Proceedings of the 15th IEEE International Symposium on Intelligent Control (ISIC 2000)
Rio, Patras, GREECE 17-19 July, 2000

THE CHALLENGE OF INTELLIGENT SYSTEMS

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Abstract. This paper analyzes the meaning of intelligence within the domain of intelligent control. Because of historical reasons, there are varying and diverse definitions of what constitutes an intelligent control system. Due to the multidisciplinary nature of intelligent control, there are no good formal measures for what is an intelligent controller or for its performance. We argue that there are characteristics which can be used to categorize a controller as being intelligent. Furthermore, the measure of how intelligent a system is should take into account a holistic view of the system's operations and design requirements. Beginning with the definition of intelligence characteristics and performance measures, we can move towards a science of intelligent systems for control.

Key words. Intelligent control, intelligent systems, performance measures

1. INTRODUCTION

"Intelligent Control" is a commonly used term, applied to an amorphous set of tools, techniques, and approaches to implementing control systems that have capabilities beyond those attainable through classical control. There is a well-developed and deep body of work entailing a theory of control. This is not the case for intelligent control, which is more of an ad hoc approach to constructing systems that generally contain some internal kernel of the more classical control, for which there is a theory.

We believe that the discipline of intelligent control and its practitioners will benefit from a more formal definition of what constitutes intelligence, as applied to controllers. First of all, it will provide a framework within which the researcher's work can be understood. The understanding of each other's work can facilitate better progress in the field overall. Performance measures for intelligent controllers can begin to be developed, providing benchmarks for system performance and helping users and designers of systems better understand the benefits of one approach versus another. The benefits would be based on quantitative measures appropriate to the system requirements.

In this paper, we analyze the history of intelligent control, its multidisciplinarity, and the higher level issues of "meta control" that characterize intelligent systems. We argue that there are characteristics that can be found in common among most, if not all, systems labeled as intelligent controllers. These characteristics suggest espousing a broader view of the elements of intelligence that are necessary for advanced systems. Within this view, we describe some possible levels of intelligence, which can guide the development of and performance measures for controllers.

2. WHAT IS INTELLIGENT CONTROL?

In the late seventies, Fu and Saridis introduced the combination of the words *Intelligent Control*. In the eighties, it was brought to widespread practice and better understanding, as shown in papers by Saridis[19], Meystel [15], and Albus [1], who jointly spearheaded this movement. The National Science Foundation (NSF) funded the first IEEE Workshop on Intelligent Control (1986, Troy, NY), and this event continued as the annual IEEE International Symposia on Intelligent Control and multiple workshops on Autonomous Intelligent Control Systems. The nascent science of Intelligent Control was actively supported by participants from multiple research groups, including those belonging to the

school of Soft Computing, established by Zadeh and focussing on fuzzy systems, neural networks, computing with words, and other techniques.

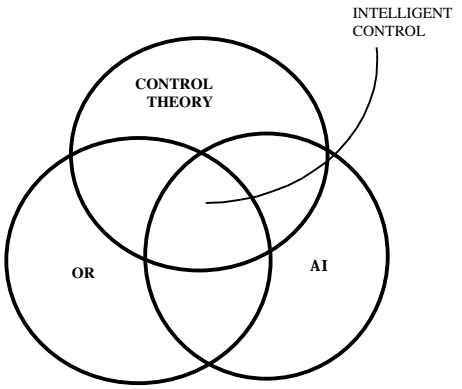

Fig. 1. Intelligent Control as of 1985

As far as methodology is concerned, the area was then and is now far from being stable. The main obstacle to stability is due to the multidisciplinarity of the intelligent control field. At the first Symposium on Intelligent Control in 1985, it was proclaimed a theoretical domain, in which control theory, AI, and operations research intersected (Fig. 1 from [19]).

Problems arose due to the reluctance of members from the different constituent disciplines to venture too far into the others' domains. For instance, specialists in control theory and automatic control tried to avoid getting involved in issues of cognitive science, psychology, biology, and ecology associated with the notion of intelligence. Specialists in the Artificial Intelligence domain (itself comprised of various, rather diverse, sub-specialities), traditionally abstained from getting involved in the mathematical control issues related to system dynamics and felt uncomfortable with domains of research that were beyond their discipline. The essence of the conflict lies in the term "intelligent," which has myriad implications. It is still impossible today to distinguish an intelligent controller from one that is not intelligent. It is also unclear whether a specialist in control theory can be considered a specialist in intelligent control, or vice versa.

3. THE TERM "INTELLIGENT CONTROL" AND ITS USAGE

As discussed above, the problem of Intelligent Control has turned out to be an intrinsically interdisciplinary one. This is why, starting in 1995, the IEEE and the National Institute of Standards and Technology (NIST), in collaboration with other agencies, organized a series of conferences intended to expand the topic of Intelligent Control towards the more consistent, yet more difficult theme of Intelligent Systems (see IEEE International Symposium on Intelligent Control (ISIC) Proceedings from 1987 up to 1999).

A recapitulation of the evolution of the term Intelligent Control would be beyond the scope of this paper. We will present some example of definitions and milestones in its development.

Fu linked a concept of intelligent control with the following features that were traditionally out of the scope of specialists in conventional control theory: decision making, image recognition, adaptation to the uncertain media, self organization, planning, and more [7].

Saridis gave the definition of Intelligent Control in [18] as a statement of expected functions:
"Intelligent Control… would replace a human mind in making decisions, planning control strategies, and learning new functions by training and performing other intelligence functions whenever the environment doesn't allow or doesn't justify the presence of a human operator…..Such systems… can solve problems, identify objects, or plan a strategy for a complicated function of a system … with intelligent functions such as simultaneous utilization of a memory, learning, or multilevel decision making in response to fuzzy or qualitative comments…"

In these excerpts, the concept of goal is not mentioned, because goal is a part of a more general statement, which includes intelligent control by necessity: "control of a process employs driving the process to effectively attain a prespecified goal" [18].

A popular and all-encompassing definition is by Albus [2]:
"… intelligence will be defined as an ability of a system to act appropriately in an uncertain environment, where appropriate action is that which increases the probability of success, and success is the achievement of behavioral subgoals that support the system's ultimate goal."

Pang describes an intelligent controller as a controller that is utilized for shaping the behavior of an intelligent system [17]. The distinct properties of this controller are to provide the following features:

- It should "know" what actions to take and when to perform them
- It should reconcile the desirable and feasible actions
- It should vary the high resolution details of control heuristics
- The acquired control heuristics should be the most suitable ones and they should change dynamically
- It should be capable of integrating multiple control heuristics

- It should dynamically plan the strategic sequence of actions
- It should be able to reason between domain and control actions. In other words, it should be able to use at least two levels of resolution simultaneously: the level of the domain actions and the domain of the control actions.

In their foreword to [21] White and Sofge wrote, "To us, 'intelligent control' should involve both intelligence and control theory. It should be based on a serious attempt to understand and replicate the phenomena that we have always called 'intelligence' – i.e., the generalized, flexible and adaptive kinds of capability that we see in the human brain."

Cai states that intelligent control possesses four features [5]. These are

- It is a hybrid control process, containing knowledge of mathematical and non-mathematical models; it has no known single algorithm for dealing with the complexity, incompleteness, and ambiguity it is confronted with.
- Its core is in the higher level that organizes the problem solving. This higher level of analysis and decision-making and planning requires related technologies, such as symbolic information processing, heuristic programming, knowledge representation, fuzzy logic, and automation of the discovery of similarity amongst the solving processes. "There exists intelligence in the artificial problem- solving process."
- It is an interdisciplinary field, requiring coordination with, and assistance from, related fields, such as artificial intelligence, cybernetics, systems theory, operations research, etc.
- It is a research area under development only recently and would experience faster and better development should a better theory for intelligent control be found.

4. CHARACTERISTICS OF INTELLIGENT CONTROL

Some definitions of intelligent control would limit it to those systems that rely on soft computing techniques, such as fuzzy logic, neural networks, and genetic algorithms. Another perspective is to analyze intelligent control systems with respect to their characteristics, which were inherent in the quotes of the previous section.

We begin by looking at control laws, which are the heart of a control system, whether it is intelligent or not. An analysis of control laws indicates that they are subservient to the control system's goal of reducing the deviation from a pre-specified trajectory and/or the final state [14] [9]. It is more typical in the present paradigm of automatic control to consider control laws to be part of a broader "control strategy" for the overall system [20] [6]. The assignment for the control law – to keep a certain variable of interest within some bounds around a reference trajectory – comes as the result of some external intelligence operating beyond the limits of the intelligence of the particular control law. Intelligent controllers tend to incorporate these assignments (and their genesis) into the function of the controller. This difference is a fundamental one.

In the fuzzy logic controllers, such as those described in [12] and [13], the fundamental transformations move the set of input information from the high resolution domain into the low resolution domain by using the tool of "fuzzification." Fuzzification plays the role of a generalization procedure, because it searches for adjacency among information units, focuses attention, and groups. Fuzzy logic controllers contain control mappings only for generalized information at the lower resolution. When the required control action is found, this lower resolution recommendation is instantiated or moved to the domain of high resolution by the process of "defuzzification." Hence, fuzzy control systems are multi-resolutional, and they move between resolutions for the purposes of achieving the required control performance.

Neural networks are a computation device for generalizing in a vicinity (spatial or temporal). They are a natural tool for moving information from higher to lower levels of resolution. Therefore, neural networks, such as described in [8], are multi-resolutional systems.

Expert System based controllers make a judgement concerning generalizations and rules to be applied at the lower resolution [11]. They too presume a multi-level, multi-resolution framework within which they operate.

Hybrid logic control systems are multi-level control systems in which lower levels of resolution are formulated in terms of logic based controllers, while the higher resolution levels are analytical controllers (e.g., PID, Kalman). Again, there is at minimum a dual-level architecture of control, with differing resolutions.

Behavior-based controllers employ a concept of superposition of the activities of multiple controllers working simultaneously, each providing for a separate type of behavior. A hierarchical structure of some sort generally underlies implementation. A low resolution level may select which behavior controller is invoked at which time, or it may arbitrate between the different proposed behaviors. Each individual behavior generation controller generates sub-goals for itself.

Although the previous examples are not an exhaustive analysis of techniques and approaches for intelligent controllers, they serve to illustrate that certain generalizations can be made about the essence of what distinguishes a controller that is intelligent from one that isn't. A meta level of control, which functions a lower level of resolution is necessary to guide the underlying control system and expand its envelope of functioning.

5. BEYOND INTELLIGENT CONTROL TO INTELLIGENT SYSTEMS

Saridis has defined the intelligent control problem as "intelligent control is postulated as the mathematical problem of finding the right sequence of internal decisions and controls for a system structured according to the principle of increasing intelligence with decreasing precision such that it minimizes its total entropy" [16].

If intelligent control is responsible for finding the right decisions and controlling the system to enact those decisions, then there must be complementary supporting functions which provide models of the world that the system is functioning in. There must be perception and world modeling processes that occur alongside with the control function. "Machine intelligence is the process of analyzing, organizing, and converting data into knowledge, where (machine) knowledge is defined to be the structured information acquired and applied to remove ignorance and uncertainty about a specific task pertaining to the intelligent machine" [4]. A procedural characterization of an intelligent system is given by " intelligence is the property of the system that emerges when the procedures of focusing attention, combinatorial search, and generalization are applied to the input information in order to produce the output" [4].

Key issues of the domain highlighted in [10] include

- "A desirable property of intelligent systems is that they are 'adaptive'…
- Intelligence is an internal property of the system, not a behavior…
- A pragmatic reason for focusing on 'intelligent' control systems is that they endow the controlled system with enhanced autonomy…"

Therefore, the overall system's behavior is what matters most in defining whether it is intelligent or not.

6. HOW TO FORMALIZE INTELLIGENCE IN CONTROL

Taking a holistic view of an "intelligent system," we can begin to consider the formalization of the organization of the system and how its performance is measured. One approach to formalism is via an Elementary Loop of Functioning (ELF), which is common to most concepts of intelligent systems. Fig. 2 shows the components of the ELF. ELFs describe a closed loop of functioning common to intelligent systems. A detailed description of the formation of hierarchies of nested loops is described in [3].

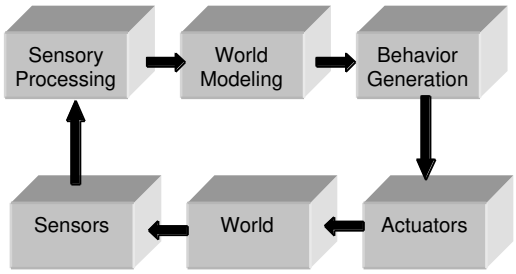

Fig. 2: An Elementary Loop of Functioning

It is our contention that the emphasis in intelligent control has been placed primarily on the Behavior Generation elements (and its constituents, such as planners and executors). Broadening the scope to consider all the elements of ELF working together within a hierarchy, we can consider the intelligence of the system as a whole. The construction of a system based on the ELF model is driven by a verbal description of the requirements for its operation – its "story." At this time, transforming the verbal story into the formal ELF is in the stages of exploratory research.

We must declare the domain of application for which we need the intelligent controller. A distinction is made between closed and open systems. Closed systems can be characterized by clear assignments of the problem to be solved and the ability to construct a complete list of concrete user specifications in terms of measurable variables. On the other hand, in open systems, the problem is not totally clear, its parts are not concrete, the variables are not all listed at the beginning of the design process, and the methods of observation and registering are not outlined. Intelligent systems based on ELFs are appropriate for the open system problem.

Defining the success of a system does depend on the expectations of the customer. In Albus' definition "success" is an appropriate word, because it becomes a source of the emerging gradations in intelligence.

Looking at the functioning of a system from the outside, we can devise degrees of intelligence, which are linked to the specifications of the controller. For example, we can define six degrees of intelligence that separate an air conditioning unit from an artificial climate control system.

1st degree of intelligence. An air conditioning unit only knows a threshold for when to turn the

compressor "on" or "off." Even the value of "accuracy" is frequently irrelevant for these systems.

2nd degree of intelligence. The system may be required to stay within some interval of temperatures, with a given accuracy, as well as some interval of humidity, with a given accuracy. The goal pursued by the system is not a single goal-state, but is rather a zone determined by an external function (in this case, based on human preferences).

3rd degree of intelligence. The system in the previous example is now able to "learn" the human's preferences, perhaps based on the number of adjustements the human makes to the desired temperature and humidity, and hence adjust the goal state. If the system learns the new goal states quickly, it may reduce the need for human interference, and be considered more successful.

4th degree of intelligence. An even more interesting situation might happen if there is more than one user, and different users have different policies of tuning the system. The Artificial Climate System that would minimize the total number of cases of human interference could be considered a system for achieving consensus in a particular multi-player game.

5th degree of intelligence. A further development of the system might be required if the owner of the unit in a hotel may want to reduce the cost of energy required for keeping the customers happy. The system can be designed so as to learn how to keep the average number of customer complaints at a minimum, while minimizing the energy consumption. A high degree of autonomy in this system allows it to assign the schedule for the functioning of its subsystems.

6th *degree of intelligence.* The previous systems are subserviently autonomous, i.e., they control their own behavior, but the goals are determined from the external user. If the system has a concept of *self*, it will try to keep all the "customers" satisfied, while being concerned about its own lifespan, reducing aging, increasing reliability, and so on.

The necessity for gradations in the measurement of success of the intelligent system leads to gradations in the measurement of the components of the ELF.

For the world modeling, or knowledge representation, we can look at parameters that are meaningful, such as the competence of the knowledge base (can it answer questions that they rest of the system poses in order to do its job?), the memory depth, the number of information units that can be handled, the number of levels in the system of representation, the number of associative links between units of information, and so on. For Behavior Generation, we can assess parameters such as the horizon of planning at each level or resolution and the size of spatial scopes of attention. For Sensory Processing, parameters to be considered include the depth of details taken into account during the processes of recognition at a single level of resolution, the number of levels of resolution that should be taken into account during recognition, and the minimum distinguishability unit in the most accurate scale.

Further development of the analysis of intelligent controllers requires construction of inner ELFs for each subsystem of the main ELF (see Fig. 3).

7. CONCLUSIONS

We have described how the field of Intelligent Control has several underlying characteristics that define its systems. We believe that the issue of control is just part of the overall intelligence in a system, hence we expand our scope to look at Intelligent Systems. In the broader scope, we can look at the capabilities of the overall system, as gauged against the user's expectations, in order to extract definitions of intelligence. We can also consider how to model the intelligent systems based on hierarchies of Elementary Loops of Functioning. The parameters for the elements of the ELFs can be subject to measurement and analysis. The measures of both the overall system's capabilities and the parameters of the constituent modules can be used to form the basis for a more formal theory of intelligent systems and the study of metrics for such systems.

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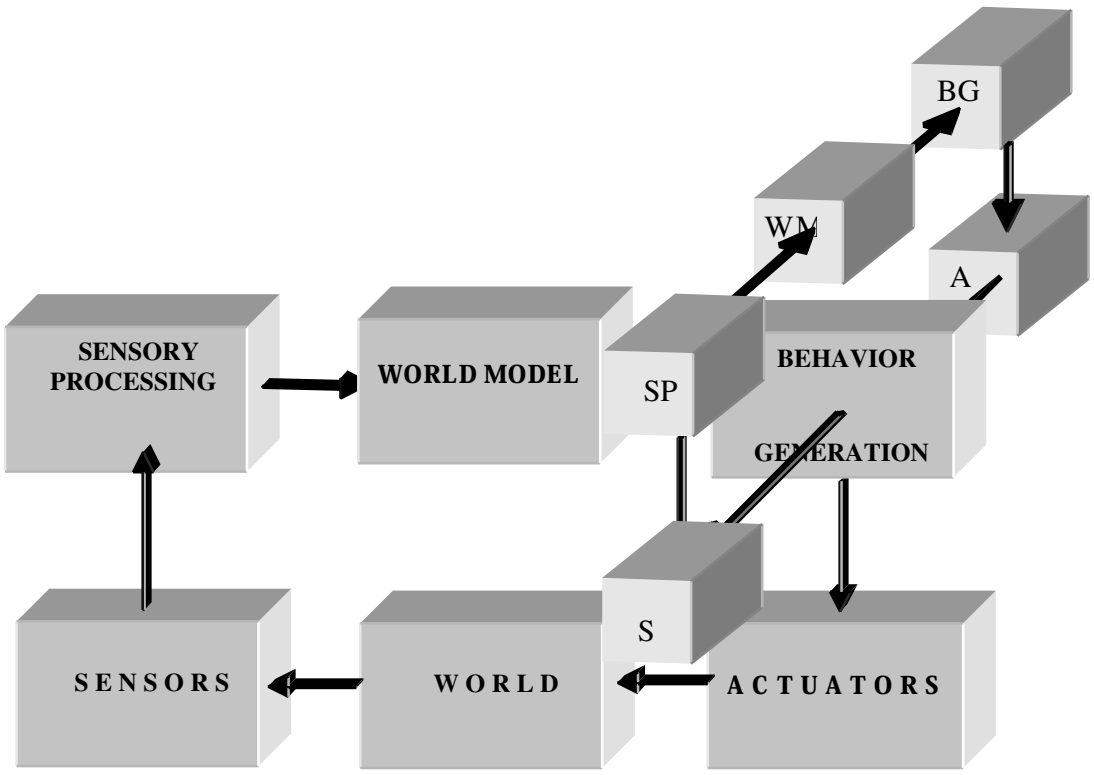

Fig. 3. ELF_{BG} pertaining to the BG-module of the main ELF