World 2000 ROBOTICS

Statistics, Market Analysis, Forecasts, Case Studies and Profitability of Robot Investment

Co-authored by:
THE INTERNATIONAL FEDERATION OF ROBOTICS

UNITED NATIONS

United Nations
Economic Commission for Europe (UN/ECE)

International Federation of Robotics

World Robotics 2000

UNITED NATIONS
New York and Geneva, 2000

NOTE

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.

World Robotics 2000 is published on the responsibility of the secretariats of ECE and IFR, and the views expressed in it should not be attributed to the Commission or to its member Governments.

Printed at United Nations, Geneva (Switzerland)

UNITED NATIONS PUBLICATION
Sales No. GV.E.00.0.14
ISBN 92-1-101029-2
ISSN 1020-1076

FOREWORD

Since their introduction at the end of the 1960s, industrial robots have undergone an impressive technological evolution. With declining real prices and continuously improved performance, robots are now widespread in industry in many countries while in others the technology is on the verge of being introduced.

Robots have become a symbol and a test of industrial automation in its most advanced form. Together with computerized numerically controlled machine tools, automated guided vehicles and host computers of various kinds, robots form the centrepiece of computer-integrated manufacturing systems.

The introduction of industrial robots is not only motivated by a wish to improve productivity but also to obtain higher and more consistent product quality. Robotics is also an important technology for eliminating workplace hazards, e.g. those related to exposure to heat, gases and chemicals or those where heavy lifting or monotonous work movements are involved.

Total accumulated yearly sales of robots since the beginning of the 1970s amounted at the end of 1999 to over 1.1 million units of which about 743,000 are estimated to be in operational use. Driven by advances in semiconductor and computer technologies and the vast potential for new applications, not only in industry but also in construction and in services (hotels, health care, laboratories, surgery etc), there is every reason to believe that robotics will continue to expand rapidly and play an increasingly important role in production rationalization.

This yearly publication, in addition to summarizing the development of **industrial robots** to date, presents time-series data for the period up to 1999 and inclusive, forecasts for the period 2000-2003 and, for the third year in a row, an analysis of the diffusion of **service robots**. It is a joint effort of the United Nations Economic Commission for Europe (UN/ECE) and the International Federation of Robotics (IFR). The two organizations have enjoyed close and fruitful cooperation in the area of robotics for many years.

Monitoring economic and social trends, developing indicators with a focus on performance and outcomes, supporting business and policy decisions with an infrastructure of good quality information and analysis, are core preoccupations and strategic objectives of the ECE Statistical Division. This Report therefore provides an outstanding illustration of what can be achieved in monitoring industrial development.

For the second time **World Robotics** includes an **editorial**, where a well-known person with a worldwide reputation is invited to give his/her view of the future of robotics. This first editorial was written in ***World Robotics 1999*** by **Mr. Marvin Runyon**, Postmaster General and Chief Executive Officer of the United States Postal Service. In the present issue there are three editorials. The first is prepared by **Mr. Björn Weichbrodt**, International Federation of Robotics (IFR) and the second by **Mr. Rolf Dieter Schraft** and **Mr. Matin Hägele**, Fraunhofer Institute for Manufacturing Engineering and Automation (IPA). The third is written by **Mr. Hadi A. Akeel** and **Mr. Gary J. Rutledge**, both from FANUC Robotics North America.

The present publication and all previous yearbooks on robotics were written by **Mr. Jan Karlsson**, teamleader ECE Statistical Division. He was also responsible for the data processing of the statistical material. **Mr. Giampaolo Mirandola**, who worked as an intern in the ECE Statistical Division, prepared chapter VII. **Ms. Daniela Parisi**, who also worked as an intern in the ECE Statistical Division, prepared several software systems for the processing of the statistical material. **Mr. Yves Clopt**, ECE, designed the cover page and made the photo set-ups. **Ms. Linette Blanchandin**, ECE Statistical Division, assisted in the text processing and the proof reading of the publication.

The valuable assistance given by the seventh ECE/IFR open-ended expert meeting on robotics, held at Comau Robotics, Torino, Italy on 9 June 2000, in reviewing the draft and preparing medium-term forecasts of the robot market, is gratefully acknowledged.

Paolo Garonna
Director
Statistical Division
UN/Economic Commission for Europe

Mike Wilson
Chairman
International Federation of Robotics

EDITORIALS

Industrial Development in Robotics

by

Mr. Björn Weichbrodt, International Federation of Robotics (IFR), Sweden

The commercial development of robotics so far has mainly been in the area of industrial robots. The automotive industry has always been and still is the main user of industrial robots, certainly using more than half of all robots at work today. This development has been both fast and slow.

Fast within the areas of established industrial applications where the number of robots in use has been growing continuously and the technology has been developed for higher precision, higher weight capacity, more programming possibilities, etc.

This development has had its ups and downs but on the average a continuous growth. To take an example, the annual volume of robots sold in Europe has approximately doubled within the last five years. About a million industrial robots have been produced in the world so far, and some 740,000 of those are still in operation.

In terms of new applications and new industrial fields, however, the development over the past years has been quite **slow**. Robots today look pretty similar to the robots of twenty years ago and the main applications in industry are still the same. It has been difficult and slow to develop new concepts. Resources for such new concepts have been limited by the very strong development within the traditional application areas which have always taken priority.

We talk about the robotics industry as maturing. This is quite true today within the commercial industrial applications. It is not true at all in new areas, such as services, where the market is only in its early phase of commercial development.

Based on the situation in this year of 2000, how may the robotics industry develop over the coming years? What will the key applications be in the coming 5-10 years. Right now worldwide robot volume development is quite strong. The first half of 2000 shows 10-15% growth compared to the first half of last year.

Let us look at some industrial and application areas, one by one and see how they may develop:

The **automotive industry** will continue to be the main user of robotics for the predictable future, certainly the coming 5 to 10 years. It will most likely show strong growth for the near future based on the existing application structure. The main robot suppliers to the automotive industries in the future will probably be the leaders of today and the business will continue to mature. There will be mergers and acquisitions among the big players in order to strengthen positions. This will involve both robots and systems. The process is already going on, for example through strong relations between Comau and Pico, ABB and Adept, Fanuc and Comau. The strong players will develop more strength. A question can be how the more local smaller robot suppliers are going to develop in this environment. The automotive industry will require stronger and more accurate robots but not autonomous robots. The price level will continue to go down each year and put strong push on rationalisation on the big robot companies. Automotive will still be the main robot application area in 5 –10 years.

The **general industry** will continue to be the second largest user of industrial robots. These are the industries outside automotive, industries producing construction equipment, glass products, wood products, aircraft, electrical assembly etc. The development in this area is already very strong but the volume is lower than for automotive because the variety of installations is much bigger and therefore systems work is very demanding. Technical development will parallel the automotive industry robots.

The **food processing** industry is now emerging as a potential big user of industrial robots. Several years of market development with low volumes has resulted in the industrial robot industry developing special robot types for the food processing industry. The growth will be quite strong in the coming 5-10 years. It will be limited, not by the over all needs, but by the time required to develop commercial customer supplier relations and the much lower technical level of most personnel in food processing compared to the automotive industry. However, the major industrial robot companies see this as a prime opportunity, because the food processing industry itself is so huge, maybe even bigger than the automotive industry, with thousands of factories around the world with need for packaging, materials handling etc.

New **industrial speciality** areas are many which put special demands on robots. I am thinking of the medical area including surgery, the nuclear area, the mining area and others that put very special demands on robots. The volume is probably not going to be big enough to justify special robot development but there will be special systems development and sensor and software developments. These are very interesting areas which will be growing but on a much lower level than the automotive areas. Here it is a question of not just helping man with certain tasks but to extend man's capabilities beyond what can be done manually. I believe the base for this development will still be the traditional industrial robots and the traditional strong robot companies of today. New speciality companies may arise to develop sensors, software and applications.

The **industrial service area** has been slowly developing for a long time but will probably develop significant volume of the coming 5-10 years. I am thinking for example of floor cleaning in public areas and in our homes, window cleaning, swimming-pool cleaning, control and support for semi automated wheelchairs, or appliances needed for the coming "smart homes". This is an area that will become very interesting although it has not yet developed volume. The most interesting fact will be the emergence of completely new suppliers of robots and related products, beyond the traditional robot makers. Many products in this area will have to be high volume, low-price products, probably manufactured by today's major appliance manufacturers. This area will make it necessary to expand on our definition of industrial robots. Some products are already on the market such as for commercial floor cleaning and lawn mowing, but they do not correspond with today's robot definitions. It will be interesting to see how these areas develop.

The **entertainment industry** will emerge as major area for special robots within the next 5-10 years. We can already see toy products of robot types for entertainment for sale mostly in Japan. This area seems to be developing very fast. But there are not only toy products but also potential humanoid robots of many kinds for direct entertainment, for use as guides in museums and other areas etc. This quite new area is also interesting because it is going to engage entirely new companies for robotics. Candidates can be major electronics companies. This will also require extension of the definition of robots in directions that we do not yet know. But this area will grow fast. Some products are already sold in volumes. The entertainment area has big financial resources. It will be a main area for papers and discussions at the ISR 2001 symposium in Korea next year.

Personal service robots represent an area that is talked about a lot, researched a lot, but there are few commercial products available yet. The major robot producing companies of today are not very interested in investing R & D money at this stage but may serve as partners in guiding technical development at Universities and Institutes. The concept of the personal service robot that can be of real help to handicapped people in their homes is very intriguing and the market would be very big for a usable commercial product. This will require substantially more autonomous functions and a robot that could work without engineering knowledge of the part of the user. It is impossible to say how fast the commercial development will be but I believe that we will see practically used products in small volume in the coming 5-10 years. A real challenge for the robotics industry with high risks and potential big rewards.

Let us try to sum up the market development, with this mixture of different robot types and application areas, with radically different maturity. I believe with all factors considered that there will be a continued strong commercial and technical development of robotics in the coming 5-10 years. The commercial development will still be based on today's concepts for the automotive or general industries where there is still substantial room for more growth. The price of robots is going down all the time while the price for manual labour increases, which will make robotics solutions more competitive, and thereby stimulate further growth. Most of this growth will be in the already established robot application areas.

***

From ServiceRobots to Robotic Assistants

by

Mr. Rolf Dieter Schraft and Mr. Martin Hägele, Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Germany

A broad spectrum of service job opportunities herald a robotics renaissance: ServiceRobots. Examples of diverse application fields are cleaning, inspection, disaster-control, waste sorting, transportation of goods in offices or hospitals and even automated refuelling of automobiles.

ServiceRobots stand for innovative products in growing markets. Robot manufacturers are beginning to enter these markets of the future by launching innovative products, which reach into new technological and application areas.

Furthermore, smart products are about to enter our daily life such as autonomous vacuum cleaners or lawn mowers, automatic golf caddies or tennis ball collectors. Even though these products may not be always in accordance to the given robot definition they draw their automation functionalities to a large extent from robot technology. The prospect of conquering new markets by intelligent and therefore attractive products has spawned numerous research and development efforts by manufacturers of customer goods, household appliance and leisure products.

What are the prospects of future robot technology and application?

Robotics and automation in general are increasingly subjected to technical developments stemming from large volume markets as figure 1 indicates. Large production quantities, which are typical for "infotainment" (informatics + entertainment), automotive and other consumer-product industries, justify the development of cheap but high performance hardware (sensors, controls, interfaces) and software as key components of intelligent products. On the other hand, robotics and automation are conquering new fields of application outside the classical shop floor where prominent examples are robots for construction, surgery and even rehabilitation, see figure 2.

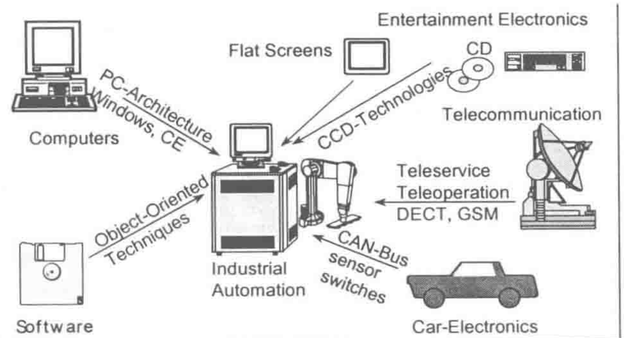


Fig.1: Migration of technologies into robotics and automation from large volume markets

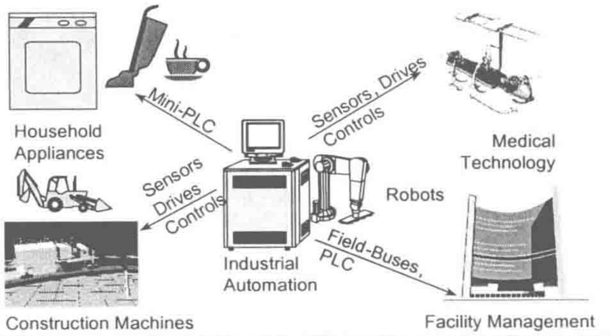


Fig. 2: Migration of robotics and automation technology from manufacturing to new application areas

The robot technology has to be seen in the more general context of mechatronics, which stands for embedding manipulation, mobility, sensing, control and cognition on a system level. The evolution of robotics will be represented by the level of machine intelligence, which can be generally expressed by:

- Autonomous behavior: automated task execution independent of other systems and outside help
- Decision making: reasoning and choice among variants of actions
- Machine learning: use of previous experience as a basis for making decisions.

Robots find their limitations if the task execution requires a level of perception, dexterity and decision making which cannot be technically realized in a cost effective or a robust way. However, within the otherwise manual task execution less demanding subtasks may still be carried out automatically. The safe and flexible cooperation between robot and operator should cover all levels from fully automatic to human assisted task execution. Robot assistants can be thought to be clever helpers in manufacturing environments (manufacturing assistant) as well as in homes (home and care assistant). Scenarios of their use will be given in the following:

Manufacturing Assistant

In future manufacturing scenarios robotic assistants will cooperate with the worker at handling, transporting or assembling tasks. A typical task would be the grasping of unsorted work pieces, assembly, the transport of work pieces or tools to a machine or cooperatively handling heavy or bulky objects. The manufacturing assistant can be mobile or fixed depending on the workspace to be covered, see figure 3.

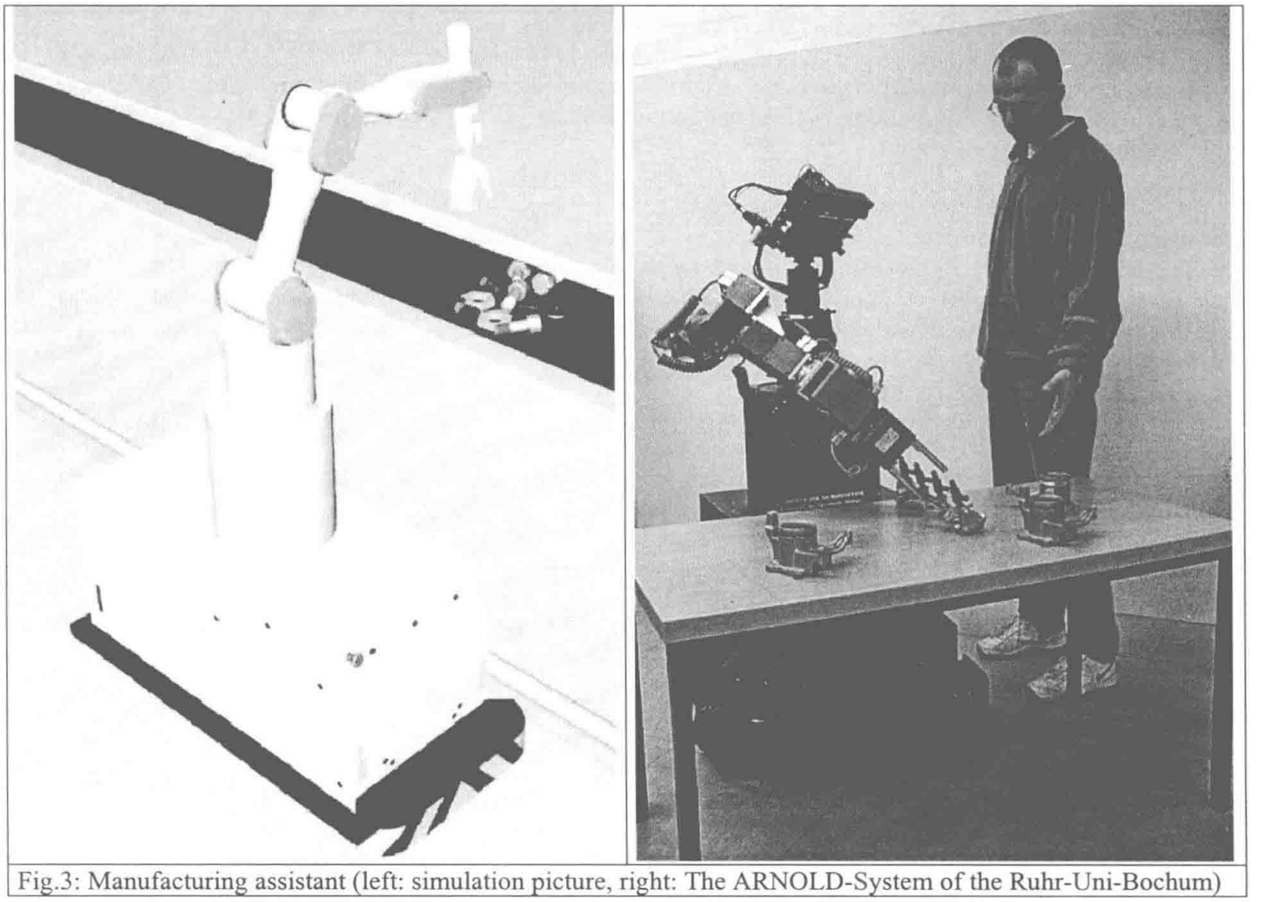


Fig.3: Manufacturing assistant (left: simulation picture, right: The ARNOLD-System of the Ruhr-Uni-Bochum)

Home and Care Assistant

A bright future of robotic assistants in natural living environments is predicted. These systems should help the elderly or the handicapped user to master his or her life without fully depending on outside help, see figure 4. Also, such a home assistant may be a luxury product relieving its owner from tiresome household work. A home and care assistant should be able to execute typical tasks such as:

- Fetch and carry selected objects
- Support in grasping, lifting and holding of objects
- Guide and support the mobility impaired user when getting up from bed or walking to the bathroom
- Give access to "infotainment" or household systems.

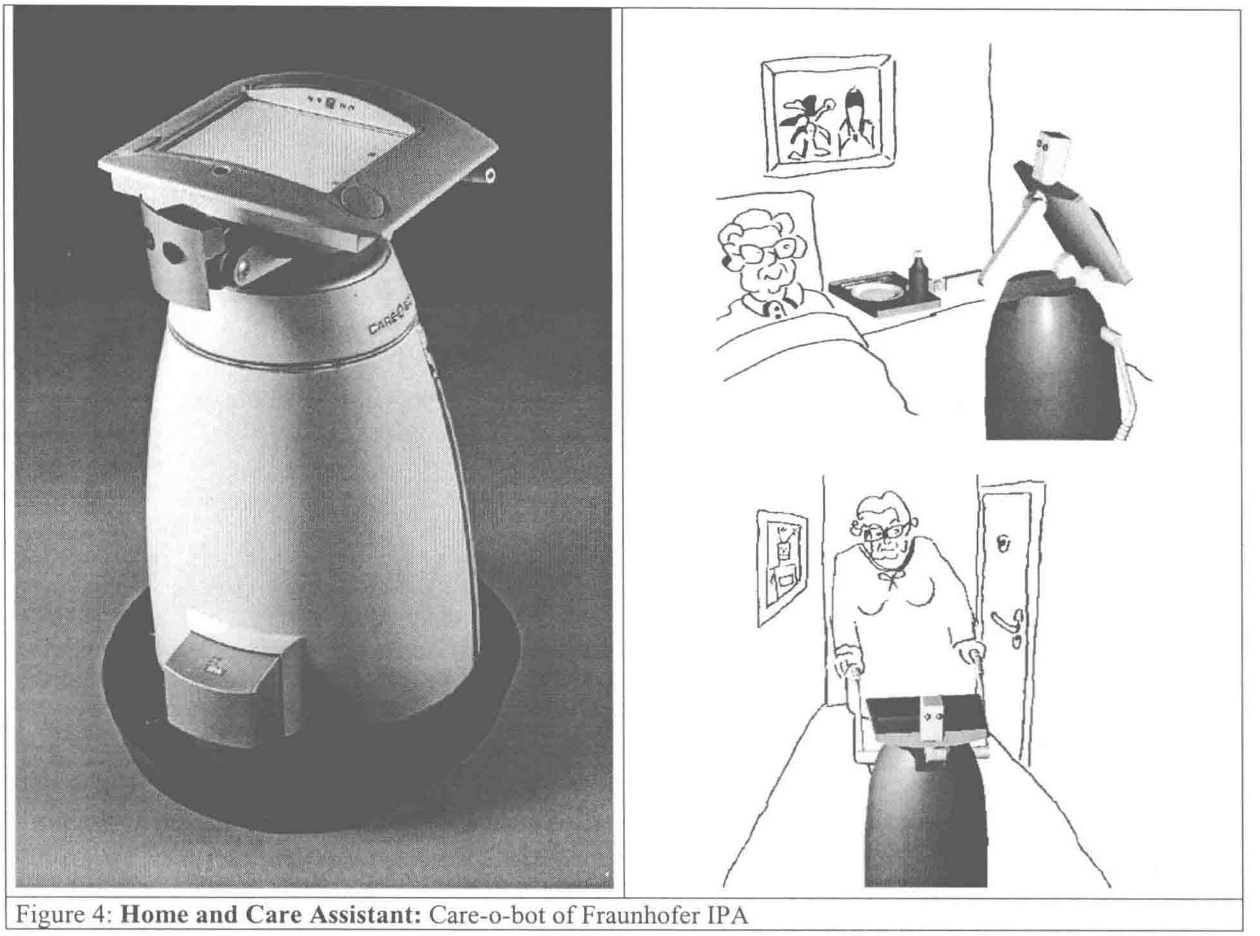


Figure 4: **Home and Care Assistant:** Care-o-bot of Fraunhofer IPA

In order for such systems to be used safely and intuitively, both types of assisting systems should possess similar key functions:

- *Intuitive channels of man-machine-communication.* User and machine should cooperate and safely interact even in complex situations. This implies that the assistant understands the user intent through natural speech, tactile or graphical interfaces.
- *Scene analysis and interpretation.* Effective co-operation depends on the recognition and perception of natural environments as well as on the understanding of tasks in their contexts.
- *Motion planning and coordination.* Human-machine motions have to be planned and quickly coordinated. For motions without physical user contact skills, such as avoiding obstacles, approaching a human, presenting objects etc., have to be performed. In the more difficult case of physical contact with the user, typical skills would comprise compliant motion, anthropomorphic grasping and manipulation by the assistive system.

These key technologies are current research topics at prominent universities, companies and research organizations. It is expected that first manufacturing assistants may appear within the next five years, the home and care assistants between 5 to 10 years.

Fraunhofer IPA intensely conducts research in the described key technologies and has committed itself to the development and application of robotic assistants. For further information please refer to http:\\www.morpha.de.

***

Technological Enhancements and Their Effect on Price/Performance Indicators of Industrial Robots

by

Mr. Hadi A. Akeel, Ph.D., Senior Vice President and Chief Engineer (retired), FANUC Robotics NA Inc. and Technical Adviser, FANUC Ltd, Japan;

and

Mr. Gary J. Rutledge, Vice President, Product Development, FANUC Robotics NA Inc.

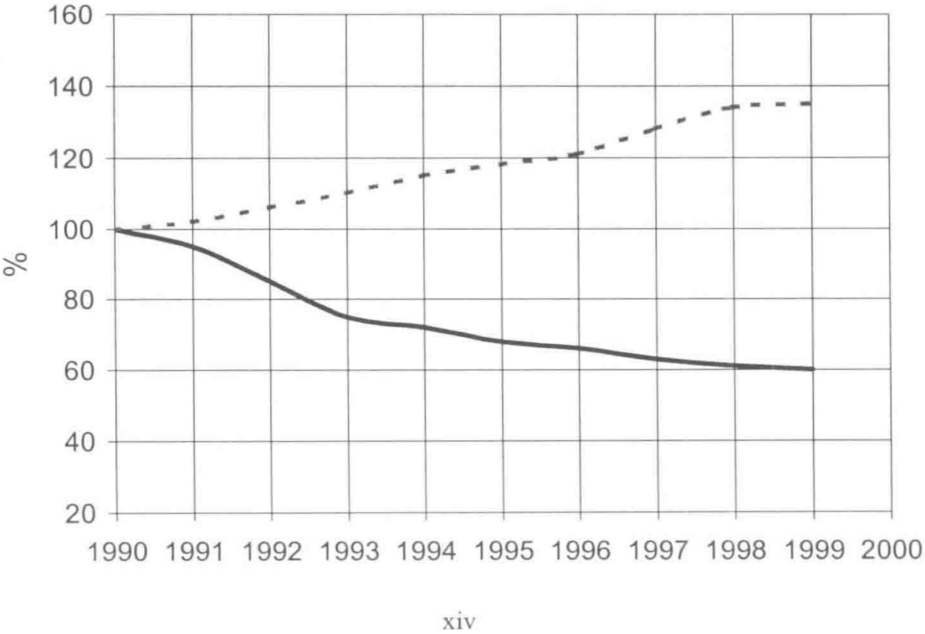
Introduction

The industrial Robot has experienced a remarkable history of effectiveness in shaping a new era of economic and higher quality manufacturing. While the cost of Industrial Robots has continued to decline, their performance, flexibility, and reliability have advanced with great strides. The control systems of robots have perhaps seen the most advances as the capabilities of the new generations of microprocessors were exploited to add new functionalities and enhance existing ones. New manufacturing methods in the electronics industry have carried through to robotics to also reduce the cost and size of the electronic control systems. This article reviews the performance and user options improvements realized over the last decade as the cost of applying Industrial Robots diminished.

Statistical Information

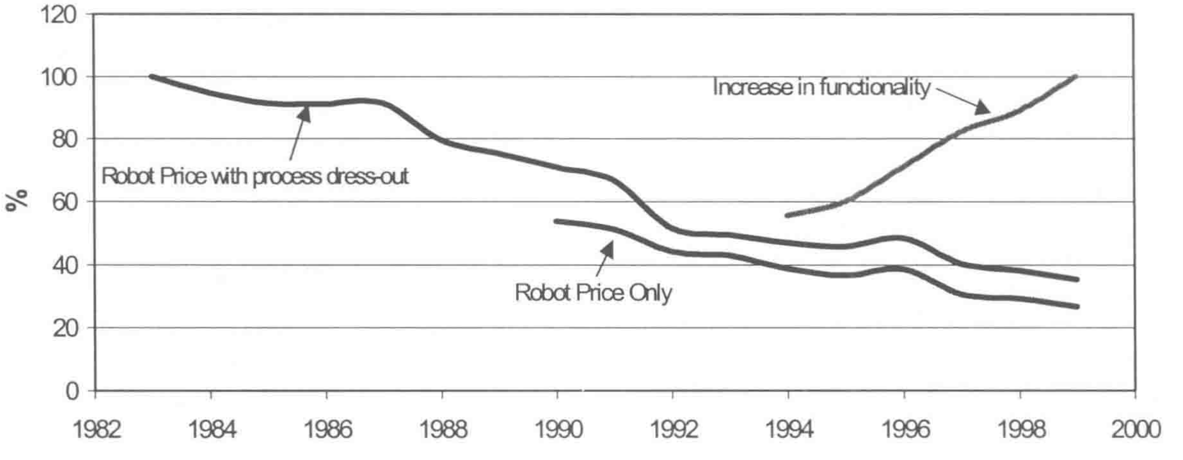
The International Federation of Robotics, IFR, collects and publishes annual reports on robot populations and price trends. The following chart, quoted from the March 27, 1999 Newsletter of IFR shows the robot price trend, as well as US labor cost trends from 1990 through 1999. The chart shows that the average price of industrial robots has been reduced by 40% over the decade while the labor cost has increased by almost the same percentage.

Figure 1. Labor Cost Versus Robot Prices



The trend is even more dramatic when the price of robots applied in some of the more dominant manufacturing processes are examined. The following Chart shows the price trend reduction of robots applied specifically for spot welding and arc welding processes.

Figure 2. Price and functionality Trends of Spot Welding Robots



The increase in functionality of figure 2 is the value of hardware and software peripherals included in the base price of the robot as a percent of those included in 1999. Added functionality increased almost two folds since 1994. The data is only available for the last 5 years but are indicative of the trend.

This dramatic decrease in the price of the dominant process robot vividly illustrates how robots have established themselves as effective productivity tools in the manufacturing industry. It also confirms how the robotics industry has grown to become most supportive of manufacturing especially in the arena of heavy industries such as automotive. The reduction in robot prices has fueled unprecedented demand for industrial robots, that the year 2000 promises to set new records for growth rate and sales at least in the US market.

Unaccounted for in the price trends are functional improvements that make the price reduction even more dramatic such as:

- The robot payload range for a typical Spot welding robot increased from 80 - 100Kg in 1990 to 120 – 150 Kg in 1999
- An increase in the robot welding productivity in spots/minute
- An increase in robot accuracy and repeatability for positioning and continuous motion
- The integration of much of the process control functions into the robot controller
- The integration of peripheral equipment, such as collision protection, originally purchased separately, into the robot's base price
- The enhanced safety of the robot operation
- The simplification of the robot programming methods.

[If such functional improvements were priced separately and assumed not to have declined in price, it's almost as if the robot has become free and the user is now paying only for control functions!]

Such cost reduction has been realized despite the increase in the cost of manufacturing in general as depicted by the increase in the cost of labor. With the increase in the consumer price index over the last decade, the effective price reduction over the last decade is appreciably more than 40%

To underscore the magnitude of the developments in robot cost effectiveness, it's worthwhile to review some of the performance enhancements of robots that occurred concurrently with their impressive price reduction. Enhancements have been realized in the mechanics, controls, performance functionality and the expansion of the robot application domain. The following discussion highlights some of those developments.

Mechanical Enhancements

a. <u>New Mechanism Configurations</u>: The last decade has witnessed the introduction and application of new types of mechanism. In addition to the traditional articulated, cartesian, spherical, and cylindrical types, the industry introduced the pendulum and parallel link mechanisms. Those new mechanisms supported specific applications that benefited from unique characteristics such as added reach or inherent speed or rigidity.

Figure 3. Parallel Mechanism Robot in Automotive Assembly

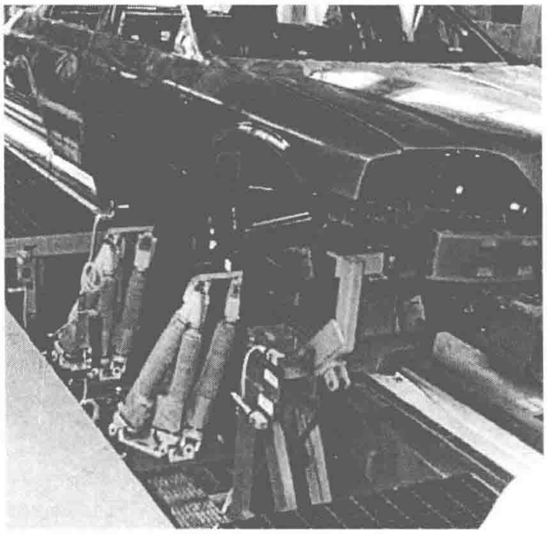
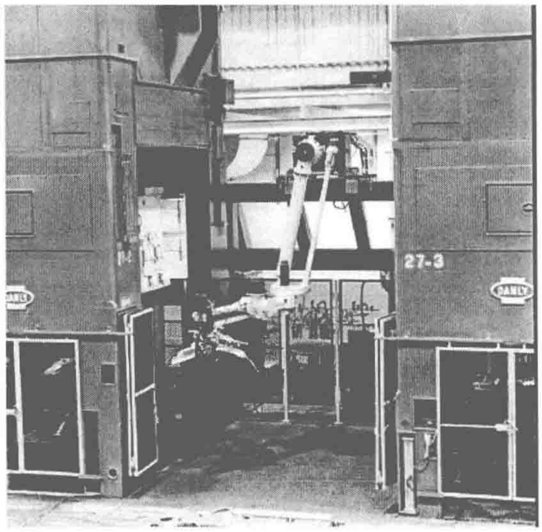


Figure 4. Pendulum Robot in Press-to-Press Transfer Operation



b. <u>Clean-room robot mechanisms</u>: Perhaps a more impressive evolution for robot mechanisms is what's being witnessed in the clean room applications of robots. Though, traditionally equipped with one or two programmable axes and not classified as robots, clean-room robots have evolved to require more than two programmable joints and are poised to make an impact on the expanded domain of industrial robots. While clean room robots are generally of the cylindrical type, some have more than one arm and are fitted with application specific end-effectors not usually encountered in traditional industrial robot applications. The stringent cleanliness requirements of those robots, some now applied in class I clean room environments, poses special challenges in the choice and design of their mechanisms and link joints for minimum contamination of their work environment.

<u>Component Modularity</u>: In the conquest to reduce manufacturing cost, robot manufacturers have resorted to modularity of components and to the sharing of components between different robot models. The supplier industry also contributed to the cost reduction and the added reliability by integrating some of the drive trains and enhancing their reliability. For example, the speed reducers have been improved drastically over the last decades. The Speed reducer module, such as Harmonic reducers and Cycloid reducers now integrate the bearings required for robot joints. The synergy between the speed reducer and the bearings is substantial resulting in enhanced economies of scale and benefiting from common manufacturing expertise.

Process Equipment Integration:

a. <u>Hollow Wrist Applications</u>: Traditionally, hollow wrists have supported paint robots where the need for internally routed process service lines is critical to the cleanliness of automotive painting. However, lately, other maintenance intensive process robots such as spot welding appear to benefit from the protection the hollow wrist provides for the process cables and hoses. Hollow wrists appear poised to expand their application domain.

b. <u>Process Functionality</u>: as late as the early nineties, the robot controller could only address the motion and programming of the robot proper. With the added capabilities of microprocessors, robot controllers can now handle a multitude of additional functions. The process control such as paint color changers, weld schedule control, robot guidance, palletizing routines, etc. had required their own independent controllers. The new generations of controllers have claimed these functions to their own resulting in appreciable savings to the users and corresponding reduction in robot unit prices with enhanced capabilities.

Performance Enhancements

The industrial robot also experienced appreciable improvements in performance, thanks to the added processing power of the robot controller and the advancements realized in motion control algorithms and structural analysis and mechanical design. Such improvements are reflected in the following critical performance parameters:

a. **Speed**: Robot processing speeds for coordinated motion has almost doubled from a typical speed of 750mm/s in 1990 to greater than 1500 mm/s in 2000.

b. **Repeatability**: The most repeatable robots in 1990 attained a repeatability of slightly better than 0.5 mm; in 2000 repeatability of better than 0.1 mm is common place even for robots with appreciable payload.

c. **Payload**: in 1990, the largest industrial robot payload, for volume manufacturing, barely attained 150 Kg.; in 2000 robots with payloads exceeding 300 Kg are common in the automotive and other heavy industries.

d. **Accuracy**: in 1990 accuracy was a wishful concern of users and an expensive dream for manufacturers. The technology was not supportive of an approach for attaining reasonable accuracy at affordable cost. With powerful controllers, improved simulation algorithms, and better mechanical design and manufacturing approach, it's possible to rely on robot accuracy for simulation of robot motion and off-line programming. Appreciable economies are now attained through the reduction of the time and labor for programming verification.

e. **Safety**: An always-critical factor in the manufacturing environment, safety of robots has been appreciably enhanced. While humans will continue to be protected by safety barriers and other safeguards, robot controllers enhanced the reliability of the robot to a high degree with a corresponding reduction in the probability of failures. Risk analysis, necessary to decide on the degree of added safeguards, can now rely on a higher degree of robot reliability and a corresponding reduction in the intensity of safeguards, hence reduced cost of safety provisions.

f. **Expansion of the Robot Domain**: In contrast to the single robot of the early 1990's, later robot models have encompassed many of the following added capabilities

1. Cell controls, formerly requiring dedicated programmable controllers
2. Process controls, formerly requiring dedicated process controllers
3. Peripheral equipment controls such as transport axes, servo-controlled grippers, color changers for painting, palletizing equipment, environmental controls of temperature, pressure, humidity, etc. can now be controlled from the robot controller.
4. Vision guidance systems, formerly requiring dedicated high power controllers

g. **Reliability**: While robots have over the years demonstrated a high level of reliability, the manufacturing world was truly amazed at how high such reliability has proven to be. The target life for industrial robots acquired by the dominant user, the automotive industry, was 5 years or 10,000 hrs in the early nineties; it's not unusual now to see users demanding reliabilities twice as high now. Though is impressive, this has been enhanced by additional improvements in the Mean Time to Repair, MTTR, including time to troubleshoot failures causes, replace components, or replace robots or controllers. Interchangeability between robots has also been greatly enhanced where replacement robots could be brought into action, with the replaced robot programs, in record time. Contributing to the enhanced reliability is a marked improvement in the industrial robot controllers Mean Time Between Failure, MTBF, parameter exceeding 50,000 hours for reputable brands. This means that the user, with proper and normal practice, can almost install the robot and not be concerned about its controller's failure for longer than the useful life of most other production equipment.

Controller Enhancements

Many of the performance enhancements mentioned can be attributed to the evolution of the robot controller. As the desktop industry has spurred development of microprocessors and integrated circuits, the robot controller has reaped the benefits.

The future of the microprocessor can be readily forecast from the "Overall Roadmap Technology Characteristics" as published by the Semiconductor Industry Association, SIA, www.semichips.org. This publication has consistently forecast the evolution of the microchip industry described by several parameters such as, transistor density, feature size, power consumption, cost etc. Table 1 shows the performance forecast of the microprocessor and DRAM memory technology for the next 14 years with tremendous promise for added power and speed for future robot controllers. The robot controller, being an industrial device and by necessity must remain stable over several years, usually lags microprocessor evolution. The forecast is therefore an indication of the future beyond the next 14 years.

Table 1 – Microprocessor Technology Advances, Representative Parameters

Year Technology Node	1999	2000	2001	2002	2003	2004	2005	2008	2011	2014
DRAM ½ Pitch, nm	180	165	150	130	120	110	100	70	50	35
Mega Transistors/cm2 At introduction	7	-----	14	-----	26	-----	47	115	284	701
Number of Package Pins Microprocessor/controller	700	-----	-----	957	-----	-----	1309	1791	2449	3350
Package Cost '/pin	0.78 – 2.71	0.78 – 2.71	-----	0.6 – 2.16	-----	-----	0.51 – .85	0.44 – .59	0.38 – 1.36	0.33 – 1.17
On-Chip Frequency, Local Clock, MHz	1250	-----	-----	2100	-----	-----	3500	6000	10000	16903
Memory generation @ production ramp (bits)	256M			1G			4G	16G	64G	256G

Computational capacity as used in robot controllers has increased 200 fold since the early 90's. This yields improved performance in two ways. First, motion throughput measures how many points the controller can process per second. This means that the robot can put more points around a curve and make a more accurate approximation with its path.

The second is algorithm complexity. With additional computational time between points, the controller can look ahead and see what's coming in the path and calculate the optimum actions to take to maximize performance while coordinating motion with other joints and other kinematic motion groups while compensating for gravity, component bend and manufacturing errors.

The Motorola 68000 processor family which was popular for robot applications in the early 90's had about 68000 transistors and required several boards to carry the components for directing a robot. A modern controller now sports a processor with 23 times the transistors in 12% of the volume. Where the robot controller was a cabinet the size of the robot, we now frequently see a small box attached to the rear of the robot for control.

The early 90's marked the peak of the programming language era for robots - Karel, Val, and Arla are the names of computer like programming languages that were adapted for writing the complex programs that made robot systems work. These languages have yielded sophisticated software packages that contain process knowledge and allow the user the ability to talk about his application in process terms to a controller that already knows quite a bit about what needs to be done.

The tremendous advances in graphics and display systems have also impacted user communication. The early 90's robot was programmed with a 4 line by 40-character LED display that transmitted all available information. Interaction with other plant computer systems was linked to a 9600-baud serial line. Today's controller has integral 10/100 megabit Ethernet and a web server so that the plant engineer can, from his desk, manipulate graphic icons relating to robot functions delivered over the plant network.

Perhaps the most striking and valuable contribution of the evolution of the robot controller is the consolidation of cell functions into the robot's domain. In the early 90's, between 50 and 60% of the engineering time associated with making a robot cell work was involved in managing the interfaces between the various pieces of control equipment that composed a cell. The robot, the PLC for I/O control, the vision system, the process loop controllers, and communications gateways all had unique interface and programming requirements. With the reduction in size of computational components, a modern robot controller is composed of a network of internal processors that manage all these functions and connect them together seamlessly in a single programming and debug environment.

In the early 90's, the time to implement a robotic system was dominated by the set-up and programming time. Robot simulation was in its infancy and while it was possible to create impressive graphic simulations of what the robots might look like in production, the actual paths of the robots differed significantly from what was predicted. Today most major manufacturers have the heart of their robot control system embedded in a module that connects to a modern simulation system and allows the prediction of the robot's path with an accuracy of within less than 2%.

As we look to the next 10 years of robot controllers we can expect to see another 200x increase in computational capacity. This will have a number of interesting impacts. Current robots can control effectively a couple of kinematic motion groups, such as two robots, as long as the interaction between the groups is low. With the additional computational capacity, the number of controlled axis, with interactions could begin to approximate the functionality of the human arm. The combination of cheap storage and faster processing will lead to larger and larger bodies of knowledge being carried on board the robot controller. Improvements in programming architecture will permit programs from different sources to cooperate in real-time systems in a safe and reliable manner. These features combined will lead to acceleration in the performance improvement curve for robots.

What the Future Holds

The impressive revolution of the microprocessor has cascaded into multitudes of products, technologies and processes dependent on it's technology. The robot, with its dependence on the power, speed and efficiency of the microprocessor stands to gain considerably. The Improved processing power, cheap high capacity memory, enhanced processor speed and the availability of peripheral supportive and modular software should help propel the industrial robot into new orbits of efficiency and effectiveness. Several performance arenas are not yet exploited effectively by the industrial robot because of the economic limitations of current processors. With the trend in cost reduction of powerful processors, those arenas will be conquered and the domain of the robot will grow. Following are some such possibilities.

1. **Sensors and Robot Intelligence**: Most promising for robot evolution is the possible enhancements in robot intelligence. The relative high cost of sensors' hardware and the cost of their integration into the robot controller have impeded developments here. The evolution of micro machining technologies such as Micro Electro-Mechanical Systems, MEMS, technology, promises to mass-produce effective and reliable sensors at low enough cost to support mass utilization of sensors in robot controllers. With the added processing power now available and forecast for the controller, multiple sensor outputs will be utilized to make the robot cognizant of its environment. Such capability allows the robot to respond to changes in the environment without operator interference, a level of intelligence highly desirable in the manufacturing environment. Furthermore, the ability of the robot to learn from its experience will be possible as learning programs will then be developed to take advantage of the available sensors' data. Programming by example will be possible not just for path programming but for other program functions such as peripheral equipment operation, input/output commands, alarm, safety response functions, etc.

2. **Mobility**: The enhanced intelligence and availability of sensors should also allow the robot to escape the confines of component accuracy and structured operating environment. Roaming robots could be common in the factory with an ability to accurately locate their position on the floor. Robots will not necessarily have to be attached to the machines they support.

3. **Trend to lower manufacturing cost**. Sensors' impact on the future of robots with the added intelligence should extend to their manufacturing cost as well as performance and versatility. With end of arm sensors the need for highly accurate structural and joint components in the robot should progressively diminish.

Lower accuracy machining should be possible, without sacrifice in reliability or performance. Sensing its target, the robot should be able to position itself accurately without taking its reference from an accurate platform as is currently required without sensors. Lower accuracy machining should allow the use of low cost materials and machine tools with corresponding reduction in the robot manufacturing cost.

4. **The vanishing Controller**. The trend to more compact and powerful electronics should eventually lead to their integration into the mechanical and structural components of the robot such that a separate controller cabinet would no longer be required.

5. **Enhanced Safety**. Sensors should also develop to allow the robot to operate at a higher level of safety with the ultimate goal of eliminating the need for costly and space hungry safeguards. With appropriate risk assessment the robot operation should prove reliable enough to sense intruders and revert to a safe state. Software reliability should be proven high enough to allow software interlocks to replace costly and failure prone and redundant hardware. The robot could become intrinsically safe and appreciable cost savings would then be realized.

6. **Voice commands for programming**. Although graphical means for generating robot path programs have proven most effective, they still require a high level of operator proficiency. Future robots should develop to become more user friendly and responsive tot he commands of less proficient operators. Voice command programming should lead to more user-friendly robots than is currently recognized.

Summary and Conclusions:

The trend towards enhanced performance and cost effectiveness of industrial robots has been an impressive accomplishment for the robot industry. This trend has realized orders of magnitude in performance improvement and corresponding reduction in cost despite the increase in the cost of manufacturing. The future promises to be a continuation of the past and present with promises for additional orders of magnitude of performance improvements, with some additional cost reduction, enhanced safety and user friendliness.

References:

1. IFR News Letter, March 27, 1999; International Federation of Robotics
2. Semiconductor Industries Association, SIA, The International Technology Roadmap for Semiconductors, 1999
3. Hadi Akeel, Robotic Technology for the 21st Century, 30th ISR Conference, 1999, Tokyo, Japan

***

CONTENTS