Control of Complex Systems

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With 142 Figures

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Complexity
is in the eye of the beholder

Preface

The world of artificial systems is reaching complexity levels that escape human understanding. Surface traffic, electricity distribution, airplanes, mobile communications, *etc.*, are examples that demonstrate that we are running into problems that are beyond classical scientific or engineering knowledge.

There is an ongoing world-wide effort to understand these systems and develop models that can capture its behavior. The reason for this work is clear, if our lack of understanding deepens, we will lose our capability to control these systems and make they behave as we want.

Researchers from many different fields are trying to understand and develop theories for complex man-made systems. This book presents research from the perspective of control and systems theory.

The book has grown out of activities in the research program Control of Complex Systems (COSY). The program has been sponsored by the European Science Foundation (ESF) which for 25 years has been one of the leading players in stimulating scientific research. ESF is a European association of more than 60 leading national science agencies spanning more than 20 countries. ESF covers has standing committees in Medical Sciences, Life and Environmental Sciences, Physical and Engineering Sciences, Humanities and Social Sciences. The COSY program was ESF's first activity in the Engineering Sciences. The program run for a period of five years starting January 1995. It supported by ESF member Organisations in Belgium, Denmark, Finland, Germany, Hungary, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

The goal of the program was to promote a multi-disciplinary activity, which will lead to a deeper understanding and development of control technology for complex system and if possible to develop a basis for a theory for them. The Programme was initially organised in four theme groups: control of non-linear and uncertain systems, fault-tolerant control systems, learning control systems and integration of complex control systems. In the second phase of the COSY Programme, strong efforts were made to increase interaction between the theme groups.

The program provided support for yearly meetings of the different groups, an annual workshop and exchange of researchers. The research itself was not supported by the program. The long range nature of the program made it possible to form research groups in different problem areas. A problem may arise at a theme group meeting, as interest grew it was possible to add researchers with complementary talent, discussions at the annual workshop provided additional views and further work was carried out by exchange of researchers. This type of activity was most noticeable in the work on fault-tolerant systems and in integration of complex systems.

The material in this book represents some of the results of the COSY program. It should also be mentioned that there was much more work done that for various reasons do not appear in the book.The book is organized as a collection of essays, many of them are written by multiple authors. There are chapters on surveys of essential areas, discussion of specific problems, case studies and benchmark problems. Complex systems appear in many different fields and it is a research area that is receiving much interest. Our work has made it clear that there are many highly interesting research problems related to the complex engineering systems that we are all benefitting from. Since these systems are man made they may be easier to deal with than many other complex systems because they are accessible for observation, experimentation and even, redesign. Our work has clearly shown that complex engineering systems is indeed a fruitful multi-disciplinary research field and that a good understanding of the control technology for them it rests on three pillars, systems modeling, communication and computing.

We would like to express our gratitude to ESF for providing support for the work and we would also like to thank Dr. Hans Karov the program director of the ESF Committee for Physical and Engineering Sciences who provided very good guidance. We would also like to thank all the participants of the program for their efforts.

MANFRED THOMA
KARL JOHAN ÅSTRÖM

Contents

1. Introduction

K. J. Åström

This Chapter serves as an introduction. It gives a broad discussion of complex systems. Particular emphasis is given to the complex man-made systems that provides electric power, communication and transportation. The role of feedback in complex systems is also discussed. A short overview of the dynamics and control is also given. The chapter ends with a presentation of the contents of the book.

1.1 Complex Systems and Control

Natural science has been very successful in explaining phenomena in the world around us. A very effective approach has been to separate parts and to investigate isolated phenomena. In this way it has been possible to explain physics in terms of atoms and elementary particles, chemistry in terms of molecules and organisms in terms of cells, *etc.* This approach, which is called reductionism, has been tremendously successful. A goal of engineering science is to develop the knowledge required to design and operate man-made systems for generation and transmission of energy, manufacturing of chemicals and pharmaceuticals and discrete components, communication, transportation, entertainment, *etc.* These systems have had a profound effect on our lives, just imagine what life would be without, electricity, telephones, radio, TV, trains and aircraft. When engineering science emerged it was natural to use the successful recipe of reductionism from natural science. This resulted in a subdivision into the fields of mining, civil engineering, mechanical engineering, electrical engineering, and chemical engineering, which served very well in the 19th century and the beginning of the 20th century. As the complexity of the man-made systems grew it became apparent that there were many important problems that could not be related to a specific engineering discipline but required an holistic view. It became essential to consider the interaction of parts that form a system instead of the parts themselves. This led to emergence of new systems oriented disciplines such as automatic control. A good characterization is given in the book of Tsien [1954]:

> *"A distinguishing feature of this new science is the total absence of considerations of energy, heat, and efficiency, which are so important in other*

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> *natural sciences. In fact, the primary concern of cybernetics is on the qualitative aspects of the interrelations among the various components of a system and the synthetic behavior of the complete mechanisms."*

The word cybernetics coined in [Wiener 1961] was often used synonymously with automatic control in the mid 1950s. Automatic control developed very rapidly and is now an essential ingredient of practically all engineering systems. The development of automatic control demonstrated clearly that there were systems principles, such as feedback, that are essential to deal with complex man-made systems. Understanding feedback and its implications is an essential task of automatic control. Feedback has been applied in a wide variety of context often with revolutionary consequences. A large body of relevant theory has also been developed.

The belief that it may be as important to investigate how different parts interact as to explore their intrinsic properties in starting to spread in many diverse fields. This type of research is often given the label complex systems. Complexity can mean many things, that a system is composed of many parts, or that a system has complex behavior. Some highly visible research has been done at the Santa Fe Institute, see [Gell-Mann 1994] and similar organizations. The books [Bak 1996], [Schroeder 1991], [Lewin 1992], and the papers [Goldenfeld and Kadanoff 1999], [Whitesides and Ismagilov 1999], [Weng, Bhall and Lyengar 1999], [Koch and Laurent 1999], [Arthur 1999] [Parrish and Edelstein-Keshet 1999], [Werner 1999], [Rind 1999] are just a few examples that illustrate the emerging interest in complexity in a wide range of fields.

1.2 Complex Engineering Systems

In this section some complex man-made systems will be discussed briefly. We will describe their functions and how they have evolved. All systems described have had a major influence on our lives and it is worth while to reflect upon what our lives would be if we did not have these systems.

1.2.1 Power Systems

The first electric power system was built by Thomas Edison in New York in 1882. The system consisted of a steam driven generator which supplied 59 customers in an area with a radius of about 1.5 km. The load consisted of incandescent lamps supplied through underground cables. From that modest beginning electrical power systems have developed into one of the largest industries in the world with networks covering practically the whole world. Power systems are very complex with many different types of generators (hydro–, thermal , wind, nuclear, *etc.*), wide distribution networks and many different consumers. It is crucial for industries and individuals that the system functions properly.

Figure 1.1 shows the Nordel network that supplies the Scandinavian countries, having a population of about 23 Million. Scaling the system in the Figure with the total world population gives and indication of the complexity of the power system. In 1998 the Nordel system had an installed capacity of about 9×10^{10} W. The Nordel system is also connected to the continental system via cables to Holland, Germany and Russia.

The need for high reliability and efficiency has made it attractive to interconnect larger and larger areas. This makes it easier to match varying demands and to guarantee a safe supply. The power systems in many European countries are connected.

The power systems must be able to meet continually changing demands on active and reactive power. In the early systems this required that the generators run at constant speed. It turned out that this problem could be solved very effectively by using feedback [Stodola 1893-1894], and [Tolle 1905]. Modern power systems depend very heavily for feedback for their function as discussed in [Kundur 1994]. A particular difficulty is that large quantities of electricity cannot be stored conveniently. This imposes severe demands to make sure that generated power matches the load. The energy should be supplied at a low cost with minimal environmental impact. There are also stringent requirements on quality *i.e.,* reliability of power delivery and constancy of frequency and voltage. The early power systems used direct current (DC) for distribution but it quickly became clear that there were significant advantages in using AC (alternating current). Most distribution is made using AC networks even if the number of high voltage direct current (HVDC) systems are increasing. The physical nature of AC transmission imposes severe restrictions on an interconnected power network because all generators must run synchronously. This requires very accurate control of the frequency. Similarly the voltages in the systems must be controlled accurately to satisfy customer demands. Feedback is used extensively in the system, in individual power stations and in control of transmission lines and networks. There are also very elaborate systems that safeguards the system in case of failures. Generators are running in spinning reserve ready to deliver power in case of failure of other generators. There are gas turbine units that can be started very quickly. It is possible to reroute power transmission in cause of line failures. Power can be supplied from external sources and load can be shed as a last resort. The power systems are mostly functioning very well. There have, however, been some failures where large regions have been without power. There are several situations where failure have been caused by complex interactions in the systems. With the deregulation that takes place world wide the problems of arranging safeguards are more difficult, see [Hauer and C.W. Taylor 1998].

The need for interconnection brought with it a need for international collaboration. This led quickly to the establishment of an international organization Cigre for exchange of experiences and standardization. Much

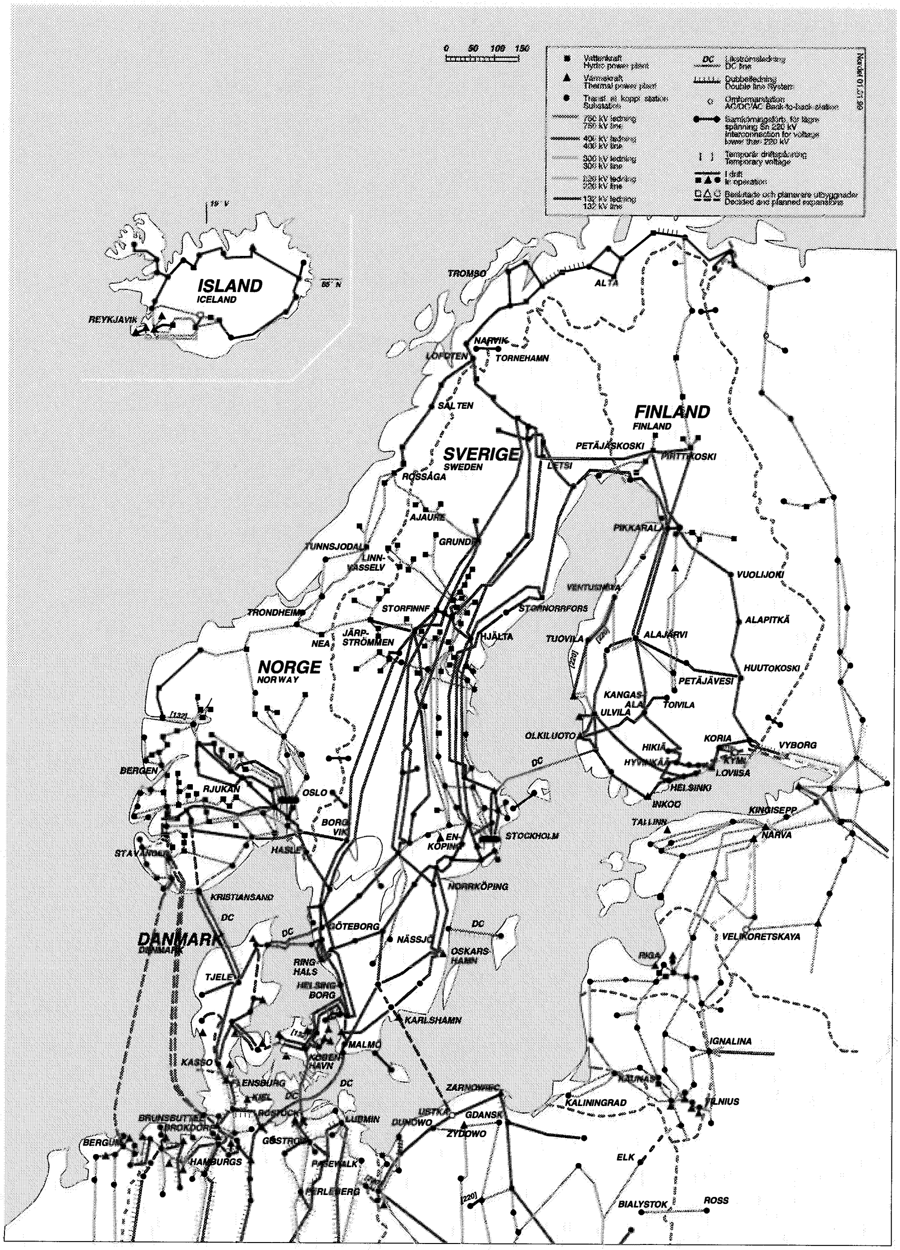

Figure 1.1. The Nordel power system that serves the Baltic countries in Northern Europe. The squares denote water power stations, the triangles thermal power stations (both nuclear and conventional) and the circles denote transformers. The lines show the major power lines. (By courtesy of Nordel.)

generation and distribution of electric power has been handled by governments in the different countries. Much deregulation is currently underway in Europe and elsewhere. This will have profound impact on the power systems. A particular problem is that an operator that delivers or generates power into an electrical power system can have major influence on the global behavior of the system. A small change in one place can have a major influence in a distant location. What requirements should be impose to safeguard the operation of the system? How should overall responsibility of the system be shared fairly?

1.2.2 Telecommunication

In the first telephone systems consisted of a central switchboard with wires to individual subscribers. Long distance telephony required the development of amplifiers for electronic signals and techniques for multiplexing several conversations over the same lines. Feedback was an enabling technology for making amplifiers. Multiplexing and coaxial cables were also important advances. Copper cables are now replaced by fiber optics and wireless which gives a very large increase of capacity.

The need for automatic switching appeared very early. Automatic switching of today's traffic in the European telecommunication network is so extensive that manual switching would require more than half of the adult population. Electro-mechanical switches were used for a long time but are now replaced by computerized systems, which admit many new services. The complexity of the systems have also increased considerably. The telephone system also required strong international organization through organizations like ITU and CCITT, a key task being standardization and exchange of experiences. In the past 20 years there have been two very remarkable developments in communication, cellular telephones and the Internet. The cellular telephones originated with the wireless Nordic Mobile Telephone Network, an ideal system for areas that are sparsely populated. The systems developed very rapidly and today a significant portion of the telephone communication is handled by cellular telephones.

The Internet grew out of a military project ARPANET initiated in the mid 1960s. The goal was to develop a command and control network that did not depend on vulnerable telephone networks. The network obtained its robustness through a strongly decentralization and dynamic routing capabilities. Because of this the system could continue to function even if several nodes and lines failed. By 1983 the protocol TCP/IP was standardized and the ARPANET was connected to the non-military network NSFNET. There was a very rapid growth and many networks in Canada, Europe and the Pacific were connected. By 1990 the Internet had grown to 3000 networks and 200000 computers. A million hosts were connected in 1992 and the size started to double each year. The growth literally exploded with the World Wide Web . There are interesting leading towards a convergence of the computing and communication. It is interesting to observe that the both cellular communication and the Internet have been growing much faster than other mass communication media such as radio and television, see Figure 1.2. Feedback plays a major role in communication systems, it appears in components such as amplifiers, in strategies for queuing and routing, power control in mobile systems, adaptive equalization, *etc.*

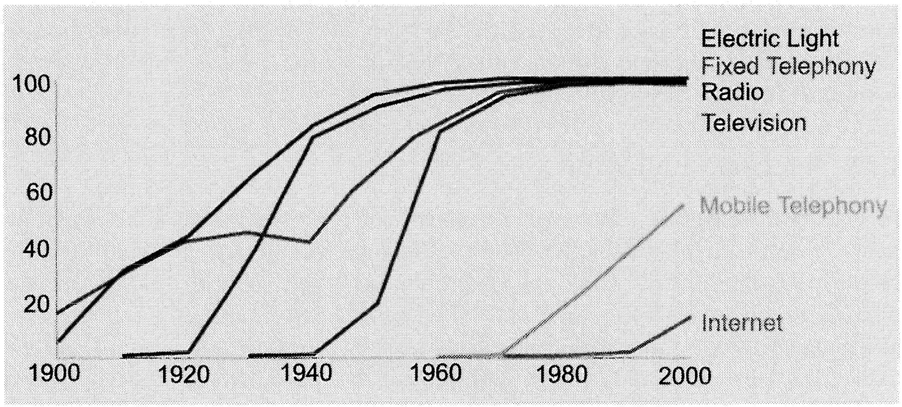

Figure 1.2. Growth of radio, TV, telephones, cellular and the Internet

1.2.3 Process Control

The emergence of chemical industry was a strong driver for automation. There were requirements to keep processes running continuously under constant conditions. This led to development of sensors and controllers for pressure, flow, temperature and composition and the standard PI (Proportional and Integral) controller. The industrial PI and PID (proportional, integral and derivative)controllers can be viewed as a special purpose devices that realizes pure feedback, see [Åström and Hägglund 1995*a*]. It is interesting to observe that devices were realized in many different technologies, mechanical, pneumatical, electric, electronic and computer based while the function remained the same. Techniques for adjusting the controllers so that they worked well in different context were also important, see [Ziegler and Nichols 1942].The development also led to industries that specialized in control devices. There was also a strong need to automate discrete operations such as start up and shut down and to have safety interlocks to ensure safe operation. Initially control, sensing and actuation were implemented as separate analog controllers while safety interlocks were implemented by relays. Later it was found convenient to centralize all controllers and all relays in control rooms to provide operators with an overview of whole process segments. When digital computers became available in the late 1950s they replaced analog hardware and relays. All major industrial process today run under computer control. A large refinery may have as many as 10000 feedback loops, a paper mill may have up to 5000 loops. Each loop represents an investment of the order of 30 k$. The standard control system have an hierarchical structure. At the lowest level there are simple loops for control of flow, pressure and temperature. They are typically PI controllers. The next level contains coordination of individual loops, optimization, logic for shut down and start up, and safety interlocks. Production planning is at the next level and at the highest loops there total plant control, management information and interfaces to the sales and. The configuration of a typical distributed control system that supports all functions is shown in Figure 1.3.

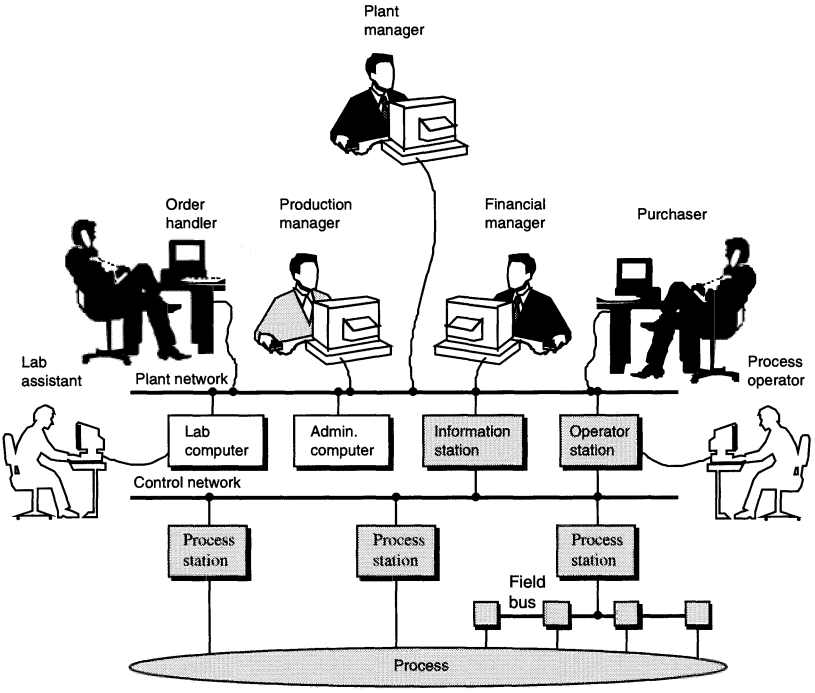

Figure 1.3. Distributed system for industrial process control systems. (By courtesy of ABB Industrial Systems, Västerås, Sweden.)

Environmental requirements have had a profound impact on the process industry. So called system closures have been a very effective way to reduce emissions, energy consumption and to increase product quality and profits. Typical measures are to use energy in outgoing product to heat incoming raw material and to reuse waste products as much as possible. These measures are used in many process stages. A result is that the dynamic behavior of the processes becomes much more complex . The large number of controllers creates another problem. It is important that the control loops are properly tuned. Even if each control loop is simple it is a major effort to keep all of them correctly tuned. Methods of automatic tuning and adaptation are very valuable. Finding good techniques for control at the higher levels are other important issues.

1.2.4 Aircraft

The examples given so far have been large systems associated with infrastructures. We will now discuss an individual system, namely aircraft. It is relevant to consider both the aircraft and the process of design and manufacturing. Feedback played a major role in the development of flight control. Aircraft with autopilots were used as early as 1912. The early systems were quite simple but the systems became very complex as technology developed. Early aircraft had a few control surfaces and very simple instrumentation. Modern military aircraft may have 20 controlled surfaces, thrust-vectoring and a large number of sensors.

The manufacturing has also changes substantially. Kitty Hawk from 1903 was designed and assembled by a few persons in a bicycle shop. The Boeing 777 has more than 3 million parts and more than 150 000 separate subsystems. The total investment was more than 1 Billion $. The development made very effective use of computer aided engineering in many phases of the design. This included computer aided design (CAD), computer aided engineering (CAE), modeling and simulation. There were more than 200 teams, with 10 to 20 members per team. A significant result was that the number of tests that had to be increased significantly. Over 2200 computers were used in the development. The Boeing 777 is often used as an example of the power of virtual engineering . The benefits quoted in comparison with design of earlier aircraft such as the 757 and the 767 are: Elimination of more than 3000 assembly interfaces without any physical prototyping. Reduction of engineering change request from 6000 to 600 and cycle times for engineering changes by 50%. A 90% reduction in material rework. Drastic improvements in assembly tolerances for fuselage. Even if these advantages are impressive the project showed clearly that existing CAE tools are limited. Dynamics, heterogeneity, and non-linearities were not dealt with systematically. Electronics and hydraulics were simulated separately, just to give some examples.

1.2.5 Automotive

There are many examples of complex systems in the automotive industry. A consequence of globalization is that design and production is distributed over many countries. Complex software systems are required to handle this. Production is also highly automated. The automotive industry is the largest user of industrial robots. The systems used to control manufacturing of cars are similar to those used for process control, they look like Figure 1.3 where then continuous process is replaced by several discrete manufacturing units. The discrete manufacturing processes consists of many sequential steps. They were originally automated using relays. In the 1970s they were replaced by special purpose computers called programmable logic controllers (PLC).

The complexity of the products is also increasing. Drastic changes in automobiles occurred because of the stringent exhaust-pollution regulations that were introduced in many countries. These regulations could be met by introducing catalytic converters and feedback control of the engines. The development of engine control had an interesting side-effects. New microprocessors with facilities for communication to sensors and actuators on the processor chip (micro-controllers) emerged. There was also a very active development of sensors and actuators. This set the scene for a more extensive use of computer controlled systems in automobiles. This is illustrated by Figure 1.4 A modern car may have up to 40 micro-controllers that are connected to sensors and actuators, typically over communication networks. Some of the functions performed by the systems are, engine control, anti-lock breaking and traction control, suspension and ride control, climate control, transmission control, cruise control, active body control, navigation. An indication is that the memory of typical micro-controllers used in automobiles have increased from 64 kB in 1988 to 2000 kB in 1998.

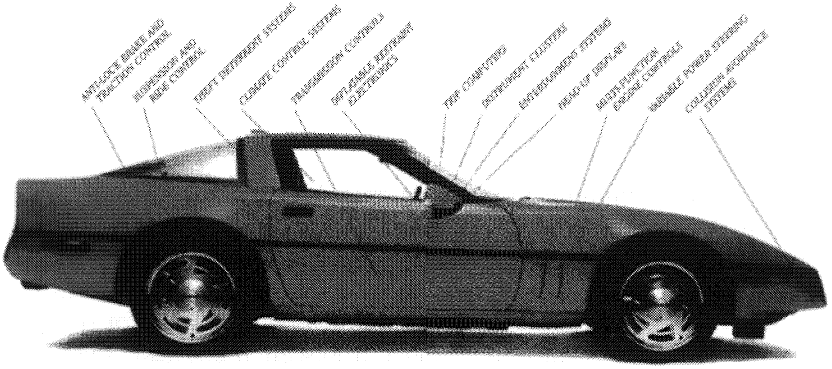

Figure 1.4. An automobile and some of its subsystems