{ij}	$l_{ij} = L_{ij}/L_N$	Rated length L_N
Force F_{ij}	$f_{ij} = F_{ij}/F_N$	Rated force F_N

Table 1: Normalized Quantities

Data of the exp. plant	Optimal reg. gains
$V_i = 1,73$	$K_i = 0,3$
$T_i = 3,8$ ms	$K_n = 30$
$T_{\Theta N} = 0,415$ s	$K_f = 2$
$l_{ij}T_N = 0,49$ s	$T_{int} = 12$ ms
$\epsilon_N = 0,004$	
$v_0 = 0 \ldots 1$	

Table 2: Data of the experimental plant and optimal regulator gains

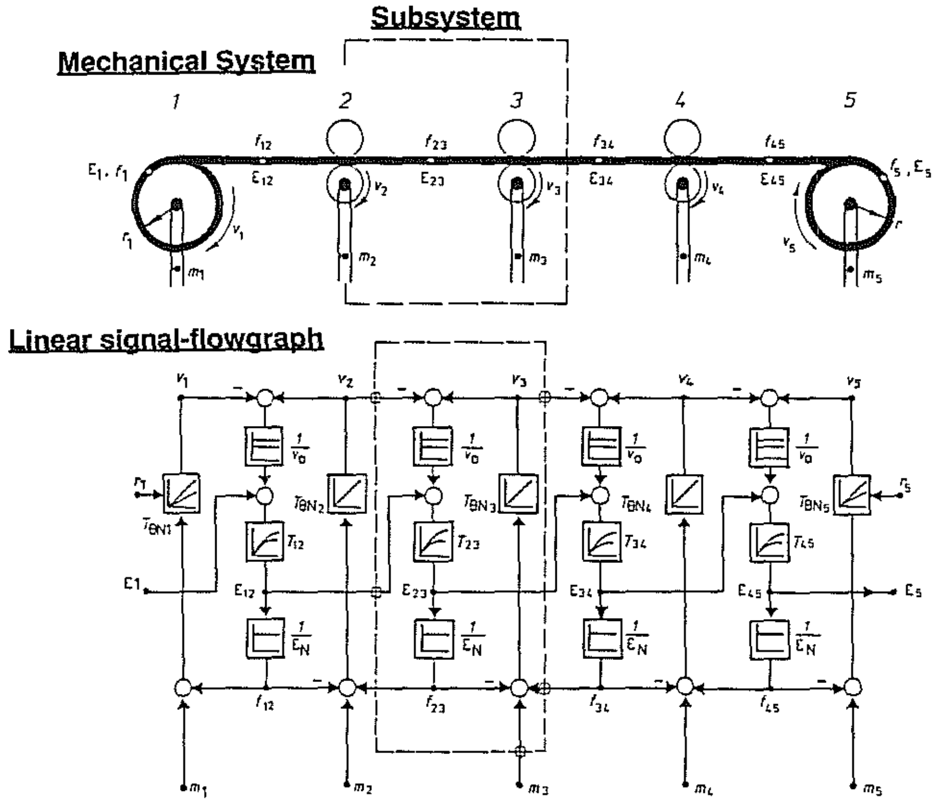
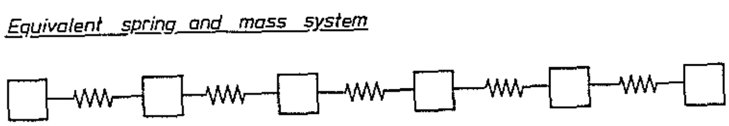


Fig. 1: Example of a processing machine



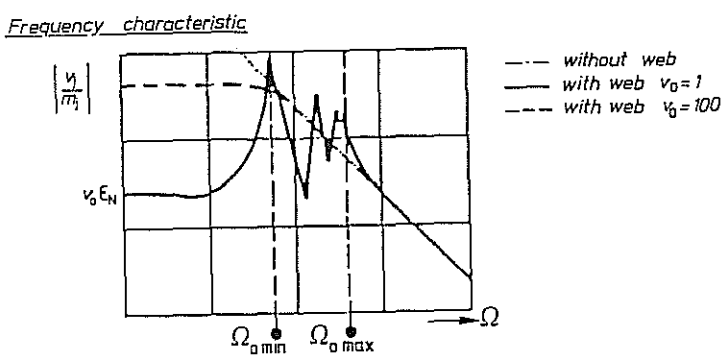


Fig. 2: Mechanical equivalent of the system

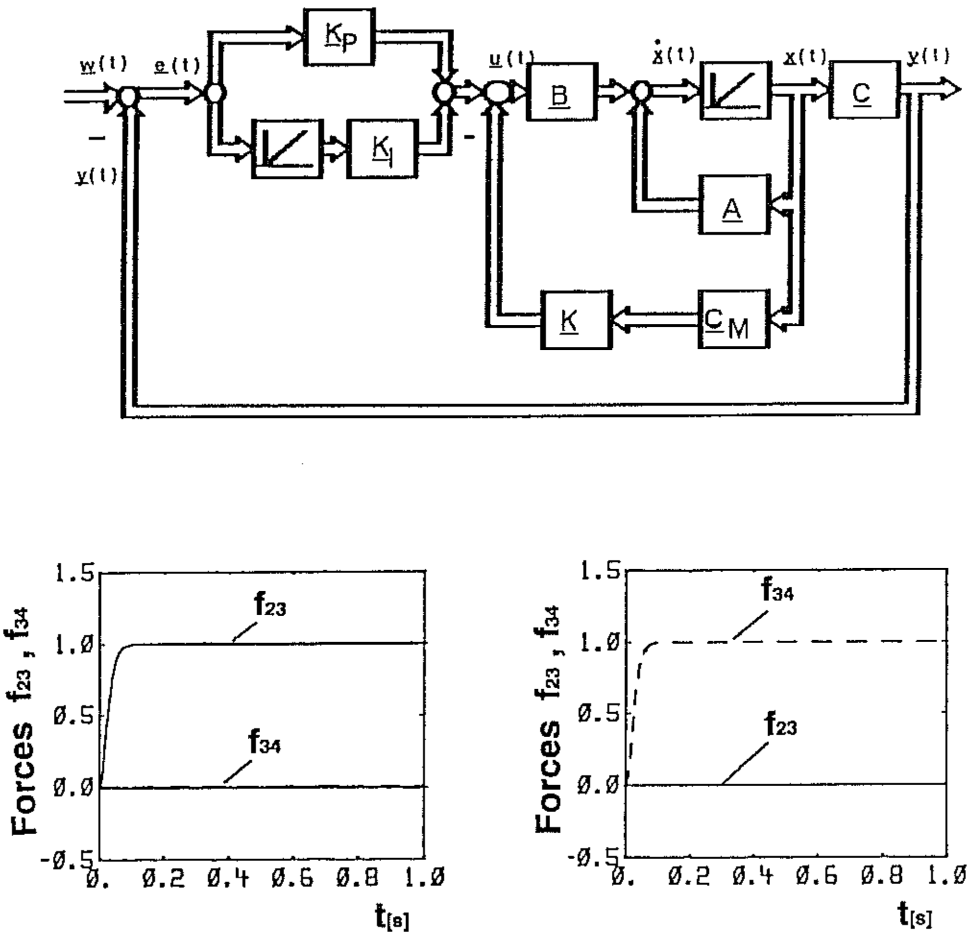


Fig. 3: State space control with matrix–PI–controller

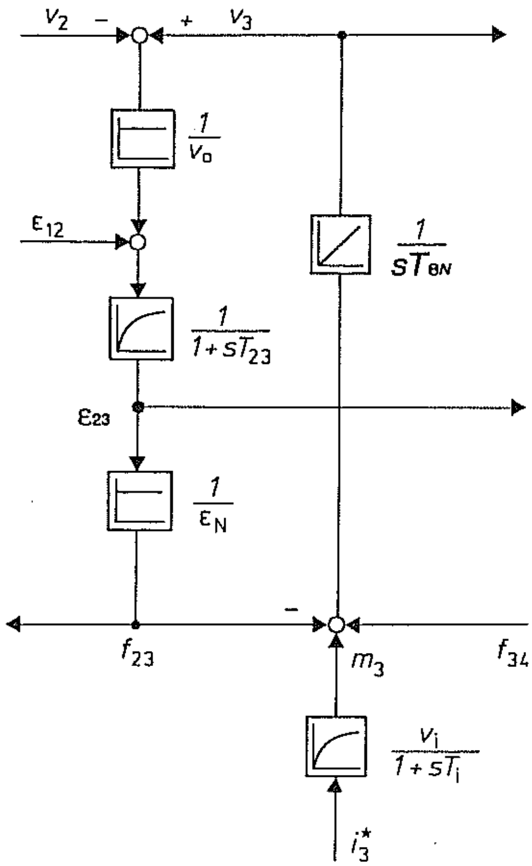


Fig. 4: Third order subsystem

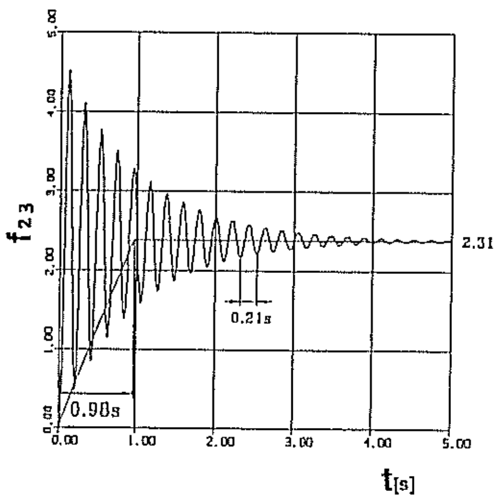


Fig. 5: Step response of the force due to the reference current

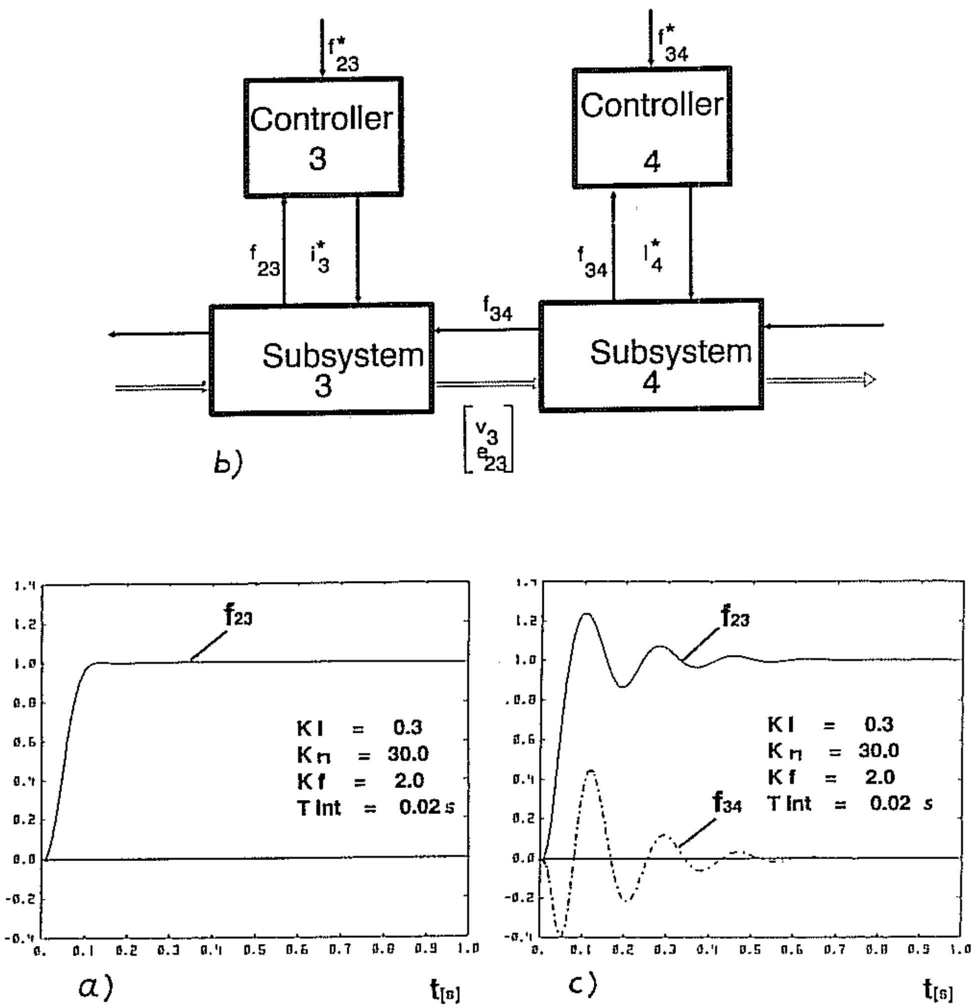


Fig. 6: State space control of two subsystems without decoupling

quantities are the current of the motor, the speed of the motor shaft and the web force. If the web force cannot be well measured, observer are used. The quality of the decoupling depends on the quality of the mechanical and electrical system. There are two disadvantages. The better the decoupling, the bigger is the trancient response time and if the number of the subsystems increases, the decoupling decreases.

The *FUZZY-CONTROL* avoids these disadvantages and provides better results even if the number of subsystems increases.

With the new control methods, the quality of machines with continuous moving webs can be improved.

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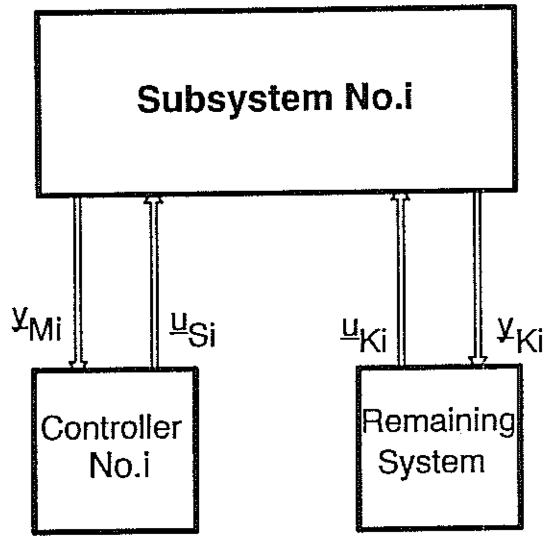


Fig. 7: Principle of the decentralized decoupling

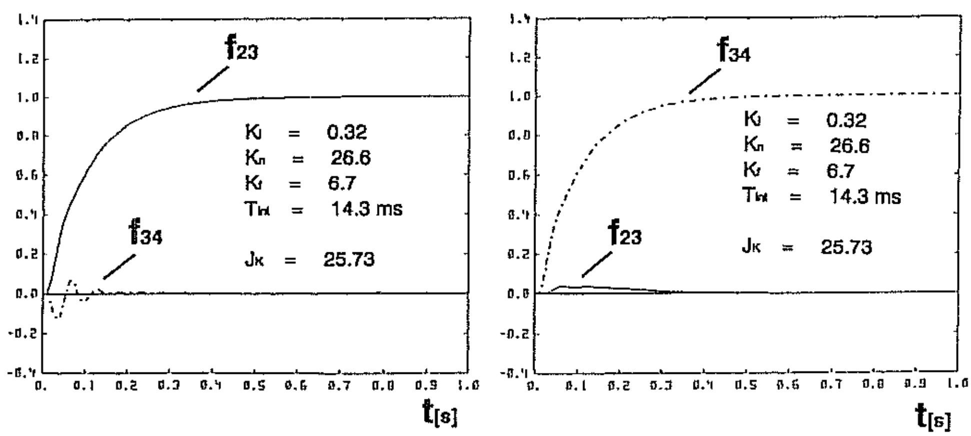


Fig. 8: Step response of two decentralized decoupled subsystems

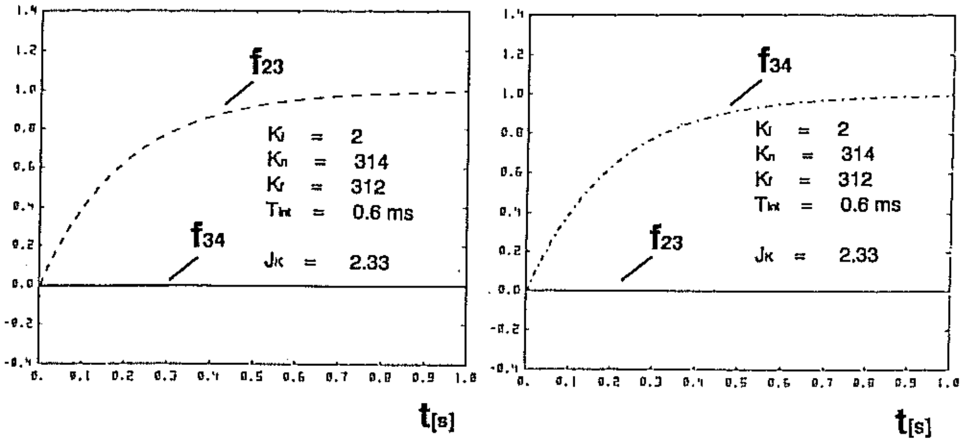


Fig. 9: Step response of two decentralized decoupled subsystems with optimal decoupling

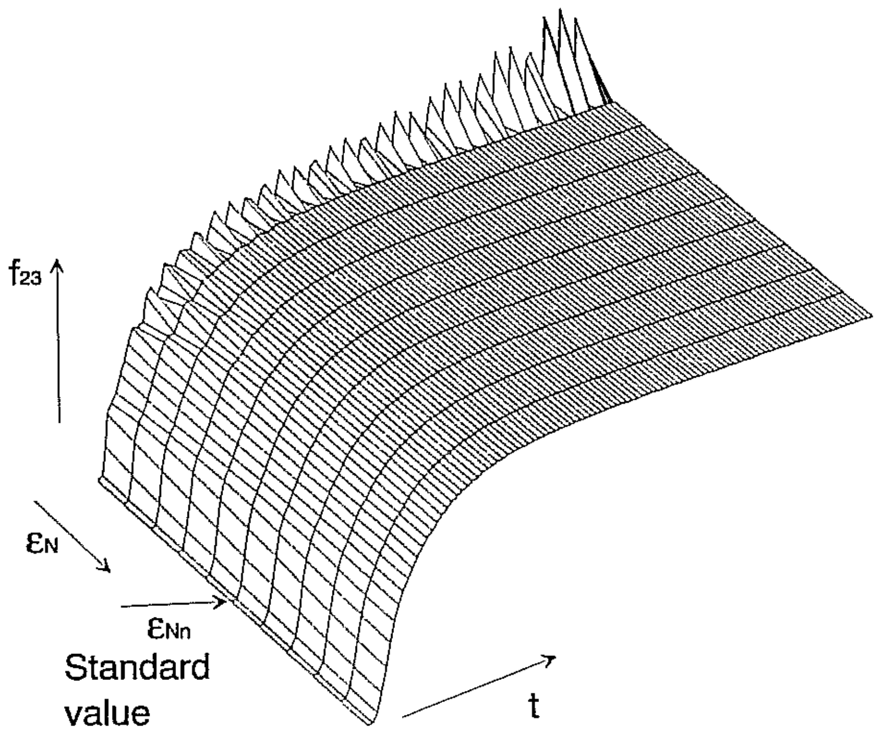
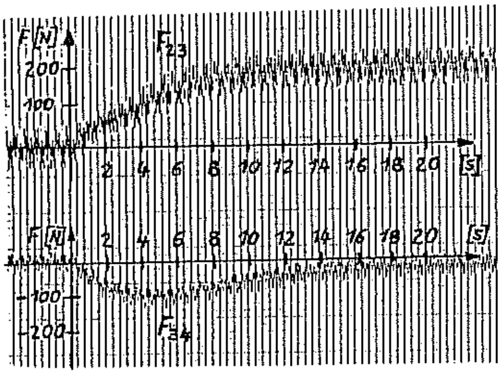
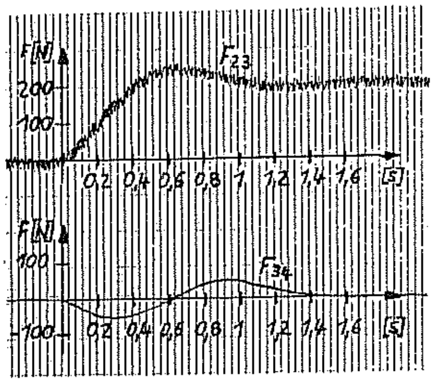


Fig. 10: Robustness of the control

State of the art

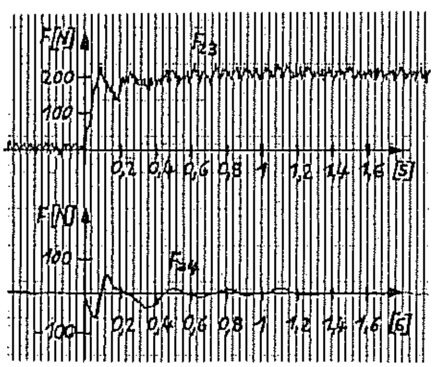


a) Open loop control of the forces

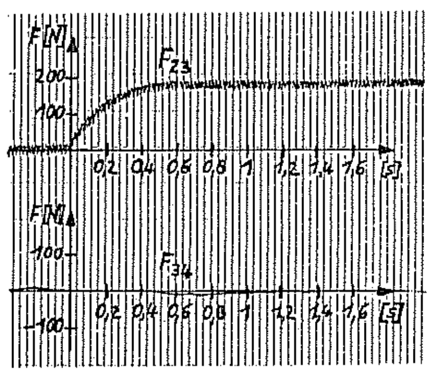


b) Cascade control with PI-Controllers

New Control



c) Decentralized state space control without decoupling



d) Decentralized decoupling

Fig. 11: Experimental results

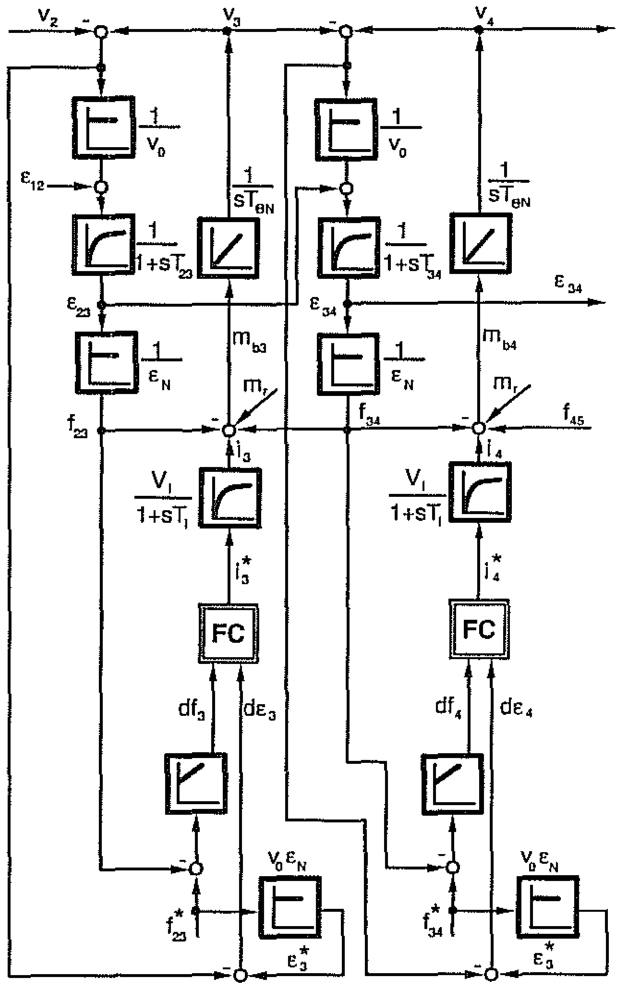


Fig. 12: Signal-flow graph of the Fuzzy Control

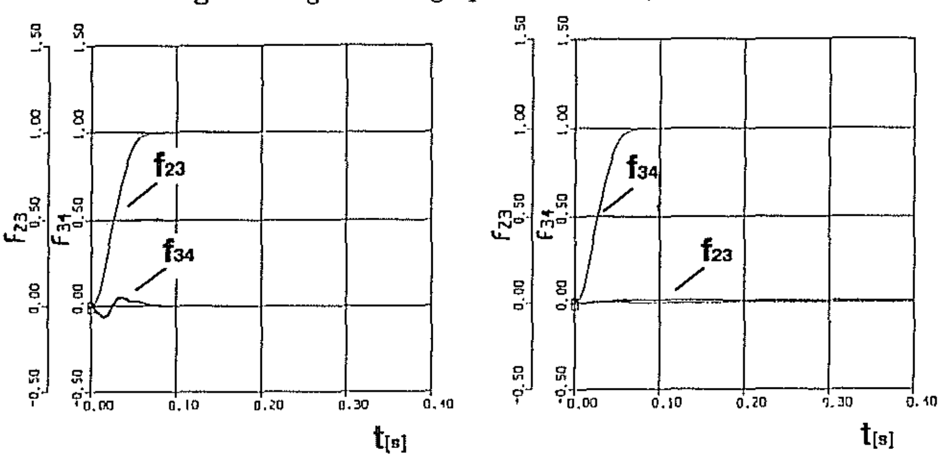


Fig. 13: Step responses of the forces due to the reference values

QUESTIONS AND ANSWERS

Q. John Shelton, OSU. What are you having to sense, are you sensing tension in all ranges of velocities?

A. We are measuring in each subsystem the current of the motor, the speed of the roller on the motor shaft, and the tension. The speed is measured with a digital sensing device. If it is difficult to measure the tension, you can use an observer which estimates the tension. It is also possible to design decentralized observers. We had no problems with this device and got the same results.