1987

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STARS Citation

Moulavi, Abol H., "Intelligent Robots" (1987). *Retrospective Theses and Dissertations*. 5070.
https://stars.library.ucf.edu/rtd/5070

INTELLIGENT ROBOTS

BY

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RESEARCH REPORT

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in the Graduate
Studies Program of the College of Engineering
University of Central Florida
Orlando, Florida

Fall Term
1987

ABSTRACT

There is an increasing need for integrating sensory feedback into the robot system. This will provide better flexibility and will improve the capacity of the robot to reason and make decisions in real time.

This report discusses the current issues related to the development and application of intelligent robots. The report surveys the essential features of an intelligent robot. These features are sensing, off-line programming, task level programing, adaptive control and knowledge representation.

Such a robot should be knowledge driven. It should "know" about objects and work plans. This knowledge should provide the capability for the robot to handle uncertainity in sensory data and to arbitrate between sensors in the event of conflicts.

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INTRODUCTION

The majority of robots in use today are of the "first generation" with little computer power. Their only "intelligent" function consists of "learning" a sequence of actions, choreographed by a human operator using a "teach-box". These robots are "deaf, dumb, and blind". The factory world around them must be arranged to accommodate their actions. Necessary constraints include precise workpiece positioning, care in specifying spatial relationships with other machines, and safety for nearby humans and equipment (Rosen 1985).

The addition of a relatively inexpensive computer processor to the robot controller led to a "second generation" of robots with enhanced capabilities. With these robots it became possible to perform, in real time, the calculations required to control the motions of each degree of freedom in a manner to effect smooth motions of the end-effector along predetermined paths.

A robot equipped with one or more advanced external sensors, interfaced with other machines, and communicating with other computers would be considered to exhibit some important aspects of intelligent behavior. Interfaced with available machine vision, proximity, and other sensor systems (e.g. tactile, force, torque), the robot would acquire randomly positioned and oriented work-pieces, inspect them for gross defects, and transport them to assigned positions in relation to other workpieces. It would do insertions or other mating functions, while correcting its actions by arbitrating between various signals from force, torque, and proximity sensors. It would perform fastening operations, and finally, it would verify acceptable completion of these intermediate assembly processes. Its computer would compile statistical data about inspection failures by quantity and type, and would communicate with neighboring systems. The foregoing scenario is just one of many feasible today. The major functional elements of such an intelligent system are the following (Rosen 1985):

1. The capability of a robot system to adapt to its immediate environment by sensing changes or differences from some specified standard conditions.
2. A learning control system based on on-line observations of the system.
3. The capability of computing, in real time, the necessary corrections for trajectories and/or manipulative actions.
4. The capability of interacting and

communicating with associated devices (such as feeders and other robots) and with other computers.

Various aspects of sensor-based control of robotic systems relevant to artificial intelligence (AI) for development of future robotic systems will be examined.

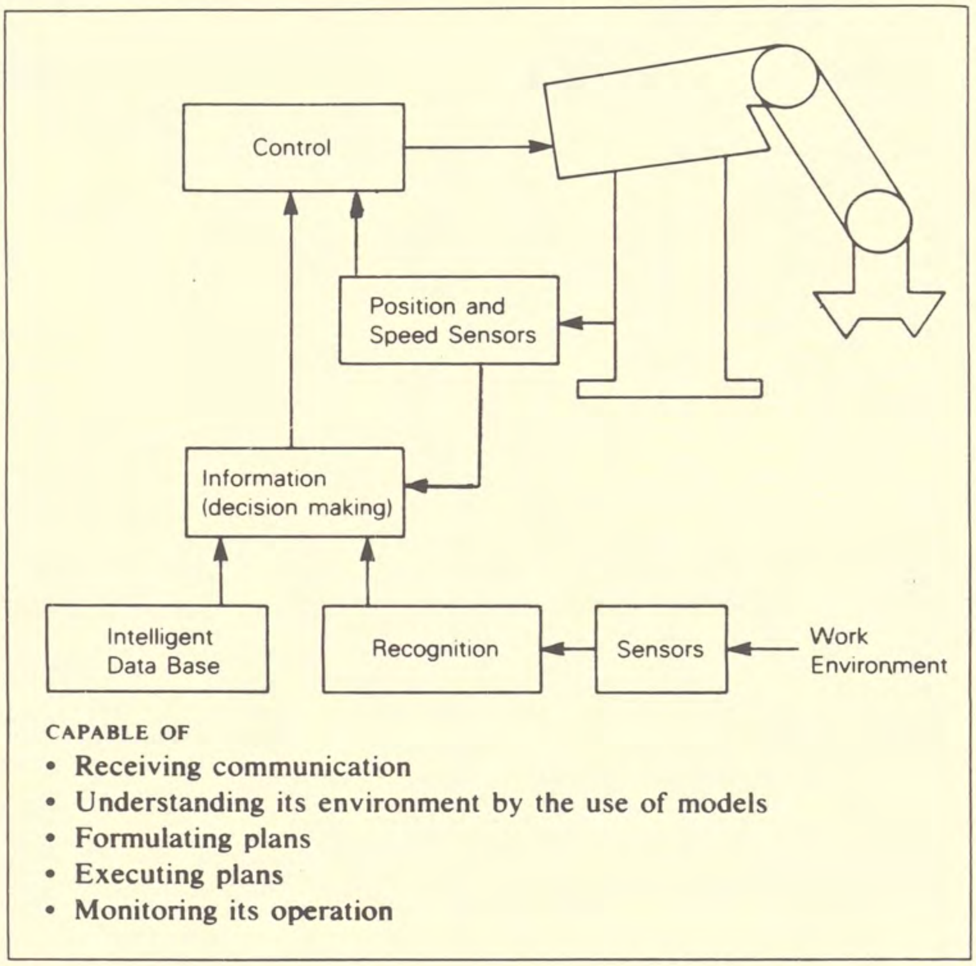
INTELLIGENT ROBOTS

Intelligent robots broaden the flexibility of automation and improve productivity of manufacturing. They relieve the robot user of the burden of specifying program details and react to uncertainties in their environment. The planner and the controller of an intelligent robot system need the following features: (1) Access to geometric models of the robot, the work cell, and objects in the work cell; (2) Access to sensor data to update the world model; (3) The capability of interpreting, reasoning and learning; and (4) The capability of generating action plans and monitoring their execution (Elmaraghy 1987).

Sensory capabilities are necessary for a robot to interact with a flexible environment. These capabilities permit adaptive motion control in which sensory information is used to modify the commands to a programmable manipulator. Sensors for robots are usually divided into contact and noncontact categories. Contact sensors may be further subdivided into tactile, and force/torque sensors, whereas noncontact sensors may be divided into proximity and vision sensors. Contact and noncontact sensors play complementary roles for sensory feedback. For example, to insert a peg into a hole, vision sensing with its coarse resolution may be used to find the hole and position the peg close to the hole (even partially inserting it if possible). Feedback from force and torque sensors would then be used for a more precise alignment of the peg with the hole. An optimum algorithm for final insertion would move the peg in such a manner as to minimize the binding force and torque (Kak and Albus 1985).

Robot intelligence requires a good deal more than simple acquisition of sensory data. In addition to sensors, the ability to organize the sensory data into task-specific models or components is needed. Model representation is a more challenging problem than the design of devices and systems for sensory input. With the rapid progress that has recently been made in all type of sensors, the achievable level of robot intelligence seems constrained primarily by this limitation on the processing of sensory information (Albus and Kak 1985).

The knowledge organization of the state-of-the art robots is at a low level. Their knowledge bases are limited to a small number of distinguishable objects and environmental situations. This level of sensory data organization is adequate for functions such as pick-and-place and simple inspection. In most such cases only one or two sensors are used for feedback, and the environment is severely constrained with respect to the other sensors. More complex inspection and assembly operations will require higher-level processing of information from a large number of sensors for the correct interpretation of geometrical relationships among different components. (Albus and Kak 1985) The components of an intelligent robot are pictured in Figure 1.



CAPABLE OF

- Receiving communication
- Understanding its environment by the use of models
- Formulating plans
- Executing plans
- Monitoring its operation

Figure 1. Intelligent robot (Schutzer 1986).

SENSORS FOR INTELLIGENT ROBOTS

In this chapter an overview on the subject of sensory capabilities for robots is presented. The aim is not to give a detailed review of this technology but to cover the capabilities, limitations and the area of application of the types of sensors used in robotics.

Contact-type Sensing

Contact-type sensors are devices which must physically touch the "target". They include tactile sensors, limit switches and force/torque sensors.

Tactile Sensors

Tactile sensing like the sensory capabilities of human hand enables the detection of touch, force, slip, and movement. Recent research has focused on the development of tactile sensors for robots with similar skin-like properties.

Tactile sensors are needed for robot grippers used in assembly applications. These sensors enable the gripper to close under servo control with sensor's pressure used for feed back. This approach prevents the gripping device to close on all parts with the same force.

Tactile sensing is still an infant technology. Despite the recent developments in transducer technologies, the constraints on tactile sensing are still technological. In addition, the ability to integrate the information into the control system still represents a major problem. The main limitation in application of this type of sensor include wear of the contact surface and the possible need for multiplexing due to a large number of sensor interconnections.

Limit Switches

Limit switches enjoy widespread acceptance in the robotics industry. Their low cost and excellent service life make them ideal in many applications such as determining the position of parts, arms, or grippers. Limit switches are frequently used for detecting the movement of parts and carriers in the work cell. The speed of the moving part influences the design of the limit switch. Limit switches are also used in conveyors and positioners that work side-by-side with robots (Strack 1987). There is a trend in the changing share of the market from the limit switches to the smaller and lighter proximity sensors (Morris 1987).

Force/torque Sensors

With force/torque sensors, robots have the capability to grasp parts of different sizes by applying the appropriate level of force for the given part. These sensors have been designed for robot arms "to feel" sudden increases in force that occur, for example, if the robot tries to place a workpiece into a filled or nonexistent position. In assembly applications, these sensors can determine if screws have become cross-threaded or if parts are jammed. The main drawback for these sensors is the considerable computation time required for calculation of offset forces.

Non-Contact Sensing

Photoelectric and proximity sensors are the dominant non-contact sensing technologies used in robotics.

Proximity Sensors

Proximity sensors are devices that indicate when one object is close to another object. One practical use of these sensors will be to detect the presence or absence of a workpart. An inductive proximity sensor detects ferromagnetic metals in its magnetic field. It comes in shielded and unshielded types. Shielded types are typically used where the sensor is to be embedded in metal. Capacitive proximity sensors sense nonmetallic objects as well as metallic objects. The advantages of proximity sensors are their low cost, extremly high reliability, and immunity to adverse environments. Proximity sensors, however, do suffer from limitations in their sensing distance and in the type of object they can sense.

Among the newer proximity sensor technologies being introduced are linear proximity switches. Linear sensors produce outputs that are truly proportional to the target distance.

Remote-amplifier proximity sensors represent another advancement in inductive technology. They are particularly advantageous in grippers where it may be difficult to physically adjust the sensors for various parts.

Photoelectric Sensors

Photoelectric sensors are widely used in robotics. Smaller sizes, longer sensing distances, and faster response times have significantly expanded their usefulness.

Fiber-optic photoelectric sensors can be quite effective in robot end-effectors. These sensors transmit light directly to the sensing area via lightweight, flexible, fiber-optic cables. With this capability, a heavier amplifier unit can be mounted at a distance in a more secure and less space-restricted area. Uses include sensing in hard-to-reach areas, such as between grippers.

The use of visible red LED (light emitting diode) technology eases the installation of photo electric switches by enabling the installer to properly aim the devices. The sensing distance for different types of photoelectric sensors vary between 5 mm to 30 meter. The advantages of photoelectric sensors include light weight, low cost, small size, and simple operation.

Dust accumulation, sensor misadjustment, and misalignment of the reflector are the common problem with these sensors. Another drawback is the high electrical current required. This would prevent the use of such sensors with robots operating in explosive atmospheres.

Ultrasonic Sensors

Manufacturers can use ultrasonic sensors for part positioning and as range finders. These sensors can detect glass, plastic, metal, or paper with an ultrasonic beam. Presence or absence or echo-ranging distance information are obtainable with these sensors (Morris 1987). Because the technology is based on sound, response times can limit their use. Trade-offs exist between high-frequency types (near 200 kHz) and low-frequency types (near 40 kHz). The high-frequency type is more immune to back-ground noise, but is more sensitive to angular position (Strack 1987). These sensors are unaffected by dust or dirt and can withstand harsh environments.

Vision Systems

Vision systems are used most appropriately where some degree of inspection is required. These systems are not intended to replace simpler "nonvision" sensors. The most important development in sensors for robots may not involve vision systems at all, but rather nonvision sensors that offer the inspection capabilities of vision without the cost, size, and operational complexity. Two major applications of vision sensing are for the control of manipulators and for automated inspection. To control manipulation, a vision system must be able to identify and locate workpieces. It must also be able to determine workpiece orientation. This ability permits a robot to deal with imprecisely positioned workpieces with random orientations.

The roles of vision and tactile sensing are often complementary. With vision sensing, a robot can identify workpieces and locate their position, whereas tactile sensing can be used for determining the local shape, orientation, and resistance to gripping pressure once the workpiece is grasped.

In a recent survey, Rosen (Kak and Albus 1985) has presented an exhaustive listing of the manipulation tasks that require vision. Major categories in this list are the following:

1. Manipulation of separated workpieces on conveyors for the purposes of sorting, packing in a container , feeding into another machine in a prescribed position, and orientation.

2. Bin picking for the same purposes as listed above.

3. Manipulation in manufacturing processes .

4. Manipulations required for assembly. For assembly tasks a manipulator with vision is capable of active accommodation, which implies that it can compensate for errors in positioning and orientation of workpieces. Finer position control of a workpiece or a tool can be accomplished by passive accommodation of a compliant wrist used for the correction of positioning errors.

The main advantages of vision systems are inherent in the ability to perform inspection tasks. Checking packaging, and contents in pharmaceutical and food industries, inspecting printed circuit boards, and inspection of glass items for cracks is not feasible by other sensing systems. The main limitation for vision systems today is their long reaction time which is primarily due to computation time. This situation could be improved by use of more efficient algorithms and computing systems capable of parallel processing. The need for a controlled environment and structured lighting imposes another limitation on such systems. Today's vision systems lack the desired accuracy for locating objects in high precision environments.

Smart Sensing

Sophisticated capabilities can directly increase a sensor's intelligence. These include compatibility with multiplexed communications, advance logic capabilities, and self-diagnostics. Integration of a large number of functions in the sensor package is not essential. Instead, many smart sensor functions can be handled by a device dedicated to performing logic functions, such as a sensor interface or programmable logic controller (PLC). With this approach multiple sensory inputs can be processed efficiently and transferred quickly to the next level of the system hierarchy. All of these activities can be done in a cost-effective manner. In addition, a hostile environment at the sensing point might require a remote location of the sensor's logic controller (Mabrey 1987).

OFF-LINE PROGRAMMING

The need for efficient programming of robots has led to the development of robot-level languages. The user must specify a detailed description of robot moves in the program. More sophisticated programming systems and languages have been developed to provide better tools which make the programming task easier. Systems with higher-level commands, graphical instructions, geometric models and some artificial intelligence concepts have been used.

Off-line programming is essential to make small and medium size production and assembly work feasible. The increasing complexity of robot applications makes the use of off-line programming even more attractive. Off-line programming requires the existence of a theoretical model of the robot and its environment (Figure 2). By using such a model we can simulate the way in which the robot would behave. The model can be used to construct the program for the robot.

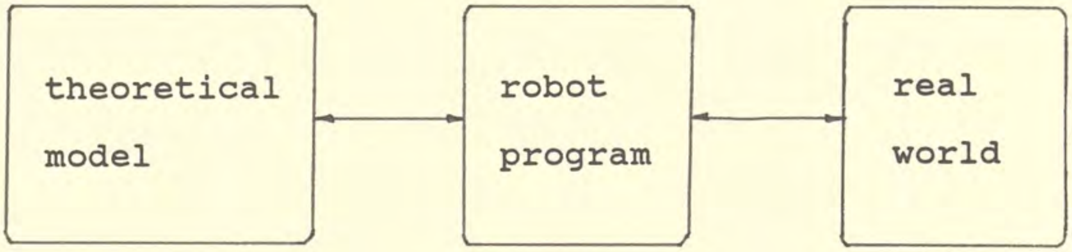


Figure 2. Theoretical Model and Its Role

The advantages of off-line programming may be summarized as following (Yong, Gleave, Green and Bonney 1985):

1. The reduction of robot downtime.
2. The removal of the programmer from potentially hazardous environments.
3. A single programming system can be used to program a number of different robot controllers.
4. An off-line programming system can access CAD/CAM data bases for parts data.
5. Complex tasks can be programmed by utilizing a high-level programming language on the off-line system.

6. A suitable simulation software can be used to verify the robot program.

The implementation of off-line programming encounters difficulties in the area of modeling, programming method and interfacing. Efficient geometric modeling is a difficult task. One way of geometric modeling is to use data stored in existing CAD systems. The data structure used must be capable of representing relationships between objects in the world. It must also reflect any changes in these relationships. The modeler should allow for the embodiment of algorithms used by the robot modeler. A robot modeler is used to model the properties of jointed mechanisms. There is no general solutions for such mechanisms. The modeling of rotational or translational motion of joints is possible, but to simulate real motion effects such as overshoot or oscillation is considered to be too complex.

The geometric and robot modelers provide the capability for controlling a robot within a world model. To define the robot movement sequences, a programming method is required. This requirement causes complications when the system is to be applied to different applications. For example, the functional requirements for robots in arc welding are significantly different from the functional requirements in spray painting.

Generalization of the programming method to run multi-robot installations is a difficult task. To convert the program description from an off-line format to a robot controller format, a form of interfacing is necessary. Due to the wide range of robot controllers and variety of programming systems, interfacing becomes a major problem. Standardization could be employed in control systems and program format. Due to commercial and practical considerations, this approach is not feasible. Competitiveness among various robot manufacturers and the use of different technology for control systems makes standardization difficult.

The compounding errors existing in the real world (robot, the robot controller, the workplace, the modeling and the programming system) can lead to discrepancies of large magnitude. For off-line programming to become a practical tool these discrepancies must be reduced. To achieve this objective the following combination of efforts are required.

1. Positional accuracy of robots must be improved.
2. Better methods for locating objects within a workplace must be applied.

3. Sensor technology should be applied to the remaining discrepancies within a system. (Yong, Gleave, Green and Bonney 1985)

TASK-LEVEL PROGRAMMING

In task-level programming, robot actions are specified only by their effects on objects. For example, the user would specify that a pin should be placed in a hole. The sequence of arm motions for insertion are not relevant. The programmers job is to describe the objective, the parts to be used, and the initial and final state.

Geometric models of the environment and of the robot are required as input. To carry out a task-level program a task planner sub-system and a world sub-system must be available.

Task Planning

Task planning includes the gross-motion planning, grasp planning, and fine-motion planning. It is necessary to plan the global motion of the robot to avoid collisions between the robot and the objects in the workspace. The grasp planner must choose where to grasp objects and to choose grasp configurations. Guarded motions are required when approaching a surface, and compliant motions are required when in contact with a surface. A task planner must be able to synthesize for these motions. In the near future a system called an assembly planner will examine the CAD data base and produce a task-level program (Perez and Brooks 1985).

Uncertainty

The presence of uncertainty in the world model affects all the planning modules and the motions. Three main sources of physical uncertainties are the robot's mechanical tolerances, parts tolerances and the initial position. Besides physical uncertainty, there is uncertainty in the system's knowledge and there is sensor inaccuracy.

World Model

The world model maintains a description of each known object in the work cell. At any instant, the information contained in the world model should be sufficient to reconstruct the current state of the cell. The world model must contain the following:

a) The geometric description of the objects, robots and the environment.

b) The physical system characteristics: for example; joint limits, acceleration bounds, control errors, and sensor accuracy.

Tasks are actually defined by sequences of states of the world model. The major sources of geometric models are CAD systems. Vision systems may eventually become a major source of models (Kak, Boyer and Chen 1986).

There are no complete task-level programming systems available today. Progress has been made on such problems as collision avoidance, path planning, automatic grasping, sensory planning and fine motion planning. The future prospects for a practical implementation of such systems is good (Kak, Boyer and Chen 1986).

USE OF EXPERT SYSTEMS

In less than 30 years, artificial intelligence (AI) has grown to a strategic industry. This technology still is in the early stages of development. However the process of building expert systems in the area of robotics, speech and vision recognition has started. artificial intelligence researchers are mainly concentrating on automatic task planning, knowledge representation, world modeling and automatic assembly.

Knowledge Representation

The main issues dealing with knowledge representation are (Elmaraghy 1987):

1. How to represent knowledge about objects, their shape and relationships.
2. The reasoning methods to use for spatial relationships between objects.
3. How to interact low-level information with high-level knowledge.

Facts and heuristics regarding the objects and the process are contained in the knowledge base. In the manufacturing domain there are two types of knowledge: static and dynamic. Static knowledge is not affected by the state of the system. Rules and inference about a particular process or instructions for a given task fall into this category. Dynamic knowledge is knowledge about the current state of the environment. This knowledge must be updated as changes occur in the state of the system, accounting for all actions taken by the robot and other operators. A separate knowledge base should be created for each type of knowledge.

Global Knowledge Base

A global knowledge base would be created to support the static information. This knowledge base would be accessed by all elements of the system. On going research is being conducted for various approaches in design of the global knowledge base. "Slot-filler" representation is used to store information about assembly plans used for task planning and distinctive features of object models used for object recognition (Yang, Safranek and Chen 1986).

Current World Model

The current status of the robots' working environment is maintained by the current world model. The location and identity of objects and the status of any environmental variables is the type of knowledge to be maintained.

Robot Learning

The simplest and most direct form of teaching is a sequence of examples. Some vision systems use this techniques to develop recognition rules. Programs have recently been developed to aid in generating rule bases for expert systems. One such program is ACLS (Analog Concept Learning System) (Paterson and Niblett 1982). After a variety of examples have been presented, ACLS can be asked to induce a rule to explain them. The rule is displayed in the form of a decision tree or as a Pascal program. ACLS has been used for classifying television images. This approach shows a faster run-time than conventional statistical pattern-recognition algorithms. Miller has introduced a new practical learning control system for robotic control (Miller 1987). This control approach is applicable to complex robotic systems involving multiple feedback sensors for both repetitive and nonrepetitive operations. A general learning algorithm is used to predict the command signal based on changes in the sensor output. The learning controller requires no prior knowledge about the relationship between the sensor outputs and the system commands. The learning is based solely on on-line observations of the system. This information can therefore be utilized automatically to achieve new control objectives.

PROPOSED SYSTEM OVERVIEW

The integration of multi-sensory information establishes a base for development of knowledge based robot control. Multi-sensory integration must be considered in association with a system capable of supporting task level programming. The knowledge-based system must be used to identify and recognize configurations in the robot world. It must provide the necessary information for the system to be capable of executing actions that are waiting for additional information.

Steiger and Matos have recently presented their approach to this problem (1986) In this chapter their work will be reviewed in more detail. As a starting point, let's consider an industrial robot system environment (assembly, pick and place,...) that we may consider as a moderately structured environment. Under these conditions, although we may meet some surprises or find that some aspects may be unknown or uncertain, most of the situations can be predicted. This situation allows for the majority of decisions to be made by anticipation. Therefore a generic plan that must perform satisfactorily during a entire work cycle, will be created by using an off-line programming approach. This plan can be tested for different scenarios using a simulation system. Possible fuzzyness factors to suit the deficiency of the real world model can be introduced. The "off-line" plan must be flexible to allow certain aspects of the task plan to be determined by sensors. Sensory information acquired during execution (on-line) will determine only these aspects. A group of "agents" are required to fill in the missing information in the executive system's architecture. These agents are coordinated by a supervisor having a "local planning" capability.

Knowledge Architecture

Task knowledge is the starting point for generic planning. It will define the setting in which the agents will operate.

World model knowledge has to maintain different levels of abstraction. Different components of the executor system will access this model. Constant flow of information is necessary to keep this model updated.

The following issues must be dealt with by the world model:

1. Relational information
2. Inference rules

3. Incomplete knowledge (How to deal with?)
4. Updating strategies

Knowledge Bases

For better system efficiency a network of knowledge bases (KBs) is suggested. To access and update the knowledge structure is an important problem. So is the direction of knowledge flow between the different components. Another problem is the flow of knowledge between different levels of abstraction. This is a knowledge updating problem which relates to sensorial information acquisition.

Agents

Agents are one of the system's key components.
a sketch of their structure is shown in Figure 3.

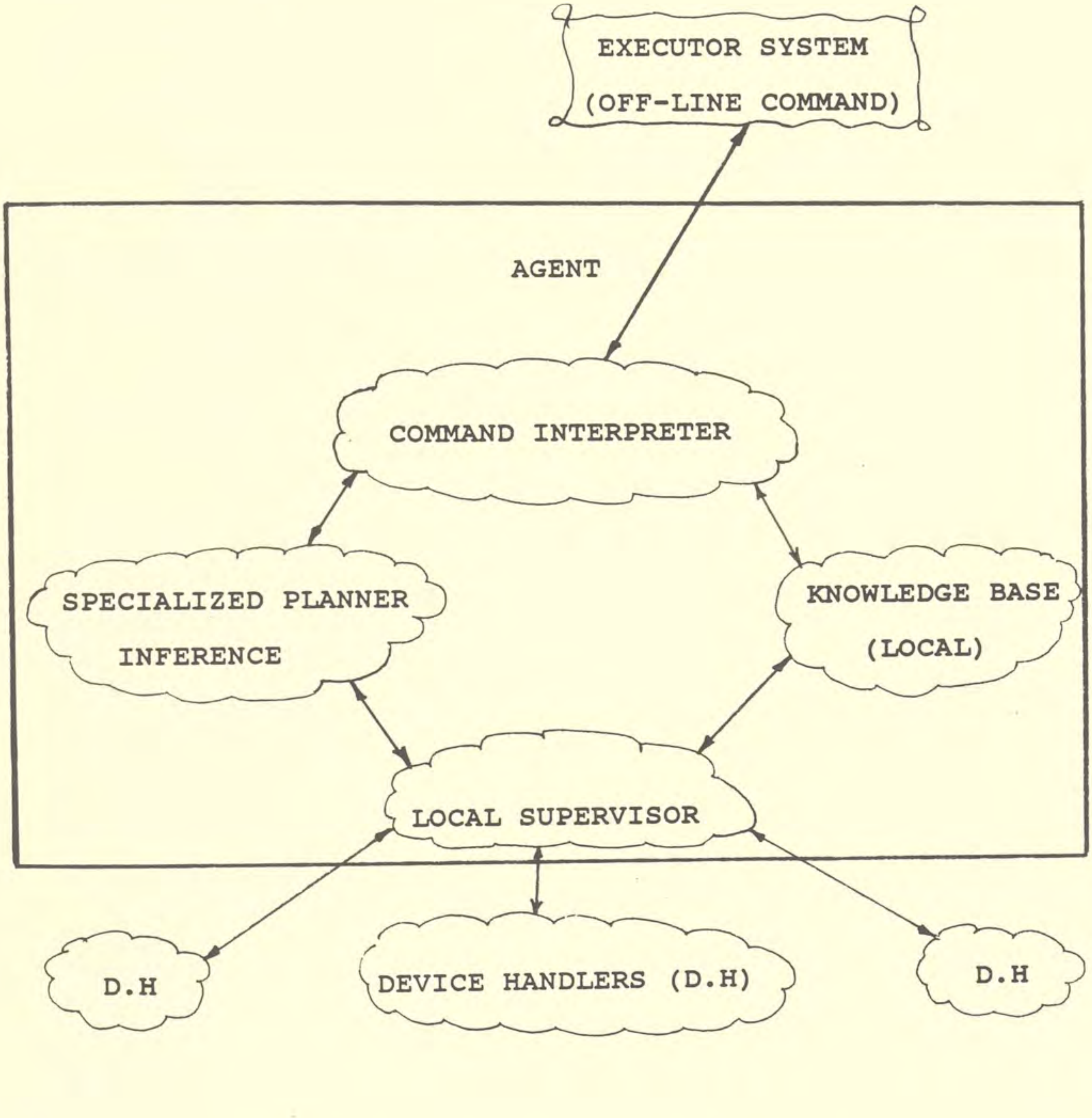


Figure 3. Components of an Agent

In this organization, the command interpreter is the module that receives commands. A specialized planner breaks down a generic action into more elementary subactions to be executed by components such as sensors and actuators. A knowledge base supports the agent's local knowledge. The local supervisor controls the physical components. The device handlers are capable of local processing and the execution of actions. Each agent can access several device handlers and each device handler can be accessed by several agents. For example, a manipulator device handler can be controlled by an actuator agent and by a tactile sensor agent.

Recognition Agent

This model considers the operation in two phases: feature selection and recognition. The feature selector is a knowledge preparer for the Recognizer. It identifies the discriminatory features and produces the set of rules that will feed the Recognizer's knowledge base. In the Selector's knowledge base (KB) several knowledge classes may exist.

1. Knowledge about the sensory components such as the available sensors, their reliability or confidence and the features they can extract.

2. Knowledge of the family of objects to be manipulated. Characteristic features such as color, material, texture and thermal conductivity, in addition to geometric information. Statistical occurrence data is also used for reformulation of the knowledge base's structure.

3. Knowledge of recognition rules. These rules are chains of "if-then" statements induced from example sets. Currently there are expert system shells on the market for the production of these rules. (Rule Master Expert System Shell from Radian Corporation has a component known as rule maker that automatically develops decision trees from example sets.) The requirement for the Selector's knowledge base is to keep in mind the robotic station's available means for feature extraction and

their respective deficiencies. The Recognizer will start the sensing action. The goal is specified by the generic plan. Knowledge is fed by the Selector to its knowledge base. The sensors are activated by the intended goal and in accordance with this knowledge, the Recognizer will send back the results to the execution supervisor.

Tuner or Adjuster

The tuner or adjuster is used, on request, to prepare the Recognizer's knowledge base. This is accomplished by on-line reformulation of the rules when such intervention is justified. These rules will be used to modify the Recognizer's knowledge base.

Tools

A special kind of expert system is needed to function in those situations involving the real-time control of robots. The most fundamental problem these programs address is timeliness. Ordinary expert programs contain no mechanisms for triggering events that must take place within a certain time frame.

A key difference between a normal expert system and one able to respond in real-time is that rules in a real-time system usually contain some reference to the history of variables or events. Rules written in this manner are executed by a real-time operating system that is part of the expert program. Low-level processes scan sensors to alert the expert system.

Another measure that ensures good speed of response is the use of sophisticated rule-searching techniques. Real-time expert systems must be able to search through and evaluate rules quickly. They generally contain mechanisms that reduce the hundreds of rules that could possibly apply in a given situation to a few likely candidates.

Other requirements will be the easy representation of rules and possibility of interfacing with external data bases. In some sophisticated systems this seems to have been fulfilled.

CONCLUSIONS

Sensory capabilities are necessary for an intelligent robot to interact with its environment. The capabilities, limitations and the area of application for different sensors were presented.

Off-line programming is an important step toward increasing the use of industrial robots in industry. Most current systems are in some stage of development. Off-line programming will increase the utility of the robot and make it safer by removing the man from the programming environment.

A key feature for the intelligent industrial robot is its ability to be programmed at the task level. Although no complete task-level systems have been implemented, progress has been made on the basic problem of task planning.

Robot learning is being considered on other than a philosophical basis. There have been practical real-time robot control system implementations based on these new learning techniques.

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