A Course in

SYSTEMS MODELLING AND CONTROL

L. S. KERSHENBAUM,
J. D. PERKINS AND D. L. PYLE
Imperial College
London SW7, England

THE GAP BETWEEN ACADEMIC research activities and industrial application in the field of process control appears to be large. Some reasons for this are immediately apparent: advances in electronics and aerospace have brought about the theory necessary to solve some control problems which were otherwise insoluble; corresponding developments in computer power have made these soluble in a reasonable amount of time; thus the area has been perceived as an interesting subject for academic research.

Nevertheless, many industrial process control problems are adequately (although not perfectly) dealt with using straightforward control techniques which are characterised by an extreme "robustness" that is, the choice of actual control constants used in classical algorithms is not too critical. Furthermore, those problems which are more difficult to cope with using classical techniques are thought to be so complex that vast amounts of time are necessary in modelling before the control activity can even begin. Furthermore, because it involves more complex mathematics, operators or even engineers are unlikely to be able to "tune" the algorithm on-line in case of some deterioration of performance. And so, despite the fact that many large plants have on-line computer control, in most cases this powerful tool is being used for little more than digital 3-term controllers, possibly with supervisory control of set points as dictated by some steady-state linear programming algorithm.

It is our belief that adequate progress has now been made by academic researchers using simulations or small-scale experiments, for us to be able to demonstrate . . . that there are certain situations in which these techniques can be used in real plants, solving real control problems.

It is our belief that adequate progress has now been made by academic researchers using simulations or small-scale experiments, for us to be able to demonstrate, both to students and to practising control engineers, that there are certain situations in which these techniques can be used in real plants, solving real control problems. We, at Imperial College, have an opportunity to carry out this program since we are equipped with large pilot plants, fully instrumented and linked with an industrial-type mini computer. Software includes conventional 3-term digital controllers plus a range of modern control algorithms which can be called upon to perform at any point in the plants.

Rather than attempt to deal with all aspects of modern control theory, we have decided to focus attention in our course on those areas in which *significant* improvement over classical control methods can be realised without an excessive amount of time spent on preliminary modelling exercises. Accordingly, we have isolated three problem areas for which classical control tech-

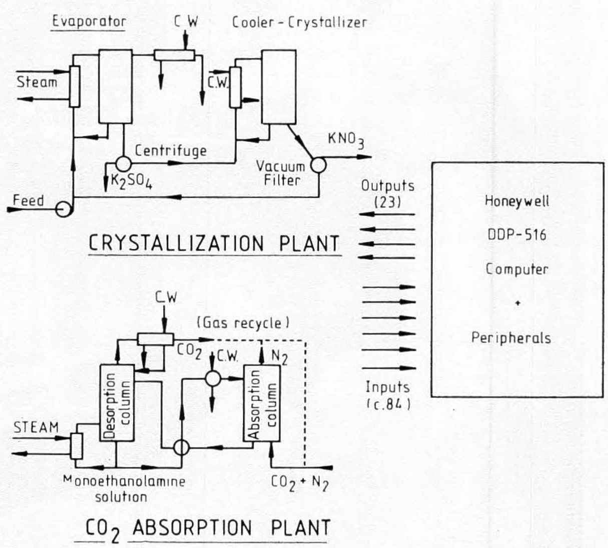
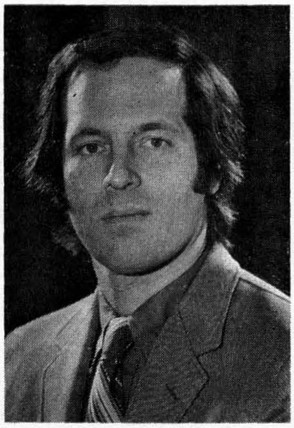
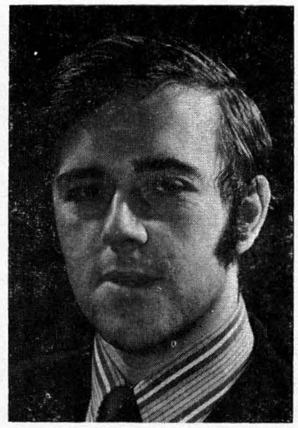
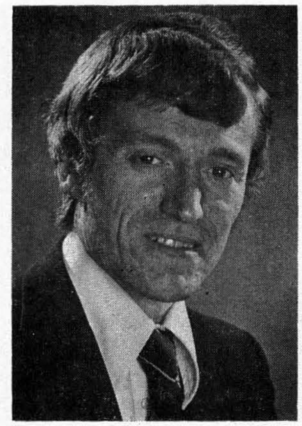


FIGURE 1. Imperial College Computer-Controlled Pilot Plant.







Dr. L. S. Kershenbaum, who is Reader in Chemical Engineering, received his PhD in Chemical Engineering from the University of Michigan in 1964. He subsequently joined the staff at Drexel University and also worked for the Du Pont Corporation in Philadelphia and in Wilmington, Delaware. He joined Imperial College in 1970, assuming responsibility for the development of research and teaching programmes utilizing the Department's computer-controlled pilot plants. In addition to this work his research interests include chemical reaction engineering and applied catalysis with special emphasis on reactions important in energy utilization. **(L)**

Dr. D. L. Pyle is a Senior Lecturer in Chemical Engineering. He graduated from the Universities of Manchester (1961) and Cambridge (PhD, 1964); before joining Imperial College he spent two years at the British Coal Utilisation Research Association.

He was largely responsible for the design of the computer-controlled plants and has had a continuing interest in research, mainly involving the crystallisation plant, and teaching in control. His research interests also include fluidisation and, more recently, problems relating to technology choice in developing countries, with special emphasis on renewable energy supplies. **(C)**

Dr. J. D. Perkins is a Lecturer in Chemical Engineering. He graduated from Imperial College (BSc, 1971; PhD, 1973), and spent four years teaching at the University of Cambridge, and one year working for ICI Agricultural Division in Billingham. He joined the staff at Imperial College in 1977. His research interests are in control, and in the computer-aided design of chemical processes. **(R)**

niques offer little guidance or assistance to the control engineer and in which modern methods are reasonably easy to implement. The three areas are

- **situations in which there is significant interaction between control loops (and in which this interaction is not easily eliminated by intermediate buffer tanks, etc.), and where multivariable control methods are appropriate**
- **the control of processes with important but unmeasured or unmeasurable variables**
- **the control of nonlinear processes in which change of load or setpoint requires periodic re-tuning of control loops.**

It is our experience that most control engineers will immediately recognize these as significant problems and will be able to place some of their own problems into one or more of these areas.

Our approach is to provide the background mathematics required for the solution of these problems, and to allow the student time to implement these algorithms on the plants. The actual method of instruction and practical experience varies with the type of group, as described below.

PLANT & COMPUTER SYSTEM

A BRIEF DESCRIPTION OF the plants and computer system is given here for reference.

The plant and computer system is illustrated schematically in Fig. 1. Two plants, a carbon dioxide absorber-desorber unit and a fractional crystallization plant, are linked to a Honeywell DDP-516 computer housed in an adjacent control room. (A third plant, a fixed-bed catalytic reactor plus associated purification unit, has recently been commissioned). Surveillance and control of all plants can be carried out simultaneously.

The measured process variables may be associated with any of the control valves by conventional control algorithms, or via special purpose, user-written programs. In particular, the latter incorporate on-line estimation, identification and optimization routines as part of their control algorithms.

The absorption/desorption plant consists of 2 columns (9m high x 0.25m diameter) for the separation of CO_2 from nitrogen using ethanolamine solution as the absorbent. The CO_2 is continuously absorbed in the solution in the absorption column, and the spent solution is continuously regenerated in the desorption column. The other plant separates two soluble salts by 2-stage fractional crystallization. One salt, potassium sulfate, precipitates and is continuously removed in the first unit (volume, 100 l) and the other salt, potassium nitrate, crystallizes and is removed from the second unit (volume, 200 l).

The plants are fully instrumented with conventional industrial instruments and various continuous and discrete analytical measurements including on-line infra-red analysis, on-line pH measurement and off-line gas chromatography. Control by the computer is achieved by standard current to pressure converters and pneumatically operated control valves.

The computer is a Honeywell DDP 516 with a 16 bit word and 32K words of core store, with a 0.96 μs memory cycle time. Hardware fixed-point arithmetic is available. The core memory is backed by a 1M word Burroughs fixed head disc with disc-core transfer by direct memory access. Programs may be written in real time extensions to Fortran 4. The system allows foreground/background operation and the use of disc resident subprograms which are loaded into core only during execution.

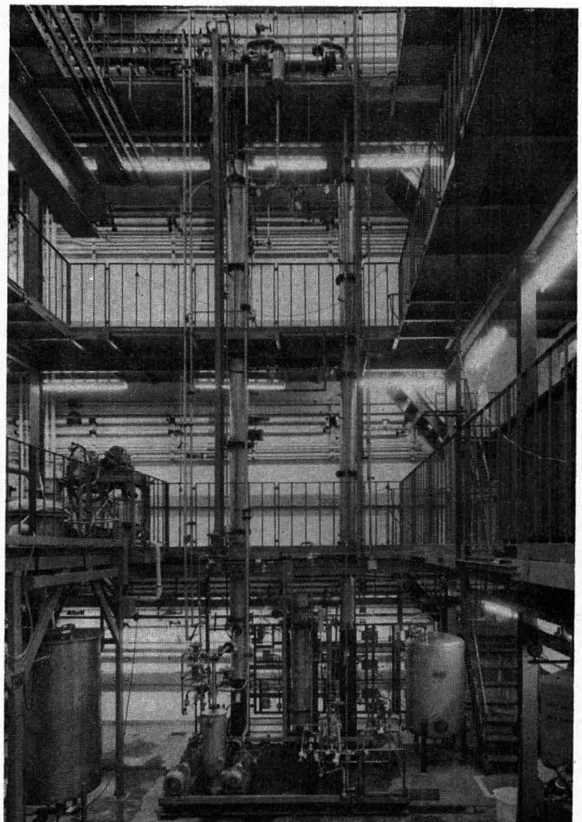
Thus, the scale of the operation is as close as possible to computer systems currently in use in typical chemical process plants.

COURSE AIMS, OBJECTIVES AND CONTENT

As we noted, rather than attempt the impossible task of covering the whole of modern control theory in one short course we chose to focus on three types of problem: multivariable control system design, estimation and filtering, and the design and use of adaptive 'self-tuning' regulators. Even with such a limited set of problems to discuss it would still be impossible to deal with all the relevant theory and practical aspects of the techniques. Instead we set out with a limited group of objectives.

First, we intended that the students should be able to *identify* process situations and problems where the techniques might be useful; this would involve the discussion of problems where classical control methods can no longer cope—for example because of interactions between process variables, where nonlinearities might be important, or where key states and parameters are unknown or unmeasurable. Secondly, the students should be able to *describe in simple terms* the basic theoretical ideas underlying the three sets of techniques. Thus, for example, we wouldn't expect a detailed understanding of all the theory of linear multivariable systems, nor would we expect the student to be able to derive from first principles the Kalman filter, but we would expect a level of understanding of the theory appropriate to the intelligent use of the methods. Thirdly, the student should be able to cast problems into the form necessary for the use of the techniques and also be able to specify the information necessary for their application. Faced with a problem of controlling a process on which insufficient information is available, for example, the student should be able to set up a dynamic model of the process and to be aware of the statistical information necessary for a filtering algorithm to function adequately. In very broad terms, then, we hoped that by the end of the course the student should recognise the limitations and inadequacies of classical control theory, while retaining an appreciation of its value—and also appreciate and value the areas where certain modern control methods might have a powerful role to play.

We can summarise what we hoped to achieve in the course in terms of three broad aims. First we would introduce the underlying theoretical ideas behind the techniques. For example, in the case of multivariable control methods, this would involve the extension of the familiar (scalar) ideas



A general view of the absorption/desorption pilot plant.

for the algebra and frequency response analysis of linear dynamic systems to the parallel (vector-matrix) analysis of multi-input, multi-output systems. In estimation theory we need some basic statistical ideas leading to the Kalman filter. Similarly, the discussion of the self-tuning regulator requires some ideas, new to most students, about the behaviour of discretised systems in order to outline a procedure for the periodic re-estimation of process parameters and the automatic re-adjustment of control constants.

The second aim of the course was to enable the students to perform the process and system modelling and specification necessary for the application of the control methods.

The third aim was to give the students the opportunity and experience of applying at least one of the techniques to a real problem. In this respect we were very fortunate in having the computer controlled pilot plants described above, where realistic problems of process interaction, or of unknown key variables, and of significant non-linearities under load changes are all present.

A short syllabus for the course is summarised in Table 1. We return below to the questions about the prerequisites required of the participants and to the methods and strategy we have adopted in attempting to realise the aims and objectives summarised above.

TABLE 1
Summary Syllabus

INTRODUCTION AND BACKGROUND.
The basic mathematics of linear systems: state representation and essentials of state space algebra and calculus; discrete time representation of continuous processes and Z-transforms; basic statistical theory.

DESIGN OF MULTIVARIABLE CONTROL SYSTEMS.
Limitations of classical control theory: interaction and stability. Algebra of multivariable systems; methods for analysis and synthesis of control schemes: decoupling, stability of multivariable systems, dominance and the development of Nyquist-type design methods.

ESTIMATION OF UNMEASURED VARIABLES.
The basic mathematics of estimation theory; the Kalman filter—the optimal estimator for linear systems; the use of the filter for the estimation of states and parameters in non-linear systems.

REGULATION OF TIME-VARYING PLANT.
An adaptive "Self-Tuning Regulator"; elimination of manual retuning; periodic re-estimation of parameters in simple linear process models; automatic adjustment of control constants as plant operating conditions change.

STRATEGY AND TEACHING METHODS

IN PRACTICE, OF COURSE, the particular teaching methods employed depend on the course participants and the time available. So far the course has been given to two rather different groups: the first was a class of master's degree students and of first-year research students. In a typical year there are around 15-20 students in the class and the majority have first degrees in chemical engineering but from a wide range of universities in Britain and abroad. Moreover the great majority of these students will have come directly from their undergraduate studies and, as a consequence, have had relatively little practical experience. For this group of students the course is allocated around 20 scheduled hours during one term (of eleven weeks). The main problems to be anticipated with such a group of students stem from their very different backgrounds and levels of attainment: some will have had a strong undergraduate course in modelling and control; others will be relatively weak in that area. Similarly, some will have a strong mathematical background and others will be much less well prepared. As a group, they probably share a lack of experience and perspective into the nature of 'real' process control problems.

The second group (to whom the course has been presented in the form of an intensive one-week programme) came from industry. This group, of 12, were all active in control or control-related work in the process industry, although they were heterogeneous to the extent in which their work implied a working knowledge of classical, let alone modern, techniques for control. There was a similar heterogeneity in their familiarity with the necessary mathematics. On the other hand, we did anticipate that their concern with both day-to-day and longer-term industrial problems would bring a sense of purpose to the class and also provide a different critical perspective on the course itself from that provided by our internal students.

For both groups the aims and objectives of the course were the same, although, of course, the detailed objectives would be adjusted as necessary. We also decided to prepare a set of quite detailed course notes which would serve for both groups. Apart from supplementary handouts in the form of computer programs or examples to be worked through, these notes are intended to be self-sufficient for the purposes of the course.

For both groups a certain level of attainment and familiarity with some basic materials was necessary. The industrial group was contacted well in advance of the course and sent a brief summary of the background we would assume and a summary of what we thought would be the most useful material. This covered some essentials of traditional control theory, matrix algebra and analysis, and some basic statistics. For this group the first day of the course was spent in discussing their, and our, perceptions of the course and its objectives, and in reviewing the background material by discussing the problems they had encountered.

A rather similar approach was taken with our own students. At the first meeting of the course we discussed the sorts of skills we would subsequently be using. The students were then directed toward the necessary background reading and to a range of examples to be used to monitor their levels of attainment and to give them practice in acquiring new or improving rusty skills. In practice this was far more difficult than we had anticipated: it was very difficult to promote the right atmosphere within the class when we met later to discuss their problems. In the end we had to resort to a rather unsatisfactory blend of discussing problems which not all the class had attempted and of exposition on our part on what *we* thought their problems might be. It is interesting that the experience with the more mature and perhaps, in many cases less well prepared, industrial group was far more satisfactory. They were far more prepared to treat us, the 'teachers,' as equals, and to want to explore a host of questions of varying levels of difficulty or sophistication. For example, there were one or two people within the group whose recall of classical control theory or of some basic algebra was very rudimentary; on the other hand, there was at least one person in the group who wanted to ask rather probing questions about the use of filtering theory.

The background notes that we had given to the participants and which were freely available to our own students had been composed (around the syllabus outlined in Table 1) to meet our course objectives. Class sessions, then, were organised not as formal lectures but rather to outline the main thrust of the theoretical ideas in the notes and the practical control methods, and to come to grips with some of the problems likely to be encountered through a series of examples. For such a strategy to be really successful a number of conditions must be satisfied: the notes should be clear and reasonably comprehensive; one needs a set of examples for exposition and for the student to work on; one needs the right sort of classroom and group conditions to encourage such a method of learning. In the case of this course the possibility, from early on, of attempting to use the techniques in practical situations was absolutely crucial. Again we were confronted with a problem, since the time available in either course and alternative demands on the students' time and interest made it impossible for each student to build up the necessary computer programs to implement any of the techniques. To try to solve this problem we had recourse to a blend of methods: we gave the students a few small problems to work on (e.g. sketching the inverse Nyquist array for a 2 x 2 system with a very simple transfer function matrix) and working on prewritten program suites either off-line, on simulation or analysis exercises, or on-line on the pilot plant.

About 40% of the scheduled course time was allocated to this sort of activity with the industrial group, which was, of course, sufficiently small to be able to break into three smaller groups to work in parallel on the various problems. Thus while one group was exploring the behaviour of the self-tuning regulator on the CO_2 absorption/desorption plant, another group would be trying out the Kalman filter on a computer terminal, while the final group would be trying out the suite of multivariable design programs which are available on the College computing system. By the end of the course one of our aims at least was more than met, since each group had had some experience with at least two, and possibly, all three of the techniques focussed on in the course. Our final discussions with the group and subsequent contacts suggest that our course objectives had been fairly satisfactorily achieved.

Our only measure of the course achievements with the postgraduate class was their performance in the end of course written examination. Three questions covering the main topics of the course were set and the students were required to attempt all of them. The results were reasonably satisfactory since the students showed a fair grasp of the principles and application methods of the topics covered in the course. However we feel it may be necessary to develop more appropriate measures of the class performance than is afforded by the traditional written examination. □