

IDENTIFICATION FOR ROBUST CONTROL

Final Technical Report

(1st year)

by

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13. ABSTRACT (Maximum 200 words) <ul style="list-style-type: none"> • Special methods that augment the robustness of adaptive control systems by estimating the time delay, too, were developed. New adaptive PID regulator algorithms based on these results were also developed as virtual instruments to reach easy portability and wide applicability. A new design method decreasing the gain sensitivity of simple PID regulators was investigated. • A new interpretation of H_∞ criteria in frequency domain was shown. This interpretation gives special "butterfly" sensitivity (or robustness) shaping regions that can easily be applied on the classical Bode plot design techniques. • New robust diagnostic and failure detection filters and systems based on these algorithms were developed. • A new approach minimizing the H_∞ mismatch error norm for n-order FIR models was developed. • A new generic optimal control scheme was introduced. This is a new structure to design optimal pole placement controllers. This scheme allows to avoid the explicit solution of a polynomial equation obtaining the transfer function elements of the optimal controller directly. The structure of the optimal controller gives a special insight to understand the operation of a feedback loop for the servo and disturbance rejection paradigm. It also gives a better way to analyze the sensitivity schemes of combined identification and control schemes. It was shown that the new generic optimal controller structure is superior to others and an iterative control refinement technique based on this method was introduced. This scheme was also extended for adaptive control, switching the formulation from the off-line iterative situation to the on-line simultaneous control and identification case. • A new concept of "maximum variance" input design for robust identification for control was developed. The very interesting and effective feature of this method is that it gradually improves the frequency spectrum of an initial reference input signal excitation approaching and concentrating on the vital medium frequency domain around the cross-over frequency. • A new MATLAB™ based package CSILLA™ capable to handle all special cases we discussed in the theoretical papers and reports was developed with gateways to the well known general word-processing and graphing programs. 			
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ABSTRACT AND INTRODUCTION

Since 1978, there has been a history of successful cooperation between control researchers at the University of Minnesota and the Hungarian Academy of Sciences. This cooperative research effort was initially sponsored by the National Science Foundation in the late 1970's and early 1980's and later it has continued on an informal basis to the present.

One of the most important areas of research in control theory is the design of feedback controllers for systems which have significant uncertainties in the plant. These uncertainties can result from a lack of precision in mathematical modeling of the plant and/or changes in the plant parameters with time. Two main techniques for design of controllers for systems with significant uncertainties are robust and adaptive control theories. System identification is an important tool in both techniques as well as in many other control design methods.

The US cooperating partner has a long experience in designing high performance robust control systems (helicopter flight control, supermaneuverable aircraft control, missile autopilots, etc.). The Hungarian partner has implemented several high performance adaptive controllers for complex processes (national load-frequency control system, chemical composition control at cement raw material handling, combined fineness and effectiveness control at closed circuit grinding mills, etc.). Both sides have long experience in modeling, structure and parameter estimation of sophisticated dynamic systems and have obtained significant achievements in robust control methodologies. Therefore a fruitful cooperation was expected from a new planned joint research effort, targeting the complex problems of simultaneous identification and control, furthermore on the interaction between systems identification and robust and adaptive control theories. Applications could include helicopter flight control and active vibration control.

During the preparation of the project and the evaluation of the preproposals the European Research Office of the US Army suggested that it was desirable to submit a separate proposal by the Hungarian side under the title "Identification For Robust Control", because the ARO is not prepared yet to handle the above type of joint projects. Finally this separate proposal was accepted requesting yearly evaluation. So this is the *final report of the first year's activity* of the Hungarian side. Besides the US and Hungarian partners promised to keep each other informed about their achievements

and try to form a loosely formalized connection according to the original ideas.

KEYWORDS

System identification; process parameter estimation; optimal, robust and adaptive filtering and control; combined identification and control; identification for control.

PROJECT SUMMARY

The research contract was signed on March 24, 1994, so the reported period is about 15 months. This period was enough to achieve significant and completed contributions. In this reported period we could make a very intensive research activity in the areas indicated and planned in the project proposal shown by the large number of papers.

Herebelow we try to summarize only those achievements that we could formalize in written publications or reports. Because most of them are submitted papers to international scientific journals and conferences, there is, of course, a certain chance that not all of our materials will be accepted. However, we hope that most of them will finally be published, because our group has a good acceptance rate.

Furthermore our recently published and submitted papers, initiated and supported by the project, are also summarized to show the development of our work. Those working papers (project reports) are also presented, which are for preparing and founding our further research.

We planned our research activities basically in three directions :

- (1) the general (classical?) robust control approach
- (2) special auxiliary solutions augmenting robustness of adaptive control
- (3) a new approach based on a generic optimal control system structure.

The general robust control approach

In this area we wanted to follow the developments in the classical robust control approaches and to reach our new contributions along these lines. (The technical details of our expectations what and how to do in our planned research were given in our project proposal.)

H_2 and H_∞ identification for control

We introduced a new interpretation of H_∞ criteria in frequency domain. This interpretation gives special "butterfly" sensitivity (or robustness) shaping regions that can easily be applied on the classical Bode plot design techniques [9], [19] and [27].

This interpretation seems to be very useful to handle the critical medium frequency domain in combined or simultaneous identification and control problems.

Various approaches to identification of dynamic systems using H_∞ criteria have been analyzed. The report [16] provides a comprehensive survey and evaluations of the linear and nonlinear methods based on interpolatory algorithms. Numeric realizations of these methods are also provided in *MATLAB*TM environment and this can serve to make comparisons using either simulated or measured data.

In [20] and [29] we considered the identification of systems with transfer function in the disc algebra. The approximate model is a finite n -order *FIR* model. Using linear least squares parameter estimation with a properly designed input signal, it is shown that the asymptotic estimates obtained from time domain data are the first n Taylor coefficients. This model has the minimum H_∞ mismatch error norm over all *FIR* models that are polynomial in the delay operator with order not exceeding n .

There is a renewed interest in the choice and selection of appropriate basis for H_∞ identification. This is illustrated by the fact that special sections have been organized in the SYSID'94 and CDC'94 symposia. In [12] we showed that a basis in the disc algebra can be obtained from the Faber-Schauder and Franklin systems. The dynamical systems with transfer functions in the disc algebra can be approximated in H_∞ norm by partial sum operators. We elaborated a linear algorithm for computation of approximate models from frequency domain data. Numeric computations and comparisons to existing, like Cesaro-mean based linear algorithms showed a faster convergence with a smaller H_∞ error norm.

Convergence analysis for deterministic case and under "unknown but bounded" noise assumptions are provided in [17].

H_∞ and robust filtering

The design of filters with H_∞ performance appears in the output estimation problem in relation to the H_∞ output feedback control. The motivation is to design a filter or observer that guarantees a given attenuation of an external disturbance signal that also appears in the filter state or output error system.

The robustness problem is related to the situation where the filter is designed on the

basis of a nominal system while there is an additive or multiplicative error transfer function between this nominal transfer function and the transfer function of the real system.

The usual solution to this robustness problem that has been published in the past few years has a dual structure when compared to the two-Riccati equation type state space solution of the output feedback H_∞ control.

In our approach we considered dynamic systems given by a LTI nominal model and by time-varying parametric perturbations in the state space matrices.

Using a basis of the Lie-algebra generated by the nominal state transition matrix and parametric disturbance matrices we construct an "auxiliary" LTI system that has invariant subspaces related to parametric perturbations that are relevant in filter design that are identical to the invariant subspaces of the original LTV system. The effect of parametric uncertainties appears in this auxiliary system as unknown but bounded L_2 external signals. Using this approach the problem can be reduced to the design of a filter to attenuate the effect of the external signal in the state or output error in L_2 norm as much as possible (worst case disturbance concept), leading to the design of H_∞ filters.

This approach was applied to the design of fault detection filters where the alarm levels of the filters can be adjusted to the maximum attenuation of system uncertainties represented by external deterministic noise in the auxiliary system. Results associated to this topics can be found in [21],[32],[34] and [36].

Our further contributions are still remarkable in designing robust diagnostic and failure detection systems that are based on special classes of system identification methodologies [6],[7],[15].

Special auxiliary solutions augmenting robustness of adaptive controls

In this area we investigated special methods that augment the robustness of classical (mostly adaptive) control systems. Our contributions are remarkable on the area of adaptive time delay estimation [1],[2],[4]. These methods considerably extend the applicability of adaptive regulator algorithms.

Besides investigating adaptive time delay estimation connected to *PID* regulators, the robustness of simple *PID* controls has also been treated. A new design principle was introduced decreasing the gain sensitivity of these regulators [11],[25]. New adaptive *PID* regulator algorithms were also developed as virtual instruments (National Instruments' *LabView*TM environment) to reach easy portability and wide applicability [3],[5].

On the basis of these theoretical results and simulation studies we start to investigate their applicabilities for helicopter models targeting to develop appropriate adaptive *PID* regulators for their control. These applications can also be interesting for ARO.

A new approach based on a generic optimal control system structure

We believe that one of the major theoretical contribution of our project will be a new regulator design approach based on a generic optimal control scheme developed by us. This is a new structure how to design optimal pole placement controllers. This new scheme allows to avoid the explicit solution of a polynomial equation obtaining the transfer function elements of the optimal controller directly [8]. Our recent papers [18], [22], [23], [28] and [31] discuss the different variants and details of this new design methodology. Many further publications are planned for the different applications of these principles.

The new design principle is quite general and applicable for nonminimum phase (inverse unstable) and delay time systems, too. The controller is easy to be implemented in computer controlled systems.

The structure of the optimal controller gives a special insight to understand the operation of a feedback loop for the servo and disturbance rejection paradigm. It is easy to see the role of the knowledge of the system model, the role and appearance of those system factors that are invariant to any control strategy.

This generic structure opens a new way to handle system uncertainties, furthermore combined modeling and control issues providing a new canonical sensitivity scheme.

We formulated a special framework, where the different separate phase of

identification for and design of robust control can properly be handled. This approach combines the classical "minimum variance" like control with the new concept of "maximum variance" input design for robust identification for control. New publications are under preparation.

This generic controller structure opens a new way how to handle system uncertainties, furthermore combined modeling and control issues providing new canonical sensitivity schemes. We investigated these new schemes and surprising new results have been obtained [24] and [30].

The properties of the simple combination of the *open-loop identification* and *closed-loop control*, the combined identification and control in a *parallel closed-loop optimal controller scheme*, in a *parallel in-loop optimal controller scheme* and in a new *generic optimal controller scheme* were investigated. It was shown that the new generic optimal controller structure is superior to the others.

The simple combination of the *open-loop identification* and *closed-loop control* does not provide good properties for iterative control refinement.

The widely used and analyzed *parallel closed-loop optimal controller scheme* is good for iterative control refinement, however, it really needs a cautious *windsurfer* approach, because its robustness is highest around the crossover frequency ω_c , which is not known a priori and can be approached only in an iterative procedure.

The *parallel in-loop optimal controller scheme* mostly applied at adaptive regulator schemes is directly not good for iterative control refinement, having improper frequency domain robustness shaping. It is however possible to use a special prefilter based on the inverse of the model based characteristic equation for the identification data to make this method similar to the previous one.

It is also interesting to know that in a noise-free case the last two methods can easily fail because the identification errors can be zero, if the control errors are zero, in spite of a nonzero modeling error. This bad feature can stop the identification at a not predictable wrong model and not continuing any iterative refinement.

The new generic optimal controller scheme seems to be best from the investigated methods, because its frequency domain robustness shaping amplifies the high

frequency uncertainties in the identification error and more accurate model is expected in the targeted high frequency domain (where we want to increase the bandwidth). It behaves also well because the identification and control errors are the same and they can vanish only at the same time.

In the first interim report it was mentioned that we formulated a special framework, where the different separate phases of identification for and design of robust control can properly be handled. This approach combines the classical "minimum variance" like control with the new concept of "maximum variance" input design at robust identification for control. In that phase this idea was only a conjecture. Using the *CSILLA*TM package (below) we could prove the nice converging properties of the new "maximum variance" reference input design algorithm [10]. This method works well both in the iterative off-line and adaptive on-line situation, too. The very interesting and effective feature of this method is that it gradually (iteratively or recursively, depending on the applied scheme) improves the frequency spectrum of an initial reference input signal excitation approaching and concentrating on the vital medium frequency domain around the cross-over frequency. This seems to be a natural way to solve the well known problem of "catch of 22" in combined identification and control paradigms, when one should know the process to generate the optimal excitation or to have apriori or "god given" frequency dependence of modeling error sensitivities.

This new principle for optimal reference input design outlines a new scheme of "trial-control", which is a special possible extension of the classical "dual-control" scheme - based on the simultaneous identification and control loops - with a third loop for optimizing the excitation [10], [33]. Several different combinations of these loops can be imagined worth studying in the near future.

The above new results were deeply analyzed and compared in the invited survey paper [10].

Elaboration of software tools

It turned out that we need special software tools to perform "*mathematical experiments*", i.e., special simulation runs to demonstrate the operation, convergence, applicability and performance behaviors of the developed methods and algorithms. A careful analysis showed that the *MATLAB*TM program and environment widely used in

the control community is basically good for our goals, if we write a couple of new routines and functions. Another point was that in this way we are compatible with our joint research partner (*U of M*, USA) and other scientific schools in this area. We finished an important package written in *MATLAB*TM, capable to handle all special cases we discussed in the theoretical papers and reports. This definitely speeded up the experimental proof of our results.

The following subsystems have been elaborated:

- combined identification and control for inverse stable processes
- combined identification and control for inverse unstable processes
- combined identification and control for inverse unstable processes with optimal reference input design
- adaptive identification and control for inverse unstable processes
- adaptive identification and control for inverse unstable processes with optimal reference input design
- comparison of step, square-wave and the new maximum-variance optimal reference input design approach
- design of robust *PID* regulators
- combined identification and design of robust *PID* regulators with optimal reference input design based on the new "catamaran" approach
- combined identification and control for first and second order roll response helicopter model
- combined identification and control for first and second order roll response helicopter model with optimal reference input design
- adaptive identification and control for first and second order roll response helicopter model
- adaptive identification and control for first and second order roll response helicopter model with optimal reference input design
- *PID* control for first and second order roll response helicopter model
- robust *PID* control for first and second order roll response helicopter model

The above newly developed package of subsystems are referred as *CSILLA*TM (Combined System Identification and control package based on *MATLAB*TM) in the following. We had to develop special gateways to the well known general word-processing and graphing programs, too, to ensure publishing quality for our plots and drawings. We used the *Apple Macintosh*TM platform, where the integrity of these

programs is provided on a very high level. Unfortunately we could use only the *Mac II* version of *MATLAB*TM available and providing an acceptable speed for our interactive and iterative simulations. However, this speed is still very far from the originally required high performance computing facilities. We try to enhance our computing infrastructure to reach the *PowerPC*TM or workstation performance in the near future.

One can see that this list is a thorough package of the covered areas. We mainly concentrated on the developed new efficient methods for combined identification and control. These are mainly off-line methods for iterative techniques. The adaptive versions of the above algorithms have also been elaborated.

Application possibilities

We started to study vehicle active suspensions based on H_2/H_∞ optimization robust control theory, which can have special interest for ARMY applications [13],[14].

We started to investigate the applicability of these new theoretical results for improving the performance of possible control schemes based on helicopter models. We used theoretical and experimental models published for roll response modeling. The roll response in the frequency range of interest is essentially second-order, owing to the coupling of the rotor regressive flapping and fuselage roll modes. A more general second order model involving the rotor flap inverse time-constant, the total flapping stiffness, the lateral stick gearing and the residual time delay, furthermore a simpler first order model represented by a time delay and the coupled fuselage/rotor dynamics given by the roll gain and the first order roll damping were considered.

The simulation studies using these helicopter models presented how to increase the robustness of *PID* regulators in this application area. The new advanced methods for combined identification and control of these models were also treated. Several adaptive schemes have also been investigated. It was also shown what is the influence and benefit if we use optimal reference signal design to improve the convergence of the combined and adaptive schemes.

These examples were used as simulation examples in our recent publications, however, we plan to write a special report on these application possibilities and results in the second year of the project.

During the project we continuously investigated further application possibilities of the newly developed methods. Some application possibilities were already mentioned, another new application was also investigated namely the application of a the generic optimal controller structure for raw material blending [26].

General remarks

An important recognition of our group and its research activity is the invitation for the principal investigator, Prof. L. Keviczky to deliver a plenary paper on our recent results at the *IFAC Symposium on "Adaptive Systems in Control and Signal Processing"* to be held in Budapest, June 14-16, 1995.

It is definitely worth mentioning that Dr. Gary Balas spent two weeks in our Laboratory last summer as a visiting professor from the *The Center for Control Sciences and Dynamical Systems, University of Minnesota*, which is our ARO partner from the US. (The first version of our application was a joint proposal, but later it was splitted to a Hungarian and a US one.) His visit played an important role to coordinate the research efforts done separately and to present jointly the scientific achievements.

PROJECT PUBLICATIONS

Papers already appeared:

- [1] **Bányász, Cs. and L. Keviczky** (1994). Recursive time delay estimation method. International Journal of Systems and Science, **25**, 11, 1857-1865.
- [2] **Bányász, Cs. and L. Keviczky** (1994). A new indirect adaptive time-delay estimation method. 10th IFAC Symposium on System Identification, SYSID'94, Copenhagen, Denmark, **3**, 549-554.
- [3] **Vajk, I., A. Soumelidis, Cs. Banyász and L. Keviczky** (1994). Adaptive controllers as virtual instruments. 10th IFAC Symposium on System Identification, SYSID'94, Copenhagen, Denmark, **2**, 291-296.

- [4] **Bányász, Cs.**, I. Vajk and **L. Keviczky** (1994). Handling delay time in low cost controllers. 2nd IFAC Symp. on Intelligent Components and Instruments for Control Applications, SICICA'94, Budapest, Hungary, 287-292.
- [5] Soumelidis, A., **Cs. Banyász, L. Keviczky** and I. Vajk (1994). On the use of virtual instruments in realizing adaptive controllers. 2nd IFAC Symp. on Intelligent Components and Instruments for Control Applications, SICICA'94, Budapest, Hungary, 246-251.
- [6] Edelmayer, A., **J. Bokor** and **L. Keviczky** (1994). An H_∞ filtering approach to robust detection of failures in dynamic systems. 33th IEEE CDC, Orlando, FL, USA, 3037-3039.
- [7] Soumelidis, A., **J. Bokor, L. Keviczky**, A. Edelmayer, P. Gáspár, Zs. Csáki and E. Varga (1994). Toward an intelligent evolutionary signal processing based failure monitoring and diagnostic system for complex plants. IFAC Conference SAFEPROCESS'94, Helsinki, Finland, 2, 760-765.
- [8] **Keviczky, L.** and **Cs. Banyász** (1994). A new structure to design optimal control systems. 1st IFAC Workshop on New Trends in Design of Control Systems, Smolenice, Slovak Republic, 102-105.
- [9] **Bányász, Cs.** and **L. Keviczky** (1994). On the interpretation of H_∞ criterion. 1st IFAC Workshop on New Trends in Design of Control Systems, Smolenice, Slovak Republic, 177-180.
- [10] **L. Keviczky** (1995). Combined identification and control: Another way (Invited plenary paper). IFAC Symposium on Adaptive Control and Signal Processing, ACASP'95, Budapest, Hungary, 13-30.
- [11] **Cs. Banyász** and **L. Keviczky** (1995). How to increase robustness of *PID* regulators. IFAC Symposium on Adaptive Control and Signal Processing, ACASP'95, Budapest, Hungary, 377-383.
- [12] **Bokor, J.**, F. Schipp and L. Gianone (1995). Approximate H_∞ identification using partial sum operators in disc algebra basis. American Control Conference, Seattle, USA, 1981-1985.

Interim reports:

- [13] **Bokor, J.** and Saad El-Khayyat (1994). Optimal linear control design of active suspension system using H_∞/H_2 controllers.
- [14] **Bokor, J.**, A. Kanbolat and L. Gianone (1994). Vehicle active suspensions based on H_2/H_∞ optimization robust control theory.
- [15] Edelmayer, A. (1994). Robust detection filter design in uncertain dynamical systems.
- [16] **Bokor, J.**, **L. Keviczky** and **Cs. Bányász** (1994). H_∞ identification: a survey and some new details.
- [17] Gianone, L., **Bokor, J.**, F. Schipp and Z. Szabó (1995). Error bounding for H_∞ identification of models parametrized in a disc algebra basis.

Publications accepted:

Herebelow those publications are listed only which are already accepted for international scientific journals or conferences and will appear this year :

- [18] **Bányász, Cs.** és **L. Keviczky** (1995). Egy új kanonikus optimális szabályozási séma (In Hungarian). Automatizálás'95 Konferencia, Budapest.
- [19] **Bányász, Cs.** és **L. Keviczky** (1995). H_∞ kritérium a frekvencia tartományban (In Hungarian). Automatizálás'95 Konferencia, Budapest.
- [20] **Bányász, Cs.**, **J. Bokor** and **L. Keviczky** (1995). Prediction error identification of FIR models with minimum H_∞ error norm property. Automatizálás'95 Konferencia, Budapest.
- [21] Edelmayer, A., **J. Bokor** and **L. Keviczky** (1995). Improving robustness of on-line failure detection and isolation methods. Automatizálás'95 Konferencia, Budapest.

- [22] **L. Keviczky and Cs. Bányász** (1995). A generic scheme for simultaneous forecasting and control (Invited paper). TIMS XXXIII International Meeting, Singapore.
- [23] **L. Keviczky and Cs. Bányász** (1995). A new regulator design method. European Control Conference, Rome, Italy.
- [24] **Bányász, Cs. and L. Keviczky** (1995). Sensitivity schemes for combined identification and control. COMCON 5, Chania, Greece.
- [25] **Bányász, Cs. and L. Keviczky** (1995). On robustness of simple *PID* regulators. COMCON 5, Chania, Greece.
- [26] **Bányász, Cs., L. Keviczky and I. Vajk** (1995). Application of a new generic optimal controller structure for raw material blending. MMM'95 IFAC Symposium, Sun City, South Africa.

Publications under review:

The following publications have been submitted to international scientific journals or conferences and they are under review now. (There is, of course, certain chance that not all of these papers will be accepted !):

- [27] **Bányász, Cs. and L. Keviczky** (1995). H_∞ criteria in frequency domain. 34th IEEE CDC, New Orleans, Louisiana, USA.
- [28] **L. Keviczky and Cs. Bányász** (1995). A new pole-placement regulator design method. 34th IEEE CDC, New Orleans, Louisiana, USA.
- [29] **Bányász, Cs., J. Bokor and L. Keviczky** (1995). ℓ_2 identification of FIR models with minimum H_∞ error norm property. 34th IEEE CDC, New Orleans, Louisiana, USA.
- [30] **Keviczky, L. and Cs. Bányász** (1996). On model sensitivity properties of some combined identification and control schemes. International Journal of Systems Science.

- [31] **Keviczky, L.** and **Cs. Bányász** (1995). A generic optimal controller scheme. International Journal of Control.
- [32] Edelmayer, A., **J. Bokor** and **L. Keviczky** (1995). Improving sensitivity of H_∞ detection filters using estimation weighting techniques. 34th IEEE CDC, New Orleans, Louisiana, USA.
- [33] **Keviczky, L.** and **Cs. Bányász** (1996). Extension of dual control: the concept of "triple control". IFAC World Congress, San Francisco, CA, USA.
- [34] **Bokor, J.**, A. Edelmayer and **L. Keviczky** (1996). Robust detection filter design for linear systems using H_∞ techniques. IFAC World Congress, San Francisco, CA, USA.
- [35] **Keviczky, L.** and Pham Huy Thoa (1996). Identification techniques for correlated noise systems with multisensors. IEEE Instrumentation/Measurement Technology Conference, IMTC'96, I3C: Integrating Intelligent Instrumentation & Control, Brussels, Belgium.
- [36] Edelmayer, A., **J. Bokor**, **F. Szigeti** and **L. Keviczky** (1996) Robust detection filter design in the presence of time varying system perturbations. IFAC Journal Automatica.

(Bold names mean project participants, plain names indicate junior colleagues and students.)

Publication statistics:

Papers published:	12
Reports published:	5
Papers appear this year:	9
<u>Papers under review:</u>	<u>10</u>
Total:	36

LIST OF PARTICIPANTS

Principal investigator: L. Keviczky
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APPENDIX: SELECTED SCIENTIFIC WORKS

COMBINED IDENTIFICATION AND CONTROL: ANOTHER WAY

HOW TO INCREASE ROBUSTNESS OF *PID* REGULATORS

H_∞ CRITERIA IN FREQUENCY DOMAIN

**APPLICATION OF A NEW GENERIC OPTIMAL CONTROLLER
STRUCTURE FOR RAW MATERIAL BLENDING**

(See in separate volume !!!)