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Aspects of Modular Mechatronics in South Africa

C.M. Kumile[1]*, N.S. Tlale*[2] *and G. Bright*[3]

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Manufacturing enterprises are facing critical challenges to reconstruct themselves in order to survive in a more competitive environment. Their success depends on their ability to adopt state-of-the-art manufacturing strategies and technologies. To increase efficiency there is need to minimise the time and cost of development and operation of manufacturing systems. Shorter product life cycles require the manufacturing systems to be able to meet frequent changes. In recent years the mechatronic philosophy has been adopted world-wide in an endeavour to improve speedy product development. The objective of this paper is to present a generic philosophy of mechatronic concepts as utilised in product design. The description and the historical perspectives of mechatronics is articulated through research findings. The role and relevance of mechatronic concepts within the South African economy will also be highlighted. Several case studies will be discussed to further enhance the understanding of the mechatronic philosophy in product design and development.

This paper intends to provide a comprehensive insight on the functions and methodologies of mechatronc systems, which consequently enables the rapid development and deployment of qualitative products within the market.

Additional Keywords: Computer integrated manufacturing (CIM), distributed mechatronics, synergetic design, modular design

1. Introduction

Global competition in manufacturing and changing consumer demands have resulted in a trend towards greater product variety, innovation, shorter product life cycles, lower unit costs and higher product quality.

As a consequence manufacturers are experiencing significant new demands and challenges to remain competitive. In particular, it is becoming strategically important for manufacturers to:

- ❑ Shorten the design to market lead-time. This results in the need to design "right-first-time" since there is not enough time to correct design errors or to re-engineer products for lower cost or higher quality.
- ❑ Ensure goods are produced to a high and consistent quality.
- ❑ Forecast production costs and lead times in order to help assess the market potential of a product prior to significant investment.
- ❑ Alter production capacity in response to changing demands without incurring significant costs or production lead-times.
- ❑ Introduce new products frequently to retain or gain market share.

Today, cost-effective electronics, microcomputers, and digital signal processors have brought space technology to appliances and consumer products. Systems with hearts of precision sensors and actuators have increased performance by orders of magnitude over what was once not possible. There are many designs where electronics and controls are combined with mechanical components, but with little synergy and poor integration, they become just a marginally useful, error-prone, expensive conglomeration. Synergism and integration in design set a *mechatronic system* apart from a traditional, multidisciplinary system[1].

This paper focuses on the development and the evolution of mechatronics as a philosophy used in product design to enhance the product characteristics as well as its speedy introduction into the volatile market. There is coverage of mechatronics education and research initiatives within various tertiary institutions of South Africa. Case studies are used to highlight typical applications of equipment designed utilising the mechatronics design methodologies.

The rest of the paper is organized as follows: first we provide a description to the term mechatronics (section 2), and the evolution of mechatronics concepts and its modules (section 3). Next, we provide the scope of mechatronics education and research initiatives within the South African tertiary institutions (section 4). We present various research case studies on product development utilizing mechatronic concepts (section 5). Finally, we present the conclusions and summary of the paper (section 6).

2. Mechatronics Description

The portmanteau "mechatronics" was first coined by Mr Tetsuro Mori, a senior engineer of the Japanese company Yaskawa, in 1969 as a combination of "mecha" of mechanisms and "tronics" of electronics. The company was granted trade mark rights on the word to describe the philosophy in design of electro-mechanical products to achieve optimum system performance[2]. Although there are many definitions of mechatronics there is still considerable debate on what it means. Numerous definitions have been made by researchers, practitioners and educators in the field of mechatronics, however, none of them can always be complete in describing mechatronics, since the field is continually evolving[3].

In the late 1980s and early 1990s, a number of attempts were made to provide a definition of mechatronics including that of the EEC/IRDAC working party on mechatronics which read: "*Mechatronics is the synergetic combination of precision*

1 Department of Mechanical Engineering, Tshwane University of Technology, P/Bag X680, Pretoria.
E-mail: KumileCM@tut.ac.za

2 Department of Materials & Manufacturing, CSIR, P.O Box 395, Pretoria

3 School of Mechanical Engineering, University of KwaZulu Natal, Durban

mechanical engineering, electronic control and systems thinking in the design of products and processes"[4]. An alternative definition took the form: "*Mechatronics represents an approach to the design of engineering systems which involves the integration of mechanical engineering, electrical and electronic engineering with software engineering and computer technology at all levels of the design process*" (see figure 1[5]). The objective of mechatronics is to design better products and production systems by making optimal use of the possibilities of mechanics, electronics and software.

This approach is not new, in fact, many companies have already been implementing mechatronic concepts for many years. However, the awareness of mechatronics as a competitive edge in the design of products and production systems is growing.

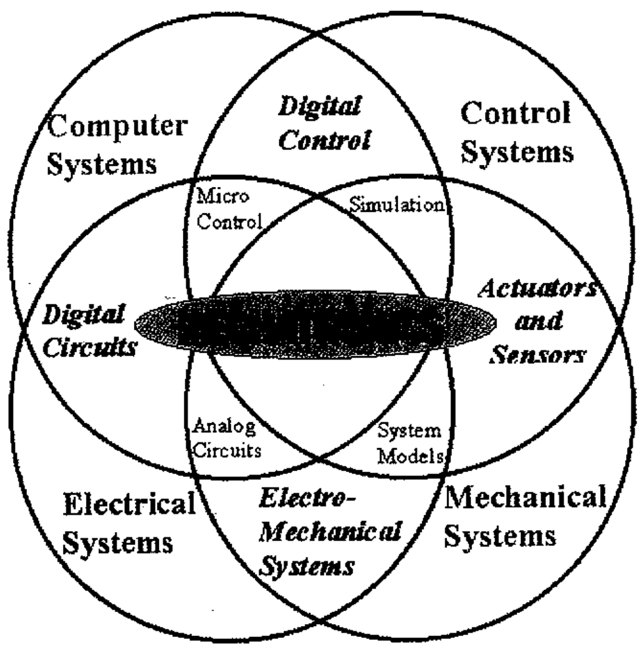

Figure 1: Mechatronic concepts[5]

3. Evolution of Mechatronics

Mechatronics grew out of the use of computer based technologies to provide increased levels of performance from mechanical systems in the area of machine tools and subsequently covered a wide range of engineering systems and products. This came from realisation, largely by mechanical engineers, that developments in electronics and software could support significant performance enhancements in purely mechanical or existing electromechanical systems. Electronics and software meanwhile continued along their own separate development paths Today mechatronics base remains substantially within mechanical engineering although it has substantially increased to various fields.

The evolution of mechatronics has gone through three stages as can be seen in figure 2. The first stage corresponds to the 1970's around the introduction of the word. During this stage, technologies used in mechatronics systems developed rather independently of each other and individually. Mechatronics was concerned mostly with servo technology used in products such as automatic door openers, vending machines, and auto focus cameras. Simple in implementation, the approach encompassed the early use of advanced control methods.

The second stage took place in the 1980s with a synergistic integration of different technologies, the notable example being in optoelectronics (i.e., an integration of optics and electronics). The concept of hardware/software co-design also started in these years as shown by figure 3.

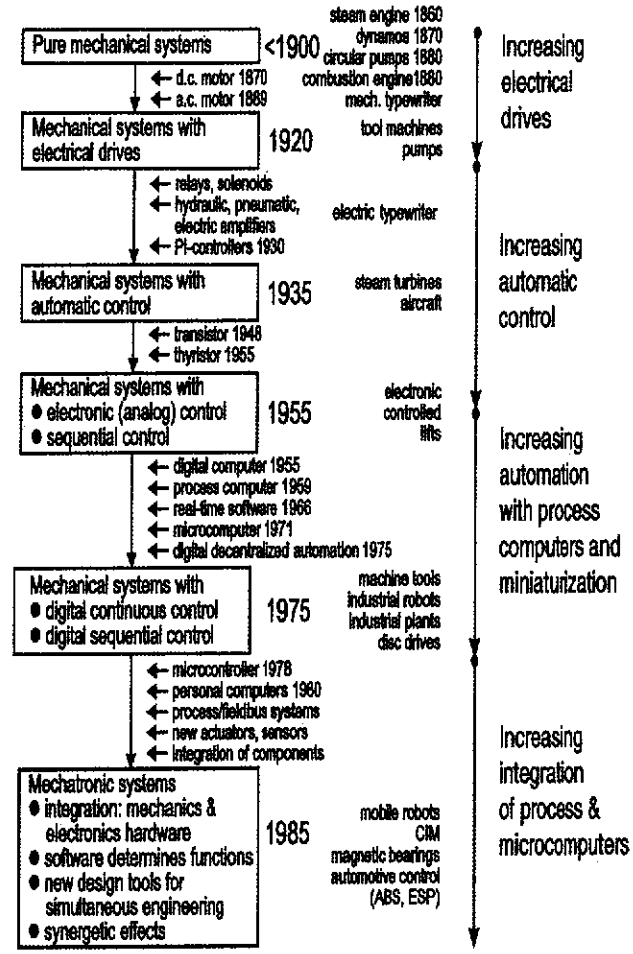

Figure 2: Historical development of mechanical, electrical and electronics systems[6]

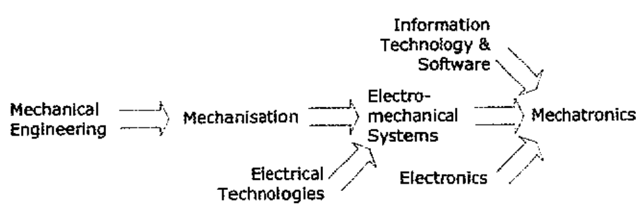

Figure 3: Evolution of mechatronics[4]

As information technology was introduced, engineers began to embed microprocessors in mechanical systems to improve their performance. Numerically controlled machines and robots became more compact, while automotive applications such as electronic engine controls and antilock-braking systems became widespread.

The third stage, in the 1990s, can be considered as the start of the mechatronics age. The most notable aspect of the third stage is the increased use of computational intelligence in mechatronic products and systems[6]. It is due to this development that we can now talk about machine intelligence quotient (MIQ). Communications technology was also added to the mix, yielding products that could be connected in large networks. This development made functions such as the remote operation of robotic manipulator arms possible. At the same time, new, smaller even micro scale sensor and actuator technologies (i.e., micromechatronics) are being used increasingly in new products. Micro electro-mechanical systems (MEMS), such as the tiny silicon accelerometers that trigger automotive air bags, are examples of the latter use.

3.1 Modular mechatronics

A mechatronic approach to engineering design is concerned with the provision of a structure within which the integration of the various technologies can be established and evaluated. In order to achieve this objective a top down and information based strategy is suggested in which the overall system is broken down into a series of blocks or modules. The role of each of these modules is then as follows:

Environment module: The environment module is concerned with those external parameters such as temperature range and load factors which will influence the operation of the complete system. Within the overall design they constitute a series of parameter boundaries within which the system must exist and function. The environment modules must therefore encompass features such as standards and codes of practice.

Assembly module: The assembly module represents the physical realization of the mechanical and structural elements of the system. It is primarily concerned with parameters such as the properties of materials, structural behaviour, form and context. Inputs to the assembly module consist of the motions provided by the actuation modules together with the conditions defined by the environment module. Output from the assembly module is provided by the measurement module. As the assembly module is concerned with the appearance of the system it must also contain an aesthetic element.

Measurement module: This is concerned with the gathering of information about system status and behaviour. Input parameters are physical properties of the assembly module while output parameters are concerned with the nature of the information to be transmitted.

Communications module: This is concerned with the transmission of information between modules within the system. Input and output conditions relate to the nature of the information to be transmitted, the distance over which it is to be transmitted and the operating environment.

Processor module: This is concerned with the processing of the information provided by the measurement and interface modules. Input parameters include measured parameters and demand settings together with system parameters such as speed of operation. The outputs from the processor modules determine the operation of the actuation modules and provide information to the interface modules.

Software module: This contains the operating instructions and defining algorithms for the system and controls the operation of the processor module. The nature and form of the software module is linked to that of the associated processor module.

Actuation module: This represents the 'muscle' required in the system to change system conditions. Input conditions are set by the output of the processor module and outputs are defined by the type of motion required.

Interface module: This is concerned with the transfer of information between levels within the system and at the highest level, with providing the necessary man-machine interface for the transfer of user information. Inputs and outputs are concerned with the nature of the information transfer involved.

4. Mechatronics Education and Research in South Africa

South Africa is a developing country that mainly uses imported manufacturing technology. In most cases the human resources requirements is imported to work on and to service these equipment. The automotive industry for example is one of the fastest growing industries in South Africa. The automotive industry is experiencing increased product complexity based on the development of electronics, micro-controllers and distributed networks systems. The automotive industry is currently in a fast and spectacular evolution towards the intelligent, safe, environmental, interconnected, and economic car. Electronics is at the basis of most of this development. New features such as automatic intelligent parking assist, blind-spot information system, navigation computers with real-time traffic updates, not to mention electronically controlled brakes or electronic power steering, are out and running in most recent high-end cars. This development is going to continue with new functionality being adopted not only in premium cars but also in the mass-market.

In South Africa, major automotive manufacturers such as BMW, Ford and Nissan are found in the close vicinity of Pretoria, while Daimler Chrysler (Mercedes) is close to East London, VW close to Port Elizabeth and Toyota in Durban. Furthermore, South Africa already supplies the right-hand drive BMW's, Toyota Corolla, Golf's and C class Mercedes Benz cars to the world market. This implies that South Africa is meeting the stringent quality standards and quantities by using mainly manual unskilled labour. Future models will include a much higher level of technical sophistication and would require human resources trained to meet these standards. Mechatronics and autotronics will feature more prominently in the next generation of cars and manufacturing equipment[7]. This creates a demand for human resources development in which partnerships between industry, research and academic institutions become crucial. South Africa is furthermore seen by the world as having a fast growing economy with a stable socio-economic climate, which is ideal for the establishment of manufacturing plants.

Various institutions (both traditional universities and universities of technology) in South Africa are engaged in mechatronics education and research. Institutions such as Tshwane University of Technology, University of Stellenbosch, Nelson Mandela Metropolitan University and University of Cape Town do offer mechatronics as a specialised degree programme, whereas other universities do offer mechatronics as a specialised subject in their BSc/BEng courses. There also have been initiatives such as annual Siemens Cyber Junk Yard competitions which is an inter-tertiary challenge aimed at exposing and stimulating real-life mechatronic engineering projects. Various educational institutions in South Africa received a sponsorship of Siemens equipment and were tasked with the design, building and implementation of a machine that will be able to demonstrate how well it can accomplish a pre-specified assignment[8].

The South African government is also promoting excellence in mechatronics and manufacturing by using the National System of Innovation that comprises centres of excellence and research chairs based at universities. There are other national strategies such as advanced manufacturing and technology strategy (AMTS), the tooling initiative, as well as the Productivity Institute of South Africa, Council for Scientific and Industrial Research (CSIR), Mintek, etc. which have provided focus on mechatronic related projects in South Africa. The thrust of the AMTS is to strengthen the competitiveness of the manufacturing sector through the implementation of targeted, high-impact projects in areas such as industry development, world-class manufacturing, innovation and research and development (R&D) as well as the development of human resources. The strategy is being expedited through the AMTS implementation unit, established and supported by the Department of Science and Technology. The AMTS has established the advanced manufacturing technology laboratory (AMTL) for robotics and mechatronics at NMMU to stimulate innovation through the design, development and prototyping of new products, and the development and transfer of relevant skills to support the automotive industry. The centre will be a resource for the entrepreneur and will cater for human resource development, from the entry-level learner to engineer; to problem solving at postgraduate level[9].

Other initiatives to promote research in mechatronics are through research flagship programmes of the AMTS in which mechatronics research projects are undertaken. Various universities and research institutions notably University of KwaZulu Natal, CSIR, Central University of Technology, Nelson Mandela Metropolitan University (NMMU), Stellenbosch University and Tshwane University of Technology have established the advanced robotics and mechatronics research network (ARMRN) to increase collaboration and enhance knowledge sharing in the field of advanced robotics and mechatronics. The ARMRN intends to host annual symposia in robotics and mechatronics to provide a platform to showcase and establish the current state of advanced robotics and mechatronics research in South Africa[10].

5. Case Studies

5.1 Wireless mechatronics controller for camera platform

A typical camera platform that is used in the film industry can be described as a three degree-of-freedom, revolute robotic manipulator. The three degrees of freedom correspond to the yaw, roll and pitch orientations of the camera platform. The base is normally fixed on a stationery or moving platform. The camera platform consists of three links and three joints that can be used to mathematical model the kinematics and dynamics behaviour of the camera platform.

The mathematical model is not presented in this paper, however it is used to optimize the software that controls the camera platform e.g. to avoid singularity configurations, where a camera platform looses a degree of freedom.

The skill of the camera operator in controlling the orientation of camera platforms in the film industry is one of the crucial factors in producing movies with precision cinematography. Some film footage requires landscapes that make it difficult for the camera operator to efficiently operate the camera platform e.g. an inclined mountain terrain with surrounding trees and bushes. These scenes often require tele-operation of the camera platform.

Tether tele-operation increases the time required to set-up the camera platform for the scene shoots, and hence increases the cost of making a movie. Tether connections limit the manner in which the camera platform can be mounted in order to achieve the best scene shooting. The development of a wireless mechatronics controller for camera platforms that was carried out in conjunction with the New Zealand film industry was reported by Tlale et al.[11].

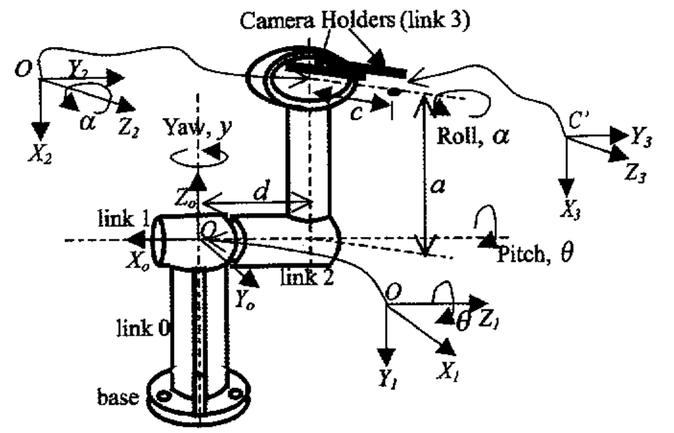

Figure 4: Schematic diagram of a camera platform

Figure 4 shows the hard-wired camera platform with its control box and the wires that connect them. A wireless mechatronics controller is developed in order to get rid of the connecting wire, i.e. the wire harness must be replaced by a wireless communication link[11]. The developed system that incorporates a wireless mechatronics controller must maintain the functionality of the hard-wired system and give better performance. Hard-wired system consists of two hand-wheels that control the roll and the yaw orientations. The joystick is used to control the pitch orientation. The two hand-wheels have adjustable viscous dampers to maintain the feel of a typical hand-wheel for conventional camera platforms. The two hand-wheels, the joystick and associated electronics are mounted on a separate control box from the camera platform. The encoders produce a quadrature signal, which is used for position, speed and direction sensing.

Figure 5 shows the developed wireless mechatronics controller, servo-controller implementing a PID routine is used to control the position and velocity of the motors within the required response time, with determinism and stability.

The control system is designed so as not to respond to control signals above a certain threshold e.g. when the hand-wheels are being freely rotated at high rotational speed.

The developed wireless communication system is required to send the position, speed and time information to the camera platform servomotor controller communication system. Several mechatronics techniques are implemented in order to design the wireless mechatronics controller for the camera platform for optimum control.

One of the strategies implemented is to make the platform end intelligent, and to process the raw data on the operator end so as to send as minimum data as possible across the wireless network, to efficiently control the camera platform. In order to reduce the rate of data that the wireless communication system is to handle, firstly, a step-down gear mechanism (with fixed

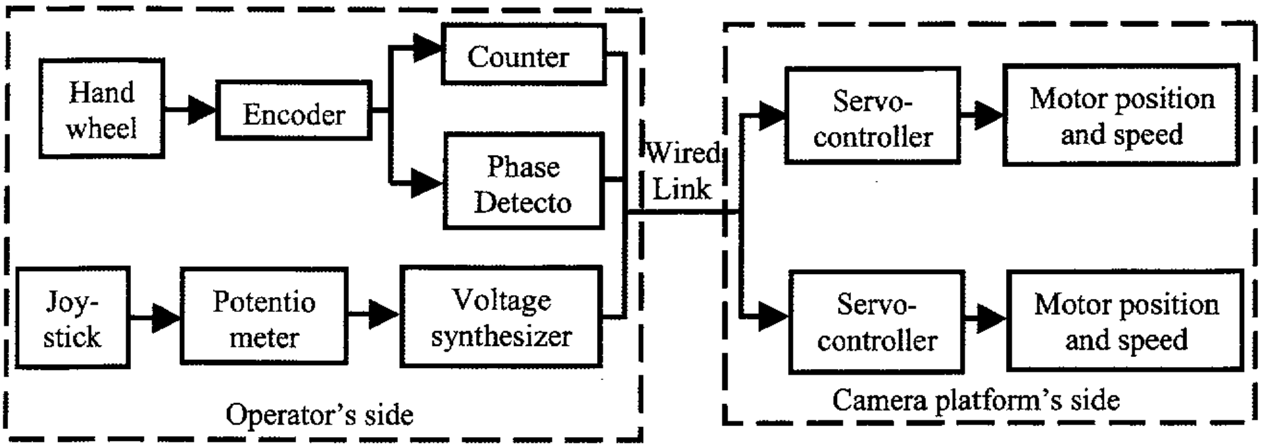

Figure 5: Control of a hard-wired camera platform

step-down ratio of ¼) is implemented on the operator side. The step-down gear mechanisms are inserted between the hand-wheels and their relative encoders. This reduces the amount of data that is needed from the encoders in order to optimally control the camera platform.

The servo-controller algorithms are changed accordingly to accommodate this change. Another strategy that is implemented is to design the software architecture of the wireless camera platform so as to be able to control the data throughput of the system.

Figure 6 shows a schematic of the architecture that is implemented. Both the operator and camera platform ends are fitted with embedded TCP/IP hardware. TCP/IP protocol is implemented as a network protocol under 'peer-to-peer' communication mode between the two communication nodes. Mechatronics design of the camera platform architecture is implemented by using software timers to trigger data acquisition and data transfer. On the operator side, a timer is used in order to trigger data acquisition from encoders' and joystick's circuitries to the dynamic RAM and receiver memory buffer. On the camera platform side, a timer is implemented in order to output data to the servo-controller from the receiver's buffer memory and dynamic RAM.

Thus, the wireless system throughput is determined by the frequency of the timer. The frequency of the timers is variable (software) and can be adjusted to give optimum performance. The timers are programmed in such a way that the memory usage was a maximum in the buffers and the RAM.

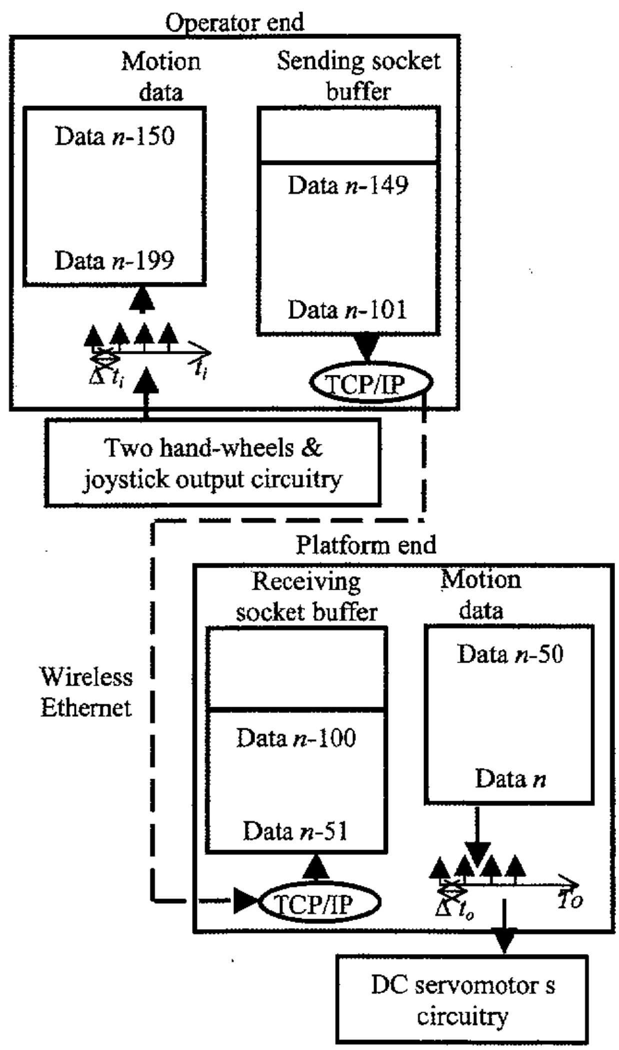

Figure 6: Flow of Control data from encoders to the DC motors' servo-controllers in the developed wireless mechatronics controller

5.2 Omni-directional AGV platforms

Automated guided vehicles (AGVs) that are controlled in real-time have become an integral part of modern reconfigurable manufacturing systems. They are used extensively in flexible manufacturing systems (FMS) to move parts and to orient them as required[12]. Many designs of omni-directional or near omni-directional vehicles have previously been proposed. Omni-directionality is the ability of mobile vehicle to move instantaneously in any direction. Different techniques can be used to achieve omni-directionality.

Two omni-directional vehicles designed and controlled implementing distributed mechatronics controllers have been described by Kumile and Tlale[13]. Omni-directionality is achieved by implementing mecanum wheels and normal wheels in each respective vehicle. The developed AGV design uses both normal and mecanum wheels.

Mecanum wheels consist of a number of rollers around the circumference of the wheel hub. The rollers are orientated at some angle ($\alpha = 45°$ in our case) from the axis of rotation of the wheel. Guidelines on the design of mecanum wheels can be found in Borenstein et al.[14] Rollers can rotate about their own axis. Mecanum wheel design that uses rollers that are held in the middle is implemented. The advantage of this design is that the wheels produce less friction while driving on general surfaces. The mecanum wheel design for this project is based on this improved wheel design. Figures 7 (a) to (d) show the mecanum wheel design and the developed mobile robot.

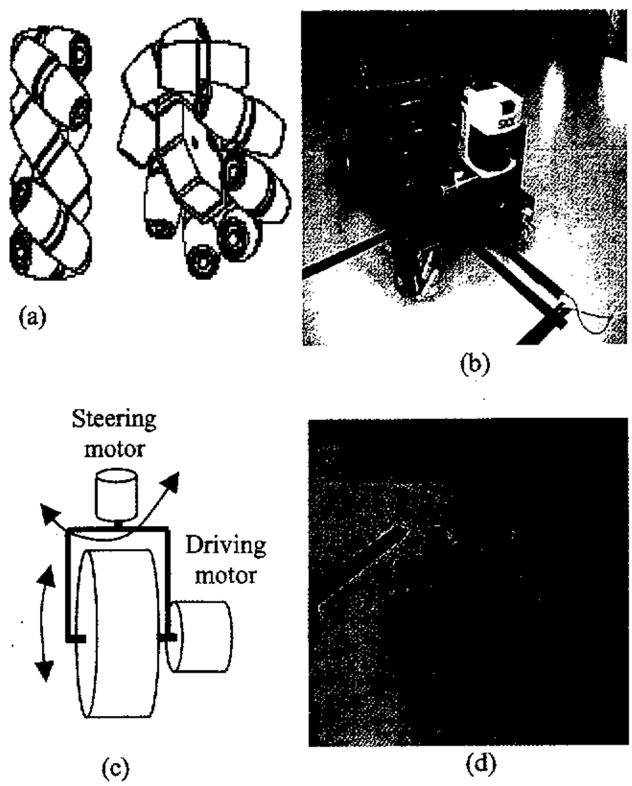

Figure 7: (a) mecanum wheel design (b) mecanum wheeled omni-directional AGV (c) concept of omni-directionality using normal wheel (d) normal wheeled omni-directional AGV

With free rotating rollers any combinations of forward, sideways and reverse movement are possible with less friction as shown in figure 8. Mecanum wheels are used to steer the AGV in the desired direction, mostly when the AGV is moving on smooth surfaces, such as those found indoors. Normal wheels are used to move the mobile AGV when it is moving on rough terrain, such as those found in outdoor environments. Pneumatic cylinders are used to change from mecanum wheel set to normal set of wheels in outdoor environments.

5.3 Hexapod wall climbing robot

Repetitive tasks have been automated using robotic system in order to reduce the operational time, improve quality and flexibility of manufacturing systems. Most of such tasks and their environments usually require horizontal mobile wall-climbing robots that have the capability to carry tools and equipments to perform the required tasks provide a more cost effective solution to the problem[15]. Such robots are termed service robots by the international service robot association (ISRA)[16]. They are defined as machines that sense, think, and act to benefit (or extend) human capabilities and to increase human productivity.

A mobile robot with the capability of climbing walls or other inclined surfaces and carrying out various tasks must be light enough so that its weight does not strain the structure, yet rugged enough to work in an exterior environment and powerful enough to carry the necessary payload. It must also have the ability to climb over obstacles since the various surfaces like building walls, etc. will normally have protrusion such as pipelines, window frames, etc and to manoeuvre reliably within an undefined environment.

It must be able to change surfaces e.g. changing between perpendicularly juxtaposed walls, or manoeuvre on uneven walls e.g. a curved wall. Clearly, wall-climbing robots need not be able to undertake all of these tasks and some applications may require only one or two such capabilities.

The developed modular wall-climbing robot implements biped robotics systems as its modules (refer figure 9). Each biped robotic system consists of two articulated legs. The minimum number of actuators and sensors in one biped module is sixteen. Addition of modules increases the number of actuators to be controlled and the number of sensors to be monitored exponentially. This presents challenges in the design of the controller for such mechatronics systems. Implementing a central microcontroller system (embedded control system) will result in hard-to-trace, untidy connection wires.

Troubleshooting and software code to control the robot will be very difficult to develop. Real-time control of the developed wall-climbing robot becomes complicated due to many actuators and sensors

In this paper, a distributed mechatronics controller of such system is presented. The controller is based on controller area network (CAN) technology. Disadvantages of distributed control systems are the delays introduced in the systems because of distributed control architecture. This includes problems that are concerned with timing, such as lag effect of zero-order hold (ZOH) and problems with respect to motion control. Problems of time variations can also be partially tackled in control design, e.g., by using robust control so that deviations from nominal timing can be tolerated[17]. Modular design of wall-climbing robot implementing two articulated legs per module (biped robotic modules) is reported in Tlale et al.[18] (refer figure 10).

Modular design improves wall-climbing robot's manoeuvrability and flexibility during surface changes or whilst walking on uneven surfaces. Design of articulated legs implements four motors to control the posture of the vacuum cups in order to achieve the best possible contact with the surface. Each leg can contain more than five sensor for effective feedback control, and additional sensors such as gyros, CCD sensors, etc. can be fitted on a module depending on robot's application. As the number of modules used in the design of the robot is increased, the number of actuators and sensors increase exponentially. This necessitates the development of the distributed mechatronics controller of such systems.

6. Summary

In this paper, the description of mechatronics as a concept has been presented. The historical development and evolution perspectives of mechatronics were articulated.

The objective of this paper was to present a generic philosophy of mechatronic concepts as utilised in product design. The description, history and evolution of mechatronics are described as articulated through research findings worldwide. The scope of mechatronics education and research initiatives within South African tertiary institutions has been highlighted. Several research case studies undertaken by the authors and collaborators have been described to further enhance the understanding of the

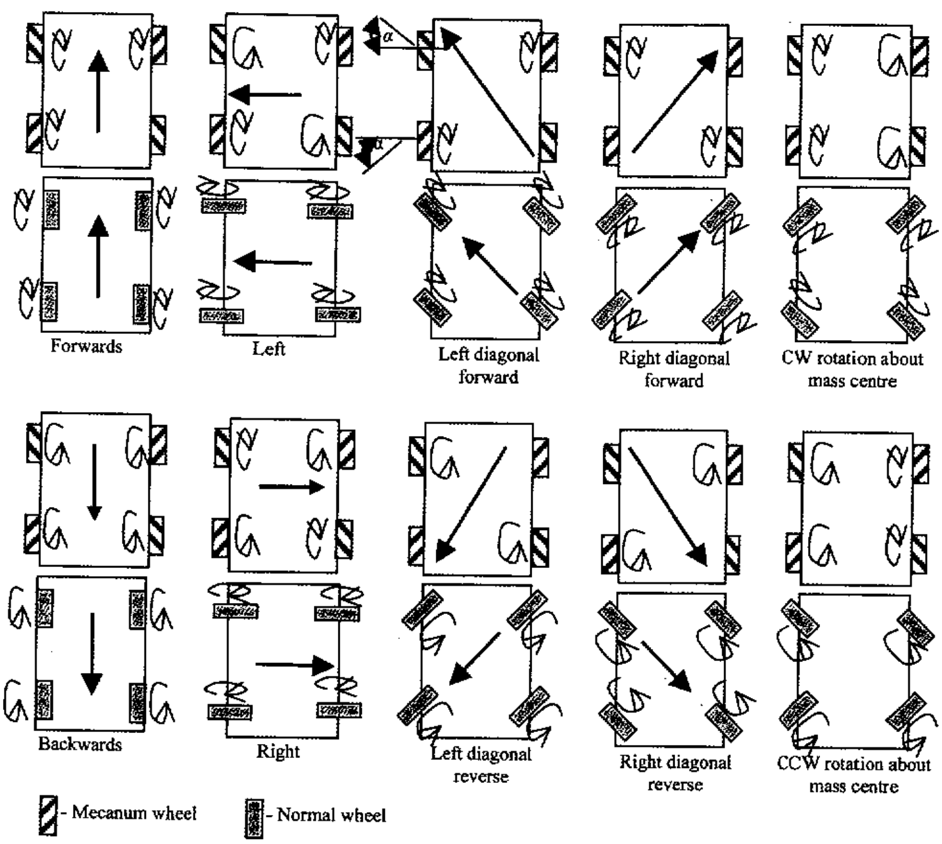

Figure 8: Directional control of omni-directional AGVs implementing mecanum wheels and normal wheels (direction of rotational speeds of wheels and mecanum wheels' roller angle α shown)

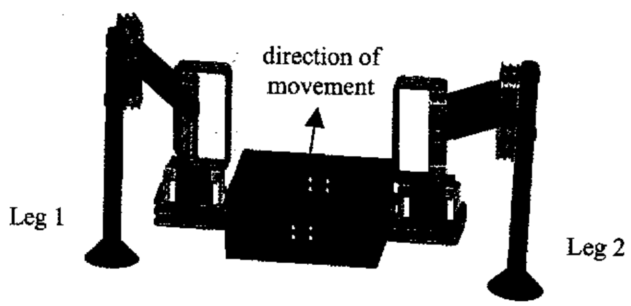

Figure 9: The biped module for wall-climbing robot

mechatronic philosophy in product design and development.

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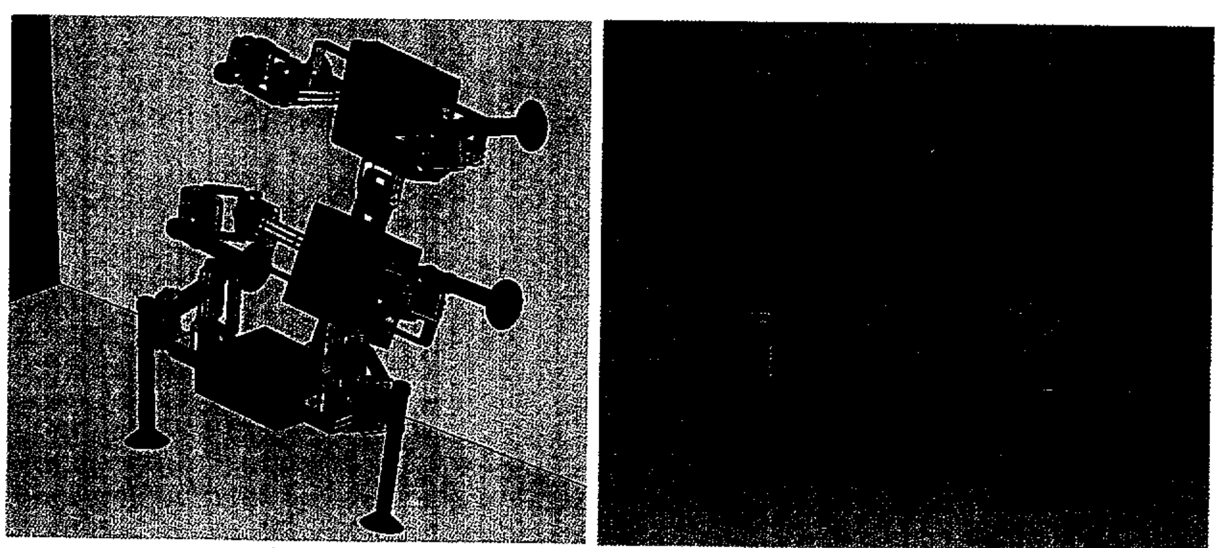

(a) (b)

Figure10: (a) concept of modular-wall-climbing robot (b) the developed wall-climbing robot

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