

Bridging the Gap between Conventional and Intelligent Control

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The Image Bank: D. Tillinghast

Researchers in the field of intelligent control are introducing new concepts and techniques for control; however, determining the value of their contributions is often difficult since quite often the researchers do not utilize conventional control engineering approaches. Here, it is explained how to relate new ideas and techniques in intelligent control to established ones in conventional control so that true advances in control can be gained and so that overstated claims and “hype” can be avoided. This is done by clarifying the meaning of “intelligent” control, and providing a control engineer’s perspective on design, modeling and representation issues; nonlinear analysis; implementation issues; and experimental evaluations for intelligent control. In developing this control engineer’s perspective, it is explained how researchers in intelligent control have been naturally led to address very difficult and important control problems. In addition, it is explained how recent advances in computing technology provide a fundamental driving force for the emerging field of intelligent control.

Conventional vs. Intelligent Control

Given a control problem, researchers working in the field of intelligent control typically consider using an approach to control that is motivated by the forms of representation and decision making in human/animal/biological systems, and often heuristi-

cally construct what turns out to be a nonlinear, perhaps adaptive controller. While simulation results are typically used to “verify” the approach and successful implementations have been achieved (e.g., via fuzzy, expert, and neural control), it is often the case that no nonlinear analysis is performed to verify the behavior of the closed loop system and quite frequently no implementation or experimental evaluation is conducted. Although it is recognized that new ideas and techniques for control are being introduced by the intelligent control community, after careful examination of the results, control theorists and practitioners can often convincingly argue and/or demonstrate that they can obtain the same or better results with conventional techniques. We cannot throw out what has been done by the control community in the excitement over intelligent control. Overall, conventional control has a much better and more well developed track record than techniques from intelligent control and this is important, especially to the practitioner seeking a reliable implementation for a control system.

At the same time it is bad for control engineers to simply ignore the field of intelligent control as being “sloppy.” Perhaps it is not as “tidy” as conventional control, but this is due to the fact that the field of intelligent control is relatively new and unexplored. Intelligent control has certain techniques and concepts to offer; the challenge is to find out what it is good for, and perhaps more importantly, what it is not good for. From a control engineer’s perspective, the best way to assess the contributions of intelligent control is to perform careful theoretical and experimental engineering analysis as has been done in the past for conventional control systems. Such an assessment will most likely tone down the often implied idea that “intelligent control can solve all of your problems.” As with the introduction of any

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new approach to control, we need a careful engineering analysis of intelligent control approaches, in the context of established ideas and techniques, to assess their advantages *and* disadvantages.

A decidedly pragmatic engineer's view of the field of intelligent control is taken here where implementations are kept in mind. This perspective was developed by working with many colleagues who share the concern about determining what the field of intelligent control has to offer to the solution of pressing real-world problems. Moreover, this perspective is certainly in transition; hence there will certainly be points in this article that need further clarification/expansion.

A comprehensive treatment of the theory, techniques, applications, and research directions in the field of intelligent control is not provided here (this is contained in [1]). A characterization of the excitement in the field of intelligent control about promising new approaches to control is not provided here (this is contained in, for example, [2]-[4]). In addition, the number of bibliographic references is kept to a minimum; the reader interested in pursuing the issues raised in this article should see the other articles in this special issue, [1]-[4], and also [5], [6] and the extensive lists of references therein.

This article does, however, *begin* to build a bridge between conventional and intelligent control that will be useful to researchers on both sides. Many researchers in artificial intelligence (AI) will perhaps find the control engineering perspective helpful in thinking about how complex real-time control systems are developed, implemented, and verified. For control engineers, the article provides a familiar perspective and language to talk about the diverse and relatively new field of intelligent control.

Intelligent Control Methodologies

While modeling issues are often discussed first when presenting an overview of an approach to control, for intelligent control it is important to first clearly explain a) what is meant by "intelligent" control, and b) how a control engineer's perspective still provides the proper framework for integrating the results from a wide variety of fields in intelligent control (including engineering, computer science, natural sciences, mathematics, and psychology) and focusing these on difficult control problems.

The Focus on "Intelligence"

Control engineers often become concerned with the use of the name "intelligent control." This concern arises partly from many researcher's apprehensions and disbeliefs in *artificial* intelligence, partly from the use of the term "intelligent" or "intelligence" and the hype that it generates (e.g., the notion that since it is "intelligent" it must automatically be better than other conventional approaches), and partly from the concern with whether modeling human behavior in a controller automatically implies that a human's tendency to make mistakes is being modeled. One dictionary defines intelligence as "the capacity to acquire and apply knowledge." The use of such a broad definition could imply that the simplest microprocessor implementing a PID controller is in fact intelligent since it continuously acquires knowledge (plant data and reference inputs) and applies it (by generating control inputs to the plant). Philosophers and psychologists, although not in complete agreement on these issues, recognize that for higher levels of intelligence there is an ability to abstract, to form concepts, to create, to synthesize and integrate

information, to solve complex problems, and so on. One could conclude that to call a controller "highly intelligent" it would have to, for instance, be cognizant of the fact that it is an intelligent controller and have the ability to contemplate its creator or how it evolved into the controller that it is. Clearly, there are different levels and types of intelligence; hence it can be argued that there may be different levels and types of intelligence for different controllers (we do know that there exists at least one type of intelligent controller - the human). What one person thinks of as true intelligence, another would think of as simple algorithmic behavior. Moreover, even if at one point in time a group of experts agree that a system exhibits intelligence, over the years, as the system is better understood, the experts often begin to classify the exhibited behavior as "algorithmic" and "unintelligent".

At this point the control engineer concerned about calling the controller "intelligent" can a) simply recognize that some definitions of intelligence are quite restrictive (and hence do not include, for example, the possibility that mistakes are made) and understand the terminology in this context, b) become concerned about what levels and types of intelligence must be present in a controller for it to be considered reasonably intelligent, c) understand that others view the term "intelligent" in its fullest possible sense and therefore consider it a *goal* to make the controller as intelligent as possible (so that it will not make mistakes), or d) view the choice of terminology as somewhat unfortunate due to the hype that it generates. In any case, many control engineers do not feel justified in calling their controller "intelligent" or they feel that the issue really doesn't matter; their main focus is on implementing a controller that will enhance the system's performance. Hence, they often prefer to leave the "intelligence" issue to persons such as psychologists, philosophers, persons in medical professions, and the computer scientists in AI who try to make computers emulate it.

There is, however, another approach to defining intelligent control where the focus is not on the intelligence of the resulting controller, but either on a) understanding how human/animal/biological systems achieve certain tasks in order to get ideas about how to solve difficult control problems, or b) on designing controllers to take on the responsibility for tasks that are normally performed by humans/animals/biological systems.

The Focus on Methodology

A "control methodology" is the set of techniques and procedures used to construct and/or implement a controller for a dynamical system. Hence, the methodology can include both the control design process and/or the type of algorithms/hardware used in the end implementation (but it is not the actual physical device that is implemented). Notice that although there are difficulties in defining and justifying the existence of an "intelligent" part of an intelligent controller, a different approach can be taken where a definition of an intelligent control methodology is provided first, and the definition of the intelligent controller is based on this: *A control methodology is an intelligent control methodology if it uses human/animal/biologically motivated techniques and procedures (e.g., forms of representation and/or decision making) to develop and/or implement a controller for a dynamical system.*

Hence, as an example, the fuzzy control methodology includes a) the use of fuzzy sets and fuzzy logic for rule-based

representation of a human's knowledge about how to control, b) fuzzy inference for modeling human deductive processes, and c) conventional or fuzzy processors for implementation. Other intelligent control methodologies include expert control (where, for example, a rule-based expert system is used), learning control (where learning theories are incorporated into controllers), the use of planning systems for control (where theories of human planning are used), neural control (which is motivated by low-level biological representations and decision making), and the use of genetic algorithms to solve control problems (where biologically motivated algorithms are used). Many intelligent control methodologies result from a synthesis of several intelligent/conventional control methodologies. Notice also that if a conventional controller is developed and implemented via a biologically motivated approach (for example, the implementation of a PID controller with a neural network), this constitutes the use of an intelligent control methodology.

Our definition of an intelligent control methodology leads to a definition of the intelligent controller: *The physical device called a controller is an intelligent controller if it is developed and/or implemented with a) an intelligent control methodology or b) conventional systems/control techniques to emulate/perform control functions that are normally performed by humans/animals/biological systems.*

Hence, the product of fuzzy (expert) control methodologies is a special type of intelligent controller called a fuzzy (expert) controller. The controller that results from the use of learning, planning, neural, or genetic algorithm approaches is an intelligent controller. The product is defined by the methodology used in its construction and/or implementation. Notice that even if we are constructing a system with no focus on utilizing particular characteristics of biological intelligent systems, but instead focus on emulating functions normally performed by intelligent beings, we will call the resulting system "intelligent" (this often happens in industry). For example, robotic systems and automatic guided vehicle systems for highways are often called "intelligent" as they are designed to perform tasks that are often performed by humans. In addition, if we use human/animal/biologically motivated computer vision systems, multi-sensor integration systems, or failure detection and identification systems to aid in the implementation of control systems we could call the controller "intelligent." Regardless of what we wish to call intelligent, it must be acknowledged that most current intelligent controllers only weakly characterize the complex functions of their biological counterparts (but this is often sufficient to meet objectives).

The control engineer may step back in at this point and ask: By the above definitions, is every conventional control methodology an intelligent control methodology, and is every controller an intelligent controller? One could probably argue this point either way depending on how broad the underlying definitions are, and in fact it can be argued that there is no clear distinction between conventional and intelligent controllers (since, for example, intelligent controllers often include both intelligent and conventional components). To help make the distinction, it is emphasized that in intelligent control the focus is on designing controllers to emulate/perform certain intelligent functions of human/animal/biological systems to solve control problems.

In the end implementation, however, nothing magical is created. The resulting intelligent controller is just a heuristically

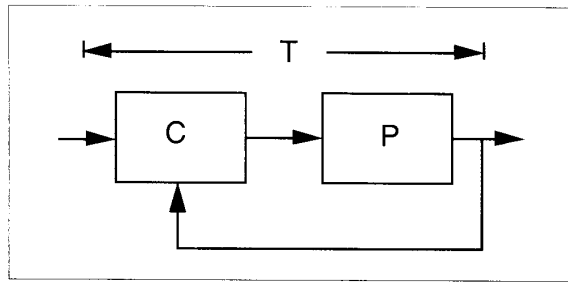


Fig. 1. Control system.

constructed nonlinear, perhaps adaptive system which is therefore amenable to control theoretic approaches to analysis. For instance, the simple direct single-input, single-output fuzzy controller is a static nonlinear map (often a sector-bounded nonlinearity), the expert controller may model certain "IF-THEN" statements in a control implementation (a type of nonlinearity) to ensure reliable operation, and many (numerical) learning controllers are types of nonlinear adaptive systems. Hence, from a control engineer's perspective the focus should not be on whether the control systems that we are implementing are exhibiting "intelligence," but rather on whether they are able to achieve higher performance with a greater degree of *autonomy* than their conventional predecessors.

The Focus on Enhancing Autonomy

Consider the general control system shown in Fig. 1 where P is a model of the plant, C represents the controller, and T represents specifications on how we would like the closed loop system to behave. For some classical control problems the scope is limited so that C and P are linear and T simply represents, for example, stability, rise time, and overshoot specifications. In this case intelligent control techniques may not be needed. As engineers, the simplest solution that works is the best one. We tend to need more complex controllers for more complex plants (where, for example, there is a significant amount of uncertainty) and more demanding closed loop specifications T .

Consider the case where

a) P is so complex that it is most convenient to represent it with ordinary differential equations and discrete event system (DES) models (or some other hybrid mix of models) and for some parts of the plant the model is not known (or it is too expensive to find), and b) T is used to characterize the desire to make the system perform well and act with *high degrees of autonomy* (i.e., so that the system performs well under significant uncertainties in the system and its environment for extended periods of time, and compensates for significant system failures without external intervention [1]).

The general control problem is how to construct C , given P , so that T holds. From a control engineer's perspective, researchers in the field of intelligent control are trying to use intelligent (and conventional) control methodologies to solve this general control problem.

In reality, researchers in intelligent control are examining portions of the above general problem and trying to make incremental progress towards a solution. For example, a simple direct fuzzy controller could be called an intelligent controller, but not an "autonomous controller," as most do not achieve high levels

of autonomous operation, but merely help enhance performance like many conventional controllers. It is important to note that researchers in intelligent control have been naturally led to focus on the very demanding general control problem described above a) in order to address pressing needs for practical applications, and b) since often there is a need to focus on representing more aspects of the plant so that they can be used to reduce the uncertainty in making high level decisions about how to perform control functions that are normally performed by humans [1].

For design, control engineers normally try to use knowledge represented in the plant model P plus "extra relevant information" (often *heuristics*) to construct a controller C . Conventional mathematical approaches to control design often initially ignore the extra relevant information and use it later when it comes time for implementation. Intelligent control techniques (e.g., fuzzy and expert control) offer somewhat more formal methods to incorporate the extra relevant information, but they often ignore the use of information from a conventional model. This can cause significant problems since knowledge of control theory is not needed to develop some intelligent controllers; hence it may not be known if problems with, for example, limit cycles and instabilities will be encountered. In addition, when using heuristic approaches it is often difficult to design for prespecified performance specifications without repeatedly iterating on the design (of course, iteration is needed for conventional methods also). The point that researchers in intelligent control sometimes miss is that they can also use conventional models/analysis to provide information about the dynamical system that can be useful in control. All relevant information is needed to attack truly difficult control problems; hence there is a need for a blending of conventional and intelligent control approaches, a synthesis of the use of information from the model and a formalization and utilization of the "extra information" that is often heuristic.

Regardless of the design approach and the type of information that is utilized in the construction of the controller, it is important that a careful engineering evaluation is conducted for the resulting intelligent control system. The first step for such analysis is to consider issues in modeling and representation.

Aspects of Modeling and Representation

Conventional approaches to modeling P include the use of ordinary differential/difference equations, partial differential equations, stochastic models, models for hierarchical and distributed systems, and so on. Control engineers use such models as a formalism to represent the plant they are trying to control for the purpose of constructing a controller to improve the performance of the system.

Some research in the field of intelligent control explores the use of alternative representation schemes. For instance, uses of natural language, computer languages, AI representation techniques such as rules, semantic nets, frames, qualitative models, and causal models are being considered. These are valid formalisms to aid in controller construction, however control theorists often have models they are more familiar with that can achieve the same representation goals. For instance, DES models ("logical" and "timed" or "performance") can be used to represent the same sorts of dynamics as many of the AI knowledge representation schemes. Moreover, *hybrid system models* that are, for instance composed of DES and differential equation models provide a wide range a representational capability.

In addressing the general control problem described above, the trend is towards trying to represent broader aspects about the plant including, for example, the effects of drastic/catastrophic failures or what is often extra heuristic information. In this way more information can be taken into account by the controller (if it is emulating a human, typically a human can consider a wide variety of information that is often not considered by a conventional controller). Also, since we are trying to expand the operating range of the plant, that is, achieve more autonomous operation, it seems natural to try to model a wider range of plant behavior. There are several problems with this trend: a) a mathematical model is never a *perfect* representation of a physical system (it is an abstraction), and b) everything that is done in theoretical analysis and design is based on the modeling assumption. Moreover, if the model of P is chosen to be too complex it will be harder to develop and utilize mathematical approaches for the analysis of the resulting closed loop system. Often we want the simplest model possible that will allow for the development of the controller C , and allow for it to be proven/demonstrated that the closed loop specifications T are met.

Do we really need a formal model? Some researchers/practitioners argue that a) for certain applications conventional models are very difficult or impossible to develop, or b) even if the model could be found, it would not be all that helpful to use it (except, perhaps in simulation) since the assumptions for many conventional control techniques would not be satisfied. Based on these types of arguments it is often said that "some intelligent control techniques (e.g., fuzzy and expert control) are great because there is no need for a model." Others counter this viewpoint by indicating that whether one thinks they are using a model or not for the development of the fuzzy (expert) controller — they are, even if it is just "in their head" (an alternative representation scheme). From a control engineer's perspective, it is roughly known what is being controlled so often there is an opportunity to develop some type of formal model. As engineers, however, the model development task is perhaps most appropriately approached with a cost/benefit analysis. To aid in such analysis, it is important to note that in the excitement about the possibility of constructing a controller without depending on the model, the *disadvantages* of not using a model are often overlooked. In particular, if no formal model is used, then:

- a) there are few, if any assumptions to be violated by a control technique and the technique can be indiscriminately applied,
- b) heuristics are all that is available to perform controller design,
- c) by ignoring a formal model, if it is available, a significant amount of information about how to control the plant is ignored,
- d) standard control theoretic analysis cannot be used to verify the operation of the resulting control system,
- e) it will be difficult to clearly characterize the limitations of various intelligent control techniques (i.e., to classify which plants can be controlled best with different intelligent *or* conventional controllers), and
- f) it may not be possible to clearly relate the results of using the intelligent controller to previous work in conventional control to definitively show that contributions are being made to the field of control.

One could conclude from the above discussions that there is no clear answer to the question of how much/what type of

modeling is needed for the plant P . However, in one school of thought there is a trend to use more sophisticated models that allow for the representation of more information — both the information that is normally represented with, for example differential equations or DES models, and the relevant heuristic information. Unfortunately, there is no standardization of models for intelligent control in the way that there is for many areas of conventional control. Hence, although it is not exactly clear how to proceed with the modeling task, it is clear that knowledge of many different types of models may be needed, depending on the task at hand.

Given the model of the plant P and/or the model of the controller C , the next task often considered by a control engineer is the use of analysis to more fully understand the behavior of P or the closed loop system, and to show that when C and P are connected, the closed loop specifications T are satisfied.

Analysis of Intelligent Control Systems

It is necessary to first establish, from a control engineer's perspective, why it is important to perform nonlinear analysis of intelligent control systems. Often, engineers are charged with the task of showing that a control system will be highly reliable due to the fact that it may be operating in a "critical environment" (e.g., where safety of humans is a concern). While current nonlinear analysis techniques do not always offer a complete verification approach for implemented controllers they do provide methods to help avoid problems such as instabilities and limit cycles. For a more complete verification and *certification*, certainly simulation and experimental evaluation also play a major role as it is discussed below. In any case, careful engineering analysis must be employed for intelligent control system evaluation. We must avoid *ad hoc* implementations of intelligent control systems since a) it is bad engineering practice, b) most likely such implementations will not be reliable, and c) ultimately they will not be trusted.

When considering the possibility of performing mathematical analysis of intelligent control systems it is important to first recognize that there are some trade-offs with the type of modeling approach used. In general, a more complex model may provide the capability to obtain a better representation of a system and may facilitate design, but it may not lend itself to straightforward analysis. If a simpler model is used, one may ignore some of the dynamic behavior of the plant and be able to get more analytical results but they may only be valid in an approximate way for the real system, or for a portion of the real system. Naturally there will be different analysis techniques that are appropriate for different models that are used.

Analysis Using Conventional Models

Most (all?) intelligent control systems are nonlinear control systems. This becomes especially apparent when an intelligent control strategy is implemented. Many intelligent controllers can be represented via conventional ordinary differential/difference equations, especially the ones typically used at the lower "execution level" of general hierarchical intelligent controllers [1], [5]. Hence, it is often the case that they are amenable to, for example, stability analysis (e.g., via the Lyapunov approach) and describing function analysis. There is in fact a growing body of literature on stability analysis of fuzzy control systems (both direct and adaptive) and some time ago, describing function

analysis of simple fuzzy control systems was performed. There is a significant amount of activity in the area of nonlinear analysis of neural control systems and results in the past on nonlinear analysis of (numerical) learning control systems. While there are often claims that some intelligent controllers (e.g., fuzzy controllers) offer "robust control" there is little mathematical analysis to justify this claim. Much more attention needs to be given to these issues, and this provides the control theorist with many new and challenging problems to consider.

Analysis Using Discrete Event System Models

As indicated above, the analysis approach is naturally chosen according to the model used. DES models (e.g., "logical," "timed," or "performance" models) are appropriate for general expert control systems, planning systems, abstract learning control and often the higher "management and coordination levels" in general intelligent control systems [1], [5]. Hence, there is the need for DES analysis techniques for these systems. In addition to modeling issues and controller synthesis, topics currently being addressed in DES theory include approaches to controllability, reachability, observability, and stability analysis. There is a need to investigate the use of such analysis approaches for the classes of intelligent control systems discussed above. There have already been some applications of DES theory to AI planning systems and there have been recent results on stability analysis of expert control systems (when an OPS-5 type expert system is used as the direct controller). Clearly, the DES theorist can be challenged with many difficult problems in the verification of intelligent control systems (especially of the complex type described in [1]).

Analysis Using Hybrid Models

For very complex, hybrid controllers (e.g., those with a hierarchical/distributed mix of intelligent and conventional controllers such as in [1]) and hybrid plants (i.e., those that have, for example, dynamics that are conveniently represented with both differential equations and DES models) there is a significant need to develop nonlinear analysis techniques for the resulting hybrid control system. While there has been recent progress in defining models and developing approaches to analysis for some hybrid systems, there is the need for much more work in this area. Many fundamental modeling and representation issues need to be reconsidered, different design objectives and control structures need to be examined, our repertoire of approaches to analysis and design needs to be expanded, and there is the need for more work in the area of simulation and experimental evaluation for hybrid systems. The importance of the solution to the hybrid control system analysis problem is based on the importance of solving the general control problem described above; that is, hybrid system analysis techniques could provide an approach to verifying the operation of intelligent controllers that seek to obtain truly autonomous operation.

Overall, the results of the analysis are only as good as the model used. The results of nonlinear analysis provide statements about the model and the physical system that are valid up to the accuracy of the model. This helps to underscore the importance of implementation and experimental evaluation of intelligent controllers.

Technology, Implementations, and Experimental Evaluation

Control engineers recognize a) the fundamental impact that technology has historically had (and will have) on the field of control, b) the significant problems that can be encountered in implementing a controller (e.g., noise, word length restrictions, hard nonlinearities), and c) the importance of evaluation of the control approaches by the use of experimental methods. Below it is explained how such issues are also relevant to the field of intelligent control.

The Impact of Technology

Computer science, engineering, and technology drive the development of control theory, control engineering, and control technology by providing alternative strategies for the functionality and implementation of controllers for dynamical systems. For instance, the introduction of the microprocessor had significant impacts on: a) the implementation and wide spread use of controllers, b) the expansion of the role of control systems over the times when they were implemented solely in an analog fashion, and c) the development of extensive theoretical results in control theory. While a portion of control theory naturally developed driven by technology, certain theoretical results allowed the technology to expand its role due to the fact that they provided methods to "guarantee" that the technology would work in critical environments (e.g., the use of stability theory for ensuring the safe operation of controllers for nuclear reactors and aircraft).

Analogous statements can be made relative to more recent developments in computer science and technology. For instance: What will the impact of highly parallel processing (e.g., via neural networks), fuzzy processors, or techniques from AI have on control engineering and the implementation of controllers? Is there a role for theoretical and experimental engineering analysis in expanding the use of intelligent control? From a control engineer's perspective, the field of intelligent control is trying to answer important questions such as these. Overall, we have computers with enhanced capabilities and we are trying to figure out what we can do with this added capability in the solution of control problems.

Implementations

Have intelligent controllers been implemented successfully? The answer is yes. There are many examples of implementations of fuzzy control via both conventional and fuzzy processors. There are also implementations of neural control and expert control and others (see [1]-[6]). There are many application areas including robotic systems, automotive systems, manufacturing systems, aircraft and spacecraft, underwater and autonomous land vehicles, process control, and consumer products which have benefited from various intelligent control techniques. However, it is the case that the field needs more implementations to focus the research on the real engineering problems. Moreover, additional real-world successes will significantly help advance the field.

For some intelligent controllers there are several additional issues that are often not encountered in the implementation of conventional controllers: a) the numeric/symbolic computation issue in implementing hybrid approaches to intelligent control (e.g., in implementing an intelligent controller that consists of a

general expert system and a fuzzy system), and b) the development of a real-time, effective, and friendly interface to users. For many intelligent controllers, real-time implementation can be very challenging since computing abstract control decisions can be very computationally intensive (e.g., for some expert, learning, and planning system approaches). But researchers in intelligent control use hierarchies and distribution to address problems with complexity and often seek to utilize new developments in computing technology.

Experimental Evaluation and Redesign

Certainly the importance of evaluation via simulation cannot be ignored, but actual implementation will often have even more advantages. It will provide a realistic assessment of complexity issues (e.g., properly assess whether the system can be implemented in real time with the available computing resources). While some researchers imply that there are computational advantages to using intelligent control over conventional control there are few, if any, conclusive studies to support this general claim for a wide variety of challenging applications (for certain applications there may be some advantages). Certainly, some technologies for intelligent control hold significant promise in providing computational advantages (e.g., neural networks) but much more study is needed to determine exactly what advantages are gained, when all things are taken into consideration (including cost). Overall, intelligent control methodologies that seek to expand capabilities in order to achieve more autonomous operation often end up more complex. On the other hand, the increase in expanded capability may be worth the price. In the end analysis though, the simplest solution that works properly is the best one.

Much can be learned about how to design effective intelligent controllers by first investigating several conventional control approaches. Such experiments with conventional control help to motivate why it may be important to switch to intelligent control (by identifying deficiencies with the conventional approach), may help to build the "knowledge base" for the intelligent controller, and may show when intelligent control is *not* needed. The knowledge gained from the implementation of the intelligent controller is also very valuable to enhancing its performance. What is learned in developing and testing the implementation can often be loaded into the knowledge base of some intelligent controllers. It is then clear that the intelligent controller should provide for more flexible incorporation of knowledge gained from the implementation (this allows for tuning the intelligent controller while conducting field tests). The facility to incorporate tuning knowledge should be more "user-friendly" (and advanced) than just allowing for the tuning of, for example, PID parameters. It should allow for the representation of more abstract information about how to improve the control of the process, that is, it should allow for the incorporation of general heuristics.

Concluding Remarks

A pragmatic view of the definition of "intelligent" control and an explanation of the focus on autonomy in intelligent control have been given. We developed a control engineering perspective on modeling and representation issues, nonlinear analysis, design, implementation, and evaluation of intelligent control systems. We discussed the importance of using a control engineering approach to assess the contributions of the field of intelligent

control. We explained how technology has provided a driving force for the field of intelligent control and have provided several research directions for control engineers working in the area of intelligent control. Overall, we have explained how the control engineer's use of modeling, analysis, design, simulation, implementation, and experimental evaluation provides a sound engineering approach to the development of intelligent control systems.

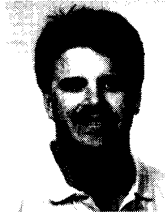
While our presentation is necessarily shallow at points and we have not considered some important issues in the interest of brevity, we hope that the ideas put forth will motivate further research in the use of careful theoretical and experimental control engineering analysis within the field of intelligent control. Finally, we hope that the reader enjoys the broad spectrum of papers contained in this Special Issue on Intelligent Control, which more fully explore several of the topics only briefly discussed here.

Acknowledgment

The author acknowledges contributions from the careful evaluations provided in the reviews of this article.

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