EDUCATIONAL ASPECTS OF USING COMPUTER AIDED DESIGN IN AUTOMATIC CONTROL

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Abstract. This paper covers aspects of utilizing Computer Aided Design (CAD) techniques for classroom exercises, laboratory experiments, and senior projects. During the past years, several CAD programs have been developed which are used by our students. Some of these programs are shortly described, and our experiences with their use by students is documented. Finally, some of the shortcomings of currently available CAD programs are discussed, and the paper points out how these could be overcome in the future.

Keywords: Computer aided system design; computer software; control system analysis; control system synthesis; digital computers; education; educational aids; interactive computation.

INTRODUCTION

With the ongoing concern for letting computers be easier accessed and used, new techniques have been developed allowing a more direct and "natural" dialogue between the computer and the human user, starting from free-form input and reaching to interactive, interpretative communication as CAD techniques.

Modern control theory is becoming a powerful tool for the design of systems due to the availability of computer programs offering a broad spectrum of methods and sophisticated algorithms.

A number of experiments have started to apply CAD techniques to assist engineering students in the manipulation of control systems. The direct interaction between user and computer system allows to experiment with the model. CAD promotes the creativity of the student or engineer. In particular, several papers have been published (e.g. in IFAC Barcelona: Trends in Automatic Control Education) which describe different concepts and philosophies being used in the development of CAD systems. From these papers, the following can be extracted:

1) There exists a trend towards interactive computation.

2) Most of the significant research activities in the development of CAD systems have been reported from Universities and Research Centers, whereas the computer manufacturers (which obviously cannot offer any dedicated task CAD programs) hesitate to release even appropriate frameworks to assist in the development of such CAD programs.

3) Most of the available CAD systems were designed and implemented by their users, that is, by engineers working in the respective area. This is a quite natural approach, as the design of a CAD system requires, first of all, a profound knowledge in the application field. Computer Scientists, usually, cannot share this knowledge with the engineers, whereas it is possible for an engineer to acquire enough programming skill to implementing a system which performs adequately, even if it is, from a computer science point of view, perhaps not a very good system. As a consequence, most available CAD systems lack the sophistication which computer science developed over the years in areas such as languages, data structures, and software engineering.

4) Most of the CAD programs in control have been designed for use on larger computer systems. Only a few of them can execute on a mini- or even microcomputer.

5) Evaluative and comparative studies of CAD systems for interactive control analysis and synthesis show that most of the available software packages are designed for a particular application field (i.e. identification, simulation, optimization, design), and that most of them are restricted to linear systems.

CONCEPTS OF CAD SYSTEMS FOR EDUCATION

This section shorthly describes why CAD systems are a valuable educational aid for teaching control, and how such CAD systems are to be structured to grant a most effective applicability for education.

The use of interactive CAD systems by students in control engineering

1) increases his ability to recognize design problems, and to structure and solve them,
2) strengthens his ability to think in models and algorithms,
3) increases his ability to investigate and appraise facts, and to draw decisions, and
4) advances the problem solving behaviour and the learning by observation (interactive analysis and design).

It is to be stated that interactive CAD is not the only means to assist the user in the design of a control system. Experience has shown that also a subprogram library (Cellier, 1977) can be a very valuable tool in student-, diploma-, and research projects. It offers a higher degree of flexibility as compared to a ready-to-use program. It gives the students the opportunity to design their own programs, to experience software being commonly used in industry, and allows to combine preprogrammed algorithms and methods required for the solution of a new problem. This approach is, however, restricted to long-term projects. It cannot be properly applied to classroom exercises where a solution of a given problem must be found in a couple of hours. The CAD programs as described in the following sections of this paper have been developed primarily for use in short-term projects such as classroom exercises and laboratory experiments. They have been partly coded by researchers and partly by students during their senior projects.

Generally speaking, the primary goal of an interactive system is to execute a program in response to receiving an input from a user at a terminal. During execution, the computer should perform some testing to detect inconsistencies such as improper inputs or incorrect sequences of processing steps. Errors detected during this parsing procedure should (as in compiler writing) never result in any abort condition, but should result in an error message being as illustrative as possible. Execution of the program must be accomplished in a way as to minimize response times.

Employing CAD in a flexible manner in order to satisfy the needs of the students requires an easy-to-use interactive program. This program has to meet the following requirements:

- suited for several levels of skill
- easy to use
- simple means of error correction
- straight forward interaction by graphical input/output
- transparency between different program modules, and ease of switching from one to another
- fast response time
- high degree of availability (multi-user system)
- open-ended for capacity increases and program enhancement.

Two different approaches can be used to control the communication between user and computer in an interactive program:

1) a command language may be used, in which the user can condense his ideas in a command line consisting of keywords, flags, and values to indicate a specific action to be taken, and
2) a question-and-answer game may be used, in which the user is prompted by the system to supply the required pieces of information one after the other.

It has been found that a command language or communication language is very appropriate for the skilled user who knows precisely what information to enter and in which sequence, since it guarantees a maximum of freedom in the choice of solution steps. On the contrary, the conversational program or question-and-answer method turned out to be quite satisfactory for the inexperienced user, since he is guided step by step through the solution of a particular problem, and is not even forced to consult a manual beforehand.

The INTOPS program (Grepper, 1977), which is shortly described hereafter, is designed for students in control engineering. The purpose of this program is closely related to the learning goals, to the educational aspects, and to the control curriculum. The program is structured to embrace the classical single-input/single-output linear control theory using frequency domain methods, and also the modern multivariable linear control theory using a state-space description in the time domain. A separate interactive simulation program allows for the analysis of nonlinear systems. The different programs communicate through a data base.

CAD PACKAGES FOR EDUCATION

The interactive program package INTOPS (INTeractive OPerationS) has been developed at the Institute for Automatic Control of the Swiss Federal Institute of Technology Zurich for educational purposes mainly. The following control problems can be solved by the use of INTOPS:

1) Analysis and synthesis of linear control systems in the frequency domain. The program part LFDOPS (Linear Frequency Domain OPerationS) operates on single-input/single-output (SISO) systems being described by their transfer function. Using the LFDOPS program, one can solve the following control problems:

   - Analysis: The following methods are available for the investigation of stability analysis, and also for both the transient and the stationary behaviour: root locus; Bode plot; Nyquist plot; Nichols plot; computation of poles; Routh and Jury stability tests; computation of time responses; determination of static error coefficients; system approximation by a pair of dominant poles; computation of loops.

   - Synthesis: Compensation in the forward path; parameter optimization by using the Parseval theorem.

   For the treatment of these control problems, the LFDOPS program places additional operation codes for polynomial definition (to enter, change and delete polynomials), for polynomial operations (addition, multiplication, division, computation of roots, partial factorization of rational expressions), and for polynomial representation (input and output of different polynomial representations) at the users disposal.

2) Analysis of linear continuous control systems in the time domain. The program part LTDOPS (Linear Time Domain OPerationS) operates on multi-input/multi-output (MIMO) systems represented by their state-space description. The LTDOPS program can be used for the solution of the following control problems:

   - Analysis: Determination of eigenvalues and eigenvectors; controllability and observability tests; determination of Kronecker invariants; simulation.

   - Control: Solution of Riccati equations; pole shifting; computation of observers, control observers, and dynamic compensators. The controlled system can be investigated by means of simulation, and also by sensitivity analysis of parameters and noise.

   - Handling of systems under the influence of noise: Computation of Kalman filters; estimation and optimal control; computation of the covariance matrices for state-, input-, and output variables.

   - Steady state decoupling: Computation of feedback and feedforward matrices for system decoupling.

   For the treatment of these control problems, additional operation codes for matrix manipulation are at the users disposal.

The interactive graphic simulation program DARE-ELEVEN (Korn, 1978) has originally been developed at the University of Arizona at Tucson. It has been implemented in order to allow interactive simulation of nonlinear systems with graphic support.

The interactive CAD programs may be used for:

1) Classroom exercises: For the purpose of better understanding of the control algorithms, the students may directly apply these different techniques to simple control problems. By use of the CAD programs, the time required to solve small control problems is reduced to such an extent that they can be successfully applied in classroom exercises.

2) Laboratory experiments: The aim of CAD experiments is the application of the control theory to more sophisticated design problems. During three hours, the student can design a control system by comparing different control algorithms to each other.

3) Student- and diploma projects: Some students are confronted with complex control problems for which new algorithms are to be coded and compared to each other. The most promising programs may, finally, be added to the CAD package in form of additional operation codes. In this way, the student learns to handle complex control problems (e.g. control of aircrafts), and the CAD package is continuously further developed.

   Other students are asked to investigate new ways of communication between user and computer system. By these means, the student can acquire principles of information processing, and he is forced to deal with fairly complex software systems.

   A third class of students applies some of the existing CAD software to the solution of their particular design problems as a part of their senior projects.

4) Demonstration during lectures: The CAD programs may also be used for demonstration purposes during lectures.

USAGE OF CAD PACKAGES IN LABORATORY EXPERIMENTS

As pointed out in the previous section, the CAD packages have been primarily used for educational purposes. Most of our experience results from laboratory experiments. For this reason, some of these experiments are described in this section.

They are organized in the following manner. The student receives beforehand a description of the task. This contains:

- a short review of the theory to be applied,
- a description and explanation of the problem to be solved, and
- the basic ideas behind the CAD program to be used.

During the lab, the student is given approximately three hours time to solve the problem.

In the following, we give a short description of two different laboratory experiments which are offered to the students, dealing with:

1) Interactive design of a compensator for a linear system. This experiment is carried out using the CAD program LFDOPS.

2) Investigation of a highly nonlinear system using simulation. This experiment is effectuated by use of the DARE-ELEVEN program.

Interactive Control Design

We consider a position control device with a DC-motor. The problem posed is to design a dynamical compensator in such a way that the compensated system meets some requirements of stationary and transient behaviour.

The educational aim of this laboratory experiment is:

- to illustrate the influence of different types of compensators (proportional, lead, lag, lead-lag), and
- to design a compensator in an interactive design process in order to meet given requirements.

During the design process, the student has to decide upon:

- what type of information concerning the systems behaviour he may use for his decision, and through which methods of analysis these pieces of information may be acquired,
- what compensator structure is needed, and how the parameters of this compensator may be determined.

To run this experiment, the student requires some knowledge of the methods of analysis and synthesis of linear control problems. The design procedure is illustrated in Fig. 1.

During this laboratory experiment, it must become clear that a design problem is more than a mathematically well defined synthesis task. The experiment proves to be successful in that it gives the student the opportunity to investigate a given design problem on his own.

Interactive Simulation Using DARE-ELEVEN

This laboratory experiment is offered to students during their fifth and sixth term. In three hours, they are supposed to simulate the world model, as presented by Forrester (1971), by use of DARE-ELEVEN. They are supposed to experience some control policies, and even to exercise a small optimization study. The students have not attended any course in simulation prior to this experiment, but they have been confronted with the state-space representation during an introductory course in systems techniques and communication.

This example has been chosen, because

- it seems to motivate students better than a "dry" technical system,
- the state variables of the model have plausible explanations and measurement units, and
- because this is the only example where our students are confronted with ill-defined systems, and where they can learn to judge computer results critically. (The students are encouraged, not to trust in a computer result just for the reason that the computer displays results with a precision of eight digits!)

The students are given the state equations and tabular functions in coded form as files on the system disk, but must weld them together to a running system description. They have, furthermore, to add statements for data storage and representation, for control strategies, etc.. They must also code the performance index and the optimization strategy on their own behalf. This experiment is usually their first contact with process computers and interactive modes of operation.

The goals of this laboratory experiment are manyfold:

- introduction to some basic principles of continuous system simulation,

- introduction to some basic techniques of nonlinear programming (gradient methods, convergence range, inequality constraints, convexity of performance index),

- introduction to highly aggregated modeling techniques, and

- cautious interpretation of results produced by the computer.

The students are given an explanatory text of 25 pages in which

- the relationship between the known state-space representation of a model and the introduced simulation system is shown,

- the concepts behind the world model are illustrated,

- the limits inherent in such a model are explained, among others by relating the decreasing birth rate in Switzerland to the shrinking number of storks, resulting in BRSMT, the Birth-Rate-from-Stork-Multiplier-Table (!), and

- an introduction to the DARE-ELEVEN system is given.

Students reported that they, usually, required about three hours to read and understand the experiment description. They were, in general, highly motivated, and we judge the success of this experiment as to be very positive.

DISCUSSION OF SHORTCOMINGS OF CURRENTLY AVAILABLE CAD SOFTWARE, AND PROSPECTIVES FOR FUTURE DEVELOPMENT

Existing CAD packages suffer, in general, from several shortcomings. As has been explained in the introduction already, most of the commonly used CAD packages have been developed by engineers with their actual application in mind. They are restricted to a particular application, and they are hardly ever combinable with any other piece of software. As interactive systems mature, there is a tendency for their functions to be expanded.

For this reason, one should try to develop a more general concept for data input/ouput which could be standardized, and which would, finally, allow to use the same data for different CAD packages. These data may be of several different types as model description data or time responses, they may be highly structured, and they may be numerous. For this task, we would require a very flexible data base system for data storage and retrieving. The connection of powerful data bases with CAD programs has not been sufficiently well studied to date.

With the growing complexity of CAD systems, the need for more sophisticated command languages becomes emminent. Much of the research which has been devoted to computer science during the past years could very profitably be applied to CAD systems in the future.

Most available CAD systems run on larger computer installations only. These installations, however, are not particularly well suited for interactive CAD. Many computing centers will not allow any interactive mode of operation at all, but run closed-shop batch-mode only. Many of the nicer features of CAD systems, as interactive graphical system definitions, will, in most cases, be restricted to use on minicomputers, to which the user has a more direct access. As soon as aspects of real-time computation become important, exclusive use of time-shared large computer systems becomes illusive. If real equipment is to be controlled, the tendency exists to carry a portable microcomputer to the equipment rather than to connect the equipment to a large computing center. This results in a demand for CAD subsystems to run on portable microcomputer devices, e.g. for data acquisition and reduction or for real-time simulation and control. Since the core memory available for programming on such computers is usually quite limited, it becomes important that CAD programs be partitioned into operational subunits which (once again) communicate data through a common data base.

Concerning the CAD packages which have already been developed and described in this article, the following enhancements may be expected:

1) Communication: Graphic system definitions may significantly simplify the communication between user and CAD package in case of complex systems being investigated. The user must be given the possibility to define basic building blocks, and to combine them to compound building blocks. These may be stored by a name and a symbolic representation in a data base. Building blocks may be composed in a hierarchical manner to form a system description. Basic building blocks for different types of systems (e.g. for continuous, discrete, or sampled data systems; for linear or nonlinear systems) may have different descriptions (e.g. in the time- or frequency domain). They should, however, be combinable to form one uniform system description. All of these operations should be executable by the user directly on a graphical screen. This would be the most "natural" way of describing complex systems since it corresponds precisely to what the engineer would do in real life.

2) Identification: In order to let the CAD system be usable for the analysis and

synthesis of real physical systems of which the mathematical description is unknown, the existing CAD package is to be enlarged by modules for identification of systems. The task of identification can be partitioned into

- data acquisition from a physical system (portable computer), and

- off-line identification (larger computer system).

These programs should be designed as stand alone programs which communicate data among each other and with other CAD programs through the data base.

3) System reduction: The investigation of large and complex systems brings about the problem of long response times and large memory requirements. These could in many cases be avoided by an appropriate reduction of the model order. Moreover, the most sophisticated model is not necessarily the best possible system representation, if, for instance, the available data are so bad that only a very rudimentary model can be validated. The appropriate model depends, furthermore, on the type of investigation for which it is used. For these reasons, appropriate algorithms for model reduction should be developed and added to the CAD system.

CONCLUSIONS

In the early seventies, a great enthusiasm existed concerning the applicability and usefulness of CAD techniques in control. This enthusiasm based on the enhanced capabilities of newer computer technologies. This primary enthusiasm meanwhile gave way to a certain disillusion, in that the development of powerful CAD systems requires a larger effort than originally imagined, and in that even the best CAD system can only help to intensify the control education, but cannot replace the classical lecture-oriented ways of teaching. However, CAD systems, if properly used, proved to be a very valuable enrichment of the control curriculum. By these means, the valuation of CAD as an educational aid became more realistic, and the goals of CAD systems could be concretized.

This paper has shown that the status quo of currently existing CAD systems is not satisfactory yet. Beside of the necessary technical improvements, which have been outlined in detail, it is important to increase the degree of availability of the CAD programs in order to make them accessible to a larger number of students.

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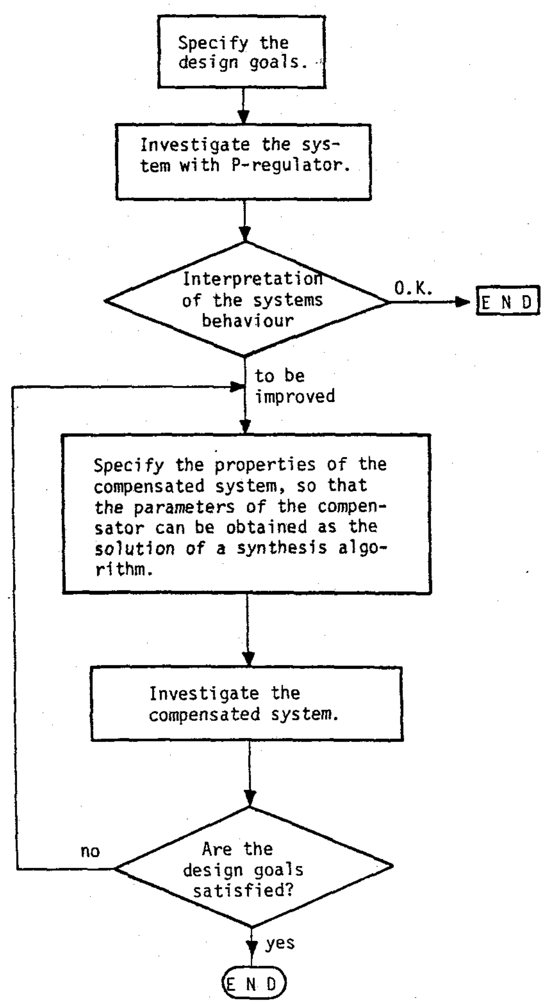

Fig. 1. Compensator design procedure