tivities, machinery, and lighting requirements in the various rooms and zones. In addition, the coordinator is responsible for improving upon the supervisor's deterministic optimization of cost and comfort by considering those variables and constraints in a building system that are "fuzzy" in nature, such as human comfort criteria. For example, when a building occupant partially opens the window blinds, he introduces an unexpected disturbance to the room temperature control system. This disturbance can be handled as a fuzzy variable or "approximate reasoning" by the coordinator. A first phase implementation of this hierarchy is being completed on a special laboratory setup composed of three rooms requiring different air conditions. A new learning scheme has been developed and implemented at the local control level which regulates, simultaneously, temperature, humidity, and air flow in each room.

New Dimensions

Intelligent control systems provide new dimensions beyond those of the conventional control systems. The ability to operate under uncertain environment, which may involve fuzzy representation, and/or symbolically described operations combined with adaptivity, learning and decision-making, make ICS much more attractive for control of systems involving ambiguity. The ICS requires integration of several disciplines and typically requires more thoughts at the development stage.

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Where is the Intelligence in Intelligent Control?

K.J. Åström

In the early development of artificial intelligence, there were strong ties to automatic control. Typical examples are the development of cybernetics, robotics, and learning and broom balancers like BOXES. After a period of consolidation which focused on specific problems in each subfield, there are now indications that benefits can be derived by cross fertilization.

Intelligence is a loaded word because of its strong association to human ability. Some interesting views on artificial intelligence are expressed in *The Emperor's New Mind*, by R. Penrose [1]. Even if AI fails to live up to human capabilities, artificial intelligence research has generated many useful ideas and techniques that can be used to make better control systems. Similarly, the AI field can be stimulated by interaction with feedback control [2]. In particular, automatic control can make very effective use of 1) programming techniques, 2) programming environments, 3) techniques for dealing with heuristics, and 4) new hardware.

AI can also benefit much by introducing dynamics and analysis. Some specific example are elaborated below.

Control System Design

Control system design includes activities like modeling, analysis, simulation, design, implementation, and verification. This activity is central to control engineering. A good control system design is a combination of many different elements - control theory, algorithms, engineering judgement, rules of thumb, etc. Efforts are underway to provide computer support for several aspects. Modeling and simulation software have been developed. There are programs for control system design.

This area is natural for application of AI methods [3,4]. A major challenge is to capture and describe good design heuristics. There are many potential applications in the software area. The CACE packages may be viewed as implementations of high level problem-solving languages. There is a great need for intelligent user interfaces that support design procedures and the use of CACE software.

Since control system design may be formalized as a high level problem-solving language [3], ideas from natural language processing can be applied. The notion of script was introduced by Roger Schank [5] to describe context in natural language processing. Although it is quite difficult to describe context in an everyday conversation, it is easy to describe the context in control system design. In [6]-[9] the authors described how scripts are used to develop an intelligent user interface for solving system identification problems. The interface contains knowledge about the problem domain (system identification) as well as about the particular software used (Idpac).

Another interesting possibility is to use the idea of auditing systems to check that a control design satisfies all specifications.

On-Line Systems

Industrial automation systems were traditionally based on relay boxes for interlocks, sequencing, and controllers. With the

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introduction of microprocessors, these were implemented as programmable logic controllers (PLC) and direct digital controllers (DDC). Since the systems are implemented in the same technology, a natural merging of the techniques of logic, sequencing, and algorithms is occurring. This has opened up many interesting possibilities of making systems with increased capabilities. For example, it is possible to process alarm signals to give more meaningful information. It is also possible to provide the alarm system with capabilities for inquiries. This is clearly an area that can benefit from use of methodologies from AI and feedback control. One observation is that logic and sequencing can be expressed very conveniently in rules. The use of an AI programming style admits system descriptions that are much more compact than those normally used for PLCs. For example, it is possible to have generic rules that apply to all processes of a certain type, allowing significant simplification in programming, modifications, and troubleshooting.

The merger of algorithms and logic is also noticeable for simple controllers. A recent standard proposal for a PID controller has, e.g., 255 different modes with associated heuristic logic.

One possibility of combining algorithms and heuristics was discussed in [10],[11] where a so-called expert control system was introduced. This system has many different algorithms for modeling, control, monitoring and supervision. All algorithms are administrated by a knowledge-based system. An implementation of such a system based on a blackboard architecture is given in [12]. Several other implementations have been made. Commercial knowledge-based systems for real time process control are available [13],[14]. These systems are used in combination with distributed systems for process control. The system [14] is imbedded in a conventional process control system. Interesting views which combine conventional control with knowledge-based systems are given in [15].

Much fundamental work remains to be done to achieve an effective combination of algorithms and logic. Finding methods to analyze systems and reason in real time are key issues.

Adaptation and Learning

Although learning has not been of strong interest in conventional AI, it is the center of neural networks. Because another paper deals with this, I will be very brief. Let me just point out that there are very strong relations between the work on learning in AI [16] and adaptive control [17]. The algorithms for training a neural network can, e.g., be interpreted as special versions of model reference adaptive systems. An interchange of ideas in this area could prove very fruitful.

Also notice that if modeling and control design can be done reliably and on-line, we have, in fact, an adaptive system.

Simple Process Controllers

Simple process controllers of the PID type are currently going through an interesting development [18]-[20]. Features like auto-tuning, adaptation and gain scheduling are currently being incorporated even in single loop controllers. To achieve this, it is necessary to automate modeling as well as control design. Modeling has been automated both by conventional system identification methods [18] and with heuristical approaches based on pattern recognition [19]. Control design has also been automated using algorithmical as well as heuristical methods. The traditional way of tuning controllers is often based on heuristic rules of the Ziegler-Nichols type [21]. Recently there have been significant efforts to improve and extend such [22]-[24].

A result of this development is that the instrument engineers now have algorithms that will help them tune the controller or will even tune the controller automatically. An interesting side effect is that it has also made gain-scheduling easy to use. Combined with an auto-tuner, it is straightforward to generate a gain schedule.

The degree of automation of the single loop control is currently limited by the designer's imagination and available computing power. Since computing power is increasing rapidly it is safe to predict further development. Natural next steps are to include diagnostics and loop auditing [25].

The reason for the active work on simple controllers is that the problems are limited, require modest development effort, and yield direct improvements. Personally I believe that the combination of AI with feedback control will show its real strength when applied to more complex systems.

New Hardware

New components are an interesting consequence of recent activity in neuron networks. There may be possibilities to obtain new components with interesting capabilities. Consider, for example, the task of implementing a small digital servo system. The hardware involved are sensors, AD and DA converters, a microprocessor and driver circuits for the actuators. Adding up a significant silicon area is necessary even to implement a simple system. The work by Carver Mead [26] on silicon neurons in analog VLSI offers interesting possibilities. Control systems can be implemented using silicon neurons. The paper in [27] describes a motor control system implemented in this way. The system is based on silicon neurons where signals are represented by positive and negative pulse trains. It is shown that a simple controller can be implemented with a handful of neurons. Such a system is easy to interface with sensors. The drive circuits are also very simple because the pulses from the controller are simply sent to power transistors. It is easy to obtain a highly reliable system by duplicating the neurons and adding the pulses. Add the possibility for learning which has not yet been implemented and we have a system with many useful properties.

Opportunities

There are opportunities to make control systems with significantly increased capability by combining methodologies from feedback control and artificial intelligence. In a simple setting this has been demonstrated by recently announced single loop controllers with capabilities for automatic tuning, gain-scheduling and adaptation [28]. There are also interesting opportunities for better CACE systems with intelligent user interfaces, where heuristics and algorithms are combined. Such systems can be used off-line and possibly on-line. Ideas, methods and hardware are available, and it appears that control engineers have many possibilities to make useful and interesting systems. It is not clear if such systems are best labeled as intelligent.

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Intelligent Control

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Over the past three decades numerous terms borrowed from psychology and biology such as adaptation, learning, pattern recognition, and self organization have been introduced into the systems literature. We have come to realize that these terms are necessarily imprecise and the ideas they are intended to connote cannot be compressed into simple statements without vital loss of content. However, we need such terms because they help us to communicate and advance the progress of our science. Intelligent control is merely the latest in this series of terms. Our efforts to define it are like those of the Supreme Court trying to define pornography: we can't state precisely what it is but we know it when we see it.

Current Status of Control Theory

As control methods have found their way into standard practice, they have opened the door to a wide spectrum of complex applications. Such complex systems are characterized by poor models, high dimensionality of the decision space, distributed sensors and decision makers, high noise levels, hierarchies, multiple time scales and/or performance criteria, complex information patterns, overwhelming amounts of data and stringent performance requirements. We can broadly classify the difficulties that arise in these systems into three categories for which established methods are insufficient. The first is computational complexity, the second is the presence of nonlinear systems with many degrees of freedom, and the third is uncertainty. In the third category are included model uncertainties, parametric uncertainties, disturbances and noise, and descriptive models of knowledge. The greater the ability to deal successfully with the above difficulties, the more intelligent is the control system. Qualitatively, a system which includes the ability to sense its environment, process the information to reduce the uncertainty, plan, generate and execute control action constitutes an intelligent control system.

Intelligent Control

A necessary consequence of using a loose definition of intelligent control is that what is considered intelligent will be very much a function of the state of knowledge and expec-

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