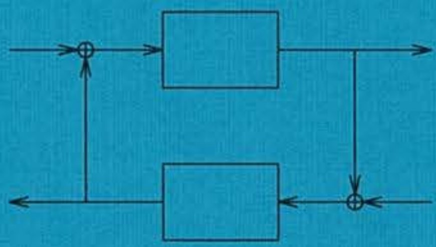
Book of Abstracts

9-th Benelux Meeting on Systems and Control

March 14 - 16, 1990
Veldhoven, The Netherlands



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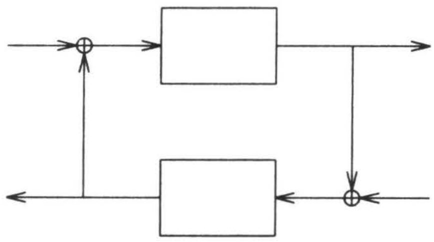

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INTRODUCTION

This book contains the abstracts of *9-th Benelux Meeting on Systems and Control* to be held March 14-16, 1990 in Veldhoven, The Netherlands. This book complements the Final Program.

Included are abstracts of:

- Plenary lectures
- Mini course
- Contributed short lectures

The abstracts are *ordered alphabetically* on the surname of the first author. The Dutch convention is used for the listing of certain surnames. For example, De Waard is listed under the letter w. The pages with abstracts are not numbered.

February 1990

DYNAMICS OF A SINGLE STAGE BIO-REACTOR TREATING AN INHIBITORY SUBSTRATE(PHENOL)

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The degradation of phenol by a mixed culture of micro-organisms was studied using a single stage continuous reactor as well as in a batch system. In the continous culture system, steady state measurements were performed and an investigation of the transient system responses to step-input changes were also conducted.

On the basis of the various experimental results the Monod-Haldane model was chosen as fairly representative of system kinetics. Results from these experiments were then fitted to the model using a non-linear parameter fitting procedure with the data sets taken individually and/or collectively.

The results from the experiments indicate that the state of the system is highly variable, and this translates into wide variations in the parameter values both with time and with reactor type. This variability is attributed to changes in some 'activity factor' associated with the biological system.

A dynamic analysis of the system indicates that the consequence of the variability for the effective control of such a system is probably very serious. Use of standard optimal techniques is complicated both by the complexity of the process and the poorly understood dynamics of the system. Due to the slow dynamics of the biomass as compared to that of the substrate an adaptive control mechanism will be the ideal choice . In our system we plan to use on-line respirometric measurements to determine the state of the system at any instant.

The paper will include details of the proposed experimental set up with the necessary instrumentation and results of related preliminary measurements.

Results from the batch and dynamic experiments which will be presented show that application of such a procedure could provide an effective method of controlling industrial biological wastewater treatment plants.

DEVELOPMENT OF AN EFFICIENT ALGORITHM FOR THE OPTIMAL CONTROL OF NONLINEAR SYSTEMS

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General optimization techniques become quickly inefficient to solve nonlinear multi-period constrained optimization problems : the required storage capacity and the computational complexity increase quadratically in terms of the number of periods which is usually very large. Many nonlinear packages like MINOS use sparse matrix techniques but are not specifically adapted to dynamic problems.

Through a judicious use of their structure, the algorithm that we propose results in a computational complexity that increases only linearly with the number of periods. This algorithm is a modified version of the Generalised Reduced Gradient which takes into account the peculiar structure of the studied problems as well in data storage as in the different steps of its execution.

In the encountered dynamic problems, the jacobian of the constraints appears to be a staircase form matrix. Since any basis matrix inherits this structure, it can be decomposed into a product of bloc bidiagonal triangular matrices through LU factorization. With such a structure, the needed data to perform algorithm computations consist in the original data and in the inverses of submatrices that are the diagonal blocs of L. The updating procedure of the basis inverse preserves the staircase structure and is thus reduced to the updating of the above defined submatrices by means of stable dyad corrections.

In the presentation, we will apply our algorithm to the optimal control of bacterial growth in a bioreactor through temperature adjustment. We also will discuss several issues about our GRG version.

Keywords : optimal control, nonlinear systems, nonlinear optimization

TRANSPUTER BASED CONTROL OF MECHATRONIC SYSTEMS

To be presented at the 11th World Congress of IFAC in Tallinn, USSR, August 13-17, 1990

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Abstract. The design of a control system is not finished with the derivation of the necessary control algorithms. The system designer has to schedule all control and calculation tasks within the sampling interval of the system. Higher sampling frequencies often improve the system performance. On the other hand, more sophisticated control algorithms require more computing time thus reducing the obtainable sampling frequencies. In this paper a systematic approach to obtain a design optimum is given. The design method is illustrated with the control of a flexible robot arm.

Keywords. *Parallel processing, Real time computer systems, Control engineering applications of computers, Robot control, Transputers, Occam.*

1 INTRODUCTION

Recently the systematic application of advanced control algorithms to mechanical systems has been given the name "mechatronics". This term originates from Japan, where in 1989 the first International Conference on Advanced Mechatronics was organized by JSME (1989). In a mechatronical design it is continuously considered whether the desired properties can be better realized by changing the mechanical construction or by adding electronic control, rather than adding the control system after finishing the design of the construction. This enables the design of systems with superior performance. Typical examples of mechatronic systems are, for instance, a compact disc player and an advanced photo camera with many electronic functions. Also robotics can be considered as part of mechatronics.
For the realization of a mechatronical system, advanced control algorithms and fast computer systems are needed. Because mechanical systems have very fast dynamics, a high sampling frequency is essential. Conventional, sequential, computer systems are too slow. By using parallel computing, the sampling frequency can be increased and more complex control algorithms can be realized. However, the use of parallel computing requires that the total concept of the realization of a real-time digital controller be reconsidered. This paper gives a systematical analysis of the problems which are met when a real-time parallel computer system is to be set up and gives solutions to various of these problems.
Although the ideas presented are more generally applicable, main emphasis will be given to the use of transputers. The transputer is a new type of processor which was designed to be used in parallel. Simultaneously with the development of the transputer a new parallel programming language has been developed: OCCAM. Together they have properties which make them especially attractive for the realization of a real-time parallel computer system. It may be expected that the transputer and other future parallel processors will have a great impact on the realization of advanced control algorithms with a very high sampling rate.
In Section 2 a description of the transputer and a short introduction to OCCAM will be given. Section 3 discusses the requirements for a scheduler in a real-time control system. It will be argued that at present there are no computers nor operating systems which are able to guarantee that the scheduling of the various tasks in a control system (sampling, computations, data logging etc.) are handled correctly. A suggestion for an optimal solution will be presented and it will be indicated how a sub-optimal solution can be realized.
One of the typical features of the transputer is that it has four external links which enable a fast data exchange to other transputers. This forms not only the basis for the parallel architecture of a transputer-based computer system, but it also enables a systematic design of a digital controller into various layers such as an interface layer, a protection layer a control layer etc.. This concept is worked out in Section 4. In Section 5 the concepts developed in this paper will be illustrated with an example of a typical mechatronical system, a flexible manipulator, where the inevitable vibrations are actively damped by a parallel control system realized with four transputers. A robust state-feedback controller, designed with a pole placement technique, is able to give the controlled system the appearance of a rigid construction. In order to exploit the parallel features of a transputer network, the controller has to be written in a parallel form. Various forms of parallelism are discussed in Sections 4, 5, and 6. They range from a general purpose form of parallelism, where the program is split up into basic elements which can be calculated in parallel, to a much coarser form of parallelism, where ad hoc some large parallel parts are selected. The performance of the transputer-based control system with various types of parallelism will be compared with a controller realized in conventional, sequential hardware. The paper concludes with some conclusions and suggestions for future research in this area.

2 THE TRANSPUTER AND OCCAM

One way out of the calculation versus sampling time dilemma has for long been sought in the use of parallel computing. In the past, many attempts to realize parallel systems with traditional processors, have failed due to the software overhead burden. The theory of Communicating Sequential Processes by Hoare (1978) forms the foundation of the programming language Occam. Occam uses the concept of processes. Communication between processes is done by means of channels. Due to the synchronization properties of these channels the restriction to one processor no longer exists. The transputer hardware development was the next logical step. By using the formal specification language Z, the correct behavior of the implementation of the Occam constructs in hardware was formally proven. The hardware - software integration resulted in the transputer - Occam combination. The transputer may be considered a building block for parallel computers. Occam enables programming across these parallel transputers.

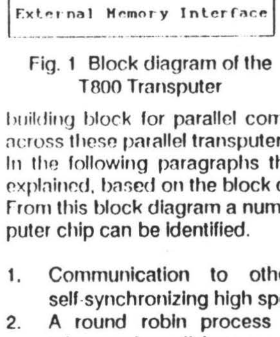


Fig. 1 Block diagram of the T800 Transputer

In the following paragraphs the operation of the transputer will be explained, based on the block diagram in fig. 1.
From this block diagram a number of significant elements of the transputer chip can be identified.

1. Communication to other transputers is performed over self-synchronizing high speed (20 Mbit/sec) serial *links*.
2. A round robin process (task) *scheduler* is implemented in micro-code realizing a process switching time of 1 μsec.
3. A built-in *floating point co-processor* realizing 1.5 MFLOPS.
4. A built-in *timer* with an accuracy of 1 μsec. in high-priority mode.
5. Fast (50 nano-seconds) *internal memory* of 4 Kbyte.

2.1 The OCCAM process

The underlying idea of Occam is the notion of a process. A process is a part of a program that starts, performs an action and then terminates. The idea is that processes may be executed in parallel. The communication between processes is done via self-synchronizing channels. A channel is a one way point-to-point connection from one process to

another. The processes may be located on different transputers. In that case the communication over channels changes into communication over links. There is no need for the programmer to worry about the implementation of the channel or link protocol, because it is implemented in micro-code on the transputer chip.
Examples of so-called primitive processes in Occam are:

x := 3	assigns the value of three to the variable x
chan1 ? p	takes a value from an input channel and puts it in p
chan2 ! q	takes the value of q and outputs it over the channel

An Occam program consists of combinations of primitive processes, so that a number of these primitive processes may be combined into a larger construction. For this purpose Occam supports the following constructs:

```
SEQ          To indicate the start of
    proc1    a series of sequential
    proc2    processes.

PAR          To indicate the start of
    proc1    a series of parallel
    proc2    processes.
```

Note that the indentation under the SEQ and PAR construct are syntactic and are used to indicate the begin and end of the construct.

2.2 Channels and Links

In Occam the communication by means of channels or links looks like:

```
PROCESS-A                    PROCESS-B
Chan.1 ! var.x  --Chan.1-->  Chan.1 ? var.a

TRANSPUTER-A                 TRANSPUTER-B
Link.2 ? var.y  <--Link.2--  Link.2 ! var.b
```

The input (?) and the output (!) processes may be considered as the synchronization between processes running on transputers A and B. If the process on transputer-A arrives at the input instruction on link.2 and transputer-B is not yet ready to provide this output, the process running on transputer-A will be de-scheduled until transputer-B signals that it is ready to send the data over link.2. At that point the inputting process on transputer-A is resumed and the data is transferred via link.2. This results in a synchronizing action between the processes running on different transputers. In this way the transputer channels provide the necessary system interconnection and synchronization. The only thing the programmer has to do, is to define the appropriate input and output actions. Internally the channel administration is kept in one memory word. This memory word will contain the most negative value to indicate that the channel has not been called yet, or a value that is interpreted as a workspace pointer of a (de-scheduled) process. The transputer channels may therefore be considered as a standard system interface because they provide the necessary system interconnection and synchronization.
The link concept is, identical to the channel concept, used to communicate between processes located on different transputers. This unifying link/channel concept is very convenient during the system design and check-out phase. Different hardware and software layers can be developed independently as long as the software and hardware interface have been defined.

2.3 Interrupts

The transputer has an interrupt signal pin connected to the event channel. This event channel is read identically to a link although no data can be transferred. It can only be used to activate a process that is waiting on an input (?) from the event channel. As soon as the event channel is activated, the waiting process is scheduled by inserting it at the back of the *ready queue* in the low priority mode, or it may be scheduled at once as a high priority process. The use of the transputer interrupt signal is illustrated in the following Occam interrupt process that is activated every time the event pin is triggered. The program starts with the definition of the process name with the external channel definition. The internal channel event is declared as the type ANY, because there is no data transport over the event channel. This event channel is associated with the actual hardware pin.

```
PROC Interrupt (CHAN OF INT16 output)
  CHAN OF ANY event:
  PLACE event AT event.in:
  WHILE TRUE                         Do for ever loop!
    SEQ                              Start sequential process
      event ? any                    Wait for interrupt
      ......execute handler code :
```

The transputer has one high-priority and one low-priority operating mode. The interrupt process should preferably be executed in the high priority mode in order to reduce the interrupt response time. Theoretical response times of approximately 55 μsec. have been reported by Welch (1987)

2.4 The Timer

The timer channel should also be considered an input channel. Times of the internal running clock are obtained by reading the timer channel and operating on the time value. The Occam code to use the timer is illustrated with the following SEQuential process that causes a delay.

```
PROC delay (VAL INT interval)
    TIMER clock:
    INT time:
    SEQ
      clock ? time
      clock ? AFTER time PLUS interval :
```

Internally the *timer queue* differs from the *ready queue* in that it is kept sorted in the sequence of the wake up times of the different timed processes.

2.5 The Scheduler

In addition to the channel protocol concept, there is another important difference between transputers and other microprocessors. That is the built-in scheduler. The transputer should be considered as handling tasks or processes rather than machine instructions. These processes are controlled by a built-in scheduler. The process administration is the main activity of the scheduler. The scheduler keeps track of the different processes by administering a list of processes in an area of memory that is called the workspace. The workspace of the current process is pointed to by the transputer register called workspace pointer. The workspaces are linked together to form a queue. The scheduler keeps track of four queues i.e. for each priority a ready queue and a timer queue. The beginning and end pointer to a queue are maintained in the transputer registers called Front pointer and Back pointer. Workspaces are added to the ready queue by reference to the back pointer and workspaces are extracted by reference to the front pointer.

2.5.1 High-priority mode

The process (or task) scheduler can operate in one of two modes i.e. the high-priority or the low-priority mode. In the high-priority mode the executing process can not be interrupted by another process (non-pre-emptive scheduling). De-scheduling can only occur when:

- a process is completed
- communication with a channel / link is not (yet) possible
- the process waits for a timer to elapse

2.5.2 Low-priority mode

In the low-priority mode the processes are, by means of time slicing, scheduled in a round-robin manner. Here processes will be de-scheduled by:

- completion of the process
- awaiting link or channel communication
- expiration of a time slice

The de-scheduled process will be added to the back of the ready queue and the process from the front of the ready queue will be executed. The time slice in a transputer is typically 1 msec. and the process switching time is of the order of 1 μsec.
In Occam the priority may be assigned using a PRIority addition to the PAR construct.

```
No priority          With priority
PAR                  PRI PAR
  process.1            process.1
  process.2            process.2
```

The processes 1 and 2 are executed in parallel, either both at the same priority, or with the PRI PAR: process 1 will be executed in high priority and process 2 in low priority. The PAR process is only finished after both processes have been executed.

3 A SCHEDULER FOR REAL-TIME CONTROL

3.1 The Sampling Process

The sampling process of a control system may, according to Bakkers (1987), be divided into:

1. Time-bounded processes, such as the sampling or actuation actions.
2. Time-limited processes such as the calculation of the control action.
3. Background and alarm processes.

The time-bounded processes have to be scheduled at specific instants. The time-limited processes should be scheduled to meet their deadline. Synchronization between these processes is required in order to guarantee that the calculation is performed before the actual control action takes place. If a control system can not inherently give this guarantee the resulting misses of the correct synchronization should:

1. result in a non detrimental control action.
2. result in error messages that are meaningful to the control engineer.
3. never cause a deadlock of the system.

3.2 Real-Time Scheduling

From the theory of real-time scheduling, Liu (1973) has defined the optimum schedule for the execution of control processes: it is the deadline driven schedule. A sub set of it is the monotonic rate schedule, which may be used in the case of fixed priorities. An example of the deadline driven scheduling rule is illustrated in fig. 2.

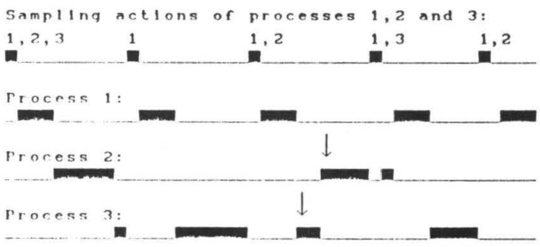


Fig. 2 Deadline driven scheduling

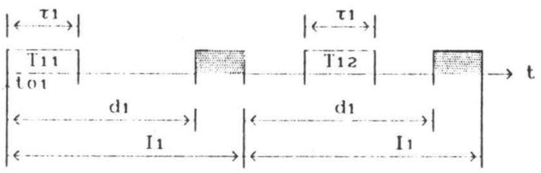
Note the position indicated where a fixed-priority monotonic rate algorithm would have resulted in a selection of process 2 instead of process 3. In general a schedule of a number of different processes, may be defined as:

$$Schedule = \{T_i\}, \{\tau_i\}, \{I_i\}, \{d_i\}, \{t_{0i}\} \qquad (1)$$

where:

T_i = one of n processes
τ_i = the time to execute process T_i
I_i = the period of process T_i
d_i = the time when proces d_i is due
t_{0i} = start of scheduling process i

This may be illustrated as follows:



The deadline-driven algorithm assigns the processor, at each decision-time, to the process whose deadline is closest. A necessary condition is caused by the fact that a processor at most may be kept busy all the time or:

$$\sum_{i=1}^{n} \frac{\tau_i}{I_i} \leq 1 \qquad (2)$$

Although this is a necessary condition, it has not been proven that this condition is also sufficient. Only for the sub case in which $d_i = I_i$ was proven that the necessary condition is also sufficient. If we also make the assumption that in a control system all sampling actions start at the same time, we have the additional requirement of:

$$t_{0i} = t_{0j} \qquad (3)$$

The optimum scheduling algorithm has not been implemented yet in industrial real-time operating systems (Stankovic, 1988). The main reasons is the computing effort necessary to keep the priority list of the processes sorted at all times. This rule however plays an important role in the manual scheduling of processes in the traditional control system design. It must be stressed however that this optimum rule is defined only for a single processor case.

With the transputer hardware it is possible to construct and program a parallel machine. The question arises how the control system design should be performed with such hardware. One should realize that the process scheduler on the transputer chip is a round robin scheduler which in low-priority mode performs a process switch about every msec. There is also a high-priority mode in which the time slicing is disabled so that the processes run till completion or are de-scheduled due to a wait for input or output. In order to realize deadline scheduling on a transputer a scheduler that accomodates priorities will have to be implemented.

In the ideal case, the realization of the priority ordering should be be performed by a hardware ordering mechanism on the microprocessor chip. A large number of priorities will have to be implemented. This will result in a fine granularity of the priorities. Because in a deadline driven priority system the priority axis is basically the time axis, this large number of priorities results in a fine resolution of the time axis, together with a reasonable cycle time for the total process cycle: of a few days. In order to restrict the length of the priority sort list to an hardware-technical implementable value, the processes that are part of a set of processes or tasks should get the same priority as their main process. This allows the use of one process queue per priority class.

The scheduling for a deadline driven scheduler should be a preemptive scheduler. This requires far more overhead than the present low-priority scheduler, that schedules only on certain instructions, like a jump. Thus ensuring that the data structure (stack) that has to be saved is minimal. If this way of thinking is adopted for the priority scheduler a so called semi-preemptive scheduler will result that performs well within the specification of the real-time requirements and also maintains a fast process switch time. The proposed priority system should accommodate:

Time bounded processes	at	Hi-Priority preemptive
Alarm processes	at	High priority
Time limited processes	at	Medium priority
User process	at	Low priority
Background processes	at	Round-robin scheduler

Future implementation of a deadline driven scheduler for the time bounded control tasks should be considered by the hardware manufacturers.

The assignment of the priorities is the task of the control engineer. He will have to analyze the time requirements of the system processes beforehand. If this extra work is not performed, the scheduler should fall back on the lowest, or round-robin, scheduler without loss of performance.

A sub optimal solution is the following. Allow enough time for all the time limited tasks to be completed on time. Add a safety margin. Because the completion of the tasks can never be *guaranteed*, timer guards should be installed to detect processes exceeding the time limit. A transputer timer process is well suited for this purpose.

4 SYSTEM ARCHITECTURE

The use of transputers in a control system design, necessitates the design of a transputer network that reflects the parallelism of the particular control system. There is no standard procedure to convert a sequential problem into a transputer topology with a corresponding parallel program. Therefore, the system architecture should be tailored to the (control) problem. There are basically three methods to obtain a parallel architecture i.e.

1. Parallelism by recognizing various *layers*. This is further worked out below.

2. *Ad-hoc* based on the properties of the problem. In this situation it is necessary to recognize dedicated parallelism of the control system. An example of this technique is used with the controller for the flexible robot arm that is described in Section 5.

3. By means of a mechanism that creates *massive parallelism* from repetetive use of basic building blocks. For distribution of these blocks over a number of processors a method developed by Hilhorst (1987), should be used to obtain an optimal distribution of the tasks over a given network. This is described in more detail in Section 6.

As a result of experience gained in the realization of several transputer-based control systems by Bakkers (1986) and Stavenuiter (1989), a layered architecture is proposed. The basic idea is that there are several layers in a practical control system as indicated in fig. 3 for a robot control system. A more detailed description of the different layers is given below.

4.1 First Layer

The first layer consists of the hardware and software directly connected to the sensors of the control system. It can be realized as the first transputer layer. This interface layer includes, for example: Analog-to-Digital, Digital-to-Analog and Resolver-to-Digital converters. The software of this layer performs primarily the sampling and control action. This layer is also the right place to perform the necessary filtering of the measured data. The processed measurements are available at the link interface input and outputs. Schematically the first layer and its interconnections to the second layer and the monitor and display may be represented as in fig 4.

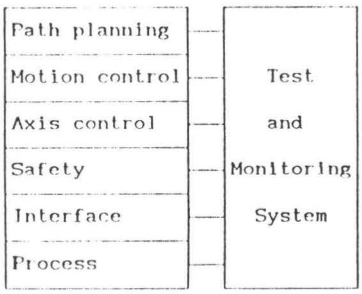


Fig. 3 Layer structure for a robot system

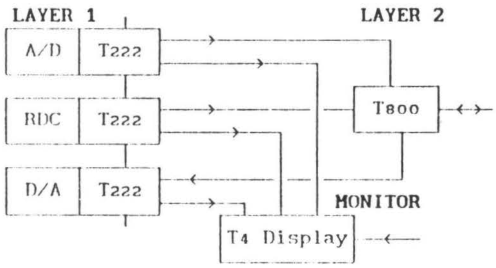


Fig. 4 Layer 1 interconnections

4.2 Second layer

The second layer consists of transputers that execute the safety software. This layer completely isolates the sensors from the rest of the control system. Actual sensor data arrive here and may be compared with the control signals to check whether the combination of the two may lead to a dangerous situation. If so, the safety software has priority and will set the control signals at a safe value. The topology of this layer could include one or more transputers, as illustrated in fig. 5. where T800 transputers are used.

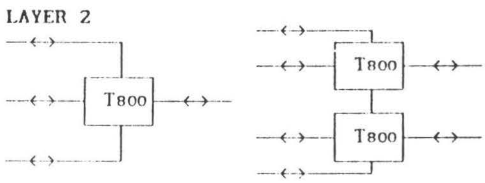


Fig. 5 Layer 2 the safety layer

4.3 Third layer

The third layer typically contains the first calculation layer, in robot terms this could be the calculation of the robot dynamics. It is not very likely that this calculation can be performed in one transputer. Therefore, as an example, a transputer network of eight transputers is given in fig. 6. For the distribution of the code over this topology the method of Hilhorst (1987) may be used. This method, based on the list scheduling analysis, also takes communication times via the links into account. By using a critical path analysis, an (almost) optimum distribution of the various processes over the different transputers can be obtained.

4.4 Test layer

This layer collects the properly buffered test data and sends it to a graphical display. It acts as a software test rig. The test data may also include warnings for synchronization errors and sensor data. The synchronization error messages enable the control system designer not only to spot errors in the system design, but also associates these errors with the exact location of the erred sampling or control process. Schematically this layer may be represented as in fig. 7.

One has to realize that parallel programs can not be tested for correct operation by the insertion of a number of write statements in the program code. The channel concept is very powerful. On the other hand it contains a possible danger. If the test data are not properly de-coupled by a-synchronous buffers, the monitor and test unit may set the pace, or worse, it may cause a deadlock of the control system.

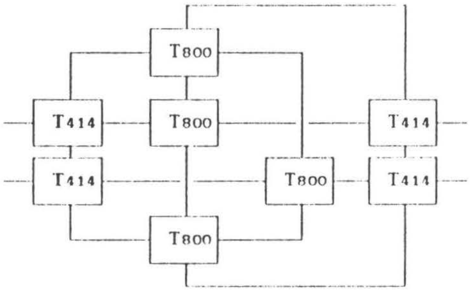


Fig. 6 Robot dynamics layer

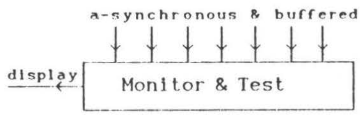


Fig. 7
The software test rig

5 CONTROL OF A FLEXIBLE ROBOT LINK

The ad-hoc parallelism will be illustrated with the example of a flexible robot link as described by Stavenuiter (1989) and Kruise (1988). It is constructed as a long aluminum strip (190 x 6 x 0.4 cm) driven by a DC motor. When controlled as a rigid system, the flexible robot link will heavily vibrate. Therefore, the vibrations and bending have to be taken into account in the controller design. The bending of an accelerating link has been described by Fukuda (1983) as:

$$W(r,t) = \sum_{n=1}^{\infty} Y_n(r)\, M_n(t) \qquad (4)$$

where:

$Y_n(r)$, called the 'mode shape' function, describes the shape of the arm at its n^{th} resonance frequency.

$M_n(t)$, the modal function, is a time dependent function which may be described by:

$$\omega_i^2 M_i + 2z_i \omega_i \dot{M}_i + \ddot{M}_i = -A_i \Phi \qquad (5)$$

where:

ω_i = the i^{th} resonance frequency
Φ = is the acceleration of the arm
z_i and A_i are arm dependent parameters

The combination $Y_i(r)M_i(t)$ is called a mode. Clearly the mode shape function cannot be controlled. However, the flexible arm can be made to rotate like a rigid one by controlling the acceleration in such a way that the modal function decays rapidly. In practice, it is not possible to control an infinite number of modes, but the model of the arm can be simplified by assuming that the motor bandwidth is less than ω_{mo}, which implies that excitation of frequencies higher than ω_{mo} may be disregarded. Furthermore, higher modes tend to have smaller amplitudes and therefore, they may be disregarded as well.

Simulations by Kruise (1988) indicate that control of the first three modes yields a satisfactory response. Furthermore, as these modes are independent, the control signal for the entire system can be computed by adding the control signals for the three modes. Taking the Laplace transform of (5) yields:

$$s^2 M_i + 2z_i\omega_i s M_i + \omega^2 M_i = -A_i s^2 \Phi \qquad (6)$$

which omitting subscripts, can be written as

$$M + \frac{2z\omega M}{s} + \frac{\omega^2 M}{s^2} = -A\Phi \qquad (7)$$

This equation can be translated into the block diagram of fig. 8. The modal function M is controlled by using state feedback, where the states are defined to be Φ, $\int M$ and $\int\int M$, where $\int M$ stands for:

$$\int_0^t M\, d\tau$$

From these states only Φ can be measured, $\int M$ and $\int\int M$ have to be estimated. The estimation is updated by measuring the vibrations of the arm by means of the strain gauges. In the case that three modes are considered to contribute to the vibrations of the arm, three pairs of strain gauges are used. A similar controller and estimator is implemented for each mode. The controller and estimator for one mode is depicted in fig. 8.

In this case a quite natural parallelism is present that may be translated into a four transputer network configuration. The calculations of each mode will be assigned to one slave transputer. The master transputer collects the data and performs preliminary data analysis. This configuration may be represented as illustrated in fig. 9.
The use of transputers makes it necessary to use parallel programming techniques. The transputer environment may be programmed in Occam

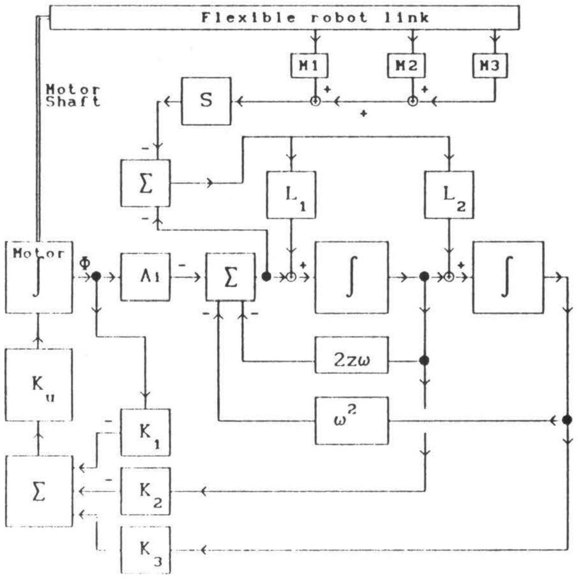


Fig. 8 One mode estimator and controller

(the preferred parallel transputer language) or in parallel C. Methods of parallel programming are given in Bakkers (1988, 1989). Code from different programming languages may be cast into an Occam harness to exploit the parallelism between processes.

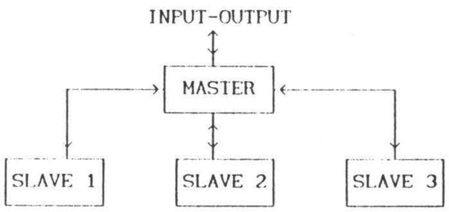


Fig. 9 Transputer network configuration

5.1 Natural system parallelism.

In the case of the flexible robot parallelism is naturally obtained by distrubuting the tasks of calculating the esitmator and the controller of the three vibration modes over three transputer. This way the natural parallelism of the different modes is reflected in the architecture of the transputer system as illustrated in fig. 9. Because this is not a rule that can be applied to any system, this technique should be considered an ad-hoc technique. The advantage is that the processing speed remains the same whether one or ten modes are calculated, of course requiring one or ten transputers. The combination of this ad-hoc system allocation together with the basic building block method, to be discussed in the next section, has been applied to the flexible robot arm.

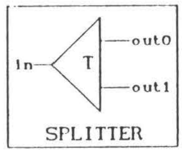
6 THE BASIC BUILDING BLOCK METHOD

A systematic way to introduce parallelism, is to start with very small processes and build a system with these elementary processes. This approach is similar to methods used im simulation programs. The internal scheduler on the transputer will realize parallelism while running these processes. If this philosophy is applied to the controller design of the flexible arm we can realize the controller of fig. 9 with the aid of only five basic elements i.e.

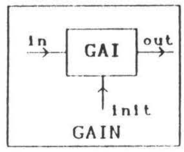
an integrator block:	int
a summer block:	sum
a minus block:	min
a gain block:	gai
a splitter block	tee

Lets first define these basic elements and then write the controller program using these basic elements.

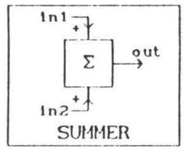
```
PROC tee (CHAN OF REAL32 in, out0, out1)
  REAL32 x :
  WHILE TRUE
    SEQ
      in ? x
      PAR
        out0 ! x
        out1 ! x :
```



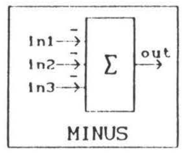

```
PROC gal (CHAN OF REAL32 in, out, init)
  REAL32 x,k :
  SEQ
    init ? k
    WHILE TRUE
      PRI ALT
        init ? k
          SKIP
        in ? x
          out ! k * x :
```



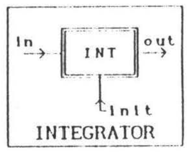

```
PROC sum (CHAN OF REAL32 in1, in2, out )
  REAL32 x1, x2 :
  WHILE TRUE
  SEQ
    PAR
      in1 ? x1
      in2 ? x2
    out !    x1 + x2 :
```




```
PROC min (CHAN OF REAL32 in1, in2, in3, out)
  REAL32 x1, x2, x3 :
  WHILE TRUE
    SEQ
      PAR
        in1 ? x1
        in2 ? x2
        in3 ? x3
      out ! -((x1 + x2) + x3 ) :
```




```
PROC int(CHAN OF REAL32 in, out, init)
  REAL32 x,t :        -- STATE
    SEQ
    init ? x;t  -- INITIALIZE STATE AND TIME
    WHILE TRUE
      PRI ALT
        init ? x;t :
          SKIP
        TRUE & SKIP
          REAL32 dx :
          SEQ
            PAR
              in ? dx      -- Input in parallel
              out ! x      -- with output
            x := x + (dx * t) :
```



The one mode estimator and controller for the flexible robot arm as illustrated in fig. 8 may be converted to consist of the basic building blocks mentioned above. The resulting block diagram is illustrated in fig. 10. The sign of some of the GAIN blocks has been changed to standardize on one SUMMER block. Note that the insertion of the SPLITTER blocks is necessary because the Occam channels are point-to-point connections. Installation of a SPLITTER block looks like a solder joint.

After the definition of the basic building blocks, the complete calculation process for one mode looks like the following Occam process. The external channels I[13] and the internal channels D[27] are not mentioned in the block diagram to avoid cluttering.

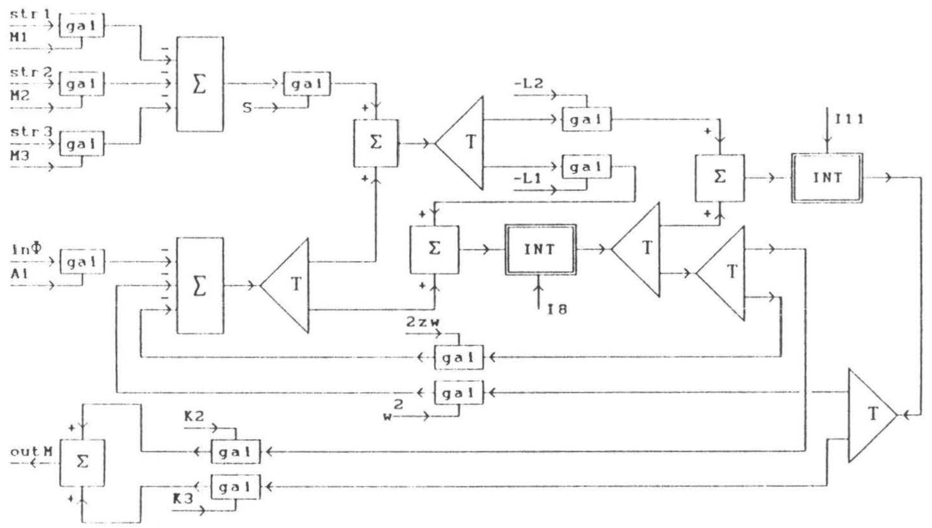


Fig. 10 Basic building-block diagram for one mode

```
PROC calc ([4]CHAN OF REAL32 in, CHAN OF REAL32 outM,
[13]CHAN OF REAL32 I)
  [27]CHAN OF REAL32 D :
  PAR
    gai ( in[0], D[0], I[0] )
    gai ( in[1], D[1], I[1] )
    gai ( in[2], D[2], I[2] )
    gai ( in[3], D[3], I[3] )
    min ( D[0], D[1], D[2], D[8] )
    min ( D[3], D[4], D[5], D[9] )
    sum ( D[6], D[7], outM )
    gai ( D[8], D[12], I[6] )
    gai ( D[10], D[6], I[4] )
    gai ( D[11], D[7], I[5] )
    tee ( D[9], D[13], D[14] )
    sum ( D[12], D[13], D[15] )
    sum ( D[16], D[14], D[17] )
    gai ( D[18], D[5], I[10] )
    gai ( D[19], D[4], I[11] )
    tee ( D[15], D[20], D[21] )
    int ( D[17], D[23], I[9] )
    sum ( D[22], D[24], D[26] )
    gai ( D[20], D[22], I[7] )
    gai ( D[21], D[16], I[8] )
    tee ( D[23], D[24], D[25] )
    tee ( D[25], D[10], D[18] )
    int ( D[26], D[27], I[11] )
    tee ( D[27], D[19], D[11] ) :
```

With these instructions the scheduler of the transputer can go to work and schedule all these parallel processes for execution. The advantage of this method is the speed of the development of the control program. The above program is for the control of one mode, therefore this program is assigned to one dedicated transputer for every mode that needs to be controlled. There are, however, some remarks to be made about this design method. Because a large number of building blocks are interconnected, there is a danger of deadlock. It is a property of so-called I/O-parallel blocks, that if combined into networks, they will exhibit deadlock free properties. An I/O parallel block executes the input and output in parallel and not sequentially. The careful use of a few I/O parallel blocks in a network will result in a deadlock free behavior of the network. For that reason the integrators in fig. 10 are I/O parallel as indicated in the corresponding Occam program, resulting in a deadlock free controller.

7 RESULTS CONCLUSIONS AND SUGGESTIONS

The controller for the flexible robot arm has been implemented on a number of different processors. The results varied as follows:

Z80 + co-processor:	16 Hz
10 MHz AT + co-processor	116 Hz
4 T414 transputers	1000 Hz
4 T800 transputers	4500 Hz

For the architecture of the system was as illustrated in fig. 9. The actual controller was implemented using the basic building blocks technique. The overall conclusion of the experience gained over a number of projects is that the application of transputers allows the design of high performance control systems. For complex systems the layered structure is the best approach to realize the parallel architecture. However, ad-hoc parallelism, as used in the control of the flexible robot arm, will give the best performance, because it minimizes the inter-transputer communication.

The basic building block technique together with the recognition of dedicated parallelism quickly results in an error-free design. For the design of more "general purpose" software for higher levels of the controller, the automatic task allocation program still has to be refined further.

The optimum scheduler for real-time systems is the deadline driven scheduler, it is recommended that this scheduler be implemented in future processors. A sub-optimal solution has been presented, where the timer process of the transputer is used to guard the timing sequence. The transputer with its built-in scheduler may at present be considered the best state-of-the-art implementation of a parallel building block for the realization of control systems.

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A PETRI-NET REPRESENTATION OF A MANNED BOTTLING LINE
(Abstract)

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A bottling line consists of approximately ten sequences of mostly mechanical operations performed by machines. The machine capacity is about 60.000 bottles per hour. The machines are linked up by conveyor belts. A machine operator monitors and operates one or more of the machines and the intermediate conveyor belts. The bottling line is manned with five to ten operators. There is no definite working cycle, the operator acts when he judges it to be necessary. For instance when a breakdown occurs the operator corrects it; hence the operator's work is event driven. When a complex breakdown occurs, the machine operator has to call in a maintenance man, who corrects the failure or carries out the repairs.

The object of the study is to optimize the performance and efficiency of the total system (humans and machines), without over- or underloading the human operator. A methodology for modeling and evaluating different task allocating strategies will be tested.
The human operator activities can be viewed as asynchronous, concurrent processing activities. For the representation of human operator tasks the theory of Discrete-Event Dynamic Systems is used. Petri-Nets are used to model the interactions between human operators as well as humans and machines.
The latter makes it necessary to model the bottling line in a Petri-Net fashion. The nature of the process asks for a description with continuous Petri-Nets. Hence the result is a Hybrid Petri-Net containing discrete and continuous transitions and places.

The aim of the paper is to discuss the use of Petri-Nets and to present some results. Starting from an existing bottling line, the human operator and the bottling line itself are modeled. An analysis is made to evaluate the method and to validate the results.

Modelling and Model Reference Adaptive Control for Fed-Batch Bakers' Yeast Fermentation

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For many years Unilever's research laboratories are active in applied research in the field of biotechnology. A project on the modelling and control of fed-batch fermentation is part of the Unilever development programme in this field.

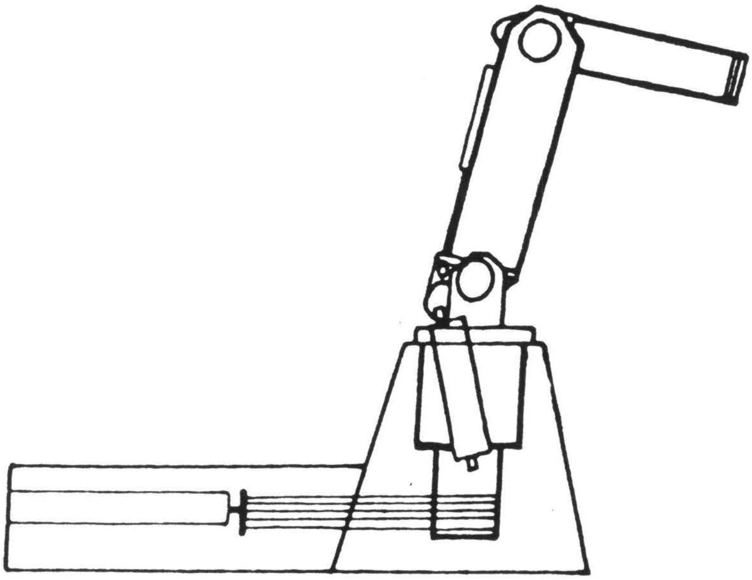
Fermentation may consist of two phases: growth of the micro-organism on a special fermentation medium followed by a production phase of metabolites eg. enzymes, penicillines, flavorings. The process of interest is bakers' yeast fermentation, regarded as strictly growth associated in an aerobic cultivation medium. The fermentation processes may be classified according to the mode chosen for process operation, eg. batch, fed-batch or continuous. Fed-batch processes are well suited for controlling the growth phase and rate of bakers' yeast. On industrial scale problems often are encountered with insufficient liquid mixing, oxygen transfer and determination of the optimal feed rate. Generally speaking the main objectives for process improvement are the productivity and quality of the yeast. The productivity can be improved through better feeding and oxygen transfer. The quality of the yeast can be improved in various empirical ways. Classical control methods often give unsatisfactory results in achieving these goals. Therefore modern control theories are being investigated for process improvement.

Model reference adaptive control was selected as a new approach in controlling the fed-batch bakers' yeast production. Two problems which appear in control of the biotechnical process are: the most important process state variables are not measurable and the process parameters are strongly time dependent. The knowledge of these state variables and time varying process parameters is essential for state feedback control. An adaptive nonlinear filter or observer based on Kalman filtering techniques was chosen for on-line state reconstruction. The dynamics of the biotechnical process are very complex and until now not completely known. Therefore the filter is based on a relatively simple mathematical reference model. State feedback control is finally achieved using a one step ahead tracking controller. Optimal growth is established by controlling the glucose concentration just above its critical value and the oxygen content of the broth at a constant level.

The model which describes the dynamic behaviour of the bakers' yeast is based on a recently developed hypothesis for the growth in a batch culture. This model is applied for simulation of the fed-batch process. The Kalman filter uses a discrete-time reference model which was derived by reduction of the complex growth model of the yeast.

The model reference adaptive control approach is an attractive way of process control because it leads to a better understanding of the physiology of the yeast cells. This knowledge can be used to improve the modelling of bakers' yeast and the production process through a better supervised controller effort. A negative side effect is that this approach requires intensive tuning and is quite computationally complex. On the other hand process control becomes very flexible and results of controlling the growth process are far better in comparison to classical PID control.

Robust–performance control of an RRR–robot



To optimize the tipposition control of a robot manipulator a robust–performance control problem is formulated. This problem is approached by applying nonlinear feedforward and linear feedback. The design of the feedforward controller is based on the inverse of a nominal model. The robust linear feedback is designed with the new and promising H_∞ control theory. The experimental setup consists of a medium sized hydraulic driven RRR–robot and a digital computer. Measurements of this system are shown and evaluated.

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H_∞ Controller Design with Robustness Margins

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ABSTRACT

The problem of robust stability of closed loop plants has received a considerable amount of attention in recent years. In particular the H_∞ approach to optimal control design has provided several promising results in the area of robust stabilization of plants with unstructured uncertainties.

Within the framework of Algebraïc system theory, see for example Desoer et al. (1980), McFarlane and Glover (1988) presented a H_∞ controller design procedure. Using this procedure the maximal achievable H_∞–error bound can be calculated explicitly and a margin on the allowable plant perturbation can be given such that the H_∞–controller robustly stabilizes the perturbed plant. McFarlane and Glover (1988) adopted the stable factor approach to represent the plant perturbations.

Here we show that by combining a normalized right coprime factorization of the plant in the H_∞ controller design procedure and a Graph metric uncertainty (studied by Vidyasagar and Kimura (1986)) description of the plant, a less conservative bound on the allowable plant perturbation can be given. Also an interpretation of this uncertainty model will be given in terms of the physical plant.

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Statistics of MA estimation with Durbin's method

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Many algorithms have been reported that give approximate maximum likelihood estimates for the parameters in a Moving Average model. These schemes are always based on the asymptotic properties of MA processes. Many papers, however, report disappointing results for applications where those methods are used in finite sets of data.

Durbin's method is an approximate maximum likelihood method. It starts with the replacement of a MA(q) model by an estimated AR(L) model, with $L > q$. The MA(q) parameters are found from the AR(L) parameters with the Levinson recursion. In the theoretical derivation, the accuracy of the MA(q) model will improve by taking a higher order L for the intermediate AR representation. For large data sets, the difference between the AR(L) and the MA(q) representation can be made arbitraryly small for increasing L, because of the theoretical equivalence of MA(q) models with AR(∞).

But this asymptotic relation is no longer valid for intermediate AR(L) models that are estimated from finite or small data records, where the relation between the accuracy of the MA(q) model and the AR order L is more complicated. For L too small, the resulting MA estimates become biased. On the other hand, the last estimated AR(L) parameters will become small in comparison with their standard deviation if L is too high. Hence, they contribute more to the uncertainty of the model than to the accuracy. Simulations show that both the variance of the MA parameters and the prediction error of the MA model increase if L is taken too high. The prediction error is defined as the squared error of prediction if the MA estimates obtained from one data set are used for prediction in another data set that comes from the same process.

Consequently, the accuracy of the final MA(q) model depends on the choice of the order L of the intermediate AR(L) model. The best choice for L depends on the number of observations and on the process characteristics. Mostly, selection of the AR order with one of the many order selection criteria turns out to be an acceptable practical solution. This means that two different orders have to be selected in MA estimation, both the intermediate AR order and the final MA order. The MA order can be selected with the residual variance obtained by substituting the estimated MA parameters in the data. The usual AR selection criteria may be used.

Structured unmodelled dynamics in MRAC

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Unmodelled process dynamics usually have a bad influence on the performance of model reference adaptive control systems. This is caused by the influence unmodelled dynamics have on the error equation: on one hand the Strictly-Positive Realness (SPRness) of this equation is violated, and on the other hand an output error on this equation occurs.
In this lecture, a method is described which can deal with unmodelled process dynamics under the condition that some structural knowledge exists about these dynamics. The method to be described is called "model decomposition" and consists of an additional structure within an existing MRAC scheme. Model decomposition tries to incorporate the unmodelled dynamics in the model output, thus making the error signal less sensitive for the unmodelled dynamics. Theoretical results show that model decomposition both makes the error transfer more close to SPRness and decreases the output error. The main advantage of the arising scheme is the possibility to use a lower-order controller than originally necessary, because the reference model output is continuously adjusted to the actual capabilities of the process.
Several simulation examples illustrate the operation of the decomposition method and real-time experiments with a gantry crane scale model show the practical useability of the method.

Stabilization of nonlinear systems by means of dynamic output feedback

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Abstract

Local asymptotic stabilization of nonlinear systems by dynamic output feedback is considered. A design based on smooth observer is proposed, dedicated toward smoothly stabilizable and smoothly detectable multi input multi output nonlinear systems (possibly with undetectable linearization) ; for this design, the problem of smooth detectability reduces to a problem of smooth stabilizability. When applied to linear systems, the design yields the Luenberger observer. As an illustration, the method is successfully performed on an example. A further step should be to achieve sufficient conditions on the nonlinear system that it be stabilizable by the dynamic output feedback.

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FLEXIBLE MANAGEMENT IN REGIONAL LAND-USE PLANNING PROBLEMS

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Land-use planning problems may be regarded as optimal control problems for a special class of socio-economic dynamical systems.
For such problems, the time horizon may vary from 5 years to 20 years or more.
Furthermore, the decisions or control actions that are taken now may affect the performance of the whole system during many years.
Since future values of some of the parameters of the system's model -- like productivities and prices -- are usually not known at the planification time, one is confronted with an optimal control problem in face of uncertainty.
Usually, the use of stochastic optimal control techniques is not possible with socio-economic systems because no reasonable information can be obtained about the statistics of the future values of the parameters.
In order to find a rational solution to this problem, the concept of flexible control or management was introduced.
Roughly speaking, a flexible control strategy is the one where the actual control actions preserve a broad enough choice set for future control actions in the eventuality of random changes in the future values of some parameters of the system's model.
More formally, we define a flexible control or management problem in the following optimisation framework:

$$\begin{cases} \max\limits_{x_1} \; c_1 x_1 \\ \max\limits_{x_1} \; \dim\{p\} \end{cases}$$

such that

$$A_1 x_1 + A_2 x_2 \geq M, \quad x_1, x_2 \geq 0$$
$$c_2 x_2 \geq z_2$$

Tracking Strategies for Asymptotically Admissible Target Paths in Economic Models

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ABSTRACT
In this paper we discuss the pros and cons of several optimal control policies that can be used to track desired target paths which are asymptotically admissible. To that end we first properly define what we mean by an asymptotically admissible target path and give a characterization of these paths in case the considered system is described by a linear, finite dimensional, time-varying difference equation that is disturbed by white noise. We illustrate some characteristics of different control policies by means of a simulation study.

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An Approach of State-Space Realization in δ-Operator

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ABSTRACT

It is well known that with a given linear system, one can find an infinite number of state-space realizations in the shift operator z (A,B,C) which parametrize the same system. All these realizations compose what we call the realization set S_Z. When implemented digitally, the realization will yield some deterioration of performance because of the finite wordlength (FWL) effects which can be classified into two forms: one is the finite wordlength implementation of the coefficients of the realization (A,B,C) . the other is the roundoff after every arithmetical operation. The first effect can be measured by a global sensitivity measure of the system transfer function w.r.t all the parameters in (A,B,C); the second by the roundoff noise gain. The very interesting problem which has attracted a lot of attention is to find out the optimal realization in the set S_Z, which minimizes the sensitivity measure (1), or the roundoff noise gain with a dynamic range constraint on the state (1)-(3). The same philosophy has been used in the implementation of a pole placement state-estimate feedback controller (4).

In this paper, we first discuss the generalization of polynomial parametrization, then we introduce the so-called δ-operator which is , in fact, a special case of polynomial parametrization. In the same way as S_Z, the realization set S_δ in δ-operator is formed, then the relationship between the two sets is set up. We then study the sensitivity behavior of the two sets. Here we seperate the sensitivity problem into two aspects: the absolute and relative sensitivity studies, which correspond to fixed and floating point implementations respectively. In the absolute sensitivity study, the optimal realization in S_δ is found, and the relationship between the two optimal realizations in S_δ and S_Z respectively are derived. This allows us to obtain the optimal realization set belonging to one realization set from the one belonging to the other realization set, instead of using the minimizing procedure once again. The theoretical results show that provided the coefficients are in the same coefficient range, the optimal realization in S_δ is better than the one in S_Z. An example is given and the results are confirmed by simulation. The relative sensitivity behavior is briefly discussed, a reasonable upper bound of relative sensitivity measure is given. It is shown that under Goodwin's assumption (5), for any realization in S_Z one can always find a realization in S_δ which has a lower value of the upper bound .

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where x_1 : the actual control action vector,

x_2 : the future control action vector,

c_1x_1 : the actual performance of the system,

c_2x_2 : the future performance of the system,

p : the space of the random parameters c_2 and A_2,

dim : the volume of p such that the constraints are satisfied,

z_2 : a minimum,satisfying level for the future performance,

M : a right-hand side value vector for the constraints.

We note that dim{p} is a measure of the flexibility of the control action x_1. Hence, the solution that we propose for this problem relies on the use of a multiple objective interactive optimisation scheme. The interactivity is necessary in order that the decision maker (the planner) can find a best trade-off between the maximisation of c_1x_1 and of dim{p} .

The practical implementation of the proposed solution as well as an example of application will be presented and discussed at the conference.

Key-words: socio-economic systems, multiple objective optimisation, optimal control.

ABSTRACT

Robust stabilization in the gap–topology

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The problem of robust stabilization can be studied in several topologies. One of the most appropriate ones is the gap–topology. In this topology sufficient conditions for robust BIBO stabilization are known in literature ([3]).

With help of these conditions it is possible to derive a method for the solution of the problem of optimally robust control in the gap–topology ([1],[2]). Given a plant P, we can find the radius of the largest ball around P that can be stabilized by one compensator, and a compensator that realizes this bound. In this talk we present several algorithms to compute this largest stability radius for systems in state–space form and a state–space realization of an optimally robust controller. All these methods have their own advantages and drawbacks. So finally the performances of the different algorithms will be compared.

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A Geometric Approach to the Structural Synthesis of Multilayer Perceptron Neural Networks

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(Summary)

Designing a multilayer perceptron for general purpose classification has important practical implications. Since the capacity of multilayer perceptron to realize arbitrary dichotomies (or two-class classifications) is limited, the basic steps in a design procedure consist of the determination of the network structure and the determination of weight and threshold values. Unfortunately, there has been no general principle or guideline available for such a synthesis task, normal design often proceeds on an *ad hoc* and empirical basis, the methods generally lead to structures exhibiting irregularities [1] [2].

Here we present a systematic geometrical design procedure to accomplish an arbitrary dichotomy for 2^m different binary inputs. The ideas underlying our approach are based on the geometry of the n-dimensional hypercube. Our design procedure is composed of two basic steps. First, the 2^m inputs which can be alternatively considered as all the vertices of an m-dimensional hypercube are transferred into the vertices of a new n-dimensional hypercube with a special structure–the so-called n-parity configuration. This transformation can be implemented with one hidden layer of neurons, which map the vertices of the input m-hypercube into the vertices of another n-hypercube (generally, $n \geq m$). More specifically, every vertex of the m-hypercube can be mapped into either even or odd vertex of the n-hypercube leading to an n dimensional parity structure. Then the next step is to solve the n-parity problem with a specially structured one-hidden-layer net with $n + 1$ neurons.

The advantage of our procedure is that each of the design steps is guided by clear geometrical considerations, thus no ambiguity is involved as to the determination of the number of layers and neurons. This is in sharp contrast with the learning based design procedures for which the structure determination is largely a trial-and-error process. For those applications where learning is absolutely necessary, our procedure can serve as the first step to set up the net configuration which can at least sufficiently guarantee the realizability for arbitrary functions.

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Time-optimality in the control of human movements

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Abstract

Our research is aiming at a better understanding of the way the nervous system controls goal directed movements. It is generally believed that in the control of movements both open-loop and closed-loop control actions take part. Together they result in an activation of muscles which generally has a triphasic shape for fast movements. The first phase consists of activation of muscles acting in the movement direction, causing acceleration of the limb. In the second phase counteracting muscles are activated, causing a deceleration of the limb. In the third activation phase accelerating muscles are activated again. This third phase is said to have a stabilizing effect on movements. However a more plausible explanation for the role of the third phase is given by Hannaford and Stark (1985, 1987); they argue that a third phase reduces movement time. However their analysis does not result in an accurate prediction of the size of the third phase under various conditions.

At the presentation a comparison will be made between the control of goal directed movements and the time-optimal control for bounded inputs. Both experimental and simulated results will be treated.

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Application of Identification Methods to a 600 MW Power Plant*

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The fluctuating demand for electrical power requires adequately designed control systems which satisfy a number of specifications regarding production, safety and environmental regulations. This applies especially to coal fired boilers, where these specifications are hard to meet due to the nature of the fuel. For an improved design of the boiler as well as the control system, insight to the dynamical behaviour is necessary. Therefore, a nonlinear simulation model, based on physical relationships and conservation laws, has been designed by Stork Boilers B.V. For verification of this model identification has been applied to a 600 MW coal fired power plant of the Benson type (EPON unit 13, Nijmegen).

We consider our experiment representative in the sense that the following aspects are inherently present in applications of system identification to industrial processes:

- A nonlinear and nonstationary situation,
- The multivariable character of the process,
- Limiting safety constraints,
- Performing experiments under closed loop conditions.

In this presentation we will concentrate on the practical aspects of system identification, especially w.r.t. the closed loop problem. This entails the following problems:

Experiment design: Data acquisition equipment, choice of operating point, control strategy, adjustment of set point disturbances which are independent and which have a specific bandwidth.

Data preprocessing and signal analysis: Postfiltering, postsampling, trend removal, nonparamatric as well as parametric methods.

Identification of parametric models: Closed loop identifiability using direct methods, least squares and recursive prediction error methods, partitioning into subsystems and choice of time step, in- and output signals for different subsystems, model validation.

*This research was sponsored by NOVEM and conducted under the supervision of Stork Boilers B.V., Hengelo.

ADAPTIVE CONTROL OF MODE-SWITCH PROCESSES

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ABSTRACT

Adaptive control of an inherently non-linear process is considered. This process is linearized around a certain "mode" of operation. Such processes are encountered frequently in the chemical process industry. For instance, the control of a chemical reactor at various operation points shows this behavior. In addition, slowly changing disturbances cause varying dynamics (for instance, the catalyst activity and fouling of a heat exchanger). To compensate for the varying dynamics in this type of plants, one needs to readjust the controller, preferably by some automatic adaptation.

As the dynamics are not changing continuously, different controllers are considered for different operating points. The selection of a controller in a particular mode of operation is governed by a storage and retrieval unit. This unit contains a number of models which are identified during the operation in the different modes and the related controllers. At the moment that a switch from mode to another occurs, one of the models in the database unit has to chosen, or a new identification has to be started. In this presentation a method will be presented for making the choice of either selecting a model out of the database unit, or starting a new identification cycle. The selection method is based on a credit and punishment assignment heuristic. The ideas will be illustrated for a SISO non-linear process. This example shows that the switching between the various models leads to improved control, while it limits the amount of disturbances of normal process operation due to test signals which otherwise would have to be applied for identification.

Nonlinear model matching: from linearity to nonlinearity

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A standard approach for dealing with synthesis problems in nonlinear control systems consists in linearizing the nonlinear system around a specific working point and, then, solving the synthesis problem for the obtained linear system. To what extent the resulting linear controller is a good approximate solution for the nonlinear problem, is, of course, questionable.

Here we will study this kind of problems concerning the so called **Model Matching Problem** (MMP) for nonlinear systems. This problem is formulated as follows: given a nonlinear control system, to be referred to as the plant P, together with another nonlinear system, to be called the model M, is it possible to design a suitable precompensator for the plant such that the input-output behavior of the precompensated plant matches that of the given model M.

In [1] it was shown that if the model can be decoupled by static state feedback, then under generic conditions on the plant the problem is solvable around an equilibrium point if and only if it is solvable for the linearization of plant and model around this equilibrium point. Although the assumption that the model is decouplable by static state feedback is certainly restrictive, it can be argued that in practical circumstances it is often desirable.

We will present this local solution and after that we will investigate the question whether we can use the feedback that solves the corresponding linear MMP in order to approximately solve the original nonlinear MMP. This investigation will be performed on two examples. First we will consider the double pendulum and secondly we will consider a two-link robot arm with one flexible joint.

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Dynamic disturbance decoupling for nonlinear systems

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Consider the following analytic nonlinear control system

$$(1) \quad \begin{cases} \dot{x} &= f(x) + g(x)u + p(x)q \\ y &= h(x) \end{cases}$$

with state $x \in I\!R^n$, inputs $u \in I\!R^m$, outputs $y \in I\!R^m$ and disturbances $q \in I\!R^q$. The dynamic disturbance decoupling problem (DDDP) is defined as follows: find, if possible, an analytic precompensator

$$(2) \quad \begin{cases} \dot{z} &= \phi(x,z) + \psi(x,z)v \\ u &= \alpha(x,z) + \beta(x,z)v \end{cases}$$

with state $z \in I\!R^\nu$ and new inputs $v \in I\!R^m$, such that the outputs y of (1,2) are not influenced by the disturbances q anymore.

It is well known that for linear systems the DDDP is solvable if and only if it is solvable by means of a static state feedback (i.e. by letting $\nu = 0$ in (2)). The conditions for solvability of the linear DDDP can be formulated algebraically -in terms of the so-called *structure at infinity*- and geometrically -in terms of *controlled invariant subspaces*-.

For nonlinear systems the solvability of the DDDP by means of a dynamic state feedback (2) is not equivalent to the solvability by means of a static state feedback. In the talk this will be demonstrated by means of an example. Moreover, we will present algebraic and geometric conditions for the solvability of the DDDP for nonlinear systems (1).

Uncertainty Analysis of Mathematical Models: an application to the soil-acidification model RESAM.

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When modelling ecological systems we are confronted with a large amount of uncertainty. This uncertainty is due to our limited knowledge of the governing mechanisms, the unavailability of sufficient and accurate measurements, and the large variability often encountered in natural processes.

Against this background an uncertainty analysis in which we study the origins and effects of the uncertainty in our models will be an indispensable tool.

We will outline the major steps in such an analysis, and present a method for performing an uncertainty study. This method is based on Monte Carlo analysis, using the Latin Hypercube Sampling technique (see (1)).

The presented procedure will be illustrated by showing results of an uncertainty analysis on the soil-acidification model RESAM (Winant Staring Centre; Wageningen) (see (2)).

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Modeling and Feedback Control of a Flexible Arm for Prescribed Frequency-Domain Tolerances

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ABSTRACT
Consider a flexible arm with a tip body, which is rotated by a motor about an axis through the fixed end of the arm. There are given (frequency-domain) specifications on the movement of the tip of the arm.

Our problem is to find a feedback loop for controling the motor torque in such a way that, the specifications should be met (whenever possible). This has to be achieved in spite of the uncertainty which may affect the parameters of the plant, or unknown disturbances. To solve the problem we first develop a (linear) mathematical model (cantilevered beam with some additional inputs). We then express our "task" as a standard control problem. Finally, the feedback loop (prefilter and compensator) is found by a rational function compensation procedure.

Bandwidth and Robustness Limitations Due to Right Half Plane Poles and Zeros

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Upper bounds on achievable bandwidth and robustness for the control of linear time invariant systems with right half plane (RHP) poles and/or zeros are derived. The closed-loop bandwidth limitation due to RHP zeros is linked to the solution of a minimax weighted sensitivity problem in which the weighting function is parameterized in terms of the desired closed-loop bandwidth. Robustness limitations with respect to a class of multiplicative and a class of additive uncertainties are computed using a specific minimax weighted complementary sensitivity and a specific minimax weighted control sensitivity respectively. For single input single output systems, the solutions of the three minimax problems amount to computation of eigenvalues, and explicit solutions are obtained for systems with a single RHP pole and/or zero. For systems with poles and/or zeros on the imaginary axis the solution due to Francis and Zames [1] is used for the computation of the optimal weighted sensitivity and its dual is derived for the computation of the optimal weighted complementary sensitivity.

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A nonzero–sum game with variable final time.

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In this paper an application of a linear–quadratic nonzero–sum game in economics is considered. Two firms in a duopoly market, extract natural gas from a nonrenewable resource which is a common property. An oligopoly market is a market which has only a few sellers who have influence on the price they ask and the output (production) they realize. Duopoly is the special case of two sellers. Necessary conditions for Nash–solutions with final time T fixed are well known [2]. In this paper however T is not fixed. The game ends whenever the resource is exhausted, so T is implicitly determined. Since there may be more than one solution we also investigate the stability properties of the obtained solutions.
In linear quadratic problems it is often assumed [1] and [2] that the valuefunctions, i.e. the maximum profits that can be obtained from any initial state and any initial time $\tau \in [0,\infty)$ are quadratic in the state. It is shown that this is not always the case.
Open loop coalitions for both a common resource and privately owned resources are considered for a two player game. An extension is made to a three player game in which it is for example possible to form a coalition of two players against the third one.

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AI IN REAL-TIME CONTROL

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During the last years research is done in the field of AI applications for control engineering. A general structure for such intelligent systems is given. This structure may contain conventional algorithms, logic decision modules and neural networks. Recent research has shown that this knowledge-based approach offers the possibility to develop robust controllers for a wide scale of processes (linear and non-linear). The elements of this structure will be discussed and a description will be given of the possibilities of AI techniques.

Special attention is paid to the real-time aspects of AI techniques. A real-time expert system shell is described, which can be coupled with real-time simulation and control package (MUSIC) in a very easy way. The structure to handle and process data is discussed and some results are given.

Control of a Pending Two-link Flexible Robot Arm

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Abstract

In the last few years much attention has been paid to the control of a single degree-of-freedom flexible robot link (Kruise et al., 1988a; Kruise and Boonstra, 1988b). In this presentation the control of a two-link pending robot arm is described. The arm under consideration can move in a vertical plane, so that gravity effects have to be taken into account. The length of each link is about one meter. The links of the robot arm are not extremely flexible. The lowest resonance frequencies of the links are about 10 Hz.

In most cases industrial robots are controlled by PID-type controllers. It is shown that such a controller cannot be used to suppress the vibrations during movement. In this presentation an eighth-order non-linear model is derived that describes the dynamics of the process accurately. The non-linearities are due to geometry and to the centrifugal forces. The controller design is based on a linearized model of the non-linear process. In the controller design the centrifugal forces are disregarded, because the velocities are not extremely high. Resolvers measure the motor angles and strain gauges provide information about the bending. Observers have to be used, because not all the states can be measured. In this presentation special attention is paid to the practical problems and solutions.

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State Space Methods for Determining the Pole-Zero Structure of a Non-Causal System

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ABSTRACT:

A rational matrix $M(s)$ that is possibly non-proper can be represented in terms of constant matrices as $M(s) = C(sE - A)^{-1}B + D$. More generally there are several ways of representing a linear system with a non-proper input-output structure. One might use a descriptor representation:

$$\sigma E\xi = A\xi + Bu$$
$$y = C\xi + Du.$$

or a pencil representation:

$$\sigma Gz = Fz$$
$$y = H_y z$$
$$u = H_u z.$$

For any operation that one might like to do with $M(s)$, one can ask whether this operation can also be performed by manipulating the constant matrices E, A, B, C and D or G, F and H respectively. An advantage of using constant matrices rather than matrices depending on s is that standard numerical software is available for operations on constant matrices. In this talk we will give expressions for the pole/zero structure at infinity of the system in terms of the matrices E, A, B, C and D or G, F and H respectively. The expressions are also meaningful in case no transfer function exists. In fact it turns out that they can be used to determine whether a transfer function exists. Other results concerning e. g. left and right invertibility of the transfer function will also be treated.

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Realization and partial fractions

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Given a transfer matrix $G(s)$, one is sometimes interested in obtaining a partial fraction decomposition of $G(s)$ with respect to two given complementary parts, say Γ_1 and Γ_2, of the extended complex plane. In other words, one would like to write $G(s)$ as a sum $G_1(s) + G_2(s)$, where $G_1(s)$ has all of its poles in Γ_1 and $G_2(s)$ has all of its poles in Γ_2. The most common examples are: $\Gamma_1 = \{\infty\}$, $\Gamma_2 = \mathbb{C}$ (decomposition in a polynomial part and a proper part), and $\Gamma_1 = \{s \mid \operatorname{Re} s < 0\}$, $\Gamma_2 = \{s \mid \operatorname{Re} s \geqslant 0\} \cup \{\infty\}$ (decomposition in a stable proper part and an unstable part). In this talk, it will be shown how minimal state space realizations for the two terms $G_1(s)$ and $G_2(s)$ can be obtained directly from a representation of $G(s)$ in matrix fractional form. The method used is essentially a generalization of Fuhrmann's realization theorem, and builds on the work in [1].

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1990 Benelux Meeting on Systems and Control

Minicourse on Robust Control and $\mathcal{H}_\infty$ Theory

Part 1: *Robust Control*

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Summary

Robust control is a new name for a classical problem in control. It deals with the question how to design control systems whose performance is not or not much affected by plant variations. *Feedback* is essential for achieving robustness. In this part of the minicourse classical and recent techniques to analyse robustness and to design robust control systems are reviewed.

The review will begin with a simple demonstration why robustness may be achieved by feedback. After making a distinction between stability robustness and performance robustness, classical measures for robustness (gain and phase margin, behavior of the loop gain at cross-over frequency) and classical design methods for robust control systems (including Horowitz's Quantitative Feedback Design method) will briefly be discussed.

Current work on robust control is introduced by defining various models of plant uncertainty, including structured and unstructured uncertainty. Concentrating on structured uncertainty leads to the *parametric* approach to robustness. We review Kharitonov-type robustness tests, and mention some parametric approaches to the design of robust control systems.

Focussing on unstructured uncertainty leads to robustness criteria based on bounds on norms of frequency functions. These include Doyle's singular values and his μ-criterion.

Various methods that have been proposed to design robust control systems will be reviewed, including Davison's generalization of the idea of integral control, the Loop Transfer Recovery variant of LQG control, and $\mathcal{H}_\infty$-optimization.

Identification of an experimental XY–table

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Abstract

Last year an identification method for mechanical manipulator models was presented (van de Molengraft, 8th BMoSaC). The basic idea of this method is the minimization of residuals on both the dynamic and measurement model. Three important features of the method are:

1. It is suitable for non–linear models. Most mechanical manipulators cannot accurately be described unless a non–linear model is used. Moreover, considering the model parameters as state variables, the degree of non–linearity is always increased.
2. It provides for estimates of the model parameters as well as the model variables. The estimates for positions, velocities and accelerations do not need to be derivatives of each other, nor need the parameter estimates to be constant.
3. It is deterministic. Generally the sum of all unmodelled phenomena will not behave like a stochastical quantity. That is why this method simply looks for the best fit to the given model structure.

It has been applied to the experimental XY–table, that was also discussed last year (Heeren, 8th BMoSaC). A three degrees of freedom model has been used for identification: two kinematic d.o.f. and one flexible d.o.f., representing the elastic deformation in the X–drive. The unknown inertia, stiffness and friction parameters in the model have been determined using measurements of the end–effector position and acceleration, the motor positions and motor currents. Next, a computed torque/PD controller based on the obtained model has been implemented, so as to judge the quality of the model. The control results have been compared with the results obtained with an ordinary PD controller.

In the presentation the various aspects of the application will be discussed and the results will be shown.

QSVD-based state space identification.

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In an earlier paper [1], a fairly simple algorithm has been presented for computing state space models for multivariable linear systems by making use of (possibly noisy) input-output measurements only. The main step in the identification procedure consists in computing **the singular value decomposition (SVD)** of a block Hankel matrix, constructed with I/O-data. This procedure clearly much resembles well known realization algorithms, that compute a state space model from the SVD of a block Hankel matrix, constructed with Markov parameters this time. These realization algorithms however suffer from severe model inconsistency, when noise is present on the data, due to loss of the Hankel structure when the "noise singular values" are implicitly set equal to zero. Moreover, the sequence of Markov parameters might be hard to obtain in some applications. Instead, the above mentioned identification scheme computes a state space model immediately from the I/O-date, which in practice turns out to be a main advantage. Furthermore, notwithstanding the use of a Hankel matrix as well, the identification procedure can be shown to provide consistent results if both the input and output data are corrupted by additive *white (measurement) noise*.

However, it turns out that in practice, the I/O-data are mostly corrupted by *coloured noise*, due to the use of various pre-filtering techniques (e.g. anti-aliasing, or bandpass filtering if a model for a limited frequency range is searched for). Under these conditions, it appears to be reasonable to assume that the noise colouring is completely defined through the filter characteristics, so that an error covariance matrix (up to a factor of proportionality) can be computed from the filter impulse response. The identification scheme can then be reformulated in a **QSVD framework** [2], wherewith any input-output error covariance matrix (possibly even rank deficient) can then be taken into account explicitly. The extended identification scheme then explicitly compensates for the filter characteristics.

The practical relevance of the generalized procedure is illustrated by means of a few examples. Finally, adaptive versions for on-line model updating can be devised as well, making use of QSVD-updating techniques.

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Generalizations of the Ordinary Singular Value Decomposition: Structure and Applications

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The *ordinary singular value decomposition* (**OSVD**) has become an important tool in the analysis and numerical solution of numerous problems. Not only does it allow for an elegant problem formulation, but at the same time it provides geometrical and algebraic insight together with an immediate numerically robust implementation.
Recently, several generalizations to the **OSVD** have been proposed and their properties analysed. The best known example is the *generalized SVD* for two matrices, as introduced in [6], which we propose to rename as the *Quotient SVD* (**QSVD**) [1]. A specific reason for this name is the relation of this matrix factorization to the **OSVD** of the 'quotient' of two matrices while the main motivation is of course the fact that there are several other similar generalizations. For instance, a *product induced SVD*, also for two matrices, was proposed in [5], where it was called the ΠSVD. We shall refer to it as the **PSVD** (see [1]). In [8], another generalization, this time for three matrices, was proposed. In [2] we have called it the *restricted SVD* (**RSVD**) and analysed its properties in detail.
As is shown in [4], all of these generalized decompositions and a whole lot more can be organised into a tree of generalizations of the **OSVD**. The **OSVD** resides at the top of this tree. The **PSVD** and **QSVD** are two different decompositions for two matrices at the next level of generality. The **RSVD** is one of the three possible factorizations for three matrices. Similar generalizations for 4, 5, etc ...matrices are obtained in a completely structured manner.
We propose to call these factorizations *generalized singular value decompositions* (**GSVD**). All of these matrices can be decomposed into three matrices: Two non-singular ones and a *quasi-diagonal* matrix. The factors are related to each other in two possible ways, which we have called a *P-step* and a *Q-step*. The particular sequence in which these steps occur, determines the name of the decomposition. For instance, the **RSVD** is a **QQ-SVD**. For 5 matrices, one of the 10 possible factorizations is the **PQPQ-SVD**. Another one is the **QQQQ-SVD** etc .... In general, the first factor of the first matrix and the last factor of the

*Dr. De Moor was a visiting research associate at the departments of Computer Science and Electrical Engineering of Stanford University. He is now a senior research associate of the Belgian Foundation for Scientific Research (NFWO). Part of this research was supported by an Advanced Research Fellowship in Science and Technology of the NATO Science Fellowships Programme and by the US-Army under contract DAAL03-87-K-0095.

last matrix in the chain are unitary. All of the block dimensions involved can be expressed in terms of the ranks of the given matrices.

All **GSVDs** form a tree of factorizations, where at level k, for k matrices, there are essentially $(2^{k-1}+2^{k/2})/2$ different factorizations when k is even, and $(2^{k-1}+2^{(k-1)/2})/2$ when k is odd. The different levels are related to each other in a recursive fashion. Any *generalized singular value decomposition* for k matrices, can be constructed from a decomposition for $k-1$ matrices. This results in an inductive and constructive proof which only uses the *ordinary singular value decomposition.*

We also discuss generalized eigenvalue problems that are related to these generalized singular value decompositions.

Finally, we shall give a survey of applications, which are mostly situated in system identification and matrix approximation problems.

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When is a nonlinear system a precompensated linear system?

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Abstract One of the most popular topics of modern nonlinear control theory has been, undoubtly, the feedback linearization problem. The problem can simply be stated as: given a nonlinear system, find, if possible, a static state feedback, so that the closed loop system is (state)equivalent to a controllable linear system. By now, a complete local solution to this problem is known and has resulted in a set of necessary and sufficient conditions for the solvability of the problem. As the class of feedback linearizable systems is extremely small (or better, nongeneric when the state space dimension exceeds one), one is led to the question of dynamic feedback linearization by allowing for dynamic state feedback. This raises two different dynamic feedback linearization problems: given a nonlinear system, find, if possible, a dynamic state feedback, such that the precompensated system is (state)equivalent to a linear system, or, given a nonlinear system, find, if possible, a linear system and dynamic compensator such that original system and the precompensated linear system are (state)equivalent. The purpose of this talk is to discuss the latter dynamic linearization problem and in particular to present preliminary results on the solvability of this problem.

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ABSTRACT

The use of Riemannian metrics for identification and approximation

Any set of linear dynamical systems can be parametrized in many ways. For identification purposes the actual choice of parametrization is important, since it can have a considerable effect on the results of an identification procedure.

In order to come to a parametrization free approach of identification we must take into account the manifold structure of spaces of linear dynamical systems. These manifolds have a highly non-Euclidean structure, but can be endowed with a Riemannian metric. Using this, it is possible to develop identification algorithms which are largely parametrization independent, as is shown in Hanzon [1-3].

In my talk I will discuss how the Riemannian metric can also be used in the field of model reduction and system approximation. By means of some low order examples the topological structure of spaces of fixed order stable linear systems will be somewhat clarified. It will also be shown that even in the case of approximation of a second-order system by a first-order one, one can have multiple optima, which all basically express different characteristics of the second-order system. These results generalize to higher-order cases.

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A time-domain approach to H_∞ worst-case design

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Up to now H_∞ worst-case design has been studied almost entirely through frequency-domain analysis. Lately this is changing, and we will give a presentation of a time-domain approach to this problem. We will consider the standard H_∞ problem in an infinite-horizon, time-invariant context. In this talk we will pay attention to the full-information case, i.e. when direct state observation is available. We have the system:

$$\begin{aligned} \dot{x} &= Ax + B_1 u + B_2 w \qquad x(0) = x_0 \\ z &= D_1 x + D_2 u \end{aligned}$$

The H_∞ control problem investigates this system with zero initial condition. To solve this problem we will look at the following "sup-inf" problem:

$$\sup_w \inf_u \|z_{u,w,x_0}\|_2^2 - \gamma^2 \|w\|_2^2$$

for arbitrary initial conditions. We will solve the latter problem based on Pontryagin's Maximum Principle, although we consider the infinite-horizon case.

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A NEW APPRACH FOR ON-LINE PATH PLANNING AND GENERATION FOR ROBOTS IN NON-STATIC ENVIRONMENTS.

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Abstract. A new method for on-line path planning and generation for robots in a non-empty, changing working-space is presented. The general objective of the entire project is to use a robot arm to grasp moving pieces or **targets** (being transported on a belt) with the aid of visual information, avoiding collision with the environment. Thus, the targets are known within certain classes.

The today's high outputs requirements of factories address the need of fast robots for production. And in dealing with them, their control algorithms must tend to be (computational) simple and to achieve anyway good performance. Therefore, the central idea of this paper is to present a relatively simple algorithm for path-planning and generation in coarse motion that may be used for a wide class of robots.

The basic idea of the whole scheme is to create a pseudo-target, called **ghost**, and make the gripper follow after it as if it were the real target to grasp. The function of the ghost is then to make believe the computer that the target is in other position and then to obligate the gripper to change its course in case of a potential collision. If the working space is obstacle-free the state of the gost matches all the time with that of the target.

The navigation algorithm is based in the well-known (Standard) Proportional Navigation (SPN) which it was extended to include the influence of both the acceleration of the target (or ghost) and that of the gripper. The introduction of this new algorithm, called Advanced Proportional Navigation (APN), makes possible to deal with (randomly and deterministically) accelerated targets yielding errors in (cartesian) position of less than 3%, relative to the total distance covered by the gripper. This feature was incorporated for both, the accelerated nature of the ghost, and the changing velocity of the belt.

Simulations have been carried out with a planar (no gravity effects), RR-type robot. The total amount of operations including path generation, inverse and direct kinematics and dynamics and a PD, decoupled control scheme yielded only 225 operations, but those concerned APN, only 57.

STOCHASTIC SYSTEMS AND THE STOCHASTIC REALIZATION PROBLEM

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ABSTRACT.

Stochastic models should be useful to describe physical systems, but stochastic modelling done on the sole basis of "physical intuition" may lead to nonsense. A variety of linear models with random noise inputs are used in identification, often introduced on the basis of "physical modelling", like "true system" plus measurement errors etc.. It may happen that these models either give poor fitting or are not "identifiable" on the basis of the observed data. This is the case for example when using linear difference equations with both "observation and input noise".

In this lecture we discuss some ideas which are believed to be useful for understanding how stochastic models should be built and used in estimation and identification.

First we distinguish between models of "phenomenological" type (called *external*) and models possessing more structure, which require the introduction of auxiliary variables (*internal* models). Stochastic realization is seen as the problem of transforming external models into internal models by itroduction of auxiliary variables. This is best seen as a mathematical problem of *parametrization* done at the purpose of achieving structure.

white noise inputs can be seen as a typical example of auxiliary variables. This should convince the audience that random input disturbances are just *internal* variables and have no more "physical" meaning than any other auxiliary variable (say the state in deterministic systems). What matters is the *external* (observable) process being modelled and it may just happen that the "physical" model describes in reality too narrow a class of stochastic processes to fit reasonably the data. Also quite likely

a physical model will not be a "canonical" representation of the external process being described. In simple cases the standard practice of converting to the "innovation representation" works, but this may turn out to be highly non trivial in more general situations (like the "errors -in-measurements" example).

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STOCHASTIC REALIZATION, NONCAUSAL ESTIMATION AND THE ALGEBRAIC RICCATI INEQUALITY.

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ABSTRACT.

This Lecture reports on joint work with Anders Lindquist, Royal Institute of Technology, Stockholm, Sweden.

The geometric formulation of stochastic realization for wide-sense stationary increments processes is reviewed. A very natural ordering among realizations is introduced, which specializes, when coordinates are introduced, to the well-known positive-semidefinite order among solutios of the Algebraic Riccati Inequality. With respect to this ordering there always is a *tightest local frame* about any given (minimal) realization of y. In coordinate-dependent terminology, the local frame consists of an orderd pair of of solutions (P_{o-}, P_{o+}) of fhe associated A.R.E., such that , for an arbitrary P solving the A.R.I., the inclusion $P_{o-} \leq P \leq P_{o+}$ is the tightest possible.

This concept has a very natural interpretation in terms of a general (non-causal) state estimation problem. The pair (P_{o-}, P_{o+}) corresponds to two y-induced realizations (filters) which determine the minimal complexity estimator of the state. In some cases it happens that $P_{o-} = P_{-}$ and $P_{o+} = P_{+}$. (The extreme solutions of the A.R.E.). In these cases the estimator has maximal dimension 2n and the overpopularized "two-filters-formula" holds.

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Behaviours in continuous time

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We will discuss in this talk an extension of the results of J.C. Willems ([1]) to the continuous time case. We will give exposure to the complicating factors which makes this situation much more difficult than the discrete time case.

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ACTIVE DAMPING OF A TRUSS STRUCTURE USING PIEZOELECTRIC ACTUATORS

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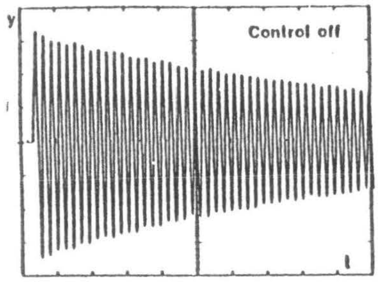
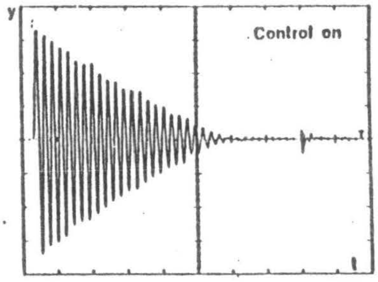
Abstract

This paper presents an active control experiment demonstrating the applicability of piezoelectric actuators. These actuators are attractive because they are simple, lightweight, compact and wide band.

The experimental set-up consists of a truss structure with an active element installed in the highest strain area, consisting of a piezoelectric actuator colocated with a force transducer. The force transducer is connected to a PC/AT via a charge amplifier and an A/D converter. The computer controls the voltage applied to the actuator in a digital manner, with a sampling frequency of 100 hz. Most of the components in the control system, including the actuator, are commercially available.

The damping ratio of the first mode has been augmented from 0.0033 to 0.03, using a single active member (see figures below).





In addition to the experimental work, the non-dimensional parameters controlling the damping augmentation are also discussed. It is established that the modal damping ratio is proportional to the fraction of strain energy stored in the active members, for the mode under consideration, and to the ratio of the piezoelectric to elastic deformation within the active members. Qualitative rules for active members placement are pointed out.

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PREDICTION ERROR METHOD FOR IDENTIFICATION OF A HEAT EXCHANGER

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ABSTRACT

The dynamic behaviour of a shell-and-tube counter flow water heat exchanger, the heating power of which can be influenced by varying the water flow, is investigated by experimental identification with Pseudo Random Binary Sequence (PRBS) test signals. Both Equation Error Model (ARX model) and Output Error Model (OE Model) Structures based on the Prediction Error Method (PEM) are used in order to do this, and the identification results are compared with each other.
Some estimation techniques for this sort of MIMO process are presented and discussed. The proposed identification scheme has proved to function well and to be convenient. It can be extended to deal with similar kinds of thermal processes.

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New results in the Triangular Decoupling Problem (TDP) for nonlinear control systems

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A classical approach for dealing with synthesis problems for nonlinear control systems consists in linearizing the nonlinear system around a certain working point and then solving the problem in question for the resulting linear system. This method has been applied in various nonlinear synthesis problems. For instance, it has been shown that under generic conditions the solvability conditions for the nonlinear input-output decoupling problem and the corresponding linear problem are the same [1]. However, when we deal with the TDP for nonlinear control systems, we show that the solvability of the TDP for the associated linearized system does not imply that the corresponding nonlinear system is locally triangular decouplable by feedback. As an additional result we formulate differential geometric conditions for the solvability of the TDP for square (same number of inputs and outputs) nonlinear systems which differ from, but are equivalent to those given in the literature (see [2]).

Finally, we show that the dynamic input-output decoupling problem is solvable if the TDP is solvable for the same nonlinear system and that the converse implication is in general untrue.

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H_∞-Control without Assumptions on Zeros on the Imaginary Axis

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Abstract We treat the H_∞-optimization problem by output measurement for a nominal plant

$$\begin{aligned} \dot{x} &= Ax + Bu + Gd \\ y &= C_y x + D_y d \\ z &= Cx + Du \end{aligned}$$

which obeys the following assumptions:

- (A, B) is stabilizable and (C_y, A) is detectable,
- D has maximal column rank and D_y has maximal row rank.

In order to characterize suboptimality of some parameter in terms of Riccati equations, one has to assume up to now that there are no zeros of

$$\begin{pmatrix} A - sI & B \\ C & D \end{pmatrix} \text{ and } \begin{pmatrix} A - sI & G \\ C_y & D_y \end{pmatrix}$$

on the imaginary axis.

In this talk we characterize suboptimality of some value with the help of the solvability of algebraic Riccati *inequalities* and sketch an elementary proof. Furthermore, we demonstrate how it is possible to check algebraically the solvability of the derived Riccati inequalities and the coupling condition on its solutions. These characterizations are applied by presenting a fast algorithm to compute the optimal H_∞-norm. We sketch how to generalize the results to the case that the plant may have zeros at infinity, i.e. the matrices D and D_y are not restricted.

Dynamics described by Second Order Differential Equations

by

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Abstract

The dynamics of mechanical systems very often are modeled by a vector second order differential equation:

$$M\ddot{x} + L\dot{x} + Kx = f$$

with x and f vectors of displacements and forces respectively. The mass matrix M usually satisfies $M=M^T>0$ and the matrices L and K denote respectively the damping and stiffness. In many cases there is also a measurement equation involved:

$$y = C_1x + C_2\dot{x}.$$

Starting from these equations one can easily represent the system as a state space realization. In this way it is clear that the set of models described by the two equations above, constitute a subset in the set of all realizations (A,B,C,D). Then the question arises, what is the subset of all realizations with vector second order dynamics, i.e. what (A,B,C,D) represents both equations above?

Here we consider controllable realizations only. Since a realization corresponding to vector second order dynamics has a state space of even dimension, we investigate a set $\mathcal{S}_{2n}$ of controllable realizations (A,B,C,D) with $A \in \mathbb{R}^{2n \times 2n}$, $n \in \mathbb{N}$. We want to characterize the subset $\mathcal{S}_{vso}$ of all realizations with vector second order dynamics. For this purpose we derive a new canonical form on the set $\mathcal{S}_{vso}$. By means of this new canonical form we show, that $(A,B,C,D) \in \mathcal{S}_{vso}$, i.e. a realization has vector second order dynamics, if a mild condition on the controllability indices is met. Finally within a set $\mathcal{S}_{2n}$ consisting of realizations with no more than n independent inputs – this is practically no severe restriction – the condition just mentioned is generically satisfied. So in any such set of realizations almost all elements could be interpreted as a mechanical system.

Locked discrete event systems

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This talk deals with discrete processes modelled as a triple $\langle B, S, A \rangle$, with A the set of possible events (the *alphabet*), B the set of possible behaviour (some subset of the set of all finite sequences of events from the alphabet), and S the trace set (a subset of B representing all completed behaviour).

Such process may be *deadlocked*, i.e., has done some behaviour x that is in B and not in S and it is impossible to continue (no next event a is possible such that xa is in B), it may be *livelocked*, i.e., has reached some behaviour x in B from which it may continue forever without ever reaching some behaviour in S, or it may be *livedeadlocked* or simply *locked*, .ie., it may be deadlocked or it may be livelocked.

In this talk we give a way to detect if a process may lock, using (finite) state graphs in which arrows are reversed, and find an algorithm to construct the largest possible subprocess that is free of lock.

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Predictive Control of a Windtunnel

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Abstract for the 9th Benelux Meeting on Systems and Control to be held March 14-16, 1990 in Veldhoven, the Netherlands.

Abstract

In this paper an application of the Unified Predictive Controller (UPC) [1] [2] is discussed. The goal is to design a controller which accurately controls the MACH number of the high speed windtunnel of the NLR (Dutch Aeronautic Laboratory) in Amsterdam. Currently a (discrete) PID controller is used for this purpose. However, in certain circumstances this controller is not able to control the MACH number within the specified bounds. This is caused by noise corrupting the system. Because the UPC controller can easily take knowledge about dynamics and the noise properties of the system into account, better results can be expected. A model of the windtunnel describing the dynamics as well as the noise properties was obtained by means of off-line identification. Based on this model and the knowledge about the noise, the UPC controller was tuned. After doing some simulations in order to gain insight into the behavior of the controller and the closed loop system, the UPC controller was implemented on the control computer of the NLR. The results achieved when controlling the actual windtunnel are compared to those obtained with NLR's PID controller. It is shown that the UPC controller achieves a better performance according to several criteria. This is mainly caused by the fact that the UPC controller uses a priori knowledge about the noise properties of the windtunnel.

Robustness Analysis for Real and Complex Perturbations applied to Electro–Mechanical Systems

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The design of control systems involves the usage of a model of the system to be controlled. If the performance requirements are high the accuracy of the model is important and differences between the model and the real system should be small. However, modelling errors always exist, for instance unmodelled parasitic dynamics, linearization errors or parameter uncertainty due to variations in the real system. To be able to design controllers which work well with the nominal model as well as with the real system it is necessary to analyze the closed–loop robustness properties for model perturbations.

In the last years much research effort has been spend to access the robustness analysis problem. The most important development is based on norm–bounded uncertainty modelling using singular values as indicators [1]. Other possibilities are simulation and state–space oriented matrix perturbations using Lyapunov stability tests. Recently the polynomial parameter variations approach with Hurwitz stability criteria has emerged.

The singular value analysis method is very appropriate for all situations with little knowledge about the perturbations, due to the use of norms. It's major disadvantage is its conservatism meaning that the uncertainty model set is much larger than necessary. For that reason Doyle [2] introduced the Structured Singular Value analysis. This method has enlarged the non–conservative applicability tremendously. Recently, an extension has been given to include also repeated as well as real parameter variations [3].

Uncertainty modelling and robustness analysis have been applied to a wind energy conversion system [4] as well as to a flexible mechanism. Using the Structured Singular Value Analysis Method robust stability can be non–conservatively analyzed. Feedback design parameters can be effectively retuned to achieve better robustness margins.

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The discrete time H_∞ control problem with measurement feedback

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Up to now H_∞ control has been studied for continuous time systems. In this talk we will present a complete solution of the discrete time H_∞ control problem. As in [1] the existence of a stabilizing dynamic output feedback which makes the H_∞ norm less than some a priori given bound γ, is equivalent to the existence of two stabilizing solutions of discrete algebraic Riccati equations which satisfy certain extra conditions. As in the continuous time case the quadratic term of these Riccati equations is indefinite.

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Real-time fault diagnosis support

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Abstract

The complexity of the supervisor's job in a modern production plant asks for automatic knowledge-based support. Thus the introduction of expert systems seems especially advantageous in such areas where the human operator exhibits knowledge-based behaviour, for instance during fault management.

Normally, much knowledge of the plant is available in the form of static and dynamic relationships, that are easily disregarded when building (rule-based) expert systems. Hence the approach to build such expert systems on the basis of a lower-level fault-finding algorithm.

An algorithm by [Cecchin, Ragot and Sauter, 1987] has been adapted to incorporate multiple errors, imperfect relationships and varying sensitivities of these for anomalous variables. In short a vector of observed deviations from the presupposed relations is matched with a (combination of) vector(s) of expected deviations from normality caused by a variable in error.

The interpretation of the approach will be elaborated on and connections will be laid with fuzzy set and coding theory. Results of simulations with the emerging algorithm will be presented showing the effects of different choices of design parameters such as the metric of the symptom space and the stopping criterion. A discussion follows regarding the usability in real-time circumstances in which the time available for reasoning bounds computational complexity and the measurements' lifetimes are limited.

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Coupled Bending and Torsional Vibrations of Flexible Beams: Modeling and Simulation

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Abstract

Modeling, simulation and control of flexible beams has been the topic of many papers in recent years. This great deal of attention is mainly due to the applications: flexible space structures and lightweight industrial robots with flexible arms. There is considerable number of papers analysing the bending or torsional vibrations independently but there are very few on the coupling problem between those vibrations. In reality we can distinct the following two types of coupled bending and torsional vibrations:

a.) a simple beam with asymmetric tip body,

b.) the center of flexure (shear center) does not coincide with the centroid of the beam's cross-section.

In case a.) the dynamic equations describing the bending and torsional vibrations are uncoupled and the coupling is due to the boundary conditions. In case b.) even the dynamic equations of motion are coupled independently of the boundary conditions.

In this presentation we consider a cantilever beam mounted on a motor shaft and rotating in a horizontal plane. We have a 4-th order partial differential equation (with 4 boundary conditions) to describe bending vibration and a 2-nd order one (with 2 boundary conditions) for torsional vibration. In case a.) it is possible to derive an analytical solution and to determine the mode shapes. We derived the distributed transfer functions (DTF) of the beam with asymmetric tip body. From the denominator of these DTF we can determine the infinite number of poles of the system. These poles depends on the parameters of the tip body. It is interesting to note that the step response consists of a finite number of oscillating components and an infinite number of exponentially decaying components! We would like to mention that from the DTF the "standard" Euler-Bernoulli beam (with or without tip mass) can be deduced as a sub-case.

Based on the DTF we can simulate the dynamic response of the coupled bending and torsional vibrations of a cantilever beam and we can analyse its sensivity to the parameters. We can also take into account the effect of the actuator, namely the motor dynamics. Based on DTF we can make a low order model with prescribed accuracy. This can be the base for controller design.

Abstract for 9th Benelux Meeting on Systems and Control March 14-16, 1990, Veldhoven, The Netherlands

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Variable Structure Control and Sliding Motion

In recent years the concept of Variable Structure Control has gained in importance. The theory of Variable Structure Systems (VSS) and Variable Structure Control (VSC) originates from the Soviet Union where it was first developed in the 1960's. Outside the Soviet Union it remained relatively unknown until the late 70's. From that period, an ever increasing flow of papers on the subject of Variable Structure Systems has been produced.

The name Variable Structure Systems is derived from the main characteristic of this kind of systems: they can vary in structure. This means that the dynamic behaviour of the system depends on the position of some sort of switch. The switch is operated such that the system behaves in a desired manner. Typically the switch determines from what source the input signal to the process must be obtained or by which rule it should be calculated. In the most simple case the input is switched between a negative and a positive constant value, thus resembling a bang-bang controller. In a more complex example multiple process inputs are independently switched between various feedback loops.

The moment of switching is determined by the state of the system. It can be proven that by a proper choice of switching function(s) the system will reach a condition called 'sliding motion'. In sliding motion the state of the system evolves along the switching surface. The aim of a Variable Structure Controller is to drive the system into this condition and keep it there. The theory of VSS shows that in sliding motion the system has excellent robustness properties and is insensitive to certain parameter variations and nonlinearities in the process. Another advantage is the fact that the resulting control law is usually extremely simple.

This paper will illustrate the application of VSS to a number of different control systems. On the basis of simulations and experiments with a DC- servo drive, the relative merits will be elucidated.

Properties of the inbedded Markov chain in random Discrete Event Systems.

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Discrete Event Dynamic Systems (DEDS) are systems whose evolution in time is described by the occurences of events (as e.q. the beginning or completion of a task in a production network).
A class of DEDS can be viewed as linear in the max–algebra. The theory of DEDS using this algebra has recently been extended to include randomly distributed transport and/or processing times ([1], [2]). The aim in these papers is to compute the average throughputtime of the system. Furthermore, in [2] a central limit theorem is proved.

For the calculation of the average throughputtime it is necessary to determine the invariant distribution of an inbedded Markov chain. In this talk properties of this Markov chain are discussed.
We are interested in whether the states of the chain are elements of a bounded set, whether the Markov chain is finite and whether it converges to the same of states for any initial valve. Answers to these questions will be given and their relevance will be shown.

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The design of an optimal reduced-order temperature controller for a diffusion/LPCVD furnace

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A diffusion/LPCVD furnace is a chemical batch reactor used in the semiconductor industry for the fabrication of semiconductor devices. Temperature control is an important issue, since most reactions taking place in the reactor are highly temperature dependent. In previous work[1] a mathematical model based on first principles was derived to describe the heat transfer inside a diffusion/LPCVD furnace, and a full order LQG controller was designed.
For actual implementation the order of the temperature controller must be reduced to comply with computing capabilities and memory requirements of the target computer.
In this presentation the method of the optimal projection equations[2] is used to derive an optimal reduced-order temperature controller. Some preliminary simulation results are presented.

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STEPS*: Software for Identification of Ill-defined Systems

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ABSTRACT

The information system (STEPS) has been designed to support the identification of ill-defined systems, and subsequent use for prediction of their behavior. Ill-definedness is brought about by unavoidable inadequacies in model structure, usually in conjunction with sparse and unreliable empirical data. The uncertainty modeling used in STEPS is based on set-theoretic concepts, i.e. the uncertainties are expressed in terms of instantaneous bounds. The set-theoretic framework is outlined briefly. To assist the identification STEPS also contains recursive parameter estimation tools based on the stochastic concept rather than the set-theoretic concept. STEPS also provides support tools for data analysis, for model structure improvement and for the construction of predictions with the model. The information system is demonstrated by applying it to the identification of a simple dissolved oxygen model.

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Minicourse on Robust Control and H_∞ Theory

Part 2: H_∞ *Theory.*

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Summary

In the last few years the H_∞ optimal control problem has been one of the central issues in the area of optimal control theory. Optimal H_∞ performance is a well motivated design objective for control systems and deals with the problem of constructing stabilizing feedback controllers which attenuate the influence of disturbances on error signals of a given plant. In this talk some of the recent developments and the main results in H_∞ control theory will be summarized. One of the major new developments in H_∞ theory has been the introduction of state space methods. In this part of the minicourse we will primarily focus on this issue. The so called standard optimal control problem will be considered and a comparison between H_∞ and H_2 performance measures will be made. Special attention will be given to the relation between H_2– and H_∞ norms of transfer functions and algebraic Riccati equations. Some important properties of indefinite Riccati equations will be summarized and the relation between the existence of solutions of Riccati equations and state space solutions of the H_∞ optimal control problem will be explained. Some specific features of optimal H_∞ controllers will be mentioned. We will address the issue of high gain feedback, and the so called separation principle. Various generalizations of the standard H_∞ control problem will be considered and some related problems in the area of game theory and identification theory will be discussed.

Parallel Algorithms and Safety-Critical Standards

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ABSTRACT

A "safety-critical" system is one whose failure may lead to loss of, or injury to, life or wallet. The percentage of computer systems that can be classified as safety-critical is steadily growing. The performance requirements of many modern applications exceed those that can be provided by single processor architectures. The complexity requirements of many modern applications exceed our capacity to implement, with an adequate level of confidence, if we are constrained to using traditional serial algorithms. Yet current codes of practice (generally imposed on suppliers by their customers or by government departments) do not allow the use of parallel mechanisms for safety-critical systems, on the grounds that their non-determinism, potential for deadlock, testing difficulties and run-time overheads render them unsuitable. This talk argues that such codes of practice are dangerously wrong for modern high-performance high-security applications. Illustrations will be made using *occam* and *transputer* models.

Modal reduction guided by Hankel singular value intervals

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Abstract:

Mechanical parts in controlled systems are usually modelled as a set of damped vibration modes obtained from finite element models. To minimize the danger of closed–loop instability due to residual modes, an excess of modes should be calculated first. Appropriate model reduction is needed to enable controller design.

It has been shown by Gregory (1984) and Blelloch (1987) that truncation of a balanced realization becomes equivalent to modal reduction in the limit of vanishing damping provided the natural frequencies are well separated. Their sufficiency condition on the separation of natural frequencies however may be very conservative. Using Gershgorin's theorem on eigenvalue regions, we can find Hankel singular value (HSV) intervals, associated with the modal realization. They may serve as indicators for modal reduction. If the damping is sufficiently small, each mode has its own HSV interval. This justifies the interpretation of modal reduction as approximately balanced reduction. If one interval contains a number of approximate HSV's, the associated modes cannot be treated independently in the reduction procedure. However, by a specific state transformation within such a set of modes, other HSV intervals can be contracted in a systematic way in order to find some interval splitting. Starting with a set of most important modes, this procedure can be used to select an increasing number of modes interactively. In this way a full balancing transformation is avoided, while modal reduction can still be interpreted as approximate balanced reduction. Besides, modal reduction is physically appealing and the associated residual system is directly available as the system of truncated modes.

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The computation of the structure at infinity of structured descriptor systems

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ABSTRACT
In this talk we consider systems that have a descriptor representation given by

$$E\dot{x}(t)=Ax(t)+Bu(t),$$
$$y(t)=Cx(t),$$

with $x(t)$ the state, $u(t)$ the input and $y(t)$ the output, and we assume that $sE-A$ is nonsingular. Furthermore, we assume that the nonzero entries in E, A, B and C are either known fixed constants, often +1 or -1, or are parameters of which the value is only known approximately.

Examples of such systems are for instance mechanical structures consisting of a number of bodies interconnected to each other by means of rigid links, springs and dampers. The constants are then determined by the interconnection laws, and the parameters represent the masses of the bodies, the spring constants and the damping factors. Other examples of the above systems are electrical networks.

In the present talk we present an algorithm for the computation of the rank and the orders of the zeroes at infinity of the transfer matrix of systems as described above. The algorithm is based on methods from matroid theory, and can be derived by the fact that the computation of the rank and the orders of the zeroes at infinity can be reformulated as a weighted matroid intersection problem, which is a problem that can be solved by means of efficient algorithms.

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Building Physical Knowledge into Statistical Models for Fault Detection and Diagnosis

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This paper presents how physical knowledge of a system can be applied in combination with statistical techniques for fault detection and diagnosis (FDD).

With the rapid progress of computers, it has now become possible to design complicated, model-based, techniques for fault detection and diagnosis. Since these techniques simulate a real time system by linear/nonlinear models, modelling has a significant impact on the behaviour of the FDD scheme. Apart from the practical modelling difficulties, the computation power required is usually very large. However, in most process plants, the main features of various operating conditions (fault/no-fault) are either known or could be found out easily. The uncertainties in the knowledge of such features (caused by insufficient knowledge or disturbances) can be represented through statistical models. Based on such models, we propose a simple fault detection and diagnosis scheme.

Two examples will be discussed concerning the incorporation of physical knowledge into statistical models for fault detection. The first example is based on a theoretical study done for a Ph. D. thesis at UMIST. In this study it is shown how faults in an anhydrous caustic soda plant can be detected and diagnosed by the Sequential Probability Ratio Test (SPRT). The second example illustrates the application of the SPRT and the least squares technique to leak detection and localization in a gas pipeline. In this case the fault detection and diagnosis methodology has been verified experimentally.

Projection Technique for the Structure Identification of MIMO Systems

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The projection technique is used to identify a parsimonly model structure of canonical vector difference equations [1] for an actual system. The structure consists of the observability indices, the autoregression orders and a parsimony structure [2] of parameters to be estimated.

The range error test [3] and the residual error test [4] can be used to determine the observability indices successfully only in the case of the white equation error. As an improvement of them a new procedure with an additional whitening projection operator [5,6], is proposed to estimate the observability indices as well as the autoregression orders in the case of the colour equation error, which can be modeled with AR. Moreover, an algorithm is also presented to determine the parsimony structure of parameters to be estimated, each element of which has significant contribution to improvement of the quality of the model in the least square sense.

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From Identification to Robust Control and from Theory to Application

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Abstract—This work studies the identification and control of multi-input multi-output (MIMO) processes. First of all a practical procedure is proposed which starts with identification experiment design, includes parameter estimation, model reduction, model uncertainty estimation, control design, robust stability tests, and end up with control system implementation. This procedure reflects the philosophy which guides our research; and it is of course an iterative procedure. In the work of Backx (1987), Backx and Damen (1989), the problems of process measurements, data acquisition, primary signal processing, model estimation, model reduction, model validation, and control design have been studied; and the developed techniques (which are the integration of the results) have been applied successfully to an 2-input 2-output glass tube production process. Their work has laid down a good basis for further research and development, and can be seen as the first iteration of the proposed procedure. Here, we try to improve the existing work by: (1) performing a (sub)optimal input design and re-estimation of the parameters; (2) estimating the upper bound matrix of the errors in transfer function estimates (Zhu, 1987), and use this knowledge of model uncertainty to test the robust stability of the control system; and finally (3) increase the system performance (in our case more disturbance reduction). The methods are applied to the same glass tube process, and the results are very promising.

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On open loop stabilizability

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In this lecture we will discuss the stabilizability of the linear time-invariant system represented by $\dot{z} = Az + bu$, where u is a one dimensional input. If the state space is finite dimensional, then it is well known that this system is open loop stabilizable if and only if it stabilizable by linear time invariant state feedback. However, if the state space is infinite dimensional, then things are more complicated. We will show that for a very large class of infinite dimensional systems, containing almost all models of practical interest, the analog of the finite dimensional case holds. Thus for these models we have open loop stabilizability implies stabilizability by a linear time invariant feedback law. This feedback law can be chosen to be continuous in the state. For the models outside this class, e.g. undamped beam equations, we will show that open loop stabilizability implies the existence of a linear time-invariant feedback law that shifts all the poles, but this operator will no longer be continuous. Furthermore we will discuss the relation between this feedback law and the Algebraic Ricatti Equation.