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How have we arrived at the present state of knowledge in process control? Is there a lesson to be learned?

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The utilization of the results of control theory in the process control field has been lagging behind other application fields such as aerospace for many years. It is argued that the availability of high capacity computing at low price will change this situation and that new powerful control techniques can now be implemented in process control.

The general technological development in the entire postwar period has been dramatic in many different disciplines. This includes our own field, control systems theory, control systems tools, and equipment and control systems applications in numerous sectors. Many of the technologies interact to a great extent and depend on one another and in some cases we can say that without one of the technologies the others would be entirely impossible. In the field of control this applies, for instance, to the interaction between modern control applications and computer technology.

It is apparent that we have at least three driving forces behind progress in most technological fields, including industrial process control. These are shown in Fig. 1.

- Theory/methods
- Problem solving
- Equipment/hardware and software

We may say that progress can be Theory driven, Problem driven or Hardware driven.

The following reviews some of the major achievements in control theory and control applications particularly in process control and places them in perspective with other technological developments. The discussion then turns to whether we could have achieved other forms of development had we done things differently.

1. Control theory

First a look at the major landmarks of control theory. Fig. 2 shows a vertical time scale from 1900 to 2000 where some names are marked to indicate important, well-known contributions.

Starting around the turn of the century, Liapunov introduced his general theory of stability of nonlinear systems before hardly anybody knew about the existence of such a problem; and in 1922 Minorsky analyzed the stability of a controlled vehicle. Next,

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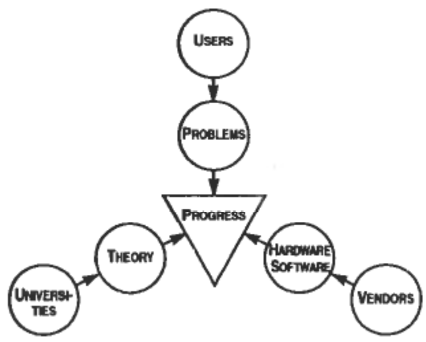

Figure 1. Three driving forces behind progress.

early in the 1930s Nyquist presented his revolutionary ideas about stability and frequency response. Black also introduced his graphical techniques and in the 1940s Wiener developed his filtering theory and the theory of optimal control. In the same decade, Bode also continued work on the frequency response methodology. Lur'e in 1942 formulated and solved a basic problem in the stability of controlled aircraft.

World War Two resulted in rapid development in control technology reviewed in the USA by James, Nichols and Phillips. Shannon presented the basis of information theory in the late 1940s.

In the 1950s Ragazzini and Zadeh and many others contributed to the understanding of sampled data systems, Bellman introduced Dynamic Programming, and Pontryagin and co-workers developed the Maximum Principle of dynamic optimal control. In 1956 the foundation for the International Federation of Automatic Control (IFAC) which has meant a lot for the development of the control community on a world-wide basis. Early in the 1960s, Kalman presented his general theory of control systems and the generalization of Wiener filtering which developed into Kalman filtering.

An exciting development took place within control theory in the 1960s which was mostly driven by the challenges from aerospace projects that attracted the attention of leading scientists. Joseph and Tou with the separation principle, Rosenbrock with optimization theory, Zames and others with a new stability theory, Athans and Falb with optimal control theory, and Kailath with estimation theory all provided a solid platform for further developments.

The number of contributions in the 1970s become almost countless with people like Astrom and his co-workers providing the basics of identification theory and adaptive systems. Polak and Mayne with constrained optimization, Bar Shalom and Tse with dual control defined by Feldbaum 10 years earlier, Narendra with a revival of Liapunov techniques, Mehra and Richalet with a reformulation of optimal control more adapted to process control. In the last part of the 1970s Ljung and others contributed significantly to identification theory while Doyle and Stein and co-workers worked on the theory of robust control systems with the help of computer-aided design tools promoted by Laub and others.

Finally, the 1980s have to a great extent been characterized by continued contributions in the fields of optimal design with emphasis on constrained optimization and new criteria such as H_∞ and further studies in robustness. Isidori gave momentum to nonlinear control theory which had been in and out for about 20 years. The decade also brought us neural nets in control theory and an explosion in Fuzzy Control introduced by Zadeh in the late 1960s. It is difficult to point out the names of the most

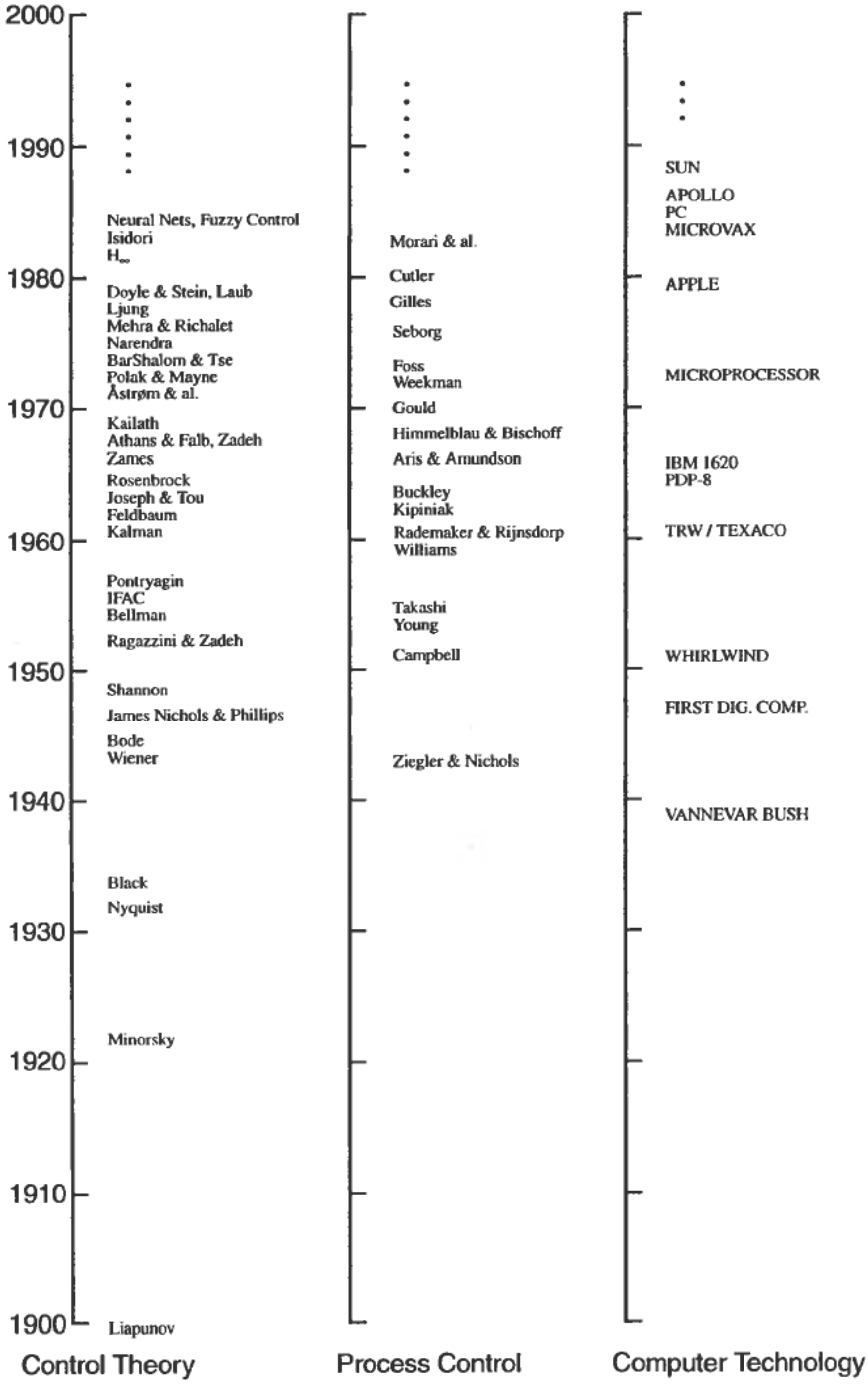

Figure 2. Landmarks in control theory, process control and computer technology.

significant contributors because literally hundreds of researchers are adding their input to the body of knowledge. Maybe it is too early to tell which are the contributions in the 1990s that will show up in the history to be written around 2000.

2. Process control

In parallel with the time axis of control theory there is a similar historical review of process control which obviously is just as old and maybe even older than control theory. However, there are few contributors apart from James Watt and his contemporaries. In 1942, Ziegler and Nichols presented their useful rules for tuning PID control loops. Then nothing really significant happened in process control fundamentals until Donald P. Campbell at MIT started to bridge the gap between control theory and process control applications in the first half of the 1950s. A. J. Young (Britain) and Takahashi (USA/Japan) promoted control theoretic ideas in process control, during the decade.

Around 1960, T. J. Williams and Rademaker/Rijnsdorp made important contributions to distillation control and Eckman was a strong promoter of process control research. Kipiniak at MIT discussed control by means of optimization and Buckley (DuPont) wrote a fine survey of process control problems around 1963. Aris and Amundson followed by Himmelblau and Bischoff had established a solid basis for the mathematical modeling of industrial processes in the mid 1960s and Gould presented a status report on process control theory in his book of 1969. Still it is true that the process control field was lagging at least 10 years behind the aerospace field in applying new control concepts.

Weekman and others had introduced complex control problems, but had not really given any solution in the early 1970s. Foss complained in 1973 about the misalignment between the established modern control theory and the needs in process control, whereas Seborg and others were active in the mid 1970s in promoting the application of modern control theory concepts to a variety of process control problems. In the late 1970s, Gilles demonstrated the use of *first principles* modeling and simulation in the control of distributed processes.

A major breakthrough happened around 1980 when Cutler demonstrated that he and his colleagues had convinced Shell management to install multivariable computer controls based on optimal control concepts. The significance of this event was *the industrial acceptance of modern control concepts* which led to an avalanche of similar industrial control projects. Many contributions came during the 1980s in the development of workable industrial control packages for *model-based predictive control* with constraints in both control and state variables. Among these Morari, Garcia and Biegler should be mentioned for their theoretical results. From around 1980 till about 1995 the number of papers on sophisticated *academic process control theory* has nearly exploded and it is hard to pinpoint the most significant contributions. However, it is quite clear that even though the implementations in the industrial process control field still lag behind the control theory by about a decade, something dramatic has happened to reduce the gap between theory and practice. A number of explanations for this can be given.

3. Computer technology

The developments in the field of computer technology are also obviously of very great interest, particularly when seen on the same time axis as the history of control theory and process control technology.

The first scientific computing device was the Vannevar Bush mechanical differential analyzer around 1939. Then during World War Two the concepts of electro-mechanical and electronic differential analyzers were developed and heavily applied in weapons systems. The first digital computer was demonstrated around 1946 and useful digital machines became available around 1950.

More or less simultaneously, the idea of using digital computers for control purposes was launched, an example was the Whirlwind project at MIT. During the entire 1950s digital techniques were applied first in the control of machine tools and finally around 1960 the first successful installation of a general purpose digital computer for process control was demonstrated by the aerospace company Thompson Ramo Woolridge (TRW) together with Texaco. Thereby the computer control field was really launched and momentous developments are still going on.

One major factor that explains much of the speed of development in the relationship between control theory and process control implementations is the available capacity of the digital computer at any time. Around 1963, the first minicomputer came on the market at an affordable price for small and medium scale process control purposes. A PDP-8 from Digital Equipment Corporation with a memory capacity of 8 kbytes cost around $40 000. With such a tiny memory it took a long time to program the simplest control algorithms in assembly language. It was practically impossible to implement any of the theoretical results that were available at the time.

The growth in computer capacity with the simultaneous reduction in price as illustrated in Fig. 3 continued in the 1970s. When the microprocessor was introduced around 1973 a new situation occurred. The fast development in computer capacity now turned into an explosion. The computer capacity that only used to be available for 'wealthy' applications was now within reach of the ordinary process control application.

Even around 1980 large scale optimization schemes could be handled which did not have to economize much with computer capacity. This led to the well-known industrial implementations of model-based predictive control. The methods employed were not particularly sophisticated and used a lot of computer capacity. But since the systems on which they were applied were rather slow, the computing speed was high enough to allow larger scale optimization calculations.

From 1980 till 1995 the reduction in cost per unit of computing capacity has continued with the result that practically all the available results in control theory are implementable in process control as long as they can be represented by a programmed algorithm.

The tremendous development in computer capacity has obviously also been followed by a similar, but not so dramatic, development in the availability of software for control purposes. In the 1960s and 1970s we were concerned with designing real-time software that would economize computer capacity. This seems to have been replaced by sophistication and an increase in the level of programming languages that increase the convenience of programming. This led to even better possibilities for implementing complex theoretical results in practical installations.

The computer control vendors who have fully utilized the developments in computer technology have been clever in marketing network-based distributed computer control solutions that are highly flexible. There are promising new trends in international standardization in '*field bus technology*' even though the old tendency is that some of the larger vendors monopolize the field. However the concept that the vendor should 'own' his customer through his specialized operating system is definitely out. It is to be hoped that this unhappy situation will not be replaced by another similar technological domination in the future. The modern distributed computer control solutions offer all necessary facilities for implementing sophisticated model-based

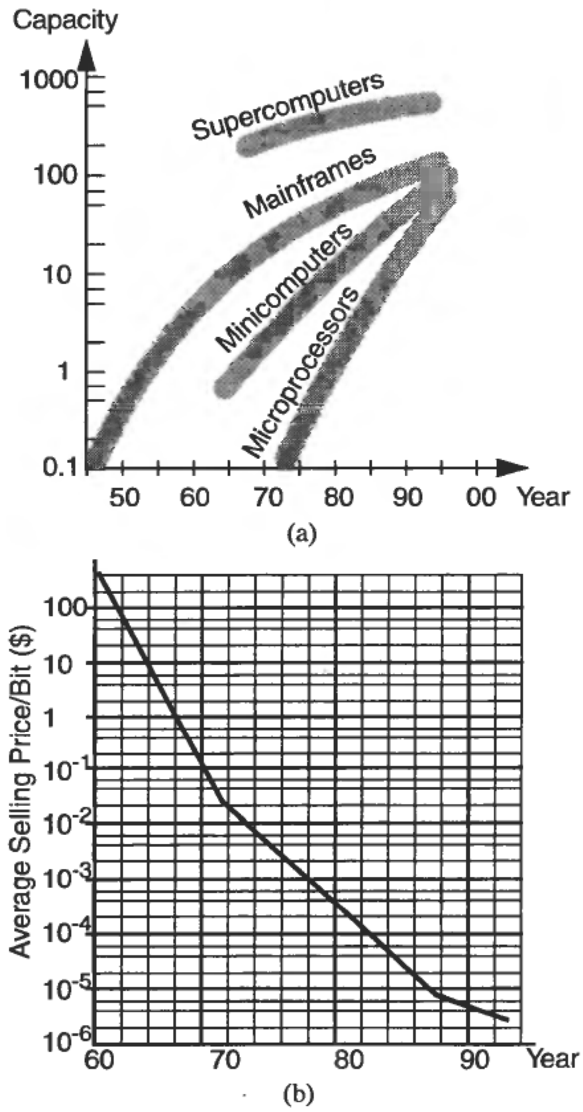

Figure 3. The growth in computer capacity at constant cost (a), and the reduction in price for memory capacity (b).

control schemes around standardized inner control loops that take care of elementary functions at a high rate and with high precision with great ease.

The latest developments in computer graphics are very promising for convenient man–machine communication when the operator interacts with the process through a *virtual reality* (VR) technology.

To sum up: it appears that process control has been lagging behind the general control theory development by about 5–10 years. *It has been the developments in computer technology that have made the large-scale industrial implementations possible.*

4. Could we have done better?

We could ask the question: would process control be in a better state if we, the teachers, the researchers, the industrial control specialists, the industrial executives and the board members had behaved differently?

Obviously this question is academic because nobody has much influence upon such behaviour. But still, in order to give some input to possible future planning activities, here are a few reflections:

- Much time and effort is used in the communication of a problem definition and its suggested solution between people belonging to different scientific and technical cultures. Even between control scientists communication is hampered by differences in conceptual definitions, mathematical notations, symbols and referencing systems. People who are supposed to be well-informed in their special sectors of science and technology often find that when reading a journal about new developments, too much effort is needed simply to break the notational barrier. Standardization of all sorts is a controversial issue and can only be realized in well-established fields after a fairly long time. Therefore in fields that are undergoing great change, there is a need for strict discipline among the contributors, so that the efficiency of communication becomes as high as possible. Educators carry a lot of responsibility in this respect and should try harder to conform to an 'international standard' when writing theoretical papers.
- There is another issue that is related to education. When a branch of science and technology has reached a certain level of maturity like control theory, control engineering and process control technology, it will be taught to a broad spectrum of students at undergraduate and graduate levels at universities as well as at technical colleges. This basic training in the fundamentals should be given in a unified manner so that when students continue from the basics to specialized fields such as control in aerospace or control in oil refineries they carry the same basic concepts and notations with them. The educational traditions at European and American universities have been different in this respect. Fundamental control theory and control engineering at European universities have been taught in one department for students from all departments whereas in the American tradition there has been a tendency that each department has its own control course. There are reasons to believe that the European concept should be preferred because it promotes cross-fertilization between the different application areas and gives the scientific fundamentals higher standing. This does not mean that chemical engineering students have to get their first course in control theory and engineering from an electrical engineering professor or vice versa. Rather, educators from different departments should share this responsibility, and it should be based on a common scientific rationale. The quantitative consequence of higher efficiency in communications between the different branches of control theory and control technology is certainly hard to estimate, but it is reasonable that maybe an advance of 5–10 years can be suggested. Still, as we have said, developments in computer technology have been the bottleneck.
- Another factor which must have caused a delay in process control relative to, for instance, aerospace both in terms of theoretical competence and equipment, is that most leading countries used much of their research capacity on military and space research for 40 years in the postwar period. Huge investments in these sectors motivated by threats of the cold war generated numerous results that were

later beneficial to the nonmilitary and industrial sectors. Whether or not these results could have been achieved without the threat of a cold war, is an open question. Politicians want to keep intensity up in research for civilian purposes and some accuse them of inventing challenges to replace the cold war such as 'the global environment', 'the energy crisis', 'urban transportation systems' and so on. But in open societies it is hard to mobilize hidden human resources against threats that are not real and tangible.

Thus, it is not entirely clear whether there would have been any dramatic changes in the state of affairs if there had been differences in the transfer of know-how. This is because innovation can be slowed down by the lack of willingness by industrial managers to risk resources to test new ideas at an early stage, and also what technology is available (e.g., computer capacity).

The question of whether there is 'a lesson to be learned' is still relevant. The past is history and the future will not repeat the past. The major *limiting factors* from the past are either removed or somebody may have learned something. In other words, the future may hold promises for improvements that have not yet been achieved.

In what ways can we expect improvements to be made in the future within the field of process control? I have selected two examples out of many. These examples obviously reflect my interests, others will probably make different suggestions.

First is a simple example: It is good academic practice to compare the performance of a suggested new theoretical solution with that of the most commonly-applied method. In control this is most often done by applying a step disturbance (or something equivalent) to a simulated process with the new and the old solution and comparing the responses. Such a comparison may be informative. But often it will not tell us anything at all. This is because most often it has not been stated clearly what the requirements of the particular responses should be or in other cases, what the consequences are in terms of quality and productivity, or safety. A new solution which requires complex computational equipment and scarcely competes in performance with the traditional and much simpler solution will obviously have a hard time convincing plant management of its validity.

Therefore high priority should be given to teach tomorrow's research and development engineers how to test their ideas properly. A test can be done analytically or numerically, by simulation or by actual implementation in a physical plant. However, there is a tradeoff, the expenses for the testing will increase from simulation to implementation, but so will the credibility of the results. A cost/benefit-analysis is also necessary, though it may be very difficult, to determine if the potential gains justify the necessary investments. I suspect that an investigation of largescale process control installations in recent years will show a large spread in the cost/benefit ratios.

A more elaborate example: One concept of process control which dominates all others during the recent decades is *model-based control.* Many of the methods of estimation and control are model-based and models appear in many forms. The improvements that can be achieved with model-based control relative to non-model-based control (for example PID) may sometimes be appreciable. But establishing a model of a large-scale process system is said to be difficult, expensive and time consuming. I feel that many statements that have been made about models for model-based control are either wrong, and misleading or dubious.

A closer look into the matter of models for modern model-based control will reveal a number of strange phenomena. Process engineers who spend a major part of their university training making mathematical models of processes based on *first principles* in physics, thermodynamics, fluid dynamics and chemistry seem to abandon all this kind of knowledge when it comes to formulating a mathematical model for the purpose of process control. Maybe this is because most process engineers learnt more at university about *static modeling* for design purposes than *dynamic modeling*. This means that they have not really been trained to make models that are useful for control purposes. Thus when they meet a classical first course in control, that teaches input–output descriptions using transfer functions, they have to switch to a world where they have little physical understanding of mass and energy balances, reaction kinetics and fluid dynamics. This is a situation which should be discussed and then corrected.

Before proceeding, let us look into why model-based control possibly will give better performance than control that is only based on input–output descriptions:

- A dynamic model that is continuously updated by the real process through measurements in the process, provides estimates of *present values* of important *internal variables (states)* in the process that are necessary for generating control actions by means of feedback. The same model can also provide estimates of *future values* of these internal quantities that are necessary for deriving *predictive control.*
- The well-known attractive features of *feedforward control* from measurable disturbances are based upon the use of models and fit naturally into the model-based state estimator scheme.
- *Measurements* derived from a complex process are not necessarily representative of *the properties* of the process that one wants to keep under control. Generally speaking, such properties must be computer based upon a sufficiently detailed model that is kept updated with reality by means of the process measurements.
- Thus it becomes more or less obvious that the model should express the relevant internal physical states rather than some artificial quantities without physical meaning (e.g., nodes in neural nets and NARMAX models).

Since most industrial processes show pronounced nonlinear behavior, the most logical way of establishing a dynamic mathematical model is to utilize 'first principles' in thermodynamics, fluid dynamics, reaction kinetics, etc., to form the basic *anatomy* or *skeleton* of the model. However, since a 'first principles', detailed, distributed model will become infinitely complex, there is a need to include empirical relationships (input/output models of inner details) in the skeleton. There are also limitations to our insight into the inner mechanisms of most processes. The type of model thus achieved could be called a *hybrid* model utilizing both apriori knowledge from process theory (thermodynamics, reaction kinetics, etc.) and empirical data from observations of reality.

Thus there seems to be a paradox that process engineers tend to be misled into abandoning their basic process theory because somebody years ago stated that 'as is well known process modeling from 'first principles' is very time consuming'. This is not correct. What is time consuming is to make empirical models because that requires experiments which are almost impossible to do before the actual process is in operation with full instrumentation.

What is needed is emphasis in process engineering and process control education on '*first-principles modeling*' so that real skills in this important discipline can be more widespread. For many university students, mathematical modeling of physical processes is a scary topic for two reasons:

- The subject is not taught properly.
- There is a major lack of tools for *computer-aided modeling*.

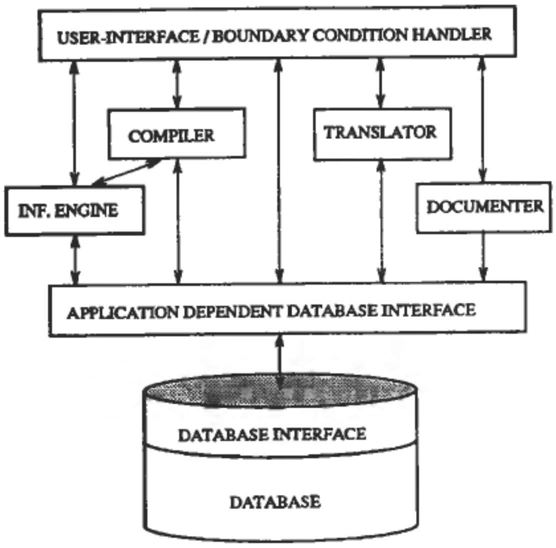

Figure 4. Structure of computer-aided modeling system.

During recent decades a number of software products have become available for the construction of dynamic mathematical models for physical and chemical processes that are used in a variety of industries. These systems are based on preprogrammed process modules that can be put together forming a complete model of the process complex.

However, since such unit processes appear in numerous varieties, each with a large number of design parameters, a library of modules has to be substantial in order to cover the needs of a computer-aided design tool. It has been pointed out that it is almost impossible to find a process module that satisfies the requirements of relevant details and precision because quite often the process has special features which require a specific model. Thus it is concluded that there is a pronounced demand for a computer-aided design tool that can generate mathematical/numerical models for arbitrary dynamic processes based on 'first principles'.

The computer-aided tool that is needed, could be described as follows and illustrated in Fig. 4:

- It is a modern, powerful workstation with high computational speed and large memory capacity.
- It has powerful graphics facilities.
- It has access to all modern software in ordinary and partial differential equations, matrix algebra, symbolic mathematics, large scale optimization methods, etc.
- It has a database containing fundamental principles and data in thermodynamics, fluid dynamics, reaction kinetics and other basic concepts in chemical and process engineering which are necessary to build a 'structurally correct' model of the process at hand.
- The database system is both local and remote. This means that the system vendor supplies access to large-scale remote databases, supplying information that is not used very frequently whereas the most commonly used information is available in the local database.
- Building, managing, maintaining and enlarging the database both in terms of

fundamental methods and data, is potentially a very attractive field of business that should soon attract the interest of investors.

- System vendors will probably find that an open architecture for both hardware and software will be beneficial to the success of their business.
- The computer-aided modeling system is an 'extended arm' to the well-trained process engineer who has insight into the basic phenomena occurring in the process to be modeled. The computer aided model building is executed through a dialogue between the computer system and the operator starting with a geometric description of the process and a formulation of possible elementary process phenomena that can take place. The computer system executes the suggested modeling of the elementary process phenomena with variable time- and spatial discretization. The operator is given a graphical display of intermediate results (in 2D or 3D) in order to have a visual check of the trustworthiness of the intermediate results. Thereby the operator can investigate the influence of approximation upon the quality of the dynamic model viewed from the final use of the model in, for example, model-based control.
- In addition to the tools for model building the total computer-aided design system should also include the most powerful toolboxes, available for the design of state and parameter estimators for nonlinear state space models and similarly the most powerful methods for multivariable process control design. Thereby the operator can make a full test of the use of the model and can adapt the model to plant data in an offline manner or online in connection with the final installation for control of the plant.

These two examples show us that a number of challenges lie ahead. Whether or not we could have achieved some of these goals at an earlier stage by behaving differently, is obviously an open question.

5. Conclusions

It has been observed that the applications of control theory in process control have been lagging behind those in other fields. It is argued that this is because two major factors, until recently, have been lacking:

- High capacity, low price computing power to implement large-scale model-based control with acceptable economic returns.
- Insight into the technological as well as business related perspectives of modern control solutions by those who influence the decisions of investors in industrial automation.

The first of these obstacles has now been eliminated and the second will gradually disappear if and when well-trained control engineers occupy executive positions in industry.

Since it is our experience that about a decade elapses between the presentation of a significant new fundamental concept and its implementation in industry it makes sound control engineering sense to invest early in good theoretical research.