Intelligent Robot Trends for 1998

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ABSTRACT

An intelligent robot is a remarkably useful combination of a manipulator, sensors and controls. The use of these machines in factory automation can improve productivity, increase product quality and improve competitiveness. This paper presents a discussion of recent technical and economic trends. Technically, the machines are faster, cheaper, more repeatable, more reliable and safer. The knowledge base of inverse kinematic and dynamic solutions and intelligent controls is increasing. More attention is being given by industry to robots, vision and motion controls. New areas of usage are emerging for service robots, remote manipulators and automated guided vehicles. Economically, the robotics industry now has a 1.1 billion-dollar market in the U.S. and is growing. Feasibility studies results are presented which also show decreasing costs for robots and unaudited healthy rates of return for a variety of robotic applications. However, the road from inspiration to successful application can be long and difficult, often taking decades to achieve a new product. A greater emphasis on mechatronics is needed in our universities. Certainly, more cooperation between government, industry and universities is needed to speed the development of intelligent robots that will benefit industry and society.

1. INTRODUCTION

There is a need for intelligent robots in every field of human endeavor. Most notable are situations which are dangerous for humans such as in outer space, under sea, under ground, as well as on the ground such as in a war zone or a left over mine field, in a volcano or earthquake or in man made situations such as in heavy traffic. In these situations it may not be possible to cost justify the robot in terms of a return on investment. However, saving lives or exploring the world and universe, are worthy goals. In other situations such as mass production where tasks must be performed repetitively perhaps millions of times per year, one can compare human and machine labor both technically and economically. In these situations, a cost justification can be developed to show that an investment in automation will, in fact, produce as good or better return on the capital investment than a standard saving method. Industries that recognize and use these advanced technologies will produce the highest quality goods at the lowest cost, capture the market for their products and lead the world.

It is well known that economic advances require two components: capital investment and technical innovation. Advances in intelligent robots also require these components. Many real and perceived intelligent robots have been identified; however, only a few have actually been reduced to practice because one of the two required components was missing. One thesis is that technical innovation in intelligent robots is currently too difficult to be easily mastered by technologists. That is, in many cases we know what to do, but not how to do it in an easy, cost effective, state of the art, engineering manner. Another way to state this thesis is as a hypothesis: of 100 engineering or scientific readers of this paper, perhaps only one is capable of designing and constructing an intelligent robot in their working life time of 30 years. If this hypothesis were correct, then 30 brilliant engineers would need to work one year to develop one intelligent robot.

In Section 2, some background in artificial intelligence and intelligent robots will be presented. In Section 3, some topics of mechatronics will be reviewed. In Section 4, some examples of intelligent systems will be described. In Section 5, economic aspects will be presented. Finally, conclusions and recommendations will be given in Section 6.

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2. INTELLIGENT ROBOTS

Intelligent robots are an ideal, a vision. All one has to do to see the intelligent robot model is to look in a mirror. Ideally, all intelligent robots move dexterously, smoothly, precisely, using multiple degrees of coordinated motion and do something like a human but that a human now doesn't have to do. They have sensors that permit them to adapt to environmental changes. They learn from the environment or from humans without making mistakes. They mimic expert human responses. They perform automatically, tirelessly, accurately. They can diagnose their own problems and repair themselves. They can reproduce, not biologically but by robots making robots. They can be used in industry for a variety of applications. A good intelligent robot solution to an important problem can start an industry and spin off a totally new technology. For example, imagine a robot that can fill your car with gas, mow your lawn, a car that can drive you to work in heavy traffic, a machine that repairs itself when it breaks down, a physician assistant for microsurgery that reconnects 40,000 axons from a severed nerve.

Intelligent robots are also a reality. Many are used today. Many more prototypes have been built. Typical applications are: high speed spot welding robots, precise seam welding robots, spray painting robots moving around the contours of an automobile body, robots palletizing variable size parcels, robots loading and unloading machines.

The components of an intelligent robot are a manipulator, sensors and controls. However, it is the architecture or the combination of these components, the paradigms programmed into the controller, the foresight and genius of the system designers, the practicality of the prototype builders, the professionalism and attention to quality of the manufacturing engineers and technicians, that makes the machine intelligent.

Just where is the intelligence in an intelligent robot? It is in the controller just as the intelligence of a human is in the neural connections of the brain. However, it is only possible to see this intelligence through some action just as it would not be possible to see intelligence in a comatose human. Where does the intelligence come from? The control program and architecture provide for real time responses to a variety of situations. If these responses are intelligent, then the robot appears intelligent.

When are intelligent robots needed? When a task is repetitive such as making a million parts per year, automation is needed. The most suitable automation may be an intelligent robot. Also, when a task is hazardous for humans, automation is needed. The best solution may be an intelligent remote manipulator. Finally, when an industry needs to be internationally competitive in cost and quality, automation is needed. Again the intelligent robot may play a significant part in the solution.

What are the benefits from using intelligent robots? Robots can do many tasks now. However, the tasks that cannot be easily done today are often characterized by a variable knowledge of the environment. Location, size, orientation, shape of the workpiece as well as of the robot must be known accurately to perform a task. Obstacles in the motion path, unusual events, breakage of tools, also create environmental uncertainty. Greater use of sensors and more intelligence should lead to a reduction of this uncertainty and because the machines can work 24 hours a day, should also lead to higher productivity. More intelligence could also lead to faster, easier setups and reduced cycle times. More intelligence should also lead to faster diagnosis of problems and better maintenance for the systems. Finally, there is the fact that to remain internationally competitive, the best technology usage is required. Waste of human or material resources is too expensive for industry and for society.

Since this paper is about factory automation, which may not be obviously considered high technology, let us begin with a few definitions. Intelligence is the most outstanding human characteristic; however, it is still not totally understood and therefore has many varying definitions, implied meanings, and levels of sophistication[1]. Human intelligence is defined in Webster's dictionary[2] several ways. Consider the two following.

1. The capacity to acquire and apply knowledge. This capacity may lead to the ability to learn or understand or to deal with new or trying situations.
2. The faculty of thought and reason. This faculty may lead to the ability to apply knowledge to manipulate one's environment.

Studies in Artificial Intelligence (AI) attempt to implement the first definition of learning or understanding usually with a mathematical or computer algorithm. Research in Machine Intelligence (MI) is directed toward designing new, useful, adaptive machines. Some of the goals of AI are:

- Finding new methods for extracting useful information from the environment using sensors.

- Developing methods for building, updating, and retaining information from a knowledge base.
- Inventing algorithms for utilizing information stored in a knowledge base to make intelligent decisions.
- Finding improved methods for translating user needs into a workable software system.
- Developing reusable software components that can expand toward an ultimate software system.

Why all the emphasis on computers and AI if we are talking about mechanical robots? Genetic engineering aside, it is only with computer control that we have any possibility of building an intelligent robot. Any comparison of the complexities of a human arm and a manipulator arm show how little we still know about arms. The best prosthetics today is poor substitutes for the originals. Also, designing a robot requires the use of many computer tools such as symbolic computation of non-linear inverse kinematic and dynamic equations, simulation of control characteristics, simulation of manipulator motions and interactions, path planning, obstacle avoidance, self diagnosis, etc.

Robot intelligence implies doing something in the real world and is often taken as the ability of a robot to adapt to changes in its environment, and possibly to learn from these adaptations. Intelligence is a difficult characteristic to guarantee in either humans or machines and is not mentioned in either the industry or standard definition. Intelligence cannot be easily measured. Only in science fiction does one try to defend a robot gone awry as lacking intelligence. In our world, the designers, manufacturers and users must answer and often pay dearly for design mistakes and manufacturing flaws.

The Robotics Industries Association (RIA) [3,4] definition of an industrial robot is: "a reprogrammable multifunctional machine designed to manipulate materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks."

The definition according to the International Standard ISO 8373:1994(E/F) for a manipulating industrial robot is: "An automatically controlled, reprogrammable multi-purpose manipulator programmable in three or more axes, which may be either fixed to place or mobile for use in industrial automation applications.

A trend[2] is: "a general inclination or tendency; a direction of movement, a course, a move in a specified direction." A factory[2] is: "a place where goods are manufactured, a plant." Automation[2] is: "automatic operation or control of a process or system or of equipment; the techniques and equipment used to bring about automatic operation or control; the condition of being automatically controlled or operated."

3. MECHATRONICS

Mechatronics is a methodology used for the optimal design of electromechanical products[5]. The Mechatronics system is multi-disciplinary, embodying four fundamental disciplines: electrical, mechanical, computer science and information technology. The mechatronics design methodology is based on a concurrent, instead of sequential, approach to design, and the use of the latest computer tools, resulting in products designed right the first time. Mechatronics covers: modeling and simulation of physical systems; sensors and transducers, actuating devices, hardware components for Mechatronics; signals, systems and controls; real- time interfacing; advanced applications and case studies.

NEW ROBOT MANIPULATOR DESIGNS

In 1985, the four common types of robot manipulators were the Cartesian, cylindrical, spherical and vertically articulated or anthropomorphic designs. Then the horizontally articulated or Selective Compliant Articulated Robot for Assembly (SCARA) was introduced. In 1995, a totally different design, a tricept, Stewart platform was displayed at the Robot and Vision Exhibition by Comeau. It was advertised as being as flexible as a robot, as precise as a machine tool and strong as a press. It seemed ideal for press fitting bearings and other tasks requiring thousands of pounds rather than tens or hundreds of pounds of force. Nearly all industrial manipulator arms can be classified into one of six categories: Cartesian, cylindrical, spherical, vertically articulated, horizontally articulated (SCARA) or Steward platform types. New designs are still possible.

FASTER

Rotational speeds of robot manipulator links of 240 degrees/second are typical. For a 1-meter joint length, this would produce linear speeds of 4 meters/second. The overall cycle time is usually more important than individual link speeds. In a great variety of applications, robots are easily made as fast or faster than humans are.

SMALLER

> "Many manufacturing applications have emerged that can't be successfully performed without robots. In the electronics industry, miniaturization is driving the demand for robots. 'The trend toward further miniaturization of products like pagers, cellular phones, and two-way radios makes it virtually impossible for humans to repeatedly place, weld or solder components accurately,' according to Jim Hager, Site Manager, Motorola Manufacturing Systems, Boynton Beach, Florida. 'Good robotic systems can handle these tasks and help Motorola achieve Six Sigma quality."[6]

Micromechanical manipulators, molecular robotics, nanorobotics are names applied to the emerging field to produce new materials and devices at a nanometer scale, perhaps by direct interaction with atomic structures[7].

REPEATABLE

The repeatability of an industrial robot refers to its ability to return to a previously taught point in space with a certain precision. Typical repeatability is on the order of + or – 0.1 mm (+ or - 0.004 inch). Accuracy is the ability to go to a target point in space and generally can be achieved with a calibration setup. The trend is to make the robot as repeatable as required by the application.

SAFER

Both industrial robots and automated guided vehicles are potentially dangerous since they move. Industrial robots in the U.S. have killed people. Safety requires administrative controls, engineering controls and training. Administrative controls such as restricted use of the equipment to qualified personnel, proper maintenance and management insistence on safe operation, is vitally important. Engineering controls such as protective fences with safety interlocks on entrances, pressure sensitive mats and light curtains, all properly installed and maintained are also more commonly used than a decade ago. Training is also important and should not be overlooked especially when a company is downsizing. Safety is not something that can be relaxed. However, more safety features and self -diagnostics can be built into the robots and work cells. Also, the use of simulations to discover interferences and potential collisions is a step in the direction of safe application.

EASIER

Using an industrial robot is easy but putting it into an intelligent workcell requires much more than the robot. Important accessories such as grippers, process tooling, safety devices, programmable logic controllers, simulation programs, etc. are needed to make robots easier to use. As an example, Adept has published the Adept MV Partner Catalog[8]. This book provides a listing of sources of third party components that have been certified to be compatible with Adept's MV controller based products. System integrators can readily incorporate these products into their designs by utilizing the product specifications, technical notes and expert resource contacts to reduce engineering time and risk.

OPEN ARCHITECTURE CONTROLS

The control system is the set of logic and power functions which allows the automatic monitoring and control of the mechanical structure and permits it to communicate with the other equipment and users in the environment. Open architecture control refers to software designs that can use or be used with products from a variety of manufacturers. The move toward open architecture controls is relatively recent but follows the trend in computers that caused a tremendous explosion in usage.

THEORETICAL KNOWLEDGE BASE

Inverse Kinematic Solutions

Most industrial robots are operated in position control mode as contrasted with velocity or force control. To move the motors to position a robot manipulator in space, an inverse kinematic solution is needed. The inverse kinematic solution must be discovered for each new manipulator design. Developing forward kinematic equations and solving them symbolically provides a mathematical result that can be used by anyone, forever.

Inverse Dynamic Solutions and Experimental Designs

Even though industrial robots are position control devices, the path between position points can be extremely important, for example, in seam welding. Since any moving system is described by a dynamic differential equation according to Newton's Second Law, the dynamic solution must also be determined in the design of a robot. This dynamic solution should be used in the design of the control system. It may not be obvious that a control system as simple as that of a robot manipulator cannot be theoretically proven to be stable. However, the dynamic system is non-linear and subject to noise from various sources. Criteria for practical stability rather than optimal stability are used today. A variety of motion control solutions have been developed but a greater understanding of non-linear systems is needed.

Integrated Robots with Vision and Sensors

For the industrial robot to be intelligent and adapt to changes in its environments such as part location, orientation, size, shape, sensors are needed. Vision is the most powerful sensor for humans and machine vision also adds adaptability to industrial robots which makes them intelligent. Many robot manufacturers now offer integrated vision and robotic systems.

Simulators and Code Generators

In the design of a robot work cell, a three dimensional simulation permits one to observe interference, avoid collisions and determine feasibility of an operation. In some modern simulation software, once a series of motions are selected, the robot code generator program can translate the motions into robot programming language automatically and download this program to the robot. This is a major simplification and improvement.

AUTOMATIC GUIDED VEHICLES

Automatically guided vehicles are becoming more feasible in factory automation. An excellent compilation of information on air, ground and undersea-unmanned vehicles was recently published[9]. The development of practical and useful unmanned autonomous vehicles continues to present a challenge to researchers and system developers. Educators are also using these challenges. Building a mobile robot is an excellent way to teach robotics. It's challenging and fun.

SERVICE ROBOTS

The service robot area is also growing. The International Service Robot Association is an individual and corporate member organization devoted to the application of robot technology to human services such as health care, education, security, space, and undersea exploration and related non-manufacturing areas. Examples of service robots include hospital food delivery robots, sentry robots, robot lawn mowers, robot vacuum cleaners, inspection robots, etc.

ROBOTS, VISION and MOTION CONTROL

The combination of robots and vision with the motion control is a trend toward understanding all the components of the intelligent robot, the manipulator, the sensors and the controls. If engineers can understand all the elements, i.e. Mechatronics, then some exciting new products and applications will be forthcoming.

4. SELECTED EXAMPLE

MIXED SIZE PALLETIZING

Warehousing can be described as the material handling functions of receiving, storing and issuing of finished goods. It is viewed in industry many times as a necessary evil that, in manufacturing terms, does not add value to a product. Yet, the warehouse/distribution function is critical to the successful business enterprise.

Warehousing is an expensive activity with its cost in the US estimated to be 5% of the Gross National Product.[10] For example, in 1988 this equated to $250 billion spent solely on warehousing operations. Briefly, the functions performed in a warehouse include information processing, receiving, storing, order picking, and load forming and shipping.

Load forming may be defined as arranging products to form a unit load for convenient subsequent handling. Research in load forming focuses on determining the optimal pallet size and on packing methodology to maximize space utilization. [10-14] the selected case study concentrates on the load forming of pallets using rectangular boxes. This restriction is not significant because the majority of stock keeping units (SKU's) in distribution facilities is boxed. Also, the methodologies developed for palletizing, with minimal changes, can apply to other load forming approaches such as container filling or palletless stacking.

Material handling is an excellent application for industrial robots. Much of this material handling is required in distribution centers. In a typical distribution center shipments are received and placed in a storage and retrieval system. When a customer's order arrives, the materials are retrieved from storage and palletized for shipment to the customer. In most cases this palletizing is of parcels of mixed size and weight and is stacked manually on the pallet.

There are several disadvantages of human palletizing. One is certainly related to cost. Even the most motivated and capable human can stack only about 6 parcels per minute, i.e. one parcel each 10 seconds. Another is related to safety and workers compensation costs. A human who performs such a repetitive motion is at risk for cumulative trauma disorders especially back injuries.

Other advantages of robotic palletizing include maximizing the usage of the pallet cube, the retention of knowledge about each parcel throughout the distribution system, increased pallet load stability, insurance of forming pallets in accordance with regulations, i.e. not stacking poisons on top of food items, and control of parcel fragility and crushability which reduces waste. Distribution centers are a necessary component in the logistics system of most manufacturing industries from food items, dry goods to computer or aircraft engine components or machine tool parts. All distributors including the defense industry, parcel industries and even medical industries are potential users of a robotic palletizing system.

The general problem of filling a three dimensional pallet with mixed size parcels may be considered as a mathematical problem of space filling of the pallet volume. That is, N parcels must be placed at positions (x_i, y_i, z_i) and the total volume filled as complete as possible. Other problems of this nature include the traveling salesman problem and the game of chess. In general these problems are called NP- complete, that is, the computation time required for an exact solution increases exponentially with N. There is no method for finding an exact solution except exhaustive search of all possible solutions. Fortunately, modern artificial intelligent techniques provided a means to good solutions. An expert system has been invented which provides solutions which satisfy a set of rules and consequently provide "good" solutions. Furthermore, the approach can be applied not only to single product palletizing, mixed layer or column palletizing, predefined order of arrival palletizing but also to the real time or randomly arriving mixed size and content palletizing. The University of Cincinnati was awarded U.S. Patent 5,175,692 for palletizing randomly arriving mixed size and content parcels. This patent has now been licensed to Motoman and is the basis of their mixed size palletizing product.

The early research was directed at formulating algorithms for real time pallet stacking of mixed size/content parcels using an expert system approach. A program was developed using an expert system called OPS5 that ran on a VAX 11/750 computer. Both pallet and work cell algorithms were considered.

Two types of inputs are required for the algorithms. The first is a database of dimensional sizes and content information for the stock keeping units (SKU's) which could be in the palletizing material handling stream. A separate effort is required to filter this data to ensure that all SKU's can be lifted by the particular robot gripper and placed by an industrial robot. Then of the SKU's which can be handled, a relational database is prepared which examines spatial relationships such as the number of boxes of one type that would form a stable base for a given number of boxes of another type. Also, content specific rules may be determined such as those related to fragility, crushability or contaminants.

The second type of input is a bill of lading for a particular pallet. Orders can be processed separately to determine the number of pallet loads required for the entire order. The main emphasis for this effort was single pallet load stacking of randomly picked SKU parcels. However, certain picking orders may be preferable and lead to faster stacking or better quality pallets. A third type of input that could be used is a pallet database.

The output of the software is the box locations for a pallet stacking arrangement. This arrangement satisfies all the rules built into the system and therefore gives a good quality pallet load. Measures of pallet quality such as percentage utilization of the available cubic space, location of the three-dimensional centroid, etc. can be easily computed from the information available. The output file can be used with appropriate calibration and translation of coordinates to give placement positions to a palletizing robot for each parcel on the pallet. The quality of the expert system pallet load is not "optimum" but rather "acceptable" quality since it satisfies all the rules.

Workcell Concept

A conceptual diagram of a robotic palletizing workcell is shown in Figure 1. The top-center block, AVisual Pallet≅, is the parent graphical user interface, the nerve center of the software system. From it, all data is relayed to and from the other software modules: the Interface Module, the barcode DLL, and the AVisual DCI≅ (a robot control interface). In the case of a palletizing job of mixed size/content boxes arriving in random order, the Interface Module would then come into play. As a job begins running, the barcode reader scans the first box; the box SKU number is passed through AVisual Pallet≅ to the

Interface where its palletizing algorithm determines the box coordinates on the job pallet or a queue pallet. This data is passed through AVisual Pallet≅ to AVisual DCI≅ which instructs the robot to palletize the box, return to the home position and wait for the next instruction. After sending the coordinates to AVisual DCI≅, if the palletizing algorithm has determined space on the job pallet for a box in the queue pallet, it sends the data to AVisual Pallet≅ that relays the coordinates to the robot through AVisual DCI≅. If there are not further instructions from the palletizing algorithm, AVisual DCI≅ instructs, through the barcode DLL, the barcode reader to scan the next box. The whole process starts over and continues until the last box is palletized. The results of a typical simulation are shown in Figure 2. Motoman, Inc. West Carrolton, OH, now offers this system. A Motoman implementation is shown in Figure 3 and described by DeCamp, et al.[12].

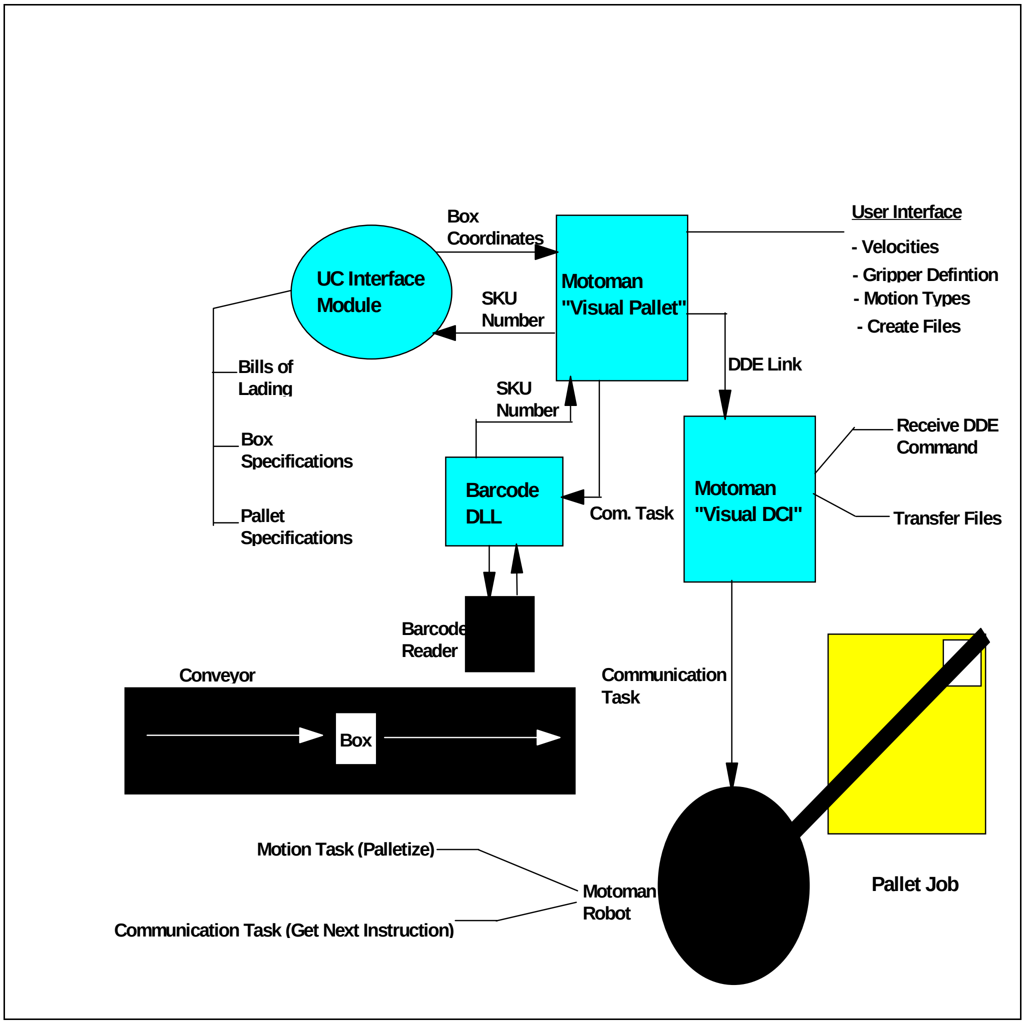

Figure 1 Workcell layout

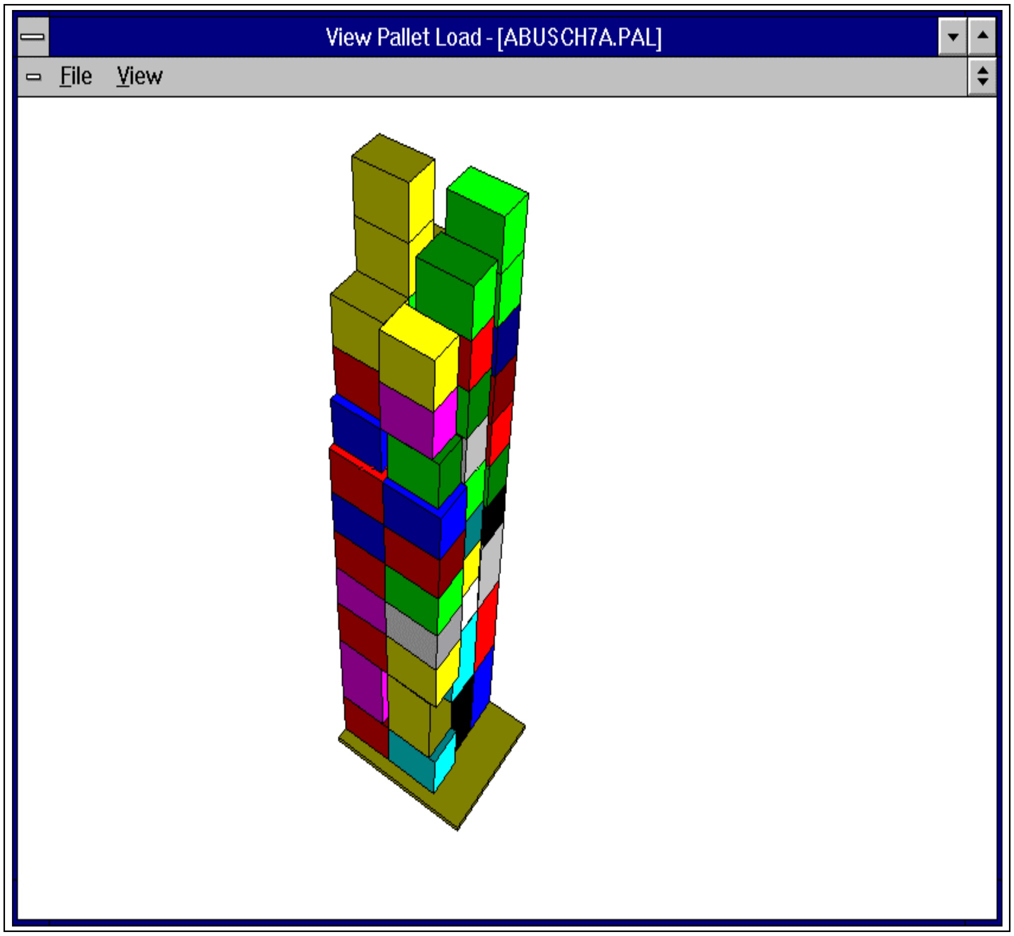

Figure 2 Simulation results.

Figure 3. Motoman mixed size/content palletizing workcell.

5. ECONOMIC ASPECTS –1.1 BILLION DOLLAR MARKET

Recent reports regarding the use of industrial robots are encouraging as shown in the following quotation.

> "Record breaking shipments from US manufacturers in 1997 totaled 12,459 robots values at $1.1 billion. This represents a 172% increase in robotic systems, and a 136% increase in revenues since 1992. According to new statistics released by the Robotics Industries Association, the world's population of installed robots at the end of 1997 exceeded 500,000. The country that has the largest population of industrial robots is Japan (400,000), followed by the USA (80,000), and the other Western European nations (120,000)." [3,4]

AGE of REALISM in ROBOTICS

New technologies go through a pattern of usage starting from zero, then increasing perhaps too far, then coming down then, then reversing and going steadily upward until the reach a downward turn at the end of their useful period. When a technology is first introduced, we may expect more than it can deliver. This period has been called the Age of Overexpectation. Following is a period of disillusionment in which less is expected than the technology can actually deliver. This period is called the Time of Nightmare. Finally, reality sets in and we learn to expect only what the technology can deliver -- the Age of Realism. The industrial robot has now reached this age of realism. The U.S. has a solid base of nearly 70,000 successful installations[4]. Broadening the robot definition to include automated guided vehicles, remote manipulators which must be supervised by a human as well as totally programmable robots, and a growing interest in personal and service robots has strengthened the technology base even more.

Since "robot" is often described in science fiction as well as in science some clarification is needed. Robotics has today developed into a solid discipline that incorporates background, knowledge and creativity of mechanical, electrical, industrial and computer engineering and other engineering and scientific fields. There are still many challenges, unsolved problems, and needed inventions.

CHEAPER

Cost is a difficult concept to pin down since there are a great variety of industrial robots and an even greater variety of applications. To provide an estimate, the following data from the RIA records for the first quarter of 1997 of shipments and new orders indicates that $300 million in new orders of 3133 robots gives an average cost of $95,754. Another estimate may be observed in the results of robotics application feasibility studies for a variety of applications done by the engineering robotics students for 1994, 1995 and 1997 shown in Tables 1, 2 and 3. In these studies, each student selected his/her application. Then they examine the characteristics of the application and determine the requirements for a robotic solution. They then select three candidate commercial robots, design a work cell with one or two robots, and perform a cycle time analysis and an economic justification.

Engineer	**Application**	**Robot**	**Robot Cost**	**Internal Rate of Return**
Aker	Material handling	Fanuc S-800	102,000	114%
Dhumal	Spot welding	Fanuc S-800	102,000	73%
Henderson	Spray painting	Fanuc P-100	70,000	37%
Karanth	Spray painting	DeVilbiss TR-4500	60,000	106%
Lean	Spray painting	ABB IRB 5002	110,000	296%
Noschang	Solder machine loading	Fanuc S-700	92,000	49%
Parisca	Carton palletizing	Fanuc S-10	60,000	58%
Srivivasa	Material handling	Adept 1850	75,000	356%
Ruiz de Luzuriaga	Silicon wafer material handling	Yamaha MXYL	25,000	144%
Shelton	Assembly	Fanuc S-10	62,000	57%
Winenger	Loading and unloading trimmer	Adept Three	39,000	284%
		AVERAGE	$72,455	143%

Table 1. Feasibility study results for 1994.

Engineer	**Application**	**Robot**	**Robot Cost**	**Internal rate of return**
Brooks	Saw blade cleaning	Fanuc M410I	87,000	40%
Damodaran	Spot welding	Motoman K100	96,380	73%
Delehanty	Loading EDM machine	Fanuc S 12	70,000	50%
Deshpande	Spray painting	Fanuc P-100	70,000	36%
Eswaran	Arc welding	Motoman K6SB	75,200	114%
Gandhi	Tolerance measurement	Fanuc S-5	50,000	69%
Hagenmaier	Material separator	Yamaha MRC 40	20,000	57%
Harvey	Vacuum cleaner	Motoman K30C	85,980	21%
Jackson	Inspection	Cyber Research Gantry with Remshaw Touch Probe	18,981	34%
Kamuf	Tire assembly	Motoman SK120 Motoman K30	88,980 77,980	84%

Kelkar	Spot welding	Kawasaki UZ-100	120,000	69%
Kumar	Frozen food handling	Motoman K 30 C	59,980	172%
Paramaguru and Ramesh	Assembly of PCB	Adept 550 AdeptOne-MV	30,000 50,000	73%
Manning	Arc welding	Fanuc ArcMate 100	53,640	139%
Pruyn	Ultrasonic inspection	Staubli Unimation RX 90	60,000	248%
Rajagopal	Dimensional inspection	Asea IRB L6/2	75,000	81%
Riedesel	Screw fastening	Panasonic SRA	30,000	183%
Roberts	Paper roll handling	Fanuc S-900H Clark GL-541	170,000 100,000	30.2%
Samu	Chicken pox vaccine packaging	Motoman S-6	60,000	56%
		AVERAGE	$70,415	86%

Table 2. Feasibility study results for 1995.

Engineer	**Application**	**Robot**	**Robot Cost**	**Internal Rate of Return**
Anisingaraju	Spot welding	Motoman K100	$86,980	79%
Auer	Syringe assembly	Adept 550	$60,000	72%
Berzsenyi	Soldering	Unix-531E III	$36,000	63%
Cao	Sink polishing	Motoman SK45	$75,000	62%
Chempananical	Engine block loading	Fanuc M-710I	$93,000	28%
Deters	Spot welding	Motoman K3	$52,000	142%
Kola	Machine loading	Motoman SK120	$90,000	38%
Narayanasamy	Machine loading	Fanuc M-6I	$80,000	52%
Paramatmuni	Spray painting	Fanuc P200 Fanuc ArcMate	$120,000 $70,000	263%
Ramamurthy	Press loading and unloading	Seiko RT3300	$16,000	81%
Ramanathan	Spot welding	Fanuc S420	$76,000	65%
Sun	Inspection	Fanuc M710I	$83,000	285%
Trinter	Jet engine core inspection	KSI Tentacle Arm	$30,000	44%
		AVERAGE	$69,141	98%

Table 3. Feasibility study results for 1997

Only the robot cost is shown in the tables; however, the total costs are tabulated in the studies. The internal rate of return shown in the table is therefore an unaudited number since these are only feasibility studies. The internal rate of return may be interpreted as the return on the investment in automation. The reciprocal of the internal rate of return is the payback period or the time in which the investment will be recovered. After the payback period the automation equipment is producing wealth. Interestingly, in almost all industrial applications with sufficient production, a robot installation is nearly always feasible. The question is whether the rate of return is sufficient. An internal rate of return of 50% or a payback period of two years is often suggested for industrial applications. This is not the case for all robotic applications. For example, robots in most space, undersea, environmental, defense and service applications are not yet proven technology and cannot be easily cost justified using the internal rate of return concept. This is not to say these are poor investments, but rather like education and research, vitally important activities that will pay off in a longer term.

MORE NUMEROUS

The growth of the robotics field in the U.S. is indicated in several ways. In 1982 the RIA indicated that 6300 industrial robots were in use in the United States with 2453 used for welding, 1060 for machine loading and unloading, 875 in casting, 1300 in material handling, 490 in painting and finishing, and the remaining 122 for assembly and other areas. According to the RIA more than 80,000 robots were at work in U.S. factories[3] in 1997.

The number of robots in use tells one important part of the story; however, another important aspect for the U.S. is the technology base of trained engineers and technicians who are familiar with industrial robots. A search of the World Wide Web resulted in more than 3,500 robotics references. The number of people is increasing who have interests and training in the cross disciplines of mechanical, electrical, computer and industrial engineering, "mechatronics." These manufacturing engineers and technicians no longer look at a task or a machine and see only the operating machine but also appreciate that the concurrence of all components and the consensus of all the humans involved are required for a successful product. Whether this concept is called total quality, consensus management, or customer awareness, it has been an important lesson to learn.

STILL BEHIND JAPAN

Even though the US market is healthy and growing, there is the fact that the US is still significantly behind Japan in the use of industrial robots, automated guided vehicles and mechatronics. The Mazak Corporation is a good example of a worldwide leader in advanced manufacturing technology. The company president, Teruyuki Yamazaki has stated[15] "The greatest secret in promoting marketing activities efficiently is to get a grasp of exactly what the market requires and to develop and offer to the market those products which will sell even when there is a recession." Robots can play a significant role in improving productivity, quality, and flexibility and time to market. The 1998 RIA estimate was that the Japanese had more robots in use than the entire rest of the world put together[3].

6. CONCLUSIONS and RECOMMENDATIONS

Intelligent robots for industry make sense technically, economically and socially. Robotic devices that increase the level of flexibility of industrial automation can directly lead to improved productivity. The feasibility of a successful implementation is high. Also, such automation is a good investment. Repetitive jobs which a robot can do, such as applying sealant to rear windows of an automobile at the rate of a million per year, or stacking boxes at the rate of 360 per hour, are unfit for humans. Repetitive motions by humans lead to cumulative trauma disorders.

It appears that most advances in intelligent robots have been "bottom up" applied research. One application at a time is being solved. Furthermore, this advance is being funded directly by industry. The limitation of this bottom up approach is that only low risk technology will be developed. If industry limits research to current products, where will new products come from?

There is also a need for "top down", high risk, research and development. New ideas need to be tried. Theoretical research that can be used by everyone and may never be seen from the bottom up use of existing technology, needs to be funded by the government. A new robot could not or should not be built until the inverse kinematic and dynamic solutions are known. Theoretical advances are needed in intelligent control theory that would at least enable us to say that robots are stable and controllable and safe before millions of these devices are put out in society. Sensor integration can be attempted in a research environment much easier that in an actual application.

Experimental robotic projects need to be encouraged in engineering schools so that our engineering students learn the fundamental principles of mechatronics in school, rather that on the job. Doesn't it make sense for our universities and colleges to have the latest and greatest engineering software and hardware tools so that the graduates can take this knowledge directly to industry?

The intelligent industrial robot is not a panacea; however, the goal of building an intelligent robot is a worthy one and leads to continual improvement. A robotic solution may be the best technically, economically and socially. However, the road from inspiration to successful application is still long and difficult, often taking decades to achieve a new product. Greater understanding of mechatronics is needed. More cooperation between government, industry and universities is needed to speed the development of intelligent robots that will benefit both industry and society.

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