ENGINEERING ARTIFICIAL INTELLIGENCE

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INTRODUCTION

The development of highly automated labor-saving factories presupposes the automation of not only manual, but also intellectual, human tasks. The automation of intellectual activity demanded a solution to a number of new problems that had not arisen previously in the theory of automatic control. Problems include the description and representation on a computer of a complex environment, automated planning and performance of a variety of various operations by mechanisms aimed at achieving a specified goal, the development of communications between humans and computers using a natural language, and a number of other problems.

The scientific discipline encompassing efforts aimed at the solution of these problems is referred to as artificial intelligence. It borders on a variety of disciplines, including mathematical logic, information theory, control theory, computing devices, programming, etc. The scope of research in the area of artificial intelligence is characterized not only by a diversity of themes, but also by its range—from the strictly abstract, aimed at the development of general principles or a theory of artificial intelligence, to engineering, aimed at the development of hardware and software for solving intellectual problems.

This book does not set out to embrace the entire area of artificial intelligence. The main purpose of a textbook is to present the fundamentals of such parts of this discipline which, to some degree, survive the test of time and may be used to design systems for a specific purpose, e.g., in robotics and automated manufacturing.

The book is based on lectures for the course "Engineering Simulation of Intelligence," which was taught by the authors at the Moscow Institute of Radio, Electronics, and Automation, to students specializing in robotic systems.

CONTENTS

CHAPTER
ONE
ARTIFICIAL INTELLIGENCE IN ROBOTICS AND FLEXIBLE MANUFACTURING SYSTEMS (FMS)

The expression "artificial intelligence" is used in a dual sense: as an engineering informational model of natural (human) intelligence and as a scientific/engineering discipline or a scientific school that deals with problems of human intelligence simulation.

Artificial intelligence today comprises an independent, rapidly developing scientific discipline. Major research conducted in the area of artificial intelligence may be reduced to the following for directions [1]:

1. Representation of knowledge objects and manipulations with them This includes the development of specialized models and languages for representing knowledge in a computer, as well as the software and hardware for their transformations (enrichment, logical processing, etc.). Research is being done in the area of the development of specialized logic systems permitting the enrichment and generalization of knowledge stored in a computer.

2. Planning of rational behavior. This includes research aimed at the development of methods for formulating goals and solutions of problems of planning operations of an automated device operating in a complex environment.

3. Man-computer communications. This area includes the problems of developing languages for effective interaction between a lay user (non-programmer). Research is being done in the area of syntax and semantics of natural languages, on methods for storing knowledge about a language in the computer memory, and on the development of special processors for implementing the transfer of text information into the internal machine notation.

4. Object recognition and learning. Research here involves perception of visual, audio, and other types of information, its processing methods, formulation of responses to the environment, and methods of adaptation of artificial systems to an environment by teaching.

1.1 THE CONCEPT OF ARTIFICIAL INTELLIGENCE SYSTEMS

Artificial intelligence systems or "intelligent systems" are those that perform functions that are considered intelligent.

The intelligent activity of man is connected to the search for solutions (actions, natural phenomena) in novel, nonstandard situations. Accordingly, a problem is termed intelligent if a plan or a precise (algorithmic) method of its solution is not known *a priori*. Here the problem and its solution are understood in a broad sense. Problem solution is any activity (by human or machine) aimed at the development of plans and actions necessary for the achievement of some specific goal, derivation of new correlations, formulation (by a machine) of sentences in a natural or familiar language, etc.

Any intellectual activity is based on knowledge of some object region within which the problems are posed and solved. The "object" or "problem region" generally refers to a set of interrelated information necessary and sufficient for the solution of a given problem or a specific set of problems. Knowledge concerning an object region includes descriptions of objects, events, and facts, as well as their interrelations.

The role of knowledge in an intellectual activity determines the characteristic feature of intelligent systems, that is, the inclusion into them of a block of knowledge representation (BR3). This block is connected with the "external" world by two transforming blocks (BR1 and BR2) which transform the knowledge about an object region (including requests) from an external (ER) into an internal (IR) representation — (BR1) and, conversely, from an internal into an external representation, (BR2), which can be "understood" by the user (see Fig. 1.1*a*). In general, an information model of the block of knowledge representation consists of an interpreting block (BI), a teaching block (BT), a solution output block (BO), and the intelligent database (IDB) (see Fig. 1.1*b*). The intelligent database, in turn, is divided into a knowledge database (KDB) and data database (DDB).

The knowledge database contains information that reflects laws and interrelationships within a given object region and permits the forecast and derivation of new facts that have not been reflected in the database.

The database includes factual, quantitative data that characterize a given object region.

In general form, knowledge in a computer is represented by some symbol (semiotic) system. The notion of a "symbol" is directly related to the notions "denotation" and "concept (attribute)." The denotation is the object denoted by a given symbol, while the attribute is a property of the denotation. The important notions in semiotic systems are extension and intention. The extension of a symbol defines a specific class of all of its permissible denotations. The intention of a symbol defines the content of a notion associated with it. Correspondingly, there are intentional and extentional types of knowledge. The intentional knowledge describes abstract objects, events, and relations, such as, VENDOR, USER, TRANSPORTATION. The extentional knowledge represents data that

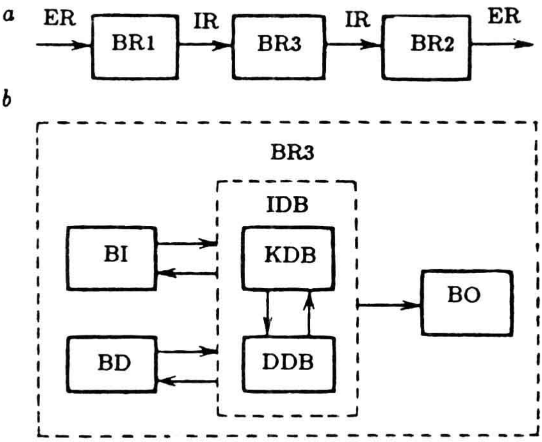

Figure 1.1 Knowledge transformation diagram (*a*) and the information model of the knowledge representation block (*b*).

characterizes specific objects, their states, and parameter values at some specific instants of time. For example, an extension of the notion VENDOR might be COMPANY A, an extension of the notion USER might be ORGANIZATION B, and an extension of the notion TRANSPORTATION might be AUTOMOBILE.

In a semiotic system, three aspects are isolated: syntatic, semantic, and pragmatic. The syntax describes the internal arrangement of a symbol system, i.e., rules of construction and transformation of complex symbolic expressions. For the natural languages, as is well known, syntax defines the correct construction of sentences and of the related text. Semantics defines relations among the symbols and their concepts, i.e., it assigns the sense and meaning to specific symbols. Pragmatism defines a symbol from the point of view of its usage or of a subject utilizing a given symbolic system.

In accordance with the above three aspects of semiotic systems, we can define three types of knowledge: syntactic, semantic, and pragmatic. The syntactic knowledge characterizes the syntactic structure of an object or an event being described that does not depend on the sense or meaning of notions used in the process. The semantic knowledge contains information that is directly related to the sense or meaning of objects or events being described. The pragmatic knowledge describes objects and events from the point of view of the problem being solved; for instance, by taking into account specific criteria applicable to the given problem.

Corresponding to the three types of knowledge, there are three types of models for their representation: syntactic, semantic, and pragmatic. The presence of semantic or pragmatic models most significantly differentiates intelligent systems from al' other various hardware-software systems that can be implemented using modern computers.

In the manufacturing industry, there are two main areas where the ideas and methods of artificial intelligence can be applied: robotic systems and management-economic and design systems. The first is associated with the development of third generation industrial robots, i.e., robots with the elements of artificial intelligence. The second is associated with the development of management-manufacturing systems on the basis of decision-making hardware and software in such endeavors as product design, technology development, planning, management, quality control, etc. In this area we have three types of intelligent systems: question-answer (dialogue) systems permitting one to interact with databases using a limited natural language; computational-logical systems permitting one to automatically select a problem solution method and to formulate the problem on the basis of the problem description in terms of the user's domain of expertise; and expert systems, or systems-consultants, permitting the generalization, storing, and use of knowledge and experience accumulated by highly qualified specialists in a given subject area.

1.2 STRUCTURE AND FUNCTIONS OF AN INTELLIGENT ROBOT

The main characteristic of an intelligent robot is its purposeful behavior in a complex, poorly-organized environment. From the point of view of artificial intelligence, the purposeful behavior may be organized by means of the transformation of knowledge concerning the current state of the environment, obtained by means of sensors, into a sequence of operations aimed at the achievement of a predetermined goal. Such a transformation must be based on *a priori* knowledge about the environment and the methods of its transformation. This means that central units within an intelligent robot are a system of knowledge representation and a developed system of operation planning. Another important characteristic of an intelligent robot is that all data acquisition and transformation processes must occur in real time.

A generalized functional block diagram of an intelligent robot is shown in Fig. 1.2. It can be broken down into three separate interrelated systems: perception, knowledge representation, planning and actuation. Let us consider each of these systems.

It is convenient to begin our analysis with the system of knowledge representation, since the other two systems, to a large degree, depend upon it. There are three aspects connected with knowledge in intelligent robots: knowledge representation; storage of knowledge; and its updating and utilization in solving problems. Knowledge representation (e.g., the mode in which it is expressed) should be chosen by taking into account the specific types of problems that the robot is intended to solve. Representation modes are treated in Chapter 2. Here the knowledge representation system will be viewed as an aggregate of four blocks: abstract

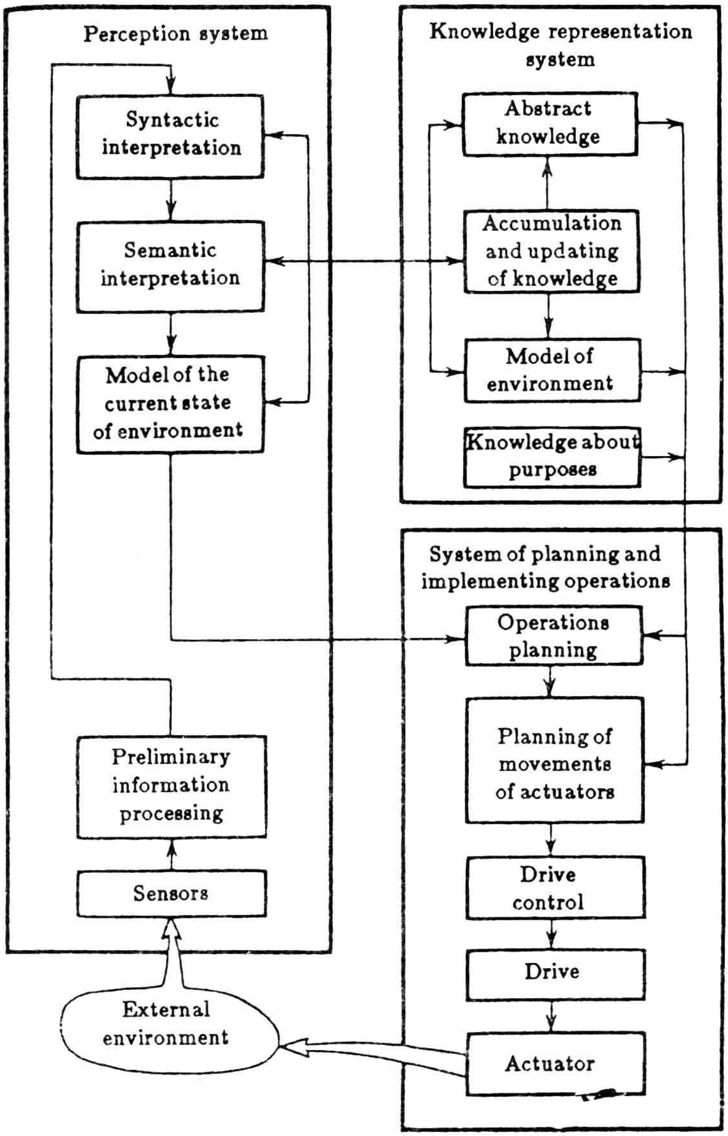

Figure 1.2 Functional block diagram of an intelligent robot.

knowledge, knowledge of the purposes, model of the robot's universe, storage and updating of knowledge.

The abstract knowledge includes information about some common laws that are valid both in the external and the internal universe environment of the robot, which are usually considered as conditionally constant. They include, for instance, physical laws within the universe.

Knowledge of the purposes is information concerning the global goals which the robot must achieve in its operation, as well as the methods of their decomposition into local goals which can be realized during intermediate steps.

The model of the robot's universe is a formal description of knowledge of the operational environment of the robot. This information is of an *a priori* nature in the sense that it was preformulated and communicated to the robot before its operation began. In a number of practical cases it is impossible to construct an initial model of the universe having the required accuracy and information content. This is particularly true for robots operating in poorly-known environments.

Current information which the robot receives during its operation may be used to increase accuracy and to broaden its knowledge of the universe. This function is performed by the block of storage and updating of knowledge. Within the block, new facts about the environment are accumulated and analyzed to ensure that they do not contradict other facts stored in the system of knowledge representation. If a new fact is not contradictory, it may be included in the model of the universe. In some cases, a decision to include a new fact into the model is preceded by a check of its validity. This entails either awaiting more data directly or indirectly confirming or refuting the fact being questioned, or performing an active experiment in the external universe to confirm or refute the fact. An analysis of a fact which contradicts facts already included in the model is performed in a similar manner. If the universe model is required to be noncontradictory, then an admission of a new fact, recognized as a valid one, demands the exclusion of all noncomplying facts. However, the noncontradiction is not a mandatory requirement imposed upon systems of knowledge representation. The "tolerance" of a system to contradictions enables its stable operation in a poorly-known environment and, to some extent, corresponds to the ability of a man to make decisions in spite of contradictions between some basic facts.

Thus, specific requirements to knowledge representation systems are:

- "tolerance" to incompleteness and contradictions. Imperfections in sensing systems and limited experience make the robot's knowledge of the universe incomplete and inaccurate. The knowledge representation system must be capable of ensuring that the robot does not stop operating when it uncovers incompleteness or inaccuracies in its knowledge. Only a reduction in the efficiency of its operation is permitted.

- the ability to evaluate new information. This is the ability to check the conformity of new information with the previously obtained data and to make a decision concerning its validity.

- the ability to learn and update knowledge. In conjunction with the ability to evaluate new information, learning ability should expand knowledge and increase its reliability.

An intelligent robot communicates with the external universe by means of its perception (sensing) system. The eventual goal of this system is the construction of a model that represents the current state of the universe. Sometimes it is said that the perception system formulates the situational knowledge of a robot, i.e., its knowledge of the current situation. As in second-generation robots, in the intelligent robots the prime source of information about the universe are sensors that include tactile, positional, force, vision, audio, and others. Sensor information is processed and presented in a convenient form for subsequent manipulations. This part of a perception system of an intelligent robot does not significantly differ from similar systems of second-generation robots equipped with perceptive systems. Subsequent transformation of information related to its syntactic and semantic interpretation is characteristic only of intelligent robots. During the syntactic interpretation, the representation of the universe is formulated using certain internal language, while the meaning of the perceived events and objects remains hidden. The semantic interpretation is related to the discovery of the meaning of the perceived information. The final procedure is the construction of a model of the current state of the universe. Let us note in passing that the syntactic and semantic interpretations, as well as the synthesis of the model of the current state of the universe, are impossible without the knowledge of the robot's universe. For this reason, the realization of these procedures is performed as an active two-way interaction with the knowledge representation system.

The main purpose of the planning and actuation system is to formulate and implement a program of operations affecting the external universe and leading to the achievement of the desired goal. Planning of activities of an intelligent robot is usually implemented as a problem solution process. In so doing, the problem is viewed in its broadest sense as the difference between the current and desired states of the universe. The plan or the problem is a sequence of operations that transform some current state of the universe into a desired state. Thus, for an assembly robot, the plan will be a sequence of operations aimed at changing the positions of parts from their current state into the desired state corresponding to the assembled product. Here the term "operation" means such operations as "join part A with part B," "screw bolt into...," etc. Obviously, to carry out these operations, they should be broken down into basic movements that can be performed by the manipulator. This function is performed by the movement planning block of the actuator that formulates the program of movements to be implemented by the drive control.

Intelligent robots are frequently referred to as "integrated." The term "integrated robot" was first used to describe a robotic system equipped with machine vision, tactile sensors, and a movement capability. At the present time, the term "integrated robot" refers to a robotic system that contains five groups of functionally completed systems [4]:

- Group V includes perceptive systems of visual, audio, tactile, and other types of information about the external environment;
- Group M includes systems for acting upon external objects (manipulators, manufacturing systems, etc.);
- Group T includes robot mobility systems;
- Group P includes systems for planning operations and problem solving;
- Group R includes communication systems between the robot and operator and/or other robots.

Any specific robot may be formed by combining all or some of the above systems. This permits the expression of the degree of robot integration by a number of systems which comprise it and permits the definition of classes of robots based on the degree of integration and types of their component systems.

Integration of order *1* apparently consists of five classes. Class M may include robot-manipulators of the first generation, Class T may include the simplest transportation robots. The remaining three classes are vacant, since the systems belonging to these groups cannot be viewed as independently robotic systems.

Integration of order *2* consists of 10 classes. Class VM may include sensualized industrial robots, Class VT may include sensualized transportation robots, and Class MT may include mobile robot-manipulators.

Integration of order *3* consists of 10 classes. For instance, Class VMP may include sensualized robot-manipulators of the third generation equipped with sensors and an activity planning system, Class VTP may include third-generation transportation robots.

Examples of integration of the *4*th order are Class VMTP robots, that is, sensualized mobile robot-manipulators with operations planning systems, and Class MTPR robots, that is, mobile robot-manipulators with speech-recognition input command interfaces.

Integration of order *5* consists, apparently, of only one class: VMTPR, i.e., a class of robots that includes all the above-mentioned systems.

Intelligent robots also include integrated autonomous robots with integration orders *3*, *4*, and *5*. Here the term "autonomous" refers to the ability to independently (or relatively independently) receive information concerning the environment and plan and to implement operations required to achieve a specified goal. The autonomous property presupposes that the robot contains systems of groups V and P.

1.3 INTELLIGENT SYSTEMS IN HIGHLY-AUTOMATED MANUFACTURING

The development of modern manufacturing has meant the continuous growth of its complexity, expressed in the broadening of the diversity of technologies that utilize new physical phenomena and engineering solutions, as well as in the acceleration of the changes and complexity of manufactured goods. The knowledge required for an effective design and utilization of manufacturing is continuously increasing, thus significantly increasing the intellectual burden upon designers and manufacturing engineers. For instance, the utilization of new types of automation based on electronic computing technology drastically increases the intellectual labor component of manufacturing personnel from manager down to laborer. Traditionally, problems of this kind were solved by increasing the specialization of individual workers, which invariably resulted in personnel increases. This approach contradicts the tendency to reduce the number of designers and manufacturing personnel and to develop labor-saving technologies.

This problem is being attacked from two directions. On the one hand, the education level of engineering, design, and manufacturing personnel is being increased; and on the other, the degree of intelligence of automated design and control systems is also being increased.

Design. The lack of engineering methods for calculating economic efficiency and functional characteristics of a Flexible Manufacturing System (FMS) complicates the design process and increases the role of knowledge and experience accrued while designing such systems, as well as of new methods for their analysis and synthesis by means of mathematical modeling. The basis for generalizing and disseminating knowledge obtained during research and experiments in developing FMS are the expert systems that may be employed, for instance, during a predesign (the feasibility study). The purpose of an expert system during this phase is to determine the economical and technological feasibility of an FMS on the basis of such parameters as productivity, type of product, mass-producibility, proposed manufacturing technologies, and others, as well as to indicate which structure classes are the best for each specific case.

One method which is widely used in automated FMS design is mathematical modeling by means of a computer (simulation, for instance). Using this method, one can conduct controlled experiments with the system model. Model development and the associated experiments require good mathematical and programming training, as well as broad engineering knowledge of FMS. This complicates the process of interactive design where the designer directly interacts with a computer in a dialogue mode. In traditional systems, "middle men" are used between the user and a computer, usually mathematicians and programmers. In intelligent systems, a direct interaction between the user and computer is provided by an intelligent interface, that is, hardware and software that permit one to conduct a dialogue in the designer's language.

Manufacturing management. One can identify at least three areas where intelligent systems may be used in manufacturing management.

1. Automated solution of problems in planning and control on the basis of computational-logical and expert systems. The necessity of using computational-logical systems stems from the following. At this time, there exists

a substantial library of mathematical methods of planning and operational management. Its utilization requires the use of mathematicians and programmers. This, however, is impossible to realize in practice at highly-automated manufacturing facilities with limited staff. As was pointed out earlier, computational-logical systems select the problem solution method and formulate a program for describing the problem and quantitative data inputted into the computer using a limited professional language of the user.

The use of expert systems stems from the fact that planning and control functions that are expected to be performed by computers are continuously broadening, which inevitably leads to the necessity to formalize knowledge and experience of appropriate specialists. The most convenient — and often the only possible — method for such formalization is the representation of knowledge in the form of semiotic models and logic derivation rules. An expert system, constructed on the basis of such models and rules, unlike a computational-logical system, does not solve a problem. Instead, it "consults" the planner or an engineer, and diagnoses complex conditions, i.e., it acts as a system-advisor.

2. Automated programming using an intelligent interface. Automatic programming systems with elements of artificial intelligence permit a nonprogrammer (an operator, for instance) to develop programs for performing industrial operations. Here one frequently uses programming systems that are based on machine drawings, since the language of graphic images (drawings, for example) is well known to manufacturing personnel. Programming may also be realized on the basis of voice commands. To receive voice, the system is equipped with a speech analyzer.

   There is some experience in outfitting industrial equipment with speech synthesizers to permit the arrangement of a voice dialogue of an operator and a computer controlling the equipment. Speech synthesizers may be used to signal the operator by voice about equipment malfunctions or special conditions of the equipment, and even for training an operator to work with the equipment*.

3. Automation of technology using machine vision systems. There is a wide class of industrial processes that may be automated using visual information. Typically, this includes assembly processes.

   There are two types of automated systems that use machine vision. In systems of the first type, visual information is used in a nonorganized environment to identify objects and to determine their position in space; in systems of the second type, information is used for controlling a process. The environment is assumed to be sufficiently organized, so that the process may be performed in accordance with a predetermined program. The realization of this program does not require any visual information. The

*See Vol. 7 of this series.

system of machine vision in this case is used to detect deviations from normal functioning. Typical examples include visual quality control of parts or blanks, correct sequence in performing a manufacturing operation, etc.