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Editor: G.N. SARIDIS

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Theory and Applications

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PREFACE

This is the first volume of a series of research annuals on *Advances in Automation and Robotics* published by JAI Press, Inc. The purpose of this series is to provide state-of-the-art information about a field that has been only recently recognized and has been experiencing exponential growth since. Such a situation should create severe problems in the selection of the proper material to be reported in a specific publication of high caliber. However, it is fortunate that such a problem never arose in the compilation of this volume. This is mainly due to the knowledge and expertise of my coauthors that made the task of editing this book a scientific experience.

Robotics and automation was not always a scientific discipline. In fact, industrial automation was introduced during World War II when many manufacturers were forced to accommodate wartime mass production. At first there were machines programmed to perform, repetitively, several tasks with minimal intervention of a human operator. Most of these machines could be found in machine shops or were parts of a semiautomated assembly line in automobile and appliance factories during the years after the war.

Industrial robots were developed during the 1950s, and their first units were produced in the early 1960s by companies like Unimation, Inc. and AMF Versatran. But what is a robot? The word, derived from the Czech *robota* (work), was first used by the Czech writer Karel Čapek in 1921 in his play *R.U.R.* (Rossum's Universal Robots) to describe machines created to replace humans. The official definition given by the Robot Institute of America is "a programmable, multifunction manipulator designed to move material, parts, tools, or specific devices through variable programmed motions for the performance of a variety of tasks." In this sense, there is a wide range of devices created to replace the human worker in hazardous and tedious tasks. As such, all automated industrial machines qualify as primitive robots.

The real revolution in robots and industrial automation took place in the late 1960s when fixed mechanical programming was replaced by a flexible digital or numerical "computer program." Numerical control (NC) machines replaced most semiautomatic machining and milling systems, and robots were developed for such tedious tasks as spot and arc welding, materials handling, painting, and so on. These machines, even though originally developed in the United States, were adapted and coordinated into the industrial mainstream by Japan during their 10-year automatization program which started in 1970. This program turned out to be so successful that in the 1980s most industrial countries in the world are modifying their manufacturing procedures around a fully automated factory to create the "Robotic Revolution." Of course, the center of such a revolution is the digital computer and the continuously evolving integrated electronics technology which made all this possible. What really made the modern robots and automated manufacturing systems different from their brothers and sisters is their flexibility and versatility, due to their reprogrammability. This is the direction of current robotic research: to develop machines to handle various human tasks in hazardous, unpleasant, or unfriendly environments.

At the present time, the problem faced by all researchers in the area of robotics and automation is the lack of a scientifically systematic approach to design robots. Such machines, endowed with one or two arms for manipulation, gripping, and tool handling and possible locomotion, have been manufactured by the heuristic principles of their ancestors, the remote manipulator and the NC machine. They may fill present industrial needs, but they definitely do not represent the prototypes of the future in pace with modern computer, integrated electronics, and control systems technologies.

This series will attempt to fill this gap and thus provide service to this growing robotics technology. This first volume presents a survey of the fundamental problems facing modern robotic systems. Such systems are cast in the intelligent machine framework which requires, in addition to high-level basic computational capability, advanced sensing, control, and locomotion systems. The chapters of this book attempt to meet the theoretical needs of such an advanced system. Chapter 1, written by me, presents hierarchically intelligent control theory as an integrating approach to the design of modern robotic systems. Chapter 2, by C. S. G. Lee, discusses the most recent formulation of kinematics and dynamics for robotic manipulators. Chapter 3, also by C. S. G. Lee, covers thoroughly the various control methods used in modern robotics. Chapter 4, by R. P. Paul, discusses the evolution of several programming languages that are associated with robots. Chapter 5, by J. Mundy, introduces the important subject of vision for sensing and feedback in robotic manipulators. Chapter 6, by R. Bajcsy, presents touch sensing as another device for understanding the environment for a robotic system. Finally, Chapter 7, by R. B. McGhee, deals with legged locomotion as an advanced technique for propelling modern robots.

The whole book covers but does not exhaust the basics of modern robotic manipulators. Future volumes will specialize in other aspects of this highly exciting discipline. From this position, though, I would like to express my gratitude to all my coauthors for their prompt response in producing such excellent contributions to this volume, Mrs. Sharon Sorell for typing parts of the manuscript, and finally the National Science Foundation for supporting my work and the work of some of my coauthors for several years, the results of which made this book possible.

G. N. Saridis
Series Editor

CONTENTS

Chapter 1

INTELLIGENT CONTROL FOR ROBOTICS AND ADVANCED AUTOMATION

G. N. Saridis

1. INTRODUCTION

In the past few years, we have been experiencing the Robotic Revolution which has been affecting the ways of industrial production. Since then, the technological image of industrial and other commercial robots has been drastically changed. The reason for this change is that robots are and will play the key role in the new industrial and research environments.

The new robots must have the ability to operate in a human-made environment, sense its details, and provide information back for processing in order to execute various tasks with minimum interaction with a human operator [40]. For this purpose, it must be endowed with arms of flexible mechanical structure in order to manipulate beyond physical obstacles, a powerful vision system for object recognition and tracking, tactile and other sensing for precise handling, adaptable hardware controls for flexible task execution, and

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legged locomotion for movement in rough terrains. But above all, it must have the machine intelligence to organize, coordinate, and execute complex diversified tasks without continuous supervision by an operator. With our modern technology and especially the evolution of the digital computer, such a robot is not a storywriter's dream but an intelligent machine of the near future. While the next chapters will discuss the details of the components of such a structure, this one will elaborate on the design and implementation of the machine intelligence for the robots of the future.

Various methodologies such as control systems theory, operations research, and artificial intelligence have been recently dealing with different aspects of

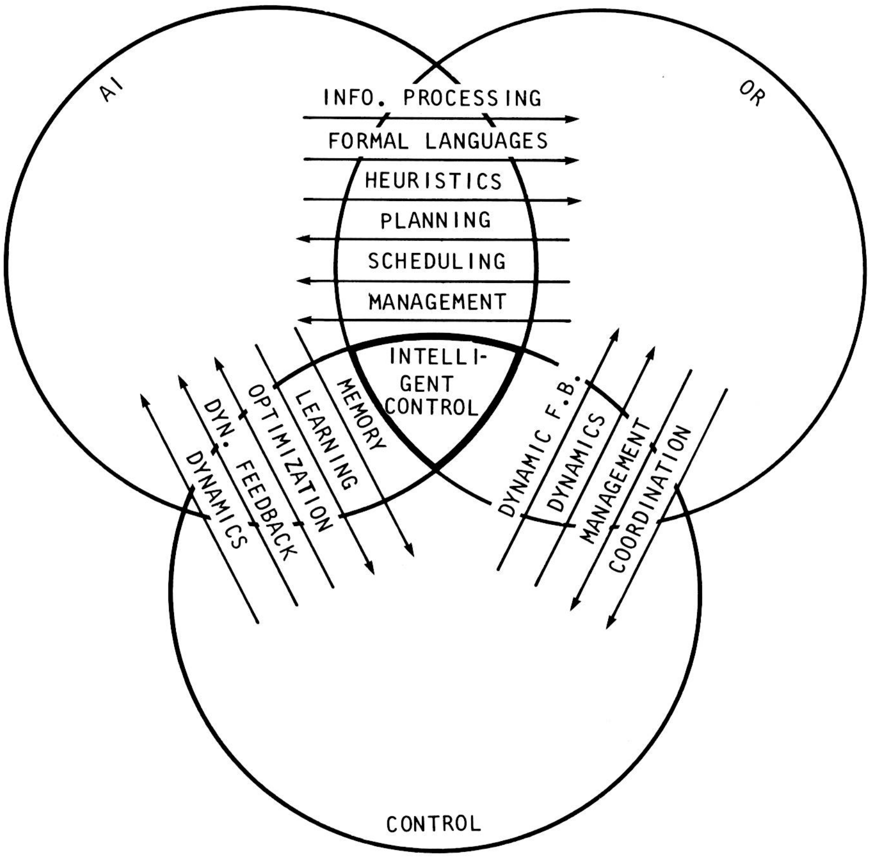

Figure 1. Intersection of artificial intelligence, operations research, and control theory and the resulting intelligent control.

machine intelligence and they may lead to the creation of intelligent control theory, as in Figure 1.

Such a discipline requires a rigorous mathematical modeling and subsequent analysis of the associated physical process and a systematic synthesis of precise controls resulting in the design and effective operation of industrial, economic, urban, and even space exploration systems that have become essential parts of the socioeconomic environment of the modern societies as in systems theory and operations research [28,38]. As the world economy is reaching a turning point due to the depletion of certain popular energy resources while higher demands are imposed from space exploration, work in hazardous environments, modernization of industrial plans, and efficient transportation of large groups of people, new methodologies are developed suitable for computer utilization and demonstrating advanced machine intelligence and decision [40]. For over 20 years, scientists have been developing the cognitive field of artificial intelligence, more or less in the image of a human brain. Significant results have been accomplished in speech recognition, image analysis and perception, data base analysis and decision making, learning, theorem proving and gains, autonomous robots, and so forth [1,8,9,13,14,16,20,23,29,30,34,35,37,49,50,51,54,55]. The discipline that couples these advanced methodologies with the system theoretic approached necessary for the solution of the current technological problems of our societies is called *intelligent controls* [12,40].

Intelligent control studies utilize the powerful high-level decision making of the digital computer with advanced mathematical modeling and synthesis techniques of system theory to produce a unified approach suitable for the engineering needs of the future.

One of the most important applications of intelligent control theory is in manipulative systems. These systems may involve the control of a general-purpose manipulator for space exploration, like the Mars-rover, or a hazardous environment robot for operation in a nuclear containment, or a hospital aid manipulator, an electrically driven prosthetic limb to replace an amputated arm or even an orthotic brace to assist paralyzed people [6,10,11,22,24,41,47,52]. Such devices impose special considerations and constraints in terms of small weight, small physical dimensions, real-time performance, human limb appearance and functionality, and most restrictive, a small number of noninteracting command sources, that is, of a command vocabulary and a small number of sensors. The above constraints exclude computationally complex algorithms or long computation time. Also, training of the operator to generate combinatorial command codes must be very limited. Hence, such systems must maximize flexibility of performance subject to a minimal input dictionary and minimal computational complexity.

This chapter will consider the general theory of intelligent controls first and then its application to general-purpose robotic manipulators.

2. COGNITIVE SYSTEMS ENGINEERING AND ARTIFICIAL INTELLIGENCE

Cognitive systems have been traditionally developed as part of the field of artificial intelligence to implement, on a computer, functions similar to the ones encountered in human behavior. Such functions as speech recognition and analysis, image and scene analysis, data base organization and dissemination, learning and high-level decision making have been based on methodologies emanating from simple logic operations to pattern recognition, linguistic, and fuzzy set theory approaches [56]. The results have been well documented in the literature [1,12,23,33,37,54,55].

In order to solve the modern technological problems that require control systems with intelligent functions such as simultaneous utilization of a memory, learning, or multilevel decision making in response to "fuzzy" or qualitative commands, a new generation of control systems have been developed. They are termed *intelligent controls* and utilize the results of cognitive systems' research effectively with various mathematical programming control techniques [28,38]. Each cognitive system associated with the specific process under consideration may be considered a subtask of the process requested by an original general qualitative command, programmed by a special high-level symbolic computer language, and sequentially executable along with decision making and control of the hardware part of the process.

Many systems have been designed to perform in the above manner. In the area of manipulators and robotics, many such systems have been developed for object handling in an industrial assembly line, remote manipulation in hazardous environments, the planet-exploration Mars vehicle, hospital aids for the disabled, and autonomous robots [2–4,11,27,33,36,42,53].

In most cases where the control process is remotely performed from the operator, its function is semiautonomous and the system must utilize some cognitive systems to understand the task requested to execute, identify the environment, and then choose the best plan to execute the task.

Various pattern recognition, linguistic, or even heuristic methods have been used to analyze and classify speech, images, or other information coming in through sensory devices as part of the cognitive system [1,5,6,23,24, 37]. Decision making and motion control have been performed by a dedicated digital computer using either kinematic methods, like trajectory tracking, or dynamic methods based on compliance, dynamic programming, or even approximately optimal and adaptive control [45,46].

Artificial intelligence has definitely provided significant contributions to the development of cognitive engineering. It always utilizes large-size mainframe computers to provide solutions to intellectual problems related to human intelligence. Vision, and other sensory systems as well as speech recognition and understanding are essential for intelligent techniques. Furthermore, manipulative and autonomous robotic systems have also been created with

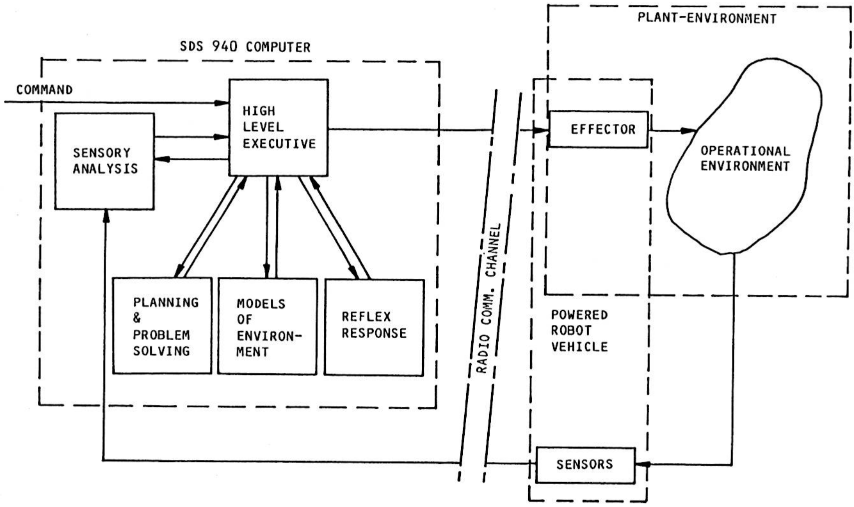

Figure 2. Artificial intelligent implementation of a robotic arm control system. This SRI's "Shakey Robot."

the use of artificial intelligence techniques. An example of robotic controls based on artificial intelligence concepts is given in Figure 2 [40].

However, modern intelligent robots require a more modest computer implementation in order to be practically feasible [12]. Machine intelligence,

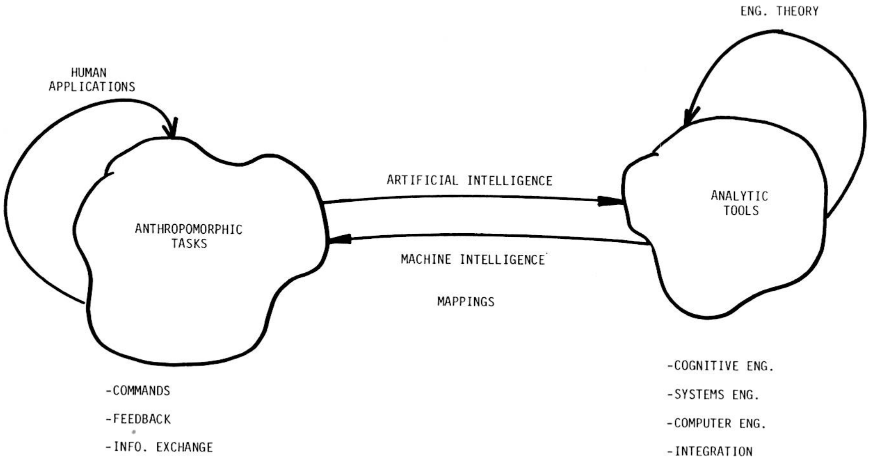

Figure 3. The problem of designing machines to execute anthropomorphic functions.

which may be thought of as the inverse mapping of artificial intelligence,—for example, the mapping from the theoretical space of engineering science to the space of human understanding and applications, shown in Figure 3—was assumed more suitable for the design of self-supported robots. The reason is that by using machine-generated intelligence and communications in a minimally man–machine interactive system, one may obtain more efficient, faster, and smaller-size computer systems to control an intelligent robot.

3. HIERARCHICALLY INTELLIGENT CONTROL THEORY

A hierarchically intelligent control approach has been proposed by Saridis as a unified theoretic approach of cognitive and control systems methodologies. The control intelligence is hierarchically distributed according to the principle of *decreasing precision with increasing intelligence* evident in all hierarchically management systems [40,41]. Such systems are composed of three basic levels of controls, although each level may contain more than one layer of tree-structured functions:

- The organization level
- The coordination level
- The hardware control level

The *organization level* is the mastermind of such a system. It accepts and interprets the input commands and related feedback from the system, defines the task to be executed, and segments it into subtasks in their appropriate order of execution. An appropriate subtask library and a learning scheme for continuous improvement provide additional intelligence to the organizer. Since the organization level takes place on a medium- to large-size computer, appropriate *translation and decision schemata* linguistically implement the desirable functions [21,41].

The *coordination level* receives instructions from the organizer and feedback information from the process for each subtask to be executed and coordinates the execution at the lowest level. The coordinator, composed usually of a decision-making automaton representing a context-free language, may assign both the performance index and end condition as well as possible penalty functions designed to avoid inaccesible areas in the space of the motion. The decisions of the coordinator are obtained with the aid of a performance library and a learning decision schema, recursively updated to minimize the cost of operation.

A *lowest-level control* process usually involves the execution of a certain motion and requires besides the knowledge of the mathematical model of the process the assignment of end conditions and a performance criterion or cost function defined by the coordinator. Optimal or approximately optimal control system theory may be used for the design of the lower-level controls of decentralized subprocesses of the overall process to be controlled [45].

The method has been successfully applied to control a general-purpose manipulator with visual feedback and voice inputs for effective end-point control tasks [31] at Purdue University's Advanced Automation Research Laboratory. Figure 4 depicts the above system. Other implications may be found in Refs. [40,46,47].

The success of implementation of such a control system depends greatly on the development and optimization of the linguistic decision schemata for high-level decision making and the effective application of modern control techniques for the optimal operation of the lowest-level control.

Hence, we have a linguistic decision schema:

$$D = \{N_i, N_o, \Sigma, \Delta, R, P, S\} \tag{1}$$

where N_i, N_o are the input and output nonterminal alphabets;

Σ, Δ are the input and output terminal alphabets;

R is the set of decision rules;

P is the set of associative probabilities;

S is the root of the trees.

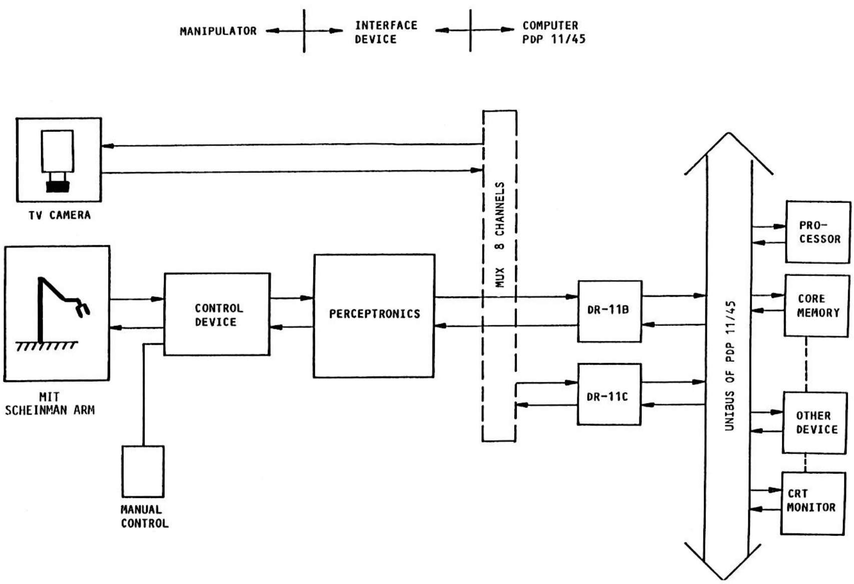

Figure 4. The Purdue AARL's hierarchically intelligent controlled robotic arm.