Professor Geoff Roberts
Mechatronics Research Centre
University of Wales College, Newport
Allt-yr-yn Campus, PO Box 180, Newport, NP9 5XR. United Kingdom.
Tel: Int. +44 1633 432441, Fax: Int +44 1633 432442, e-mail: g.roberts@newport.ac.uk

INTELLIGENT MECHATRONICS

Abstract: Over the last decade there has been an exponential growth in machatronics and intelligent systems activity, a growth which has led to the development of exciting new products which are in everyday use. The paper will trace the origins of mechatronics and demonstrate how the concept has grown from its beginnings in Japanese manufacturing industry to become universally accepted as an important enabling methodology for improved product design and profitability. The parallel development of the intelligent systems paradigms of fuzzy logic, artificial neural networks and genetic algorithms will also be discussed and it will be shown how the two subjects have become inexorably linked. The overall aim of the paper is to demonstrate how the synergistic combination of these two areas has provided the driving force for innovative applications ranging from cameras and domestic washing machines to motor vehicles, ships and industrial processes.

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1. Introduction

The title of this article comprises two words, which although presented as a couple need first to be discussed individually in order that the remaining parts of the paper may be fully appreciated. The two-word title was chosen deliberately so as to highlight the important connection between the two areas which until recently have been treated separately. The paper is structured as follows; section 2 will trace the origin of mechatronics and demonstrate how the concept has grown from its beginnings in Japanese manufacturing industry to become universally accepted as an important enabling methodology for improved product design and profitability. The parallel development of the intelligent systems paradigms of fuzzy logic, artificial neural networks and genetic algorithms will be discussed in section 3. In section 4 some examples of intelligent mechatronic products and processes will be presented and it will be seen that mechatronics systems and intelligent systems have become inexorably linked. The paper concludes with some observations on future directions for intelligent mechatronics.

2. Mechatronic Systems

It is not the intention here to give a detailed exposition on mechatronics, the aim is to briefly trace the development of mechatronics from its origins in Japanese manufacturing industry to its world-wide acceptance as design methodology. More detailed descriptions of mechatronics and applications thereof can be found in the many articles and books available, of which references 1-4 are recommended reading.

Mechatronics is a word which came into use in the early Seventies. It is generally considered that the word originated from Japan and was coined as a result of a recognition by Japanese industry that for increased efficiency in manufacturing and systems design it was necessary for engineers and technicians from the disciplines of *mecha*nics and elec*tronics* to work as teams rather than separately. In the West however the concept was more commonly known as systems engineering and systems design groups or teams would include expertise drawn from the disciplines of electrical engineering, mechanical engineering, control engineering, computing and mathematics.

It is important to realise that mechatronics should not be considered as a discipline in its own right but rather as an integrated, systems-level methodology for the design, development and operation of a wide range of engineering products and processes. Bradley[4] suggests that if the principles and features associated with a mechatronic approach to product design and development are valid for a range of products under consideration and if such principles and features are themselves a significant means of gaining a competitive advantage then it is likely that the company will benefit from the adoption of a product development strategy based on mechatronic concepts and principals.

There are many definitions of mechatronics but none has become universally accepted, although the definition formulated in 1986 by the Industrial Research and Development Advisory Committee (IRDAC) of the European Union is generally accepted as a reasonable starting point. The IRDAC wording is:

> **„The term 'mechatronics' refers to a synergistic combination of precision engineering, electronic control and systems thinking in the design of products and manufacturing processes. It is an interdisciplinary subject that draws on the constituent disciplines and includes subjects not normally associated with one of the above"**

Whilst there is agreement that the IRDAC definition is a good starting point it is regarded by many as being somewhat dated, having been overtaken by the developments in CAD systems and embedded microprocessor systems. It is however generally agreed that mechatronics describes the synergistic integration of electronic engineering, mechanical engineering, control engineering, information technology and informatics. The key words here are *synergistic integration,* as it is these words which symbolise the raison d'etre of mechatronic systems. This is an important distinction which can be usefully demonstrated by contrasting the traditional role of control engineers, i.e. that of designing controllers or control strategies which 'optimise' performance of systems which already exist, to the mechatronics approach which as a result of the synergistic integration of the separate disciplines aims to 'optimise' all aspects of the product or process, thereby simplifying the control engineer's task.

The broad definition of mechatronics means that the majority of engineering systems can be classified as mechatronic systems and thus we are surrounded by mechatronic systems and continually use them for both work and leisure. Mechatronics is increasingly becoming accepted as a methodology in its own right. This may in part be due to the huge inward investment in the West from Japanese companies but also owes its acceptance to modern industrys' need for a multi-skilled workforce. The acceptance of mechatronics as a methodology is reflected in the high level of associated activity. In the UK for example;

- The UK Mechatronics Forum was formed in 1990 (this is jointly sponsored by the IEE and the IMechE).
- UK universities now offer mechatronics courses and the number of courses offered is growing annually. (The Spring 1997 UK Mechatronics Forum's Newsletter identified a total of forty-six National Diploma, BSc, BEng and Masters courses offered in the UK which include Mechatronics in their titles).
- Many companies have established mechatronics research and development units or departments.
- There are currently seven Professors of Mechatronics in UK universities.

Similar levels of mechatronic related activity have also been recorded in America and Europe and a number of national and international mechatronics conferences have been held and are planned for the future. It is clear therefore that mechatronics is having an increasing influence on manufacturing, product design, education and training and is therefore impacting on all aspects of life.

3. Intelligent Systems

Again only a brief overview of the subject will be presented here. The intention is to provide sufficient background information to enable an appreciation of the intelligent mechatronic systems presented in the next section.

It is interesting to consider the dictionary definition of intelligent which specifies „an ability to vary behaviour in response to varying situations, requirements and past experience". However, whilst this broad definition encompasses many classical and modern control techniques, e.g. adaptive, predictive and self-tuning control, it is only those control techniques based upon human reasoning and biological systems found in humans and animals, i.e. Fuzzy Logic, Artificial Neural Networks and Genetic Algorithms, which are collectively accepted in the literature as being intelligent.

In recent years there has been an almost exponential growth in the application of these intelligent control paradigms. This growth is indicated graphically by the output from the Bath Information and Data Services (BIDS) database shown in Figure 1. It should be noted that although the curves given in Figure 1 are derived from one source they are indicative of the level of activity and give also some insight into the development, and use, of the three paradigms from 1981 to 1987. In the Eighties for example there was no genetic algorithm work recorded and relatively little activity and relatively slow rates of increase recorded for fuzzy logic and artificial neural networks. In the early Nineties however the sudden increase in both fuzzy logic and artificial neural network applications mirrors the similar increase in computing power and availability of proprietary CAD software.

The figure also confirms the fact that it was not until the mid-Nineties that numbers of genetic algorithm applications started to increase significantly. The flattening of the curve for genetic algorithm applications in 1996 is probably due to the fact that recently genetic algorithms have become subsumed under the generic heading of evolutionary computing which is not included in the data presented in Figure 1.

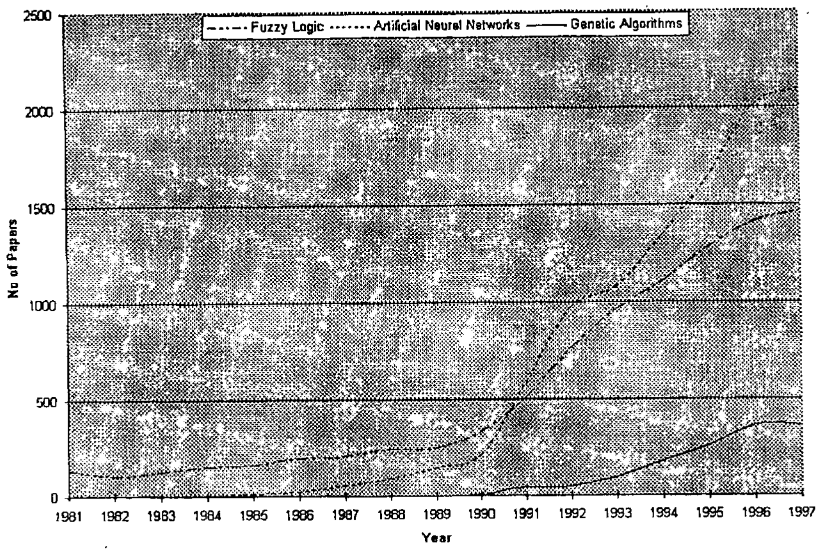

Figure 1: Intelligent control applications 1981-1997 [source: BIDS Database]

In the following, the salient features of the three intelligent paradigms are briefly described. More detailed information is available in the references provided. It should be remembered however that although the three paradigms are presented separately, in practice there is a range of so-called hybrid applications for example neural and fuzzy approaches are often combined, [5], [6], and neural networks and fuzzy systems may be trained with genetic algorithms [7].

3.1 Fuzzy Logic

Zadeh [8], Yager and Zadeh [9] describe fuzzy logic as a means of dealing with imprecision and approximate reasoning and have shown that a fuzzy controller can be designed to emulate the deductive process and action-taking characteristics of human operators. Probably the most important aspect of fuzzy systems is the use of linguistic labels such as *small, medium, big* etc. in the sets of „if -then" rules which characterise fuzzy logic. Figure 2 shows the basic structure of a fuzzy controller, which comprises four components:

- The rule base that holds a set of „if-then" rules which are quantified through appropriate fuzzy sets to represent expert knowledge.
- The fuzzy inference system that decides which rules are relevant to a particular situation or input, and applies actions indicated by these rules.
- Input fuzzification, which converts the input value into a form that can be used by the fuzzy inference system to determine which rules are relevant.
- Output defuzzification, which combines the conclusions reached by the fuzzy inference system to produce the control input to the system or process.

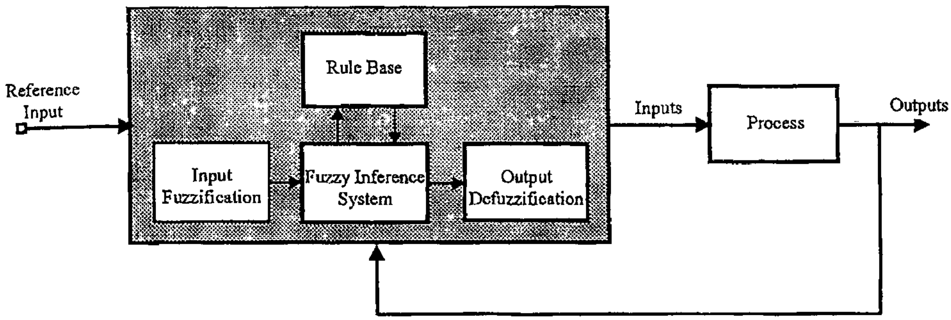

Figure 2: Fuzzy logic controller structure

One of the main advantages of fuzzy logic controllers is that the rules may be formulated without a precise definition of the system's dynamics. The control actions are normally formulated such that the system input is determined from knowledge of the expected system's response to the input. Although this process is best achieved through consultation with the expert operator or by observation of his/her actions, the fuzzy rules may be formulated from an understanding of the system's dynamical behaviour. This process illustrates the fundamental difference to fuzzy controller design compared with more traditional model-based controller designs. Whereas the latter is concerned with designs to meet performance specifications, i.e. damping, speed of response, steady-state error, etc., fuzzy controller design is focused on predicting system behaviour in response to specific inputs. It should be noted that overall there are no significant differences between the behaviour of the resulting controllers, they are merely non-linear and often adaptive and robust.

3.2 Artificial Neural Networks

Studies of the human brain show that it comprises approximately 10^{11} neurons [10], each consists of a cell body, numerous fibres (dendrites) extending from the cell body and a long fibre (axon) which carries signals to other neurons. The axon branches into strands and substrands at the end of which are synapses which form the weighted connection between neurons. Typically each axon makes a few thousand synapses with other neurons. The process of sending a signal from one neuron to another is a complex electro-chemical process which is beyond the scope of this article. However, the principal is that if the weighted sum of the inputs arriving at a cell in any time instant is above a threshold level the neuron „fires" and sends a signal along its axon to the synapses with other neurons. Thus, as a result of the complex neuron interconnection structure described above, data patterns representing a particular event will have unique propagation paths through the brain.

It is considered that a recognition of the uniqueness of propagation paths within the brain structure and a better understanding of the functions carried out by biological neurons provided the impetus for the development of simulated neurons and Artificial Neural Networks to try and emulate the data or information processing properties of biological neurons. In the brain, neurons are arranged in groups or maps and are interconnected by pathways. This basic structure is incorporated into Artificial Neural Networks, where simulated neurons are normally arranged in regular layers connected by different weights. The most widely used is the feedforward layered network or multi-layer perceptron. Figure 3 gives an example of such a network. Here the circles are the simulated neurons and the links represent the weighted connections, information flow is in one direction only. It should be noted that there are several neuron simulation models and a wide range of neuron interconnection structures. For example, recurrent networks are configured with internal connections that feedback to other layers or themselves. This allows the network to accommodate unidirectional data flow, as occurs in biological structures, and enables networks to distinguish separate input patterns from the same input sequence and so discern temporal patterns, a function which is beyond the feedforward network without pre-processing of the inputs.

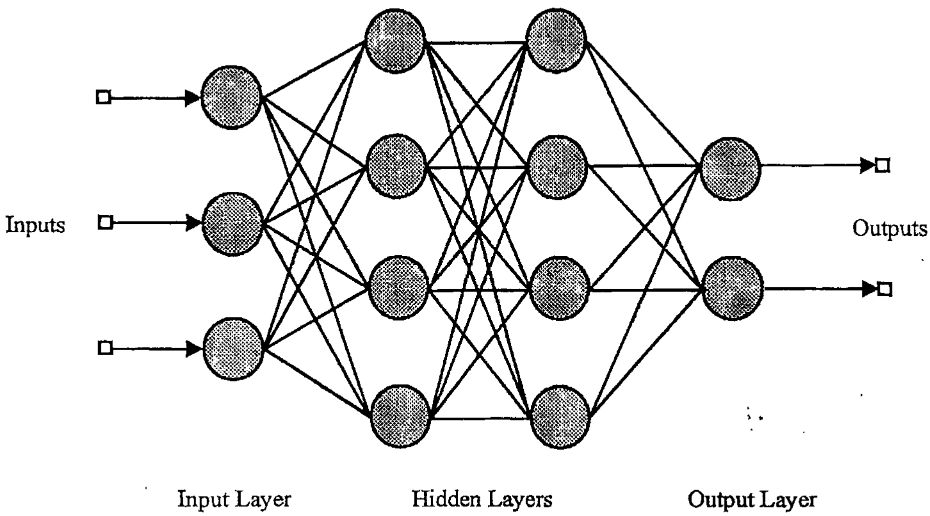

Figure 3: Feedforward artificial neural network

Clearly the network shown in Figure 3 varies considerably in size, structure and complexity from the biological neurons outlined above. Despite this fundamental difference such networks have been trained to approximate continuous non-linear functions and have been used successfully in a wide range of applications [11]. Training involves supervised learning, reinforcement learning or unsupervised learning. The former involves providing the network with two data patterns, the input pattern and its corresponding output pattern. This enables a function called the teacher to be derived which enables adjustment of the interconnection weights in order to minimise the error between the actual and the desired output. Reinforcement learning, or learning with a critic, works by deriving an error when an input target is not available for training. In this case the network obtains an error measure from an application dependant performance parameter, weight connections are adjusted and the network receives a reward/penalty signal. Training proceeds so as to maximise the likelihood of receiving further rewards and minimising the chance of penalty. With unsupervised learning there is no external error feedback signal to aid classification, as in pattern recognition applications. In this case the network is required to establish similarities and regularities in the input data sequence.

3.3 Genetic Algorithms

A genetic algorithm is a general-purpose search and optimisation method which utilises the Darwinian principals of genetic evolution and natural selection found in biological systems. In this respect genetic algorithms embody the concept of the natural selection process, i.e. *the survival of the fittest* where *fittest* or a *fittest* measure is quantified by performance objectives. Essentially a genetic algorithm will undertake parallel, stochastic but directed searches to evolve an appropriate solution which meets the performance specification to the greatest extent possible. The operation of genetic algorithm may be represented by the flow chart shown in Figure 4. Here potential solutions to a given problem will consist of a number of parameters converted into 0s or 1s, which are termed chromosomes. An individual chromosome is therefore a member of a population of chromosomes or population string in which the genetic algorithm performs the search.

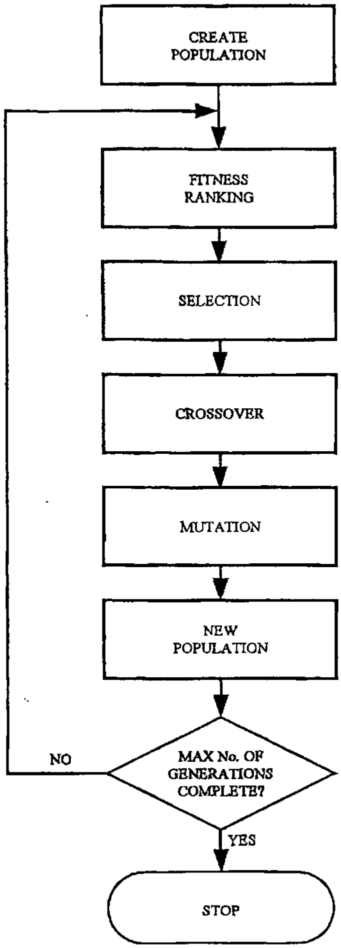

Figure 4: Flow chart for basic genetic algorithm

As shown by Figure 4, the genetic algorithm uses the genetic operators of „reproduction" (to represent the 'survival of the fittest' or **selection**), **crossover** (to represent mating) and **mutation** (to represent introduction of new material, to increase the search space and to avoid locally optimal solutions), coupled with the **fitness** measure (a numerical objective measure of the goodness of the solution, which is problem specific) to generate successive generations of the population. After many generations the genetic algorithm will produce an optimised or best solution possible. For a more detailed explanation of genetic algorithms and applications see references [12] and [13].

At present the main use of genetic algorithms is for system design optimisation, although there have been a number of applications where artificial neural networks and fuzzy controllers have been tuned using genetic algorithms. The most significant drawback associated with using genetic algorithms is the long computational time required to obtain the best solution which means that currently genetic algorithms are essentially an off-line design paradigm.

4 Intelligent Mechatronic Systems

Clearly, given the broad definition of mechatronics there is insufficient space here to describe the wide spectrum of intelligent mechatronics applications. Figure 1 is indicative of the level of activity, there are however a number of interesting examples where the application of intelligent mechatronics has led to the production of innovative products and enhanced designs or design solutions where no solution previously existed. Some examples of intelligent mechatronics are briefly described below. Their inclusion is either because of the impact they have or will have on our daily lives or because of the way the approaches have resulted in superior products which would have been difficult or impossible to produce through conventional methods.

The first two examples concern the use of fuzzy logic in domestic washing machine and low-cost auto-focus cameras. Example three describes the development of an innovative fuzzy logic autopilot for small ships. The fourth example considers the concept of utilising intelligent paradigms for intelligent motoring. Finally the use of intelligent paradigms in assisting with the production of products in the factory environment is discussed.

4.1 Washing Machines

With automatic washing machines parameters such as the length of wash time, water temperature and water levels are dependant upon the amount of clothes to be washed and the type and degree of soiling. Because of varying quantities of clothes and different levels of soiling, washing machines can be extremely inefficient in terms of water usage and energy consumption. Although the user is presented with a number of programmes from which to select the most appropriate, the control of wash time and the amount of water to be used is in fact very limited and the actual setting is selected very much on a trial and error basis. However, by incorporating fuzzy logic and simple sensors to measure the weight and the dirtiness of the wash, washing machines are becoming truly automatic. The dirtiness of the wash i.e. the degree and the type of dirt on the clothes, is obtained via optical sensors. The degree of dirt is determined by evaluating the transparency of the wash water for a fixed amount of water i.e. the less transparent the water the dirtier the clothes, whereas the type of dirt is classified by measuring the time to reach transparency saturation i.e. the time when the rate of change of transparency is zero or below a set value. The information on wash weight and type of dirt is used through the fuzzy inferencing system to select the appropriate wash programme. In its simplest form a fuzzy logic controller contains rules such as: If saturation time *is long (i.e. greasy)* and transparency is *low* then wash time is *very long.*

Such rules mimic typical human selection processes and it is clear that by using different combinations of these and other conditions, the rule base necessary for fully automatic wash control may be developed.

4.2 Camera Automatic Focus

The automatic focusing system in cameras uses a measurement of distance from the camera to the centre of the scene being photographed. The method is however unsatisfactory when the subject of interest in not in the centre of the picture or if there is more than one subject, the result is perfect focus for background or distance information and poor focus for the desired subject(s) of the picture. Measuring more than one distance is a means of overcoming this problem and it has been found that the use of fuzzy logic is an attractive method to determine correct focal distance. Typically three distances are measured i.e. centre, right and left. Each input distance has three linguistic labels: *near, medium* and *far*, and each output from the fuzzy inferencing system representing likelihood values of these three distances may have up to four labels i.e. *low, medium, high* and *very high.* The principal of establishing the rules for the fuzzy inferencing system is based upon the idea that the likelihood that a subject being at a medium distance (typically 10 metres) is *high* and becomes lower as the distance increases.

4.3 A fuzzy autopilot for small ships

As stated previously one of the main strengths of fuzzy logic control is the ability to replicate the actions of experienced human operators when controlling highly non-linear systems. One area where this capability has been exploited is in the design of autopilots for small ships [14] The motivation here was to improve upon the existing low-cost PID-based autopilots, which as a result of their factory set controller gains and very limited user adjustment generally resulted in unsatisfactory performance. The failure of the PID autopilots stems not only from the wide range of dynamical behaviour exhibited by an individual boat and the wide range of boats to which they are fitted but also because owners have little experience or knowledge on how to best achieve the optimum gain settings to match their boat's characteristics and at the same time matching their particular requirements.

The main thrust of the research programme was to develop a generic fuzzy logic autopilot such that the rule base and inference system incorporated the necessary robustness to accommodate significant changes in model parameters and the different requirements for course-keeping and course-changing. It was found that in order to meet these exacting requirements it was necessary to include an element of learning into the control algorithm, which was achieved based on the self-organising approach proposed by Procyk and Mamdani [15]. The devised self-organising fuzzy autopilot was extensively evaluated in simulation and at sea [16] and resulted in an innovative new product being brought to market.

4.4 Intelligent Motoring

The automotive industry was perhaps the first to wholeheartedly embrace the concept of mechatronics as a design philosophy. Traditionally the motor car included a number of discrete electrical and mechanical components or sub systems, each of which was designed as a stand alone unit. However, in recent years the motor industry has undergone a revolution in manufacturing and production methods which has lead to automated manufacture and the development and inclusion of mechatronic sub-systems in cars for improved comfort, safety, efficiency and reliability. For example:

- Engine management systems
- On-line monitoring and fault diagnosis
- Central locking
- Seat, sun roof and window adjustment
- ABS braking
- Traction control
- Airbags
- Cruise control
- Climate control.

Whilst some of the above sub-systems have been included to maintain a market edge or break into new markets, there is no doubt that the adoption of the mechatronics philosophy by the motor industry has contributed to the enormous improvements in reliability and maintainability.

In addition to improvements in the motor car itself, the inclusion of sophisticated microprocessor-based control and monitoring sub-systems has enabled the development of automated traffic control systems which utilise the on-board data and sub-systems, together with information provided by forward looking sensors and telematic links to roadside beacons or data points, to facilitate improved safety and traffic management. This move towards the so-called 'drive-by-wire' is an extremely active area of research and development activity with a number of high-cost, high-profile projects which have been or are being undertaken in America, Japan and Europe. In Europe for example, the major European cooperative programme PROMETHEUS - PROgraMme for European Traffic with Highest Efficiency and Unprecedented Safety and its successor PROMOTE - PROgramme for MObility and Transportation in Europe have made significant contributions to motor car safety and traffic management. In particular products such as advisory and automated systems for collision avoidance - the blind spot monitor, intelligent cruise control, enhanced night vision, automated lane keeping support, route guidance and travel and traffic information systems have been developed, evaluated and are now available. On-going research is directed towards developing automated urban drive control systems, whereby information from roadside beacons, such as traffic congestion or the future state of traffic lights can be used to automatically adjust forward speed in order to minimise braking, improve traffic flow and maximise fuel economy.

4.5 Intelligent Manufacturing

The successful operation of automated manufacturing systems, many of which themselves maybe classified mechatronic systems, requires the simultaneous co-ordination and management of a large number of sub-systems. It is in this environment where intelligent applications are most widespread and is especially important since manufacturing is a primary generator of social and economic wealth and is one of the principal means of raising standards of living. There are many examples where fuzzy logic and artificial neural networks are utilised for the control of individual machines, robotic manufacturing and assembly devices and materials handling [17]. Intelligent sensors and intelligent actuators are becoming commonplace and artificial neural networks and genetic algorithms are being used for more efficient scheduling, for inventory and production control, for improved fault prediction and diagnosis, for performance and trend analysis and as aids for management decision making and planning [18].

This *optimisation of the process* through the use of intelligent systems is continuing and is the theme of the multi-national, industry-driven Intelligent Manufacturing Systems (IMS) initiative, which started in 1995. Countries involved are Australia, Canada, the EU-Norway, Switzerland, Japan and the USA with the possibility of Korea joining in the near future.. Currently projects with a value of some US$240 million are being undertaken through the IMS initiative and more are planned. The overall aim of the IMS programme is the sharing of technologies experience thereby leading to increased efficiency, improved quality control and greater profitability by way of improved products, less downtime and increased productivity. More information about the IMS initiative can be found on the IMS website: http://www.ims.org/

5. Concluding Remarks

The significant advances in computing, in particular processor speeds and memory capacity coupled with the significant reduction in their unit costs has resulted in increased use by industry and academia of computer-based tools for product and process design, development and evaluation and for implementation in the form of embedded microprocessors for control, data acquisition, fault monitoring and diagnosis etc. The increases in processor speed and memory capacity has also led to the inclusion of more sophisticated design and evaluation algorithms and processes, many of which contain the intelligent paradigms of fuzzy logic, artificial neural networks and genetic algorithms. This means that not only do many products or processes contain intelligent controllers, but there has also been an increase in utilising intelligent paradigms for product design, for sensors and actuators and for on-line data acquisition and management information systems.

The continuing development of algorithms which will extend the capabilities of intelligent paradigms suggests that rate of growth in applications depicted by figure 2 will continue for the foreseeable future. The challenges are to build on this momentum and to establish reliable mathematical relationships which guarantee system stability and can be used to define safety critical aspects and also to devise efficient genetic algorithms and artificial neural network architectures for on-line operation. In this way the potential for enhanced performance offered by intelligent mechatronics may be realised in all sectors.

It is clear therefore that the early definitions of mechatronics have now been overtaken by the rapid advances in computing capabilities and it is suggested that because mechatronics systems and intelligent applications are inexorably linked a more up to date statement of the meaning of mechatronics is:

> **„The term 'mechatronics' refers to a synergistic integration of precision engineering, electronic control, informatics and intelligent systems in products and the design of products and manufacturing processes."**

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