Robotica (1998) volume 16, pp. 371–379. Printed in the United Kingdom © 1998 Cambridge University Press

Reports and surveys

ROBOTICS AND AUTOMATION WORLDWIDE

1. Australia

Robot Etherbot. At Monash University researchers report the development of a portable mobile robot system called 'Etherbot'. It carries no computer aboard but instead, the calculations required to determine the robot's location and the shortest obstacle-free path to a desired destination are carried on a nearby workstation. This is a Silicon Graphics workstation with which the robot communicates via a 2Mb radio Ethernet link. This reduces the payload and increases the time that the robot can travel before its batteries need recharging.

The prototype Etherbot travels at a speed of 200 mm/s inside a building; it utilises previously placed passive bar-code beacons to determine its whereabouts and an on-board range finder to map its environment. The project was described in a paper presented by Professor Ray Jarvis to the International Symposium on Experimental Robotics in Barcelona, Spain last year. Professor Jarvis said that Etherbots could be constructed at comparatively low cost and used to deliver internal office mail or to transport elderly or infirm people in a nursing home.

Robots to clear landmines. There has been much discussion worldwide about the safest and most efficient ways of clearing landmines. Recently, researchers world-wide have been developing suitable methods. The use of robots in such hazardous situations is already well appreciated. At the University of Western Australia, Professor John Trevelyan has shown much interst in the potential applications of robots for landmine clearance. He has recently discussed the issues in an article published in the *Industrial Robot* (**24**, No. 2, 114–125, 1997). It would appear that although this task is very dangerous for people to carry out, current limits and costs of robot technology appear to rule out robotic landmine clearance in the short term. It is believed, however, that a study of the ways that robots could assist has led to the development of non-robotic tools at the University of Western Australia. They are very likely to help human landmine clearance operators by reducing their effort and increasing their safety.

High-school competition for robots in a maze. A national competition for high-school students entitled 'The Great Bilby Race' is being developed by Professor John Billingsley of the University of Southern Queensland. In the competition each team will design a robot to traverse a maze. A grant of some A$ 10,000 from the Australian Department of Industry, Science and Tourism has been made available to support the endeavour.

2. Germany

New technology will change the way in which individuals can identify themselves. Advances in security chip technology means that systems can be produced which are capable, even remotely, of ensuring the identity of the individual who is requiring access to any secured domain whether it be a hotel room lock or a computer system. It will enable the ultimate smartcard to be produced and may solve the challenge of ensuring legitimate entry to secure computer systems and to certain areas of store, say the files on a hard disk. High amongst the potential applications of such a system is that it would enable the users of the Internet to verify transactions.

The Siemens security system, it is claimed, may well allow this verification. It is based on the fingerprint. Developments of fingerprint-systems are not new, but efficient accurate systems that give a 100% security are not easy to come by, as many potential developers have found.

This system is well advanced in its trials and will be incorporated in a Smartcard that will be available in the Autumn of 1998. The card will be similar to the standard credit card but will have a sensor about the size of a postage stamp built into it. This sensor will incorporate 65,000 points — the pixels of the image to be stored, which will model a fingerprint as they are depressed by a user's touch. The system requires the user on receipt of the card to touch the sensor which will then read the pattern of the finger and store the fingerprint for future use. Whenever the card is then subsequently used a reader containing the designed software will check its database to compare and decide if the current user is, indeed, the valid owner of the card.

The new Siemens system contains software which the company say uses the same principles as those used in police fingerprinting recognition systems. This involves a process where rather than model every line on the fingertip pattern the computer program searches for places where they begin and end. These points are called *munitial* points

https://doi.org/10.1017/S0263574798000836 Published online by Cambridge University Press

and they are used worldwide as the basis for the storage and identification of fingerprints. In this system, it is claimed, that as long as 12 of these points can be read the program is able to identify a fingerprint.

Whilst searching for a better way of identifying an individual it is always recognised that whatever system is produced by a human it is also likely to be defeated by a human. Many security systems installed at great cost in computer systems have been broken by hackers.

In the case of security systems everyone has been looking for a better way of verifying the identity of the user. No body can mimic, the company say, a fingerprint, and you always carry your finger prints around with you. It means that you do not have to memorise a security code, password, pocket a key, or remember your mother's maiden name — a favourite with so many credit card companies. Hence the great advantage of the fingerprint as a means of convenient identification. Advances in computer technology have provided the means of ensuring accurate and efficient verification. The company Siemens were then faced with defeating the fraudster who already costs the credit card companies millions of pounds each year. The most obvious fraud would involve the use of a finger which was not alive. To defeat this the card currently produced has a heat sensor that detects if the finger being scanned is alive. Unfortunately, a spokesman from the Siemens Security Chip Division, Munich, Germany, admits that at present the current prototype system can be fooled in the first hour after amputation. The developers say, however, that they are working on technology that will check for blood flow through the finger and also to see if the skin is responding in the same way as it would if it were alive. The aim the company says is to make sure the smartcard is smart and impossible to trick. So far the fraudster has found a way and during the coming year we will have the opportunity of monitoring the success of the new ID card.

Although the Smartcard is the most obvious application for this technology there are other systems being developed including the 'retina identification', image/photographic recognition, voice recognition, etc., which may become more suitable for some applications. Currently, there are plans, however, to produce computers that incorporate this technology. This would allow users to identify themselves quite easily to computing sytems and could be extended to allow verification in a variety of electronic transmission applications. The Internet has already been cited by the developing company, and any method of verifying Internet transactions would be particularly welcomed.

Its use in security applications to replace keys and passwords is inevitable, and its use wil replace a number of conventional security systems. Applications in the automobile industry where car keys would be dispensed with, are but obvious targets for change.

3. United Kingdom

The worldwide concern about the legal protection of software has led the U.K. Patent Office to organise a one-day meeting to discuss the problems involved. Held in March 1998 it was initially about meeting the challenges of harmonisation and development of software patents in Europe. The legal protection of some of Europe's most innovative industries moved up on the agenda at the conference, which was held in London (UK).

Organised by the UK Patent Office with the support of the European Commission it had the full backing of the UK's Presidency of the European Union. The meeting was of direct importance to the European software industry, not only to management but also to software designers, researchers and other development personnel in Europe, and also thorughout the world where concern about software protection has become paramount. The European Software Industry alone, we were told, is worth an estimated ECU 80 billion, that is some £54 billion. It has now an estimated 6 to 7% annual growth. What worries software specialists and those who market it is how their rights can be preserved and legally safeguarded.

The conference organisers said that: The primary questions addressed at the conference were whether the European patent system fully supports software development and what, if any, the measures are that should be taken to optimise the contribution that software patents could make to innovation and the competitiveness of European Industry. Information about the meeting was available on the Web Site: www.patent.gov.uk. There is little doubt that a great deal more will be heard about software protection in the future and with growth rates set to rise dramatically over the new millennium legal measures have to be devised and put into being, not only in the Euorpean Community, but worldwide.

ROBOTS AND NEUROSCIENCES

There have always been computers that have assisted in the design of new machines and even reports of computers that can automatically design and produce new versions of themselves. Now we are told that chips have been developed that design themselves. Researchers are now said to be using the principles of evolution in processor logic design.

At the University of Sussex at Brighton, U.K. a researcher, Adrian Thompson, is reported to have found a way of allowing microprocessor hardware to use the principles of Darwinian evolution to create its own designs. As a result, we are told, he does not understand how the circuits work, only that they are far more efficient than any human could design.

The work is being carried out at the University of Sussex's Centre for Computational Neuroscience and Robotics. At the basis of the development was the researchers ideas to produce a breed of 'self-designing' circuits whilst actually thinking about a project to build neural network chips. The production of efficient neural chips for networking has taxed artificial intelligence workers for nearly a decade. *AI* researchers have simulated the human brain with networks of artificial neurons either in software form or as 'hard-wired' networks on chips.

In an interview recorded in the *Computer Bulletin*, **Volume 10**, Part 1, pp. 18–20 (1998) and conducted by

https://doi.org/10.1017/S0263574798000836 Published online by Cambridge University Press

Clive Davidson for the 'Leading Edge' features, Adrian Thompson explains that either way existing techniques imposed a biological design on a completely foreign media. The human brain, the article said, has evolved over millions of years, taking advantage of the inherent physical, chemical, electrical and other properties of organic matter. What if, it stated, we could re-run evolution, only this time in silicon? Would it produce a design customised to the properties of the silicon? The problem was how to introduce the wet, vital forces of evolution, with its processes of mating, mutation and reproduction, into the dry mechanical world of silicon. To do this the researcher found his solution in genetic algorithms and field programmable gate arrays.

Genetic algorithms it will be recalled, are programs that simulate evolutionary processes to 'breed' the best solutions to a problem where there are a number of possible solutions. This is done by the developer expressing a set of arbitrary solutions as strings of binary code (the initial population). Then the algorithm checks each member of this population to test its suitability for solving the proposed problem (the fitness test). It deletes those that do badly and makes copies of those that do well. Some of the solutions are allowed to interchange parts of their code strings (Mating process). In this process some mutation is introduced by allowing 'random switching' of bits in the population of strings, e.g. from 1 to 0 and vice-versa. The whole cycle of fitness test-mating-reproduction is repeated with the process ending when new iterations do not offer any improvements in the evolved solution.

Whilst genetic algorithms could provide the means of simulation of evolution the problem of transferring this process to the silicon world still remained to be solved. This solution, it seems, appeared when a new generation of programmable chips came on the scene. This was because conventional microprocessors have their logic circuits hardwired onto the silicon. But Field Programmable Gate Arrays (FPGAs) have an array of components and the designer is able to specify the logic and the interconnections in software before downloading them onto the chips. It therefore became possible to make a genetic algorithm create the circuit designs in software and have the opportunity of running the 'fitness tests' on the physical circuits. His subsequent experiments using this theory proved to be successful. The FPGA manufacturer Xilinx Development, Edinburgh, Scotland, UK, who initially provided a new FPGA that could be repeatedly reprogrammed and had no limit on what circuits could be implemented, are now the sponsors for the project at the University Centre.

Applications of the methodology are already in evidence. These include:

- Traffic controls — controlling flows of traffic such as telecommunications signals is already of interest to British Telecommunications (BT)
- Space Industry — where more compact devices are needed

Although the development is attracting much attention, issues such as the robustness of the circuit designs have to be addressed. In particular, how robust are the circuits to changes in their environment? Present research is over a temperature range of around 10°C and when this is raised or lowered the circuits malfunction. New experiments are being carried out to create circuits that are more tolerant to temperature changes and to hardware faults and the 'fitness' test changed accordingly. The article says that:

There is no reason to think that evolution cannot find a strategy that would handle a wide range of temperatures. Evolution is particularly good at creating fault tolerant systems and this could be one of the major attractions of evolved designs.

Even the solution of the robustness problems may not be enough to satisfy sceptics who ask: How acceptable is a safety-critical component of a system if it has been artificially evolved and nobodoy knows how it works? That is the view of Dr. Inman Harvey, a research fellow in evolutionary robotics at the University Centre. The answer we are told is that it will mean accepting that we already rely on systems designed by conventional means that we cannot prove will work under all conditions and in the rigorous testing of the evolved devices.

Most readers will have already recognised the parallel with the application of Darwin's Theory of Evolution in many other contexts involving computer technology. Models of evolution, for exmaple, have been structured on computer systems where human genetic traits have been represented as strings for a whole population. The string subjected to random processes, for example diseases, climate changes, etc. and then a 'fitness' test followed by a 'mating' process and a 'reproduction' stage. Computing machines lend themselves to such cyclic processes as seen in the numerous application of iterative techniques to numerical problems. There would appear to be no reason why such a process involving 'evolved hardware' should not herald new processes that will lead to the production of new generations of machines of all descriptions. Whether we will, finally, be able to tell how such machines work is currently worrying researchers like Adrian Thompson of Sussex University. Whether we need to know is, of course, another question. We note, however, that evolution in the human species has not yet ended and the future may hold many surprises concerning our own evolved state.

U.K. INNOVATION IN IT

There is no better way of measuring progress in Information Technology in a country than by examining the nominations for IT Awards. In the United Kingdom there are many competitive award schemes which are run by the major organisations and institutions that are concerned with IT. Foremost amongst these are the endeavours of the British Computer Society (BCS) which this year celebrates its 25th BCS IT Awards competition. The huge variety of UK innovations in information technology and its applications is reflected in the nomination list and, of course, in the list of the finalists. This, the BSC says, is a landmark year and there were 64 nominations which were reduced to 11 final projects by the investigating panel of BCS members. A very

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elaborate and searching examination of the projects is undertaken and all entries are visited and questioned in detail. Of the final projects, 11 win medals and three have been selected by the panel of judges as award winners.

It has to be noticed that BCS IT Awards are designed to recognise both IT excellence and the benefit to industry and to the society at large. Some of the factors used in the judgements include innovation, development speed, cost savings, commercial success or user acceptance. It is important to appreciate the record of past winners, many of which have gone on to international fame as world-leading IT products, or have become mainstay applications systems giving competitive advantage to the companies that developed them. Other projects, the BCS believes, have helped to save lives, revolutionise information handling and given disabled people their independence.

This year's finalists and award winners appear to be no exception. The judges believe that CREST has revolutionised securities trading. Cambridge University's iris recognition for security, is already being adopted in different systems. BT's system for developing applications, when over 3,250 different securities are held on the system and 80%–90% of these holdings exist solely as electronic entries within CREST. This project surely is an excellent example of the 'automation' of real systems.

Further details are available on: tel: 0171 459 3034; e-mail: bg@crestco.co.uk. and on the site: http://www.crestco.co.uk.

Iris Recognition: from the Computer Laboratory at the University of Cambridge, UK, the system which relies on 'peering into someone's eye' has become the basis of one of the latest security systems. The need to provide better and more secure methods to positively identify an individual — whether to operate an ATM or to gain access to a home or workplace is now paramount. Many of these efforts have concentrated on physical, biometric attributes of the indivdiual, and this is one such system. The iris of a person's eye is patterned with a complex chaotic texture. This pattern remains unchanged throughout the life of a person. It exists, the developers say, sealed inside the eyeball, protected from tampering, damage — or forgery!

The system works in real time. Images are captured from a video camera. They can be taken at distances of up to three feet and do not even need to be precisely focused. A sequence of 10 video frames is captured for registration purposes. Ordinary image recognition techniques are applied to the video frames to find the eye, the position of eyelids and the centre of the pupil. Once this has been done the texture in successive concentric iris segments is encoded using 2-D Gabor wavelets through specially developed mathematical transformations. These complex sequences of equations, which have been developed by John Daugman of Cambridge University's Computing Laboratory, reduce the complexities of the iris pattern to a 256-bit IrisCode that uniquely represents the eye.

An exactly similar process is used for recognition — with one extra refinement. The variation of the iris size from frame to frame is checked. This normally varies involuntarily by 2%–3% — if it appears to vary by less then identification is aborted. This rules out the use of glass eyes or contact lenses with an iris image on them. Based on intelligent agent software could change the whole way in which companies are structured and negotiate with each other.

An important feature of recognition systems is the need to steer a midcourse between the Scylla of false acceptance and the Charybdis of false rejection, a report on the project informs us. In many systems false acceptances can only be rejected at the price of increasing the false rejections to an unacceptable level and vice-versa. For the Cambridge System, we are told, this is not so. There is no overlap between acceptance and rejection. The large number of degrees of freedom extracted from the iris image gives a confidence level with astronomical odds against errors of either type occurring when searches compare the observed IrisCode with the stored database of registered users.

The Cambridge System and its complex algorithms have been patented and licensed to a number of companies — mostly in the USA and Japan. Other uses that are being investigated include access control, the replacement of identity cards or personal identification numbers, and passport control.

Further detials are available on: tel: 01223 332300; e-mail: john.daugman@cl.cam.ac.uk and on the site: http//www.cl.cam.ac.uk/users/jgd1000/irisrecog.ps.gz.

The winners of this competition are announced in November 1998 at a celebratory lunch and exhibition in central London*. Details of the projects selected as finalists and award winners are as follows:

1. CREST

CREST is a new computerised settlement system for transfers of corporate UK and Irish securities on the Stock Exchange. Before its inaguration in July 1996 it was handed over to an independent organisation, Crestco, to operate and develop the service. Users connect to CREST by secure networks provided by British Telecom's (BT) Synegra subsidiary and SWIFT, the international banking message system. All messages are numbered and use passwords and encrypted authentication codes to guarantee security. Users can input transactions either from a dealer's screen using a GUI provided by Crestco, or by a file transfer from their back-office computer using specially developed software packages. CREST checks all deals to ensure that the stock and the quantity agree. On settlement day further checks ensure that the seller has stock to meet the transfer and the buyers remain within their credit limits. Details are then sent to the register for that stock. The transfer must be registered within a two-hour deadline. Each night CREST reconciles its stock records with all the registrars and provides updated information to each member's bank about its cash position. The CREST system is designed to deal with 1,800 transactions a minute and runs on one of the largest hardware configurations of its type — 16 Tandem fault-tolerant processors. The software includes Tandem's special Remote Database Facility which ensures that the live and stand-by databases remain synchronised across their 90 mirrored disc pairs. Hardware enhancements are planned for this year to provide additional capacity so that CREST

https://doi.org/10.1017/S0263574798000836 Published online by Cambridge University Press

can take on responsibility for gilts (UK government stock) and for unit trust investments. The system receives some 4 million messages a day from its 260 directly connected users. They represent about 120,000 stock transfers with a value of some £18 bn. This in itself is a great achievement particularly.

2. ABW ZEUS
From the British Telecom (BT) Laboratories, regarded as one of the foremost world centres for research into the development of 'intelligent agents'. The work of the Intelligent Systems Research Group has already resulted in 10 patents, we are told, and three internal BT awards or prizes.

ZEUS is a toolkit of components which designers can extend and integrate to build specific applications. ZEUS can also provide advanced visualisation, statistical and debugging facilities. This toolkit approach avoids starting from scratch each time when constructing further projects and has speeded up development by 50% and 95%. With ZEUS users only have to provide code for the problem-specific aspects of the agent-based project they are building. ZEUS produces the code for the rest.

This includes communication, co-operation, visualisation, task execution, error handling. A prime example given of the type of project that ZEUS has enabled is the BT project 'Agent-based Workflow (ABW)', which is a revolutionary new approach to managing distributed business processesd and work activities which provides a vision of how large organisations might be structured and managed in the future.

ABW builds, we are told, upon earlier academic and industrial work which was supported by the Department of Trade and the Engineering and Physical Sciences Research Council of the UK, and seeks to model the business process as a sequence of interacting interdependent steps taking place in a virtual market place'. For a demonstration of realistic complexity, the task chosen was a key internal BT problem of providing quotes for services in response to customer requests. This job involves seeking agreements with other sections or departments to undertake specific elements of the process at defined times. These negotiations are mediated by autonomous intelligent agents. They carry out different tasks of the process at different phases: sometimes they receive requests and negotiate details of the service they are to provide; at other times they have to allocate and control the resources needed to do this. The development of this project is being actively pursued, and it is confidently believed that this developing applications based system using intelligent agent software could change the way in which companies are structured and negotiate with each other.

3. Final projects and medallists
Amongst those chosen are the projects:

* *Mobile Data Terminal System* — UK's Cleveland Constabulary have developed special mobile data terminals and a gateway interface to the command and control systems, and to the databases beyond it. (See e-mail for information: crossley@ram.co.uk).
* *Dynamic Workforce Scheduler* — BT Laboratories project involved the development of a dynamic scheduling capability that can be continuously adjusted to cope with additional unexpected calls (see e-mail for information: azarmin@info.bt.co.uk).
* *Multimedia TextEase* — developed by Softease Limited. TextEase ia a page layout tool that copes with multimedia as well as text. It is aimed at use in the home and in primary schools and in the early years in secondary schools. It was designed to be as simple to use as a pencil on a page or using glue and scissors — the original 'cut and paste'. It is initially based on Acorn Archimedes and it has now been ported to Windows (further information on e-mail: and page: geoff@softease.co.uk and http://www.softease.co.uk).
* *The Mirror* — The Mirror is said to be an unusual and quite remarkable project that foresees a world in which the boundaries between television and interactive 3D real-time computing 'blur' — resulting in an experience described as 'inhabited television'. Developed by the BT Laboratories as a pioneering project between themselves and the BBC, Sony and Illuminations — the production company for the associated TV programme 'The Net', it provides an example of real innovation (further information from: e-mail: graham.walker@bt-sys.bt.co.uk and on: htt://vb.labs.bt.com/SharedSpaces).
* *Project Camelot* — developed by ICS Technology in the field of industrial control systems. The project has developed the Trusted ICS controller which was one of the first processors to comply with emerging international safety standards. It provides both hardware and software elements. The systems are used to build complete client systems with the safety-critical elements analysed using techniques researched at the UK's York University (further information: e-mail: jont@icstech.co.uk and the page: http:/www.icsgroup.co.uk).
* *CRAMM V3.0* — stands for CCTA Risk Analysis and Management Methodology. The current version is owned by the Security Service and is supported by Cap Gemini, Logica and Insight. It provides a way to access risks to information systems and to suggest security measures to meet those risks. The developers say that CRAMM ensures that all relevant factors are considered, in a logical, rigorous yet flexible fashion. This it does by providing a framework to lead the management of an organisation through the whole risk assessment process in three phases. The security procedures are said to have been selected from a library of over 2000 measures contained within the system. It has, currently, some 225 users spread over 11 countries and we are told that it is recommended by over 50 security consultants (further information from: e-mail: john.carr@capgemini.co.uk and steved@insight.co.uk; also on the pages: http"//www.insight.co.uk).
* *EPACT* — means Electronic Prescribing Analysis and Cost and was pioneered by the North West Health Authority. It analyses the basic medical prescription

https://doi.org/10.1017/S0263574798000836 Published online by Cambridge University Press

information and helps the work of the UK Fraud Identification Unit. It deals with between 35 m and 45 m a month and in 1996 the total value of the items exceeded £34.5 bn. Trials have started to enable its use over the Internet (for further information: e-mail: info@ppa.nhs.uk and on the pages: http://www.ppa.org.uk).

* *MAPLEX* — Automatic systems to put names on maps developed by the University of Glamorgan, Wales. It has been bought and used by seven of the world's major map makers. It has now been taken over by the major US geographic information systems firm: Environmental Systems Research Institute (further details from: e-mail: cbjones@glamorgan.ac.uk).

WORLD ROBOT FORECASTS

The United Nations Information Service* have issued details of the statistics concerning the world's robots. The publication — *World Industrial Robots 1997 — Statistics, Analysis and Forecasts to 2000***, provides a fascinating array of statistics about robot sales; operational stock; market value; robot density; forecasts and results for the first half of 1997.

It tells us that 1996 marked the second consecutive year of double digit growth in world robot investment. It also says that the world robot market forecast is to increase by 13% per year in 1996–2000. It also provides us with the prediction that by the end of the year 2000 there will be almost one million robots in operation worldwide. The main details of these forecasts and the relevant statistics and comments are included as follows:

*UN/ECE Information Office, CH-1211 Geneva 10, Switzerland. Phone: (+41 22) 917 44 44; Fax: (+41 22) 917 05 05; E-mail: info.ece@unece.org; Internet home page: http://www.unece.org.
**Obtainable from the following address priced at US$ 120: Sales and Marketing Section, United Nations, Palais des Nations, CH-1211, Geneva 10, Switzerland. Phone: (+41 22) 917 26 06/26 12/26 13; Fax: (+41 22) 917 00 27; E-mail: unpubli@unog.ch.

1. Shipments (sales)

Worldwide sales of industrial robots peaked in 1990 when they reached almost 81,000 units. Following the recession in 1991–1993, sales of robots plummeted to about 55,000 units in 1993. With the economic recovery a surge in robot investment followed. In 1995, the world market surged by almost 29% over 1994 and in 1996 global sales increased by 11%, reaching about 80,500 units, or more or less the same level as the record year of 1990 (see Table 1 and Figure 1).

The large drop in sales between 1990 and 1993 is mainly explained by the sharp fall in the supply of robots in Japan, from 60,000 units ot under 30,000 units in 1994. After this trough the market started to recover although hesitant and by 1996 the Japanese market reached almost 39,000 units, up almost 7% over 1995.

After the three year of yearly growth rates of the order of 30% the market in the United States fell by 5% in 1996 (in terms of value, however, it increased by 4%). Modest increase over 1995 was recorded in Italy (+3%). For the third year in a row France showed double digit growth, almost 23% in 1996 over 1995. The market in the United Kingdom experienced a roller coaster, from an increase of 84% in 1994 to −27% in 1995 and back to +41% in 1996. The German market showed incredible strength, increasing by over 40% per year in both 1995 and 1996, more than compensating for the depressed years of 1991–1993.

2. The value of the world robot market in 1991–1996

In 1990, the world market can be estimated at $7.3 billion. In the trough year of 1993, the world market had fallen to $3.4 billion. It increased slightly to $3.8 billion in 1994. In 1995, the world market surged to some $5.2 billion. In 1996, the world market for robots amounted to about $5.3 billion.

The sharp fall in the world market between 1990 and 1993 was mainly caused by the plummeting Japanese market, from $5.2 billion in 1990 to $1.8 billion in both

Table 1. Number of robots installed in 1996 and estimate of the operational stock at end 1996. Forecast for year 2000

Country	Installations made during the year 1996	Installations made during the year Forecast 2000	Operational stock at year end 1996	Operational stock at year end Forecast 2000
Japan	38,914	73,800	399,629	527,500
United States	9,709	13,800	70,858	99,200
Germany	10,425	7,500	60,000	76,900
Italy	3,200	4,000	25,363	34,600
France	1,697	2,400	14,784	19,000
United Kingdom	1,116	1,800	8,751	12,300
Total above	65,061	103,300	579,385	769,500
Other western Europe a/	3,716	5,700	24,328	39,600
Asia-4 b/	9,349	17,000	37,175	91,000
Other countries	2,403	5,100	36,686	47,800
Grand total	80,529	131,100	677,574	947,900

Sources: ECE, IFR and national robot associations.
a/ Austria, Benelux, the Nordic countries, Spain and Switzerland.
b/ Australia, Republic of Korea, Singapore and Taiwan Province of China.

https://doi.org/10.1017/S0263574798000836 Published online by Cambridge University Press

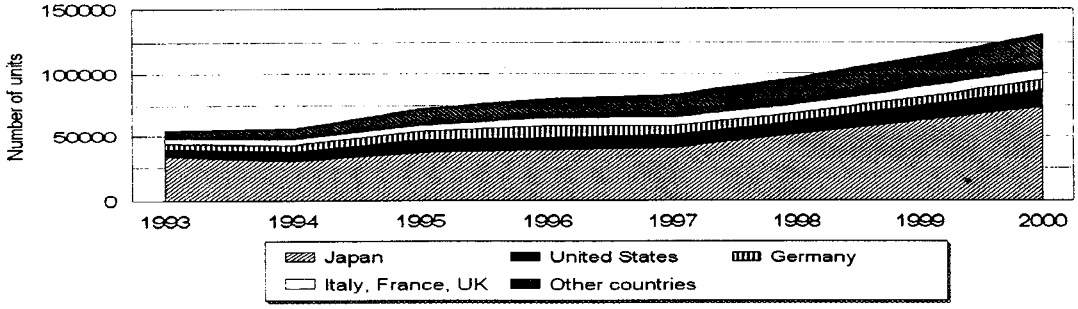

Fig. 1. Installations made during the year.

1993 and 1994. In 1996, the Japanese market had reached \$2.3 billion. Its share of the world market fell from an estimated 71% in 1990 to about 42% in 1996. The market in the United States, on the other hand, increased both in nominal and relative terms, from \$485 million 1990 to almost \$950 million in 1996 and from almost 7% of the world market to 18%. It should be noted, however, that the estimates for 1996 are, for several reasons, regarded to have higher accuracy than those of previous years. In reality, the fall in the market between 1990 and 1995 might therefore have been less significant than shown here.

3. Robot density in selected countries

When comparing the rate of diffusion of industrial robots in various countries, the robot stock, expressed in the total number of units, can sometimes be a misleading measure. In order to take into account the differences in the size of the manufacturing industry in various countries, it is preferable to use a measure of robot density. One such measure of robot density is the number of robots per 10,000 persons employed in the manufacturing industry.

The Republic of Korea had an impressive average yearly growth rate of 47% between 1991 and 1996. In the latter year, however, it “only” increased by 16%. The group Other western Europe (Austria, Benelux, the Nordic countries, Spain and Switzerland) had a market growth of 24% over 1995.

4. Estimates of worldwide operational stock of industrial robots

Total accumulated yearly sales, since industrial robots started to be introduced in industry at the end of the 1960s, amounted at the end of 1996 to some 860,000 units (see Table 1 and Figure 2). Many of the early robots have, however, by now been taken out of service. The stock of industrial robots in actual operation is therefore lower. The United Nations Economic Commission for Europe (UN/ ECE) and the International Federation of Robotics (IFR) estimate the total worldwide stock of operational industrial robots at the end of 1996 at just under 680,000 units compared with about 640,000 units at the end of 1995, representing an increase of 6% over 1995, or the same increase as in 1995 over 1994.

Japan accounts for more than half of the world robot stock. However, the net increase in the Japanese robot stock, as well as in the gross domestic shipments (sales) of robots, fell sharply in the period 1992–1994. The net increase in the robot stock in 1994 was less than a fifth of the record year of 1990, underscoring the depth of the Japanese recession. In 1996, the operational stock grew by about 12,000 units, from a supply of new installations of almost 39,000 units, to just under 400,000 units.

5. Unit value and relative prices of robots

Unit value of robots for United States Germany, Italy, France and United Kingdom peaked at just under \$110,000

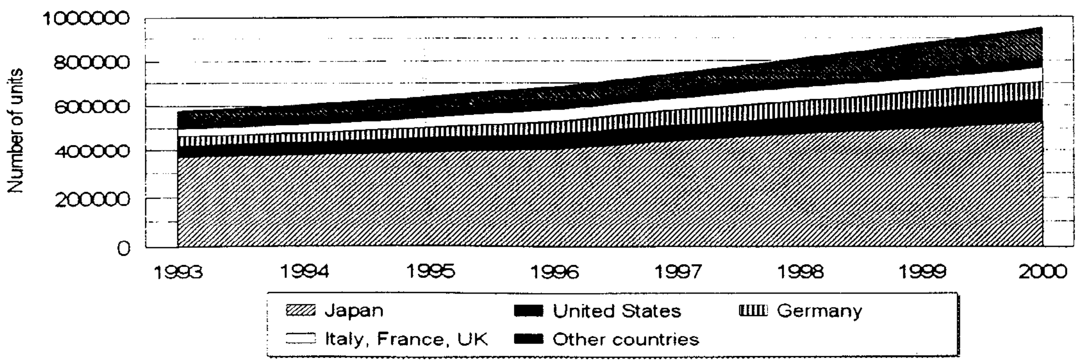

Fig. 2. Operational stock at year end.

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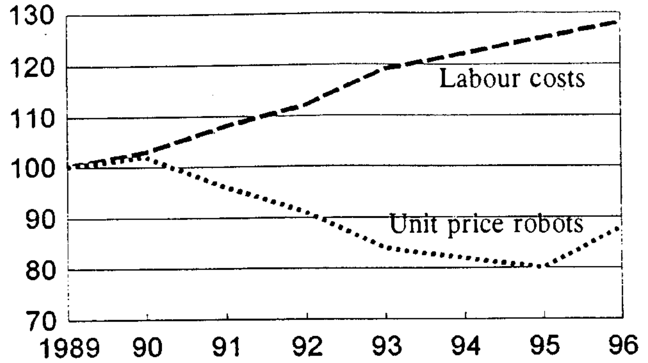

Fig. 3. Index of labour compensation in the business sector and index of average robot unit price in the United States (1989–1996).

in 1991 (it should be noted, however, that the unit price only accounts for 30% on average of the total system cost). By 1994 they had fallen to $82,000 but rose slightly to $85,000 in 1996.

The relative price of robots, i.e. the price of robots for a given set of performance indicators in relation to labour costs and to other types of machinery, manually operated, has been falling rapidly. Since 1989, prices of robots relative to employee compensation in the business sector have fallen by between 30% and 50% in the United States, Germany and France, although there was a slight reversal of this trend in 1996 in the first two countries. It should be noted, however, that these calculations of relative prices does not take into account the improvements made in the quality and efficiency of robots, factors which would, if included, have made relative prices fall even more. Data on different types of robots being installed strongly indicate for many countries that there has been a gradual shift towards a higher share of more sophisticated robots. The calculations of relative prices above thus underestimate the true relative prices. Figure 3 compares index of labour compensation in the business sector in the United States with index of the average unit price of robots being installed, illustrating the so-called "crocodile gap".

Two types of robot densities are calculated. The first relates all types of robots to the number of persons engaged in manufacturing industries while the second measures only the more advanced types of robots, that is, trajectory-operated robots and adaptive robots and/or robots with four axes or more.

Japan has by far the highest density of advanced robots. In 1996, it amounted to 225 units (265 when counting all types of robots) per 10,000 persons engaged in manufacturing industries. The Republic of Korea had the second highest with 75 units, followed by Germany with 71, Sweden with 54 and Italy with 47 units. In the other countries in western Europe, Australia and the United States the density ranged between about 15 and just under 40. The countries in central and eastern Europe had densities in the range of 2–5.

Figure 4 below shows the 1995 robot densities (number of robots per 10,000 people empoyees) broken down by industries for some of the major robot using countries. In the motor vehicle industry there were over 830 robots for every 10,000 persons employed in Japan. In Italy the corresponding density was estimated at 400 (which might be an overestimate), while it reached 370 in the United States, 260 in Germany, 250 in Sweden, 200 in France and 130 in the United Kingdom. As one robot generally performs the tasks of at least two persons it could be said that robots in the Japanese motor vehicle industry correspond to some 20% of the labour force.

6. *Forecasts 1997-2000*

Yearly sales

After two years of booming robot demand, the market in 1997 is projected to increase by just 4%, largely a result of sharp falls in the market in Germany and a slow down in the growth in Japan, France and the United Kingdom (see Table 1 and Figure 1). In the United States, on the other hand, growth will pick up again after the temporary halt in 1996.It is projected that growth in 1997 will reach at least 10% over

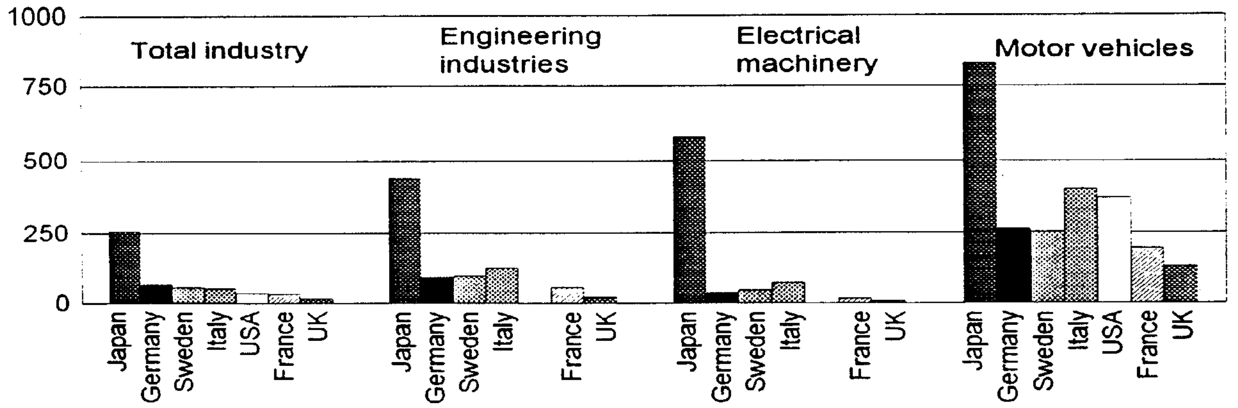

Fig. 4. Number of robots per 10,000 employees, broken down by industries.

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1996. Europe, other than the foresaid countries, and Asia will also be buoyant markets – a rather optimistic forecast!

For the period 1998–2000, worldwide growth is expected to reach a yearly average of just over 15%. In absolute numbers this implies that sales will increase from just over 80,500 units in 1996 to about 131,000 units in year 2000.

In the period 1996–2000, the gross yearly supply in Japan is forecast to almost double, from 39,000 to 74,000 units. In this context it should be noted that a very large share of the new robots supplied will replace older robots taken out of operation. In 1996, for instance, more than two thirds of the Japanese supply were replacement investment. In the United States supply in the period 1996–2000 is projected to increase from 9,700 to 13,800 units, down from the record and exceptional level of 10,400 in 1996 to 7,500 units in Germany, from 3,200 to 4,000 units in Italy, from 1,700 to 2,400 units in France and from 1,100 to 1,800 units in the United Kingdom.

The combined supply of Australia, Republic of Korea, Singapore and Taiwan province of China is forecast to grow from 9,300 units in 1996 to 17,000 in 2000. As was previosly shown, the Republic of Korea is now the world's fourth largest robot market both in terms of units and values.

In the eight smaller western European countries the market is forecast to increase from 3,700 units in 1996 to 5,700 units in 2000.

7. *Results in the first half of 1997*

Looking at the first half of 1997, shipments surged by 35% in terms of units, over the same period in 1996, and by 31% in terms of value. The actual shipments of the first half of 1997 corresponded to 62% of the projected total 1997 shipments. In the period 1992–1996, the first half years' shipments as a percentage of the full year shipments varied between 43% and 49%, indicating that the projected value for 1997 will be more than realized.

8. *Operational stock*

In terms of units, it is estimated that the worldwide stock of operational industrial robots will increase from just under 680,000 units at the end of 1996 to just under 950,000 at the end of 2000, of which more than half in Japan, just under 100,000 in the United States, 77,000 in Germany, 35,000 in Italy, 19,000 in France and 12,000 in the United Kingdom (see Table 1 and Figure 2). As, in the same time, the number of personnel in industry in the best case will be stable or only grow modestly, the density of robots measured as the number of robots per 1,000 workers will continue to surge.

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