An Integrated Framework for Input, Output and Control Structure Selection: Advanced Control Diagnostics

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Abstract

This paper aims at formulating an integrated approach to the overall problem of control structure selection and identifying open issues and problems. It is based on the assumption that there exists a progenitor model of the linear type for the process, which however may not be well defined. We then use structural analysis of the system theoretic framework, the interaction measures and the results for evaluation of alternative decentralisation schemes, to specify a step by step approach to the control structure selection. The problem of handling alternative criteria is also considered and basic elements of a system procedure are given. There are many open issues, which are identified and are still open and thus the proposed structural approach should be considered as the first step to the development of an integrated methodology that involves the following major steps:

(a) Classification of system model variables and definition of well structured progenitor model.
(b) Definition of effective input, output structure based on operability, controllability criteria.
(c) Determining the structure of the control scheme by evaluation of alternative decentralised structures.

1 Introduction

The problem of control structure selection, [12] and [13] may be seen as involving three major steps: (a) Classification of variables and definition of system progenitor models; (b) Definition of effective sets of inputs, outputs and; (c) Structuring of the feedback coupling of the control scheme. The overall structural methodology that has been adopted in SESDIP project suggests a natural procedure for the study of the above three problems and poses a number of concrete problems for each of the three areas. The ordering of subproblems we address in each of the above families is based on the generality of the issues and progression from simple models to more detailed dynamic models.

The classification of variables is a problem that is not always solved using physical modelling arguments. Very frequently it may lead to progenitor models which are not well defined. The specific issues involved in the selection of a well defined progenitor model and the procedure that can be used to define a well behaved model are considered in section (2). The structuring of an effective input, output structure is considered in section (3), where a procedure progressing from generic properties on unstructured models, to graph properties, parameter dependent invariants and performance indicators is suggested which reflects our overall structural philosophy. Having decided the required input, output structure of the feedback scheme, i.e. centralised versus decentralised, and if decentralised, then the exact nature of decentralisation that involves the partitioning and pairing, as well as order of dynamics for the particular channels. The methodology and diagnostics are based on the use of simple models first and then progressively move to more detailed models and more detailed structural criteria. The current emphasis in the approach is the screening of the bad choices and then leave the final selection to performance dependent criteria. An overview of the methodology we develop here is described in Figure (1).

2 Classification of Variables and Definition of Well Structured Progenitor Models

We assume that we are given a linearised model, described in state space form by a matrix pencil model $F\dot{\underline{\xi}} = G\underline{\xi}$, or by an autoregressive model $P(p)\underline{\xi} = \underline{0}$ with a large number of exogenous variables, potential measurements and controlled variables and a given number of states.

General Problem: Define an oriented effective model that has the "best" possible properties and a control structure that allows the solvability of a number of important control problems that may be posed.

The model that is given is partially nonoriented, since the exogenous variables are not classified to control variables and disturbances. An approach that may be followed to tackle the above problem is as follows:

Step 1. Using knowledge of the physics, chemistry of the problem as well as assuming a given system boundary

[11] we classify the exogenous variables into: (a) potential control variables and (b) disturbances.

Remark 1. (a) Resolving the issues involved above we use physical modelling arguments (knowledge of process) and knowledge, specification of the system boundaries (design scope, assumption). (b) For linearised dynamic progenitor models, model orientation problems involving partitioning of invariant structure may be used as a supplement to the physical partitioning of variables. The solution of mixed physical, algebraic orientation problems is still an open issue.

The result of this step is an oriented model (separation of control, disturbance variables and outputs), described by a state space model *S(A,B,C,D)*, or by a transfer function matrix $H(s)$, but not necessarily well defined. In fact, the inputs, outputs may not be independent and the input, output transfer function may not be of full rank.

Step 2. The selection of a well structured, progenitor model (or a family of well structured models) such that the matrices *B*, *C* have full rank and the transfer function *H(s)* has full rank. This involves the computation of the normal rank ρ of the transfer function.

Remark 2. ρ defines the maximal number of output variables that may be independently controlled (output function controllability criterion). Furthermore, ρ defines the minimal number of independent inputs required for control of ρ outputs (if it is less than ρ, then we control fewer variables).

The number ρ emerges as one of the most basic structural characteristics that determines fundamental problems of the final model and will be referred to as the *system rank.* Some important problems associated with the estimation of ρ on nonoriented and uncertain models are:

Problem 1. Determine the maximal possible value of the rank ρ that may be predicted and achieved from the properties of the original implicit model.

The above problem may be studied within the area of Model Orientation Problems [14] and is linked to the partitioning of invariants of implicit systems. This problem is referred to as *Implicit Description System Rank Evaluation Problem.* A related problem is defined below:

Problem 2. For systems described by a transfer function matrix *H(s)*, which however may have dynamic uncertainty (variable dynamic complexity), derive robust estimates of the system rank ρ as a function of dynamic complexity.

The above problem will be referred to as *Robust System Rank Estimation Problem* and it is one of the open issues that has not been previously considered.

Remark 3. If $H(s) \in \mathcal{R}^{q \times r}(s)$, and $rank_{\mathcal{R}(s)}\{H(s)\} = \rho < \min(q,r)$, then $N_l\{H(s)\} \neq \{0\}$ and $N_r\{H(s)\} \neq \{0\}$. Furthermore, the following properties hold true:

a) If $N_r\{H(s)\} \neq \{0\}$ and there exist constant vectors in it, then

$$rank\left\{\begin{bmatrix} B \\ D \end{bmatrix}\right\} < r \text{ and } rank(B) < r \tag{1a}$$

Furthermore, if n_r denotes the right nullity of a matrix

$$n_r\left\{\begin{bmatrix} B \\ D \end{bmatrix}\right\} = r - \rho \tag{1b}$$

then all right indices of *H(s)* are zero, and the system is called *totally input degenerate.*

b) If $N_l\{H(s)\} \neq \{0\}$ and there exist constant vectors in it, then

$$rank\{[C \quad D]\} < q \text{ and } rank(C) < q \tag{2a}$$

Furthermore, if n_l denotes the left nullity of a matrix

$$n_l\{[C \quad D]\} = q - \rho \tag{2b}$$

then all the left indices of *H(s)* are zero, and the system is called *totally output degenerate.*

For a general system $H(s) \in \mathcal{R}^{q \times r}(s)$ we define the indices

$$t_r = r - rank\left\{\begin{bmatrix} B' & D' \end{bmatrix}'\right\} \leq r - \rho \tag{3a}$$

$$t_l = q - rank\{[C \quad D]\} \leq q - \rho \tag{3b}$$

as the *input, output redundancy indices* of the *H(s)* model, and with this notation total input (output) degeneracy is when $t_r = r - \rho$, $(t_l = q - \rho)$, i.e. when there are non-zero right (left) indices.

Problem 3. If $t_r > 0$, select a subset $rank\left\{\begin{bmatrix} B' & D' \end{bmatrix}'\right\}$ of independent inputs and if $t_l > 0$ a subset of $rank\{[C \quad D]\}$ outputs.

This problem is referred to as *Estimation of Input, Output Redundancy Problem* and it is one of the problems of redesign of process instrumentation. The solution to the above problem is achieved in an optimal way by using the "best uncorrupted basis" algorithm (see [16]). The result of such selection is a smaller dimension progenitor model.

$$H'(s) \in \mathcal{R}^{q' \times r'}(s), \quad q' \leq q, \; r' \leq r \tag{4}$$

where $rank\{[C' \quad D']\}$ and $rank\{[B'' \quad C'']^t\}$ are full and thus, there are no zero minimal indices in $N_l\{H'(s)\}$ and $N_r\{H'(s)\}$. However, we might have

$$rank\{H'(s)\} = \rho' < \min\{q',r'\} \qquad (5)$$

Problem 4. For a progenitor model with no input, output redundancy, but with $\rho' < \min\{q',r'\}$ define a redesign procedure, possibly of the instrumentation scheme to produce a progenitor model which is nondegenerate.

Problem (4) is an open issue, as far as redesign of a badly designed system and will be referred to as the *Elimination of Essential Redundancy Problem.* A solution may be provided by using subsets of inputs, outputs such that the resulting subsystem has full rank. The issue now is to select maximal cardinality subsets of inputs, outputs to achieve the nondegeneracy property. The parametrisation of all possible such schemes is also an important issue that has to be resolved here. The result of the solution of Problem (4) is a family of well structured Progenitor Models.

3 Definition of Effective Input-Output Structure

We consider a well structured Progenitor Model represented by the transfer function matrix $H(s) \in \mathcal{R}^{q \times r}(s)$. Such a model may be of excessively large dimensions and the problem which is considered here is the definition of a smaller dimension model

$$\tilde{H}(s) \in \mathcal{R}^{m \times p}(s),\ m \le q,\ p \le r \qquad (6)$$

which has inadequate input, output structure for the control and measurement requirements of the problem. The selection of the effective input, output structure is based on criteria using system properties on models which are progressively more detailed. Such a framework involves the following steps:

Step 3. Determine the minimal required cardinality of the input, output structure, which is required to guarantee certain control and measurement properties.

If m, p are the effective numbers of outputs, inputs respectively, then assuming that n is the McMillan degree of the $\tilde{H}(s)$ progenitor model, we can use the results on the generic solvability of control problems described in [5], as well as any structural information, such as Segré Index to define desirable values for m, p. The results on the generic values of the structural invariants, as well as their classification described in [11] are also essential here. An important subtask for this activity is:

Task 1. Develop a library of structural conditions and a procedure for working out the optimal values of m, p given the control and measurement requirements. •

The integral part of the above analysis is the solution of the following problem:

Problem 5. Identify robustly the basic structural characteristics, such as McMillan degree, orders of infinite zeros, Segré characteristic, etc. on early models which may be characterised by uncertainty in dynamics and parameters. •

This problem is referred to as *Structural Identification Problem* and this area is still in its early stages of development. It is worth noting that in this step we require the least possible information from the progenitor model to decide on the required number of inputs and outputs. A special case of this problem related to McMillan degree is discussed in [18].

Step 4. Define all possible pairs of subsets of the input, output structure which are needed to guarantee basic structural properties, such as structural controllability, observability, system vulnerability etc. •

In this step we exploit the fundamental underlying graph structure of the progenitor model, which requires some more detailed information. We use graph theory for such an evaluation and some of the first results in this area are represented in [10]. The aim of this investigation is to produce more well structured alternatives, than those specified by the investigation in Step (3), which have to be further investigated with criteria which are more detailed than those of the graph type structure.

Step 5. Evaluate the pairs of input, output structures produced by the previous step and specify new alternatives using parameter depended structural invariants such as zeros, specific values, controllability, observability indices, properties of Plücker matrices, Forney orders, etc. •

At this stage we progress to the stage where linear models with given parameters (rather that graph models) are used and the whole family of model projection problems is deployed to evaluate existing structures and proceed to the definition of more well structured alternatives. This is the area where structure assignment, or structure formation avoidance problems are used. The results in [2], [3] and [12] and a related research paper on Model Projection and structure assignment [14] are important here. Once more, this is an area where the project has introduced a framework and has made some important steps. However there is still much to be done in this area. The results of this investigation is the definition of a smaller set of input, output structure alternatives, which probably have to be further evaluated with some additional criteria. In fact, the definition of certain structure assignment problems, such as that in [17], may lead to a parametrisation of the possible solutions from this set requires alternative means which are provided by the following step.

Step 6. Specify the free parameters, or use the free variables in the parametric form of solution of structure assignment, or structure avoidance of the previous step by exploiting criteria based on the values of performance indicators, such as energy transfer, or requirements, degree of controllability, observability, robustness of properties under system uncertainty etc. •

At this stage we deal with a well structured linear model, or a family with free parameters which satisfy certain structural conditions. The problem we face is to retain the achieved structural features and achieve some additional properties for the input, output structure by tuning parameters. We may use a great variety of performance tests and criteria, such as energy requirements for control and observation, as it has been developed in [9], as well as other properties such as maximising the degree of controllability, observability, reduction of sensitivity to parameter uncertainty, etc. The current stage of development of this area is dominated by the effort to define meaningful tests and criteria. The next stage has to do with the formulation of appropriate optimisation problems for achieving the best possible tuning.

It should be noticed that the analysis so far is based on structural characteristics first, which determine the potential for control performance and progressively more to performance indicators shaping, after having specified the basic structure. The overall philosophy which underlines this approach is to sort out first the structure formation by solving well defined synthesis problems, define families of such solutions and then use multiobjective optimisation for selection of free parameters in the available alternatives. The result of this procedure is a well structured model $\tilde{H}(s) \in \mathcal{R}^{m \times p}(s)$, on which the control design problem has to be addressed. The important subproblem of this major activity is the definition of the structure of the control scheme, i.e., sorting out issues on decentralisation, versus centralisation.

4 Structuring of Control Scheme: Evaluation of Decentralised Options

The problem we now address is the selection of the structure of the compensation scheme that involves answering questions on whether we have to use centralised, or decentralised schemes; if decentralisation is needed, then to decide on the partitioning of the input, output channels, as well as the way we have to couple them in a feedback, or precompensation configuration. An integral part of this design stage is also the specification of the required order of dynamics. With the exception of the work on interaction analysis [17], this is the first attempt to develop an integrated approach to the structuring of the Control Scheme problem. Our approach involves the following steps.

Step 7. Use knowledge on the process, geographical location of process units and operational requirements, such as the nature of optimisation problem, to define a first appraisal of options as for centralisation versus decentralisation. If decentralisation is needed, then the physical arguments lead to the first structuring of the decentralisation scheme, referred to as *feasible decentralisation.*

This step aims to take into account the particulars of the application area and nature of the problem. This knowledge is indispensable and it is part of the overall problem specification. What is expected at this stage is the development of the first structuring of the schemes in terms of superblocks, which themselves may require some further structuring subsequently. It is worth mentioning that the requirements of the overall problem decomposition, based on either on performance optimisation (operational), or subproblem design have to be taken here into account. This area is dominated by the process dependent specifics, heuristics, but there is also need for work which has to be based on the systematic study of the problem decomposition (operational and design aspects). This area of work may be considered as a part of the control structure selection on a whole plant.

Step 8. Use results on the generic solvability of decentralised control problems to produce a first parametrisation of alternatives.

The study of decentralised control problems has produced some results characterising generic solvability of control problems which lead to parametrisation of possible partitions of input, output channels which permit solvability of control problems. These results depend on structural characteristics such as the McMillan degree and the numbers of inputs, outputs. A review of this methodology and available results is given in [5]. This analysis is the first step in the evaluation of the alternative schemes, based on advanced control methodologies.

Step 9. Use of graph analysis methodology and the concept of structural fixed modes for evaluation of alternatives defined by the previous step.

For systems which have an explicit graph structure, a procedure for evaluating alternatives based on the exclusion of structural fixed modes may be used as a first structural methodology that uses the most basic structural aspect, the system graph. It is clear that the results have explicit deeper structural characteristics based on the graph rather than those of the previous step.

Step 10. Use of interaction analysis diagnostics based on steady state models, or simple dynamic models to evaluate the alternatives produced at the previous stage.

Progressing from graph models to steady state, or simple dynamic models, we may use the large number of diagnostics of the RGA, BRGA type to evaluate further the options specified in the last step. In [7], there is a variety of tests for interaction analysis based on simple models. After this stage we may progress to further evaluation described below.

Step 11. Advanced structure selection diagnostics based on linear dynamic models and parameter dependent structural characteristics.

At this stage we proceed with the evaluation of the available options using linear models and parameter dependent properties such as fixed modes (non structural), almost fixed modes under various dynamic modes, properties of the rank of decentralised Plücker matrices, strong instability and minimum phase phenomena, etc. Report [6] describes the exterior algebra diagnostics which include a large number of tests, as well as paper [8] on decentralised Markov parameters. Within this family the Decentralised Markov parameters are first used, since the computations involved are relatively simple, and then we proceed to the more complex algebra tests. In all these studies we use as a test the avoidance of formation of undesirable characteristics (fixed, almost fixed modes, loss of rank of Plücker matrices) or preconditioning of properties (full rank of Plücker matrices). In fact, the decentralised Markov parameter test also provides the means to modify the centralised input, output structure in order to guarantee certain properties.

Step 12. On a full dynamics linear model, use diagnostics based on performance indicators to evaluate the alternative decentralisation schemes, which have been specified by the previous stage.

Having exhausted all structural methodologies and tests to reduce the set of options (necessary conditions have been mostly used) we now use computationally intensive methodologies such as singular value analysis structural singular values, properties of cost balanced realisations, energy requirements for coupling, etc. Such an area of diagnostics is quite rich, but there is still need for improvement, as well as sorting out alternative criteria.

5 Conclusions

An attempt has been made for the first time to provide an integrated methodology for selection, classification of process variables, shaping of the input, output structure and evaluation of alternative decentralisation schemes. The overall approach has been based on exploiting the different aspects of the underlying system structure going progressively from unstructured model diagnostics, to graph structure based results, to model parameter dependent invariants and finally performance indicators. This structural methodology reflects the overall structural philosophy and it is quite logical for the overall problem. In fact, starting with a large number of options we first use simple theory and criteria and progressively by reducing the set of options we start using more detailed and meaningful criteria, which however are associated with more computationally intensive procedures. What we have provided so far is an overall methodology and in the various steps, new, as well as known results. There are many areas which need development if we are to move to an integrated and substantial structure selection diagnostics framework. Generating the different alternatives in a systematic, and not in an ad hoc manner, sorting out the multiobjective decision problem of alternative criteria and finally moving for evaluation to design are open challenges in the future. So far we have relied on the structural approach which is quite meaningful at early stages and for sorting out many options. At the later stages there is a need to develop optimisation methodologies for tuning parameters within a given selected structure. This is also an important area for future research, where tools from the H-∞ optimisation methodology may combine with the structural approaches to provide powerful hybrid methodologies.

OVERALL METHODOLOGY FOR CONTROL STRUCTURE EVALUATION AND SELECTION

AREA (A): Classification of System Model Variables and Definition of Well Structured Models

Step 1. Physical Classification of Variables: Family of Progenitor Models

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Step 2. Selection of Well Structured Progenitor Models

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AREA (B): Definition of Effective Input, Output Structure

Step 3. Minimal Input, Output Cardinality and Genericity

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Step 4. Minimal Graph Based Required Input, Output Structure

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Step 5. Evaluation of Alternatives Based on Invariants

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Step 6. Final Evaluation of Input, Output Structure Based on Performing Indicators

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AREA (C): Structuring of The Control Scheme

Step 7. Physical Structuring of Control Scheme

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Step 8. Parametrisation of Alternatives Based on Genericity

⇓

Step 9. Graph Analysis Evaluation

⇓

Step 10. Interaction Analysis And Simple Models

⇓

Step 11. Advanced Structure Selection Diagnostics Based on Structural Features of Full Models

⇓

Step 12. Advanced Structure Selection Diagnostics Based on Performance Indicators of Full Models

Figure (1): *Overall Methodology for Control Structure Selection*

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