COMPUTER AIDED CONTROL SYSTEM DESIGN

Methods, Tools and Related Topics

Edited by

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World Scientific

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Foreword

The TEMPUS Join European Project "Education in Control Systems and Information Technology" has initiated various activities within several participating institutions from the European Community and Poland. The emphasis was put during the first year of project realization on direct control system design supported by suitable computer based tools. These tools for *Computer Aided Control System Design (CACSD)* are now used in current industrial practice. Student of control engineering should acquire experience in using those tools and be then able to contribute towards their development.

With this objective in mind the Summer School on CACSD was organized and took place in the Institute of Automatic Control of the Warsaw University of Technology in September 1991. A Core Course for this school was prepared in the School of Electronic and Electrical Engineering of the University of Birmingham. The material for the Core Course consisted of several articles presenting various concepts, tools and case studies within the framework of CACSD.

Since wider context should be kept in mind, several specialists have been asked to present lectures on related topics. Those lectures introduced and discussed many concepts and techniques, like multi-layer and multi-level structures, software tools and fast computational algorithms for on-line control implementation, techniques for modeling discrete event systems and other issues.

After the school it was felt that the material presented there was well worth to be published in the form of a book. The current state of the art of CACSD tools and their applications described in much detail by specialists from several countries, including professional design engineers from the Cambridge Control, should be useful both in teaching the advanced courses in CACSD and in engineering practice. The articles on the related topics can be helpful to get a better grasp of concepts and techniques for building *integrated control systems of the future.*

The book is organized as follows. The leading article by W. Findeisen, M.A. Brdyś and K. Malinowski presents an overview of basic concepts and issues related to control systems, structures and algorithms. Since this book is mostly concerned with computer based support tools for direct control design, particular attention is focused on this control layer. References are made to other articles in order to relate their contents to the main notions introduced in the leading article. A broad view of control structures is also presented and related to the contents of the articles contained in the second part of the book. Therefore the leading article can be seen as an extended technical introduction to the book.

Main body of the book is organized into two parts. The first contains the articles on CACSD, while in the second, several articles on the related topics have been included.

The editors would like to use this opportunity to thank all authors of the articles included in this book as well as to express gratitude to all persons who contributed to the success of the Summer School. It is hoped that their efforts will bring even greater profit to the academic and industrial community when this book is made available.

Contents

Control problems and control systems; an overview

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Abstract

This article presents an overview of basic concepts and issues related to control systems, structures and algorithms. The principal objective is to introduce the concept of a multi-layer functional hierarchy and to discuss both the tasks and the means to achieve those tasks within a framework of different layers. Since this book is mostly concerned with computer based support tools for analysis and design of direct control algorithms, particular attention is focused on this control layer. Decentralized and hierarchical control or decision structures and algorithms can be required when the controlled process is a large or a complicated one; hence basic concepts are also presented and briefly discussed. Within the text references are made, when appropriate, to other articles included in this volume, with the aim to relate problems and issues considered henceforth with the main notions introduced in this article.

1 Introduction; controlled process and control system

Control problems and structures are considered and investigated in a vast body of literature as they arise in numerous applications and form essential components of industrial, transportation, communication and environmental systems. It is, however, surprisingly rare that one is presented with a clear picture of what a control system or a control structure is and with most important concepts and issues related to such system or structure. Since many important ideas and problems in control can only be explained and well understood when discussed bearing the full picture in mind, it is very important to provide such a picture. This, in particular, will make it easier for a student to understand the role played by different techniques and tools described in this book.

Within the body of this article references are made, when appropriate, to other articles included in this book, with the aim to relate problems and issues considered henceforth with the main introduced notions and concepts. No other references to the literature are made, as they can be found in those other articles.

Let us begin by introducing *a controlled process*. This is assumed to be *a given* entity which provides specified products or services. Basic inputs and outputs to a controlled process are depicted in fig. 1.

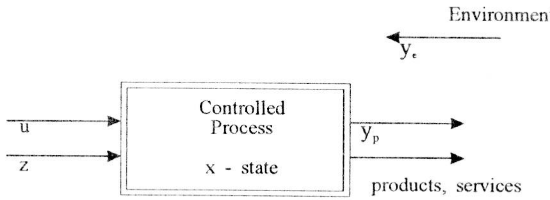

Figure 1 : The controlled process

Control is performed through the *manipulated inputs* (u), which can be adjusted within a specified range in order to enforce desired behavior of the process. The values of manipulated inputs can be changed either continuously in time or in specified, usually equally spaced, time instants or, finally, in not a priori predetermined instants, when something happens or may happen. The first case, with the continuous time, is for example typical in situations when one is concerned with operation of a chemical plant, with flight control of an aircraft, transportation of gas or electricity etc. The second case, with the discrete time, can arise after a priori discretization of a continuous time base or on its own – when process dynamics should naturally be described in discrete time. Imagine for example a production facility or an inventory storage in which material and product handling is described in, say, units per shift. The third case is concerned with a family of discrete event systems, representing many manufacturing or service systems, where events like for example an arrival of a customer, a call a request or a breakdown of a machine are occurring and may happen at any time. This book is concerned mostly with control problems and algorithms for processes with continuous or discrete time. Discrete event systems are discussed only in the article by N. Koussoulas who provides an excellent introduction and review of techniques for modeling and analysis of that kind of processes.

Apart from manipulated inputs u there are usually other external inputs to the process. Those are the uncontrolled inputs z, which are formed within the environment of the process. They are eventually an important source of uncertainty with respect to process operation. Inputs z are not necessarily disturbances to be – if possible – eliminated, they can also make an essential contribution to process operation and one may wish to accommodate them properly. Consider, for example loads in a power network, natural inflow to a water storage reservoir or a stream of incoming data packets in a communication network.

Evolution of a dynamic process depends not only on the present values of inputs but also upon cumulated effects of the past operation. In most cases those effects are represented by current process state x – i.e. by $x(t)$, where t denotes current time. Internal mechanisms defining the process behavior can be in some cases known quite precisely but, more often than not, they are also uncertain or largely unknown due to complexity of underlaying physical phenomena or to, partially or wholly, unpredictable changes of process characteristics. Basic knowledge about internal process mechanism is gained through modeling and identification and is at these days usually codified in terms of a computer based model which allows for calculating state and output values when given input trajectories and the required additional information, for example in terms of the initial state. At this point it is worthwhile to note that the concept of a state is much more powerful in case of continuous processes, where one can introduce *state variables* and equations describing *the rate of change* of those variables. In case of discrete systems it is only possible to talk about *the state values* – a number of which is in most cases enormous; this leads to fundamental difficulties when performing analysis and design of discrete systems.

Behavior of the process is observed through measurements y_p, which represent physical or other quantities accessible through specialized sensors and transducers. Also behavior of the environment can be observed through measurements y. They can be very important in case when they provide useful direct information about the values of inputs z or information about the evolution of processes which are behind generation of those inputs. Models describing this generation are complementary to a model of the process itself.

Finally, the process delivers products or services. It is the volumes and properties of those products that one is usually most concerned about.

The values of u, z, x, y_p and y_e may either change continuously or may attain only discrete values. In the first situation we talk about a continuous process, in the second about a discrete process. Quite often a mixed continuous-discrete case arises when some inputs or states can vary continuously while others are restricted to attain discrete values. It is important to note, that the notions of continuity or discreteness of process state and inputs are separate from the notion of a continuous or a discrete time – although of course processes with continuous time usually involve continuous state and inputs. On the other hand, discrete event systems, for example, involve typically discrete state and input values.

Desired behavior of the process is initially specified through rationally defined primary objectives (goals). Control objectives can be stated, for example, explicitly in terms of desired levels of some of the monitored variables. Typical objective of this category can be a desired reference trajectory to be followed. In fact most of classical control problems involve goals of such type. However, control objectives can be also given in terms of constraints to be observed and performance index, or indices, to be maximized or minimized. Those objectives may often be defined only for a large controlled process, say for a technological plant or a communication network, where the introduction of explicit performance measures, for example in terms of costs or profits, is possible in a natural way. This may well lead to a necessity to consider complex processes and to develop specialized tools for this purpose. Concepts related to decentralized and hierarchical techniques for analysis and control of complex processes are briefly presented in further sections of this article. Methods for hierarchical control of steady-state operated processes are in more detail introduced and discussed in the article by P.D. Roberts.

The controller is an entity which will enforce the desired behavior – as specified by the control objectives – of the controlled process through the manipulated variables u. The values of inputs u are adjusted , using *a decision mechanism,* on-line, i.e. in *real time*, based upon the observations of y_p and y_e. In fact it is the on-line use of these observations which makes the control problem so much different from an open loop optimization of input trajectories. The task faced by an engineer who wishes to design a controller for a given process depends both on the complexity of this process – including mechanisms of the uncontrolled input generation – and on the way in which the control objectives are specified and finally, on the on-line information available.

Together, the controlled process and the controller form *the control system.* Control system, depicted in fig. 2, is influenced by the environment both through input z and the information y_e concerning – directly or indirectly – this input.

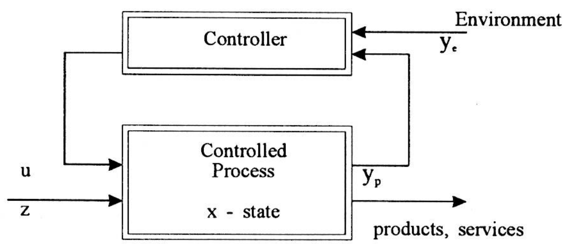

Figure 2 : The control system

2 Complex processes

It has already been observed that the control objectives may be often rationally defined only for a sufficiently large, complex, process. It may also happen that due to strong links between the process and its environment one has to consider an incorporation of a part of this environment into the process itself. This will happen, for example, if an important link is detected between the outputs of the initial process and some input z. In such case the controlled process will have to be redefined in order to encapsulate this link.

In case when one has to deal with a complex system it is important to recognize the nature of this complexity since it will influence further control design. At this point three cases are worth to mention:

- the process is composed of several *sub-processes* which are physically interlinked through *interaction couplings*,
- the process is composed of separate sub-processes but sharing *a common resource*, i.e. one of the control objectives is to observe a common constraint (global constraint) on inputs to several sub-processes,
- the controlled process is composed of separate sub-processes and there are no global constraints but a nonseparable *global goal* (performance measure) is defined for all sub-processes.

It is obvious that the above cases are not mutually exclusive and that, for example, one may have to cope with the situation in which there are several interlinked sub-processes, common constraints and a global goal.

Each sub-process will usually have its own manipulated input and an external uncontrolled input. In case when separate, independent, controllers are designed for different sub-processes we talk about *a decentralized control structure.* It is only in special cases when one can design such completely decentralized controller, but we will often have a decentralized control at the bottom (direct) layer of a vertical control hierarchy, which will be introduced in the next section.

When considering a complex system one may encounter a situation in which there are local decision makers concerned with their sub-processes and where those decision makers are goal conscious and have local objectives to follow – while these local objectives may be in partial disagreement with the overall control objectives as defined for the process as a whole. Such situation is typical, however, rather in the case when a management problem is considered. It will be further assumed in this article that we are concerned with a control problem case, in which no goal conscious agents a priori exist and that any part of the controller will be implementing such decision mechanisms which will be regarded as being appropriate from the global point of view.

3 Multi-layer control

Design of a controller as a single entity with a homogeneous centralized decision mechanism is possible only in situation in which the process is not a complex one and when the control objectives are simple enough. Such is the case when, for example, one is asked to provide for a controller which should stabilize angular velocity of the shaft of an engine under varying load. In more complicated situation a straightforward task of designing and then implementing a decision mechanism in a general form

$$u_t = \mathcal{R}_t(y_{[t_0,t]})$$

is too difficult and in many cases just impossible. In the above formula u_t denotes the value of u at the current control intervention instant t and $y_{[t_0,t]} = (y_{p[t_0,t]}, y_{e[t_0,t]})$ denotes currently available observation history.

One of the most important reasons that is likely to make the go-for-uniform-decision-mechanism an invalid approach is the complexity of the control problem together with a necessity to adjust the values of manipulated variables on a frequent basis. This in particular would create need to perform complex data processing in a very short time and thus would require extremely powerful real-time computer system. This issue can be even better appreciated after reading the article on the current status and the future of real-time systems by B. Fuhrt and W.A. Halang.

Well established way to cope with a design of a controller in case of a difficult, complex, control problem is to introduce *a multi-layer, vertical, control hierarchy.* A multi-layer controller consists of a number of *layers*, each of which is constructed so as to perform functions providing specified services for an upper level and to determine, at a given time scale, instructions required for operation of a lower layer (those instructions can be interpreted as the services requested from a lower layer). Control system with a multi-layer controller is depicted in fig. 3.

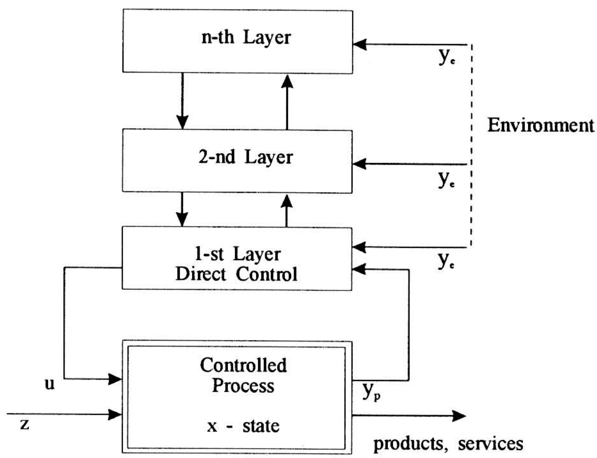

Figure 3 : Multi-layer control system

It is the first layer which performs functions related to direct manipulation of input u, i.e. it performs direct control of a process and so we will refer to it as to *the direct control layer.* This layer together with its decision mechanism has to be present in any automatic control system. In fact, quite often direct control layer is the only one, for example if the initial control objectives are stated in a simple way. In most cases direct control is concerned with regulation or tracking a desired trajectory.

As far as both the number of layers and their functions are concerned they may vary considerably and depend on a particular design. It is important, however, to note that the frequency of interventions as we move upwards the hierarchy is decreased while decision mechanisms become more complex and more optimization oriented.

From the point of view of each layer all what is below can be considered as the system controlled by this layer, say below the i-th layer there is a system which we denote by $S(i-1)$. Of course $S(0)$ is the initial controlled process itself.

At various layers different models (descriptions) of the controlled system will be appropriate, also different vocabulary may be used in communication between each pair of layers and, finally, different information with respect to process behavior as well as with respect to the outside world is required. The rule seems to be that while the required information regarding the physical process gets less detailed and, perhaps, less accurate as we move upwards the hierarchy, the information required with respect to the outside world (process environment) gets more rich and plays more important role.

The controlled system is not left alone. Above the controller there usually is *the management layer* (or layers). One may then ask what actually is control and what we mean by the management. In other words, which layer together with its decision mechanism belongs still to the controller and which should be already classified as a management layer. There is no a simple answer to this question. Possibly, one may associate a given layer with a controller whenever the associated decision mechanism is fully specified and the operation at this layer is, or can be, automated; that is, at least in normal operation, no actions by human beings are required. In case when important decisions have to be madein in-real time by human operators and the decision mechanisms are not fully algorithmized we should classify such layer as belonging to the management part of the system. It is important to note at this point, that as controlled processes grow in size and complexity and as more and more advanced algorithmic, computational and software tools become available, the more layers are being included into *a control hierarchy.*

4 Direct control

It has been stated above that the first control layer, concerned directly with setting the manipulated input to the controlled process, has to be present in any automatic control system. Most of this book is in fact devoted to decision mechanisms for direct control; in particular to the computer aided design of such mechanisms.

Control tasks defined for direct control stem from original, initial, overall control objectives, yet they are usually defined in much more simple and straightforward way. For example it may be required that the direct control stabilizes given dynamic technological process and regulates specified outputs of this process – *the controlled variables* – to a set of desired set points. The set-point values are determined either by the higher control layer or by the process operator himself. For example speed and