Computer Aided Design of Control Systems

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Abstract

Methods for computer aided analysis and design of control systems are developed. The techniques are based on interactive computer graphics. Packages for data analysis and system identification (IDPAC), model analysis (MODPAC), simulation (SIMNON), state space design (SYNPAC), and polynomial design (POLPAC) are described. The packages are all designed around a module (Intrac) which handles the interaction. Intrac can be used to obtain an interactive package from a set of Fortran subroutines.

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1. INTRODUCTION

The development of the digital computer opens new possibilities to do engineering design. Thirty years ago the major techniques for analysis and design of control systems were based on pencil and paper analysis in combination with graphics. When a digital computer is available the analysis and design can be done in very different ways. The purpose of this project was to explore different ways of using a digital computer in the fields of analysis and design of automatic control systems. The basic idea is to combine an engineer's experience and overview with the computing power of a digital computer in order to obtain efficient design tools. The approach includes both development of design techniques, which use the computational power of the digital computer, and the design of an interactive man-machine interface, which allows the engineer to interact with the computer. These two aspects were considered in the project. Control system design includes many different steps such as modeling, data analysis, identification, analysis, simulation, design and implementation. The algorithms needed and the type of interaction required in these phases are quite different. To get a good picture of the whole problem it was therefore decided to consider in the project examples of all the different steps. A brief review of the project and the major results are given in this report. We refer to the references for details.

2. OBJECTIVES

The objectives of the project were the following:

- To make advanced methods for analysis and design of control systems easily accessible to engineers, researchers, and students.

- To explore the potentials of interactive graphics for control system design.

The digital computer has had a significant impact on the methods used in control engineering. Many of the techniques developed over the past 25 years require that a digital computer can be used for the calculations. It has turned out that even with a digital computer and a good subroutine library it is a substantial effort to use many of the techniques. This tend to limit the usefulness of the methods substantially. In other words the methods are simply not cost effective. Another disadvantage of the conventional approach is that the problem solver often interacts with the computer indirectly through a programmer. This can lead to misunderstandings and mistakes. It is also a waste of resources. A major goal of the project was thus to investigate if it was possible to create an environment for problem solving so that the person with a problem could interact directly with the computer without intermediaries. The system should be so flexible and so easy to use that a person who understands the basic ideas of a technique should be able to get results even if he is not familiar with particular details of the numerical method. The system could thus also serve as a good learning tool.

Graphics has always played a major role in engineering. The first books used in engineering education were books of drawings of machines by Leonardo da Vinci. Ever since various forms of graphical representations have been used extensively. In control engineering many of the major design tools are still graphical. The availability of computer graphics thus seems to be a useful way to interact with the user.

The way graphics was used was constrained by the hardware that was available when the project was started. A minicomputer with 32 k bytes of core memory, a 512 k disk file and a storage oscilloscope was used originally. This amount of hardware is considered very modest today. There are now, however, also advanced color graphics which admit other types of interaction.

3. RESULTS

The project has resulted in

- ideas on the use of interaction for analysis and design of control systems,
- a comprehensive set of program packages,
- theory for design of multivariable control systems,
- four PhD dissertations, eleven MSc dissertations and many publications.

An overview of these results are given below. Further details are given in the references.

Interaction

When the project was started, it was by no means obvious how the interaction should be organized. The predominant approach at the time when the project was started was to use a fairly rigid question and answer dialog. This was for example used by our collegues in England (Imperial College and UMIST), Germany (University of Stuttgart) and Switzerland (ETH) with whom we have maintained close contact throughout the project. It was also common to mix the code for the interaction into the application routines.

In our project we discovered at an early stage that the question and answer approach was too rigid for an experienced user. The main disadvantage is that the computer is in command of the work rather than the user. It was therefore decided at a fairly early stage in the project to make the interaction command oriented. This had the unexpected effect that it was possible to create new commands easily. It was thus possible to use the packages in ways which were not anticipated when the packages were designed. The decision to use commands instead of a question and answer dialog thus had far reaching consequences. The commands can in fact be viewed as a high level problem oriented language. The ideas on interaction are further elaborated in Wieslander (1979), which is one of the main references.

Program Packages

A major result of the project is a comprehensive set of program packages:

Intrac
Idpac
Modpac
Simnon
Synpac
Polpac

which cover a wide range of control systems problems. The major work on the package Simnon was supported by ITM but it is part of the design suite. The different packages are described in detail in the references. A short description of their major features are given below.

INTRAC

The core of the interactive programs is a set of subroutines called Intrac. These routines handle the interaction between the user and the application packages. Intrac can be viewed as a tool which makes it possible to convert a collection of Fortran subroutines into an interactive package. Intrac thus handles command decoding. It also has a macrofacility. The macro handles:

- formal arguments in the commands,
- commands for control of execution of a macro,
- a facility for collecting a sequence of commands into a new command.
- input and output,
- commands which facilitates implementing a question and answer dialog,

o nesting of macros.

Intrac has a clean and welldefined interface to the application routines. This is in fact what makes it such a good tool for building the packages. It is a large advantage for the user that the interaction is implemented in this way. The interaction, the macro commands, and many general application commands for data handling and editing, are the same in all packages. This makes it easy to learn a new package.

Intrac has also been used to implement other packages by other groups. ITM has e.g. used Intrac in several applications. A detailed description of Intrac is done by its creators Wieslander and Elmqvist (1978).

IDPAC

Idpac is a package for data analysis and system identification. It contains commands for manipulation and plotting of data, correlation analysis, spectral analysis and parametric system identification. The basic techniques for parametric identification that are implemented are the least squares method and the maximum likelihood method. By using the macro facility it is however possible to generate commands for most of the parametric identification methods which are proposed in literature. There are also commands for model validation. Idpac can be viewed as a convenient way of packaging the research in systems identification that has been done at our department for a period of 15 years.

Idpac has gone through several steps of development. The latest version is described in Wieslander (1980b). The report edited by Gustavsson (1979a) is a tutorial on the package which has been used in courses. The reports Gustavsson (1979b and 1979c) contains many examples. The paper Åström (1980) gives the relevant theory for the parametric identification methods. It also contains a comprehensive set of examples of using Idpac.

MODPAC

There are many ways to describe a control system. Nonparametric methods in the time and frequency domain can be used. Parametric descriptions like state equations and rational transfer functions can also be used. There are also many ways in which state equations can be transformed. For digital control is is necessary to go between continuous time and discrete time representations. All these problems can be handled by Modpac. The package also has facilities for finding the Kalman decomposition of a system.

Modpac is described in Wieslander (1980c).

SIMNON

Simnon is a package for interactive simulation of nonlinear continuous time and discrete time systems. The package also includes noise generators, timedelays, a facility for using data files from Idpac as inputs to the system and an optimizer. Simnon has also gone through several stages of development. See Elmqvist (1973, 1975 and 1978a). Examples of using Simnon are found in a large number of MSc dissertations.

SYNPAC

Synpac is a state space oriented design package. It includes facilities for calculating state feedbacks, Kalman filters, and observers for continuous and discrete time LQG problems. It also has facilities for transforming continuous time problems into discrete time problems. This is necessary for digital control. There are also commands to design feedforward control. Synpac was one of the first packages that was implemented. A test version was made as an MSc project. See Noven (1972). Based on experiences from later work it has been improved and updated considerably. The current version is described in Wieslander (1980d). Applications of Synpac to the design of a realistic autopilot of an aircraft is described in Åström and Elgcrona (1976).

POLPAC

Polpac is a polynomial oriented design package for multi-output single-input systems. It includes algorithms for pole placement, minimum variance control, and LQG control. The package also has facilities for classical design using root loci and Bode diagrams.

Portability

The programs were initially developed on a minicomputer PDP-15. The programs were written in Fortran. A considerable effort was also devoted to development of subroutine libraries and programming standards. The advantage of using a larger computer for progam development was soon apparent. More powerful program development tools could then be used. The major development work was then shifted to a Univac 1108 at the university computing centre. Since there was a considerable interest from persons outside our own group to use the program a substantial effort went into making the programs portable.

It took a considerable effort to make portable code. This work included development of a complete set of Fortran routines for file, character and string handling. A plotting library in Fortran was also developed. These routines are interfaced with a welldefined small set of assembler coded routines. A series of manuals and implementation guides have also been prepared. See Schönthal (1977, 1978, 1980a, 1980b, and 1980c) and Essebo (1980).

A result of the efforts is that the packages are indeed portable. Packages are currently running on the following computers PDP-15, PDP-11, DEC-10, Vax 11/780, NOVA-3, ECLIPS, IBM 1800, IBM-360, CDC 1700, CDC-6400, HP-3000, Honeywell, SEL-32, Univac 1100, PRIME-750. Implementations on Nord computers are also planned.

Generalities

To summarize, the packages are coordinated and designed in a uniform way, since they are all based on the interaction module Intrac. This makes the different packages easy to use. Common data structures are also used in the programs. A datafile from Idpac can thus be used as an input signal file in Simnon etc. It is interesting to observe that many of these features were inspired by visitors who wanted to use the programs in new ways.

The packages are command driven. It is easy to create new commands either by using the macros in Intrac or by adding new commands and new applications directly in Intrac. The programs are separated into packages for expedience only. The packages are quite large as is seen from the Table 3.1. It is more manageable to keep them separate. It is, however, easy to generate special new packages based on commands available and new commands.

It is possible to solve many different types of control problems using the packages although they are by no means complete.

Theory for Multivariable Systems

At the start of the project it was clear that theory was lacking in several important areas, notably in the theory of multivariable systems. Work was therefore initiated in this field. The design problem for multivariable systems was investigated in Bengtsson (1973). Further work on this problem was done by Bengtsson. See the extensive list of

	Source code k lines	Program size kbytes
Intrac	7	90
Idpac	37	470
Modpac	41	570
Simnon	25	360
Synpac	43	630

Table 3.1 - Examples of program sizes.

publications in Section 8. Techniques for designing feedforward compensators and reduced order state feedback were developed. These methods have been incorporated in Synpac.

Further work on control systems design was made by Pernebo (1978). Inspired by Rosenbrock (1970) and others Pernebo used algebraic system theory to develop design techniques. Algorithms based on this approach are discussed in Pernebo (1980a and 1980b). Åström (1979c) has also given a comprehensive design technique for multi-output single-input systems based on the polynomial approach. These ideas are incorporated into Polpac.

Dissertations

Four PhD dissertations have been completed on problems that are closely related to the project, Bengtsson (1973), Elmqvist (1978), Pernebo (1978) and Wieslander (1979). See Appendix A. Several MSc dissertations have also been completed in the project. A list is given in Appendix B. Masters projects have to a large extent been used to test ideas and as feasibility studies.

State of the Art

As a result of the project we are now in the forefront of CAD in the control system community. This is e.g. manifested by a recent research proposal to NSF in the United States. See Spang and Gerhardt (1981).

4. INFORMATION DISSEMINATION

The interactive program packages are very powerful tools for solving control problems. They represent an effective way to package powerful theory in such a way that it is easy to apply to real problems. The availability of packages will have a drastic influence on the way control engineering will be practiced in the future. With the packages the engineer has very powerful tools available at his fingertips. The packages are thus one way to make control theory cost effective.

The packages have been used

- at our department,
- at other universities,
- in industry.

In this Section we will describe some ways in which the packages have already been used. We will also speculate a little on the future uses of the packages.

Uses at the Department of Automatic Control

A primitive version of the package Synpac was used as early as 1972 in connection with research projects. We have continued to use the packages ever since. The major reason was that the packages were very powerful problemsolving tools. A person can come to the computer terminal with a control problem and he can leave with a complete solution, or at least with a good approximation. The results are well documented in terms of listings and printing quality graphs. An important feature is that the problem is solved directly by the person in charge without needs for programmers as intermediaries.

The early use of the packages provided very good feedback to the development of the packages. At the early stages there was a continuous dialog between users and implementors. Very valuable input was also provided by visitors who often had different ideas on how to use the programs.

All staff members of the department and a large number of the students, who have done MSc dissertations, have used the packages. We have also used the programs in some of our advanced courses. The identification package Idpac and the nonlinear simulation package Simnon have been used most. We have found that Idpac is a very good tool to teach system identification. It is possible for the students to gain a lot of experience by working with real data. Similarly we have found that Synpac is an excellent tool for teaching LQG design. The students can work with realistic problems with reasonable effort.

It has also been our experience that the students who have experience in using the programs are good vehicles for transferring the programs to industry. It is difficult to appreciate the power of the packages if one does not have experience in using them.

So far the programs have not been used in the general courses. The reason has simply been lack of suitable hardware. To use the packages it is necessary to have a graphics terminal and a computer with a reasonable capacity. The computational facilities at Lund Institute of Technology have however recently been upgraded. There are now rooms with graphical terminals available for student use. In the spring of 1981 we will therefore try to use the programs in some of our regular courses.

Several courses are now beeing revised. In connection with this we are planning to make extended use of the programs. The simulation language Simnon will e.g. be used as a standard language for documenting models. We are also planning model libraries which will make it possible to use realistic examples in the courses. Similarly Idpac files will be used as the standard way to document data. Use of the programs will be standard techniques in many of our courses. It can be expected that this will also increase the industrial uses of the packages.

Use at Other Departments

The packages have been made freely available for use at other universities. Different packages have been installed at the universities of Lund, Stockholm, Göteborg, Linköping, Luleå and Umeå in Sweden at DTH in Denmark, at NTH in Norway, at the Technical University in Helsinki, at Imperial College in London and at University of California in Berkeley. Apart from departments of automatic control the programs have been used at departments of statistics (Idpac) and mathematics (Simnon).

Use in Industry and Research Institutes

The programs have also been made available to industry on a licence basis. The programs are currently used at

Time sharing services,
Träforskningsinstitutet in Stockholm,
Foa in Stockholm
Statens Skeppsprovningsanstalt in Göteborg,
Saab-Scania in Linköping,
ASEA in Västerås,
Angpanneföreningen in Stockholm and Malmö,
Sydkraft in Malmö,
Billerud-Uddeholm in Karlstad.

Several industrial users are also running the programs at the university computing centers from terminals. This is in fact the way we recommend new users to start.

We are currently discussing licence agreements with several industries both in Sweden and abroad. There is e.g. a possibility that Simnon will be used as a standard tool for documenting and monitoring the dynamic behaviour of nuclear power stations in Sweden.

The industrial use of the packages is interesting and encouraging. It was not anticipated when the project was initiated.

To spread knowledge of the packages we have also given a number of courses on the use of interactive computing. The following short courses have been given:

Interactive Computing for Dynamical Systems.
Lund May 22-23, 1975.

Use of Interactive Computing for Analysing
Dynamical Systems.
Lund June 1-2, 1976.

System Identification using Idpac.
Lund April 2-5, and May 8-11, 1979.

Simulation of Dynamical Systems.
Lund May 5-6, 1980.

We are planning to run courses of this type regularly in the future.

5. FUTURE WORK

In this Section we will give a few remarks on the current state of the project and some speculations on possible future work. We will start with a quick summary of the current situation.

The Current State

We have a collection of packages. They are very powerful tools for solving many different control problems. The packages are, however, neither complete nor perfect. The packages will be used as standard tools for teaching and research. They are also used in industry to a modest extent. We will continue to maintain the packages and to make moderate extensions of them in connection with the teaching.

In retrospect it was very important to keep the activity above a critical level. The effort required to make the programs portable was in retrospect very useful for the programs to be used outside the department. At times it felt like a very heavy burden because we were not doing new things just improving old. However we learned a lot about software and portability.

The Future

Since the interactive packages seem to be so useful, why should we not continue with the project and do further extensions and improvements.

Firstly, the packages are no longer good PhD projects. With our current approach it can safely be said that the innovation involved in making another package is marginal.

Secondly, it requires substantial resources to develop the packages. A permanent staff of 2-3 persons full time on a project is a minimum. This is a substantial commitment of resources in our environment.

Thirdly, there are dramatic changes in hardware and software under way. It is our opinion that these developments will drastically change the conditions for designing interactive packages. This is further elaborated below.

Better Numerics

There has been substantial advances in numerical software for linear algebra over the past five years. A substantial effort has gone into subroutine packages such as Eispack and Linpack which are now available in the public domain. A similar effort has not yet been devoted to the numerical calculations required for analysis and design of control systems. Within the project a modest activity was made to organize a Scandinavian Control Library of subroutines for control problems. Since 1965 we have also maintained a library at our department. It can, however, be safely said that much work still remains on the numerics. To stimulate activity in this direction we organized an international workshop on Numerical Problems in Automatic Control in Lund in september 1980. The workshop was very well received and there may perhaps be payoffs over the next ten year period.

Interaction Techniques

Interactive computer graphics is now started to be used in many places for many different problems. Consequently there is an accumulation of knowledge which can be incorporated into future packages.

Hardware

When the project was started we received criticism from some potential industrial users because our computer was too large. One remark was that anything which uses more that 16 kbytes of fast memory is totally impractical for industrial use. Fortunately these predictions have not come true. The hardware now available make it reasonable to use much larger computers. According to one source (Carnegie Mellon) the personal scientific computer available in the mid eighties will have a fast memory of 2-8 Mbytes, a disc of 300 Mbytes and a high resolution graphics screen.

Even if this will not be true it is clear that the packages we are currently using can be implemented very conveniently on machines currently available.

Our use of graphics is fairly limited. It was dictated by the characteristics of a terminal with a storage tube, which was the only facility available at reasonable cost when the design was frozen. It is obvious that refresh graphics and high resolution color graphics offer many other possibilities.

Collaboration with Professor Polak at UC Berkeley

We have found an interesting way to follow some of these recent developments. A joint project with prof. L Polak at University of California in Berkeley has been started. Prof Polak is interested in investigating the possibilities of using optimization methods as a basis for design of control systems. This requires a more intense man-machine interaction because the optimization can be made very efficient by putting a man in the iteration loop. Prof Polak also uses color graphics. We have provided prof Polak with our software (Intrac) which gave him a flying start. In return we will have full access to his results. One of our programmers, T. Essebo, has also visited Berkeley for two summers. We may also do more joint work with Polak in the future.

Software

This is the key factor for deciding on future work since it is the most time consuming effort. When the project was started the possibilities of using the programming languages Fortran, Basic or APL were investigated. The advantage of Basic and APL was that they were interactive languages. They were discarded because they gave programs which were too slow. APL also suffered from not being very portable. The possibilities of using Basic or APL with Fortran subroutines for the calculations were also investigated. This could not be done in a portable way. It was thus decided to use Fortran and to provide the interaction ourselves with Intrac.

It is clear that Fortran is not a good language for implementing the interaction. This could be done better and much easier with a language like Pascal. Unfortunately there is however not yet a standard Pascal language available. The Ada language may be another possibility. Compilers for Ada will however not be available until after a few years. Because of good libraries like Eispack and Linpack are available in Fortran but not yet in Pascal or Ada it may be necessary to use several languages.

A real break-through would be an incremental compiler for an ADA-like language. This would give the users good algorithms and data structuring facilities in the same language. Incremental compilation would also give the user a very good interaction capability. Note the similarity between interactive use of a program and interactive program development and debugging.

Conclusions

A synthesis of the facts stated above has led us to the conclusion that it is wise for us to stop substantial development of packages for a while. We will maintain the existing packages and we will make marginal additions. We will, however, not undertake any substantial new development until the development of the modern programming languages will stabilize. In the meantime we will follow the possibilities offered by the new hardware for computing and graphics closely by means of projects like the Berkeley project. We will also investigate the possibilities offered by the new languages in exploratory studies. None of these activities will require much effort. They can largely be done by MSc-projects. We will also continue to stimulate activities in good numerics for control.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on our experiences we would like to make the following statements and recommendations.

Interactive computing is an important tool for the engineer. This project has shown that the productivity in analysing and designing control systems can be increased substantially by using this tool.

Computer Aided Design seems to appear in many branches in engineering. Crossfertilization between different application areas should be encouraged. The results from this project can perhaps be used in the CAD/CAM area.

Numerical methods for analysis and design of control systems should be improved. This is probably done better by numerical analysts than by control scientists.

STU should be prepared to support new projects in the area, when the languages currently under development stabilize. The field of computer aided analysis and design of control systems may then be a good field for a national project.

7. ACKNOWLEDGEMENTS

Since the project has extended over a long period many persons have contributed. Johan Wieslander has been the project leader throughout the project. Johan has also contributed the major ideas on interaction. K J Åström has also been engaged in the entire project. He has given guidance on structure, methods and applications. Hilding Elmqvist has given major contributions. What was initially intended to be a minor extension became a major cornerstone thanks to Elmqvist's ideas. He also gave major contributions to the interaction module Intrac.

Very valuable advice was given by Sture Lindahl. He used early versions of the programs on large problems. Through this work he was able to give very valuable suggestions on modifications and extensions.

The major theoretical work was done by Gunnar Bengtsson and Lars Pernebo in the area of multivariable control. This work was incorporated into the design packages. Ivar Gustavsson also contributed to the identification package Idpac.

We have been fortunate to have good support from able programmers throughout the project. Tord Noven and Staffan Selander did valuable work at the early stages. The major programming was done by Tommy Essebo and Tomas Schönthal. They undertook the burden of making the programs portable. Ann-Britt Nilsson also participated in the later stages of the project.

Per-Olof Gutman has participated by writing simple user's manuals.

The project was also influenced by several visitors who gave good suggestions on the use of the packages. It was very useful to have access to persons who did not have preconceived notions about the packages. Special thanks are due to Ken Bollinger and Rod Bell. Several commands that relate to the interaction between the packages are due to them.

Valuable feedback has also been obtained from industrial users. Particular thanks are due to Sten Bergman Sydkraft Malmö, Jan Erik Aspernäs STFI Stockholm, Åke Hansson Billerud Uddeholm, and Ton van Overbeek LiTH Linköping.

Throughout the project we have also benefitted from interaction with collegues engaged in similar activities at other universities. Particular thanks are due to prof Jens Balchen and dr Arne Tysso of NTH in Trondheim, prof David Mayne Imperial College London, prof Neil Munro UMIST Manchester, prof Alistair MacFarlane Cambridge, prof Rolf Iserman Stuttgart, prof Mohammed Mansour and dr Francois Cellier ETH Zurich.

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APPENDIX A - PhD DISSERTATIONS

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