Control structure design : a survey

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Control Structure Design: A Survey

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Abstract

The paper focuses on the selection of measured and manipulated variables and decentralized control configurations as a sub-problem of control system design. It outlines the key ideas of various methods encountered in literature and recommends topics for future research.

1. Introduction

The design of a control system as in Fig. 1 involves the following steps: definition of the control objectives z , derivation of a nominal model G_0 (Δ represents modeling errors), *Control Structure Design (CSD)*, controller design K , control system evaluation and tuning, and finally, controller implementation. In this paper, CSD is defined as the stage of control system design in which the number, the place and the kind of manipulated variables u (w represents exogenous inputs, e.g., disturbances, sensor noise and reference signals) and measurements y are selected, followed by selection of the structural interconnections between measured and manipulated variables. The first phase in CSD will be called the Input Output (IO) selection phase. It is emphasized that in this context the word "output" refers to *measured* variables and not to variables to be controlled; the latter have to be formulated preceding CSD. The second phase in CSD will be called the Control Configuration (CC) selection phase. CC selection must be performed when designing decentralized control systems, and refers to the process of specifying which outputs are used to determine each input, i.e., the structural interconnections in K are specified.

Figure 1: General representation of a control system

Contrary to controller design, CSD has only been paid limited attention to. Nevertheless, an appropriate selection and interconnection of measured and manipulated variables is as important as controller design itself: a wrong choice for the controller structure may put fundamental limitations on the system's performance, which cannot be overcome by advanced controller design [18]. Moreover, the *complexity* of a control system, which in this context is defined as the sum of the number of inputs and outputs and the number of feedback interconnections between them, is largely determined by the underlying control structure. Usually, a more complex control system will be more expensive, less reliable, and harder to maintain [29].

The main contributions of this paper are the following. Firstly, it provides an overview of CSD methods, which is believed to be rather complete. Secondly, a set of criteria is proposed which may serve as a basis for a preliminary classification of CSD methods from literature, or newly developed ones.

In Section 2, some examples of CSD are mentioned, revealing that CSD is important in a wide variety of control applications. Section 3 proposes some criteria which a CSD method desirably accounts for. In Section 4, key ideas of various IO and CC selection methods from literature are listed. Two approaches for CSD which offer good prospects, indicated by their ability to address the criteria in Section 3, are discussed in Section 5. Finally, Section 6 provides remarks on the state of the art in CSD and suggests topics for future investigations.

2. Applications

Obviously, a straightforward algorithm for CSD is particularly important for large-scale control systems, i.e., systems for which a large number of potential inputs, outputs and controller configurations exists. As a consequence, it is not surprising that the greater part of literature on CSD stems from

process control. In this research area, CSD is related to, *e.g.*, the optimal placement of temperature sensors in distillation columns [16, 19, 24], IO selection for double-effect evaporators [25, 27], input selection for heavy oil fractionators [31], IO and CC selection for the fluidized catalytic cracking process [13], and CC selection for distillation columns [11, 33] and boiler furnaces [22, 29]. In [29], the Tennessee Eastman plant-wide control problem is used to illustrate a method for CSD. In [20], CSD is applied to a thermally integrated distillation sequence.

However, CSD also plays a crucial role in aircraft control [29, 32] and in the design of active suspensions for vehicles [2, 34]. Furthermore, a proper placement of sensors and actuators is of great importance for controlling flexible structures, see, *e.g.*, [1, 6, 28]. The selection of actuator locations for satellite attitude control is discussed in [26].

For a detailed survey of applications for CSD, the reader is referred to [34, Chapter 5].

3. Important aspects for CSD

In practice, CSD is often carried out in an intuitive and ad hoc fashion rather than systematically: engineers use experience, simulation and trial and error to guide IO and CC selection. Particularly for large-scale systems, favorable candidate control structures may easily be overlooked. Since the number of alternative control structures grows extremely rapidly as the complexity of the system to be controlled increases, ad hoc and inefficient search techniques for CSD are rendered impractical for such systems. Therefore, research should be aimed at the development of more systematic and quantitative approaches to CSD, in order to replace the more qualitative ones based on engineering heuristics.

Assessing existing tools or developing new ones for CSD, a set of criteria is needed. Since it is infeasible to account for all possible criteria, only a restricted set is suggested here, which is believed to represent the most important properties the "ideal" CSD procedure should possess.

- It must be possible to achieve *robust performance* with the controller structure. This property implies both *robust stability* and *nominal performance*, which could themselves serve for screening candidate control structures.
- It must be possible to impose the maximally allowable *control system complexity*.
- Desirably, the CSD method is *generally applicable*, *i.e.*, the method should be suitable for a large

class of control systems, *e.g.*, nonlinear systems, systems with an unequal number of inputs and outputs, and control systems for which a particular frequency range is of special interest.

- *Independence of the controller design method* (*e.g.*, PID, $\mathcal{H}_\infty$, sliding mode control) *and tuning* is very important for initial screening of a large number of candidates: it must be possible to eliminate those candidates for which there does not exist any controller satisfying the control objectives. Especially in the case of a huge number of alternative structures, a controller dependent approach is undesirable, since this requires the controller structure and the controller itself to be designed simultaneously, which may be very time-consuming.

- Usually, CSD is based on testing all individual candidates for a set of feasibility criteria; candidates which do not satisfy a criterion are excluded from further considerations. In that case, the design is iterative and indirect. Preferably, a CSD method *directly* yields one, or maybe some, favorable control structures given the control system specifications.

- *Efficiency*, which is related to the amount of analytical and computational effort, is also an important property. It must be possible to quickly and easily evaluate huge numbers of candidate control structures.

- Finally, a CSD method must be *effective*, *i.e.*, it must be able to eliminate infeasible candidates and maintain feasible ones. Note that effectiveness calls for necessary and sufficient conditions as feasibility tests. Unfortunately, such conditions often require the design of the controller, and may therefore be inefficient for initial screening purposes.

4. Key ideas in CSD

In this section, the fundamental ideas of various IO and CC selection methods encountered in literature are listed, the greater part of which is developed for *linear* systems. In Section 5, some additional concepts are amplified. For a more extensive review and more detailed discussion on the various methods, the reader is referred to [34].

4.1. Key ideas in IO selection

- In [30], selection of inputs is performed based on *control power and speed*, *i.e.*, the influence of the inputs on the variables to be controlled should be large. A related concept for input selection, applying the Morari Resiliency Index, can be found in [35].
- It is well-known that *Right Half Plane (RHP) poles and zeros* of the plant impose limitations on the achievable performance [9]. In [12, 32], it is suggested that IO selection must achieve that a mini-

mum number of RHP zeros occurs, and that they are as far away from the imaginary axis as possible.

- Structural *controllability* and *observability* concepts are often used for IO selection, see, *e.g.*, [25]. In [6, 26, 32], quantitative measures for controllability and observability are suggested as screening tools.

- A procedure for generating alternative feasible IO sets based on the *cause-and-effect* graph of the system at steady-state, is discussed in [10]. In fact, the method uses state accessibility as a criterion for input selection [25]. Since *nonlinear* systems can also be represented by cause-and-effect graphs, the method is expected to be applicable to such systems as well.

- In [16], measurements are selected such that the accuracy of the state estimates is the best possible. A related method is proposed in [28], in which noisy actuators and sensors, both with dynamics, are chosen to *minimize certain cost functions in LQG control*.

- *Economic optimality* while maintaining good controllability characteristics is the motive for IO selection in [27]. The minimum plant condition number and the location of RHP zeros are used as controllability indicators.

- The *Singular Value Decomposition* (SVD) of the plant is often encountered as an IO selection tool, see, *e.g.*, [24] for measurement selection and [15] for input selection.

4.2. Key ideas in CC selection

- In [12], it is stated that a decentralized control configuration should be chosen to *avoid unstable decentralizedly fixed eigenvalues*.

- In [8], CC selection is based on the *relative degree* of an output with respect to an input, as a characterization of dynamic interactions in a system. The proposed method is also suitable for *nonlinear* control systems. Furthermore, it seems to offer prospects for IO selection as well.

- The so-called *Relative Gain Array* (RGA, see, *e.g.*, [33]) is undoubtedly the most widespread measure for interaction analysis and CC selection for fully decentralized (*i.e.*, a diagonal controller is used) control systems. The Block Relative Gain [22] generalizes the RGA to block-diagonal controllers. Closely related concepts are the Dynamic Block Relative Gain [3], the Performance Relative Gain Array [33] and the relative sensitivity [4]. In [21], the (Dynamic) Nonlinear Block Relative Gain is introduced as a CC selection tool for *nonlinear* systems.

- In [14], a measure for *potential interaction* between control loops is proposed to determine preferable IO

pairings in fully decentralized control systems.

- The *numerical invertability* of the plant at steady-state is shown to be a physically meaningful measure for interaction analysis and IO pairing in [23].

- *Closed-loop integrity*, which refers to the ability of a decentralized control system to remain stable if one or more control loops are out of service, is the motive for CC selection in, *e.g.*, [7].

- In [17], a *SVD-based* method is developed which indicates loops that interact minimally with other loops, and thereby the IO pairings which are preferred to control the system.

- In [12], the *direct Nyquist array*, which stems from stability margin considerations, is proposed as another tool for IO pairing.

5. Two CSD methods highlighted

In this section, the key ideas for two additional approaches for CSD are treated in more detail. Based on the set of criteria in Section 3, the methods of interest seem quite promising for *linear* systems [34, Chapter 6 and 7]. It is emphasized that *not all* criteria are satisfactorily addressed.

5.1. Method based on robust stability and performance degradation

In [29], a method for CSD is proposed, which is implemented in the MATLAB Control Configuration Design Toolbox. Feasible control structures are obtained by successively performing IO selection and CC selection.

The fundamental idea for IO selection is maintenance of robust stabilizability of a control system under additive ∞ -norm bounded perturbations Δ , see Fig. 2. A necessary condition is derived for the existence of a controller which achieves robust stability and makes the largest singular value of the nominal closed-loop sensitivity $S = (I + P_0 C)^{-1}$ smaller than a specified value in a specified (low) frequency region. The latter property is interpreted as a performance measure, since S is crucial for both tracking and disturbance rejection problems. The condition is expressed as a computationally simple test on the condition number of the nominal plant P_0 , with rows and columns corresponding to the selected outputs y and inputs u . Candidate IO sets which do not satisfy the criterion are rejected.

Next, a proper (block) diagonal decentralized controller configuration is searched for. The selection criterion is based on the idea that the performance degradation must be restricted, which is due to application of a decentralized configuration instead of

Figure 2: Additively perturbed control system

the centralized one. In a centralized control system each input u is determined by feedback from all measurements y , i.e., full information exchange takes place. In a decentralized control system there is only a limited information flow through the controller, by which the performance may suffer. Candidate configurations for which the expected performance degradation is larger than a specified measure are rejected.

A major disadvantage of the CSD method described above is the prior assumption that the selected measurements y are strongly related to the variables to be controlled z , which in principle may be different (see Fig. 1). Under this assumption and the with set-up of Fig. 2, one tries to control z by means of controlling y . However, since the IO selection criterion only accounts for robust stability, an IO set may be selected for which the system is robustly stabilizable indeed, yet for which the control objectives in z can not be satisfied anymore, and is therefore infeasible. In addition, CC selection is based on performance degradation with respect to the measured variables. This is not consistent, since performance is incorporated in the variables to be controlled z . A method which circumvents these problems is discussed in the following section.

5.2. Method based on robust performance

In [18] the concept of structured singular value μ is used for measurement selection, while in [11] it is shown to be a useful tool for configuration selection; in [5, 31] methods are proposed to perform both IO and CC selection by applying μ -based screening tools.

Consider Fig. 3 with G_0 the generalized plant including the nominal plant model and weighting functions, K the controller, Δ_u the uncertainties and Δ_p a fictitious perturbation block introduced to account for performance; w , u , z and y have the same meaning as in Fig. 1. Robust performance is achieved for all $\|\Delta\|_\infty \leq 1$ if and only if $\mu_\Delta(F_l(G_0, K)) < 1$, with $\Delta = \text{diag}(\Delta_u, \Delta_p)$ and $F_l(G_0, K)$ the nominal closed-loop system. The usefulness of the μ -framework lies in the fact that it allows many uncer-

Figure 3: Control system set-up for μ -analysis

tainty and performance specifications to be captured simultaneously.

In [31], μ -based selection tools are derived for satisfaction of constraints, robust stability, combined constraints satisfaction and robust stability, nominal Decentralized Integral Controllability (DIC, see, e.g., [5]), and combined constraints satisfaction, robust stability and DIC. Unfortunately, these tests are restricted to steady-state and are based on maintenance of integral control under uncertainty. In practice, the dynamic behavior of the system may be more important, which the suggested tools are unable to address.

Screening tools for CSD applying the structured singular value, both for controllers designed by robust loopshaping and tools independent of the design method, are developed in [5]. Again, the majority of them is derived under the assumption of integral control and restricted to steady state. The practical usefulness of the tools and the possibility of generalization to frequencies other than zero is currently investigated by the authors of this paper.

6. Discussion

To date, a CSD method which meets the set of criteria in Section 3 does not exist. Even the most promising methods show severe shortcomings. Therefore, further investigations will be performed. In the near future, our research will be aimed at achieving the following goal:

Minimize the number of measured and manipulated variables selected and the interconnections between them, subject to the achievement of robust performance.

That is, even in the presence of modeling errors, stability and performance must be achievable with the selected controller structure. Developing new tools,

non-square control systems and dynamic aspects deserve special attention. Additionally, measured variables y and variables to be controlled z must be clearly distinguished and treated separately; this is possible by representations as in Fig. 3.

For nonlinear control systems, almost nothing is known. Ideally, CSD for these systems is based on robust performance as well. Therefore, it will be investigated if it is possible to generalize $\mathcal{H}_\infty$ - and μ -based selection tools to nonlinear systems.

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