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The Internet of Things – The future or the end of mechatronics

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ABSTRACT

The advent and increasing implementation of user configured and user oriented systems structured around the use of cloud configured information and the *Internet of Things* is presenting a new range and class of challenges to the underlying concepts of integration and transfer of functionality around which mechatronics is structured. It is suggested that the ways in which system designers and educators in particular respond to and manage these changes and challenges is going to have a significant impact on the way in which both the *Internet of Things* and mechatronics develop over time. The paper places the relationship between the *Internet of Things* and mechatronics into perspective and considers the issues and challenges facing systems designers and implementers in relation to managing the dynamics of the changes required.

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1. Introduction

The concept of mechatronics was introduced nearly 50 years ago in order to express and reflect the increasing use of computers such as the PDP series for the control of a range of essentially mechanical processes and systems [1–3]. Further, the introduction and increasing availability at reducing cost of integrated circuit technologies, and the advent of the first microprocessors, offered the potential to create new forms of integrated electronics which would form the core of new and novel systems in applications such as manufacturing and vehicle technologies and result in new ranges and types of consumer goods such as the Sony *Walkman* [4].

Fig. 1 shows the results of a simple search on Google Scholar for the number of articles incorporating either or both of '*mechatronic*' or '*mechatronics*' in their title in the period from 1969 to 2013. Fig. 2 shows the results of a similar but more sophisticated search using *Web of Knowledge* and *IEEE Xplore*. Taken together, these figures clearly show that the development of the mechatronics concept as an integrating theme or philosophy within product and system design did not really come to the fore until the early 1980s. Around the same time more sophisticated microprocessors, along with other electronic components such as Field Programmable Gate Arrays (FPGAs), became available and enabled the development of increasingly complex and powerful mechatronic systems, facilitating their introduction into a range of consumer goods, vehicles and manufacturing technologies.

It was also around this time that academic programs and courses, at both the masters and undergraduate levels, in mechatronics began to be introduced on a significant, and worldwide, basis.

Thus, by the end of the 1980s, the underlying concepts of mechatronics were perhaps felt to have been defined, and that it was then more a matter of establishing rather than developing the discipline [1,5–10].

Subsequent years, and in particular developments in information technology and electronics, have suggested that this view was misplaced and that instead of consolidating around a specific expression of the mechatronics concept, there has been an increasing diversification of both content and concept. This can be seen by reference to Fig. 3 which shows the spread of topics identified as mechatronic in a keyword search using *Web of Knowledge* and *IEEE Xplore*.

The differential rate of development in the core mechatronic subjects of information technology, electronics & computing and mechanical engineering is then suggested by Fig. 4. Though this figure is highly subjective, and indeed personal, in nature, the extent of development since the inception of the mechatronics ideology can perhaps best be illustrated by the comparison of

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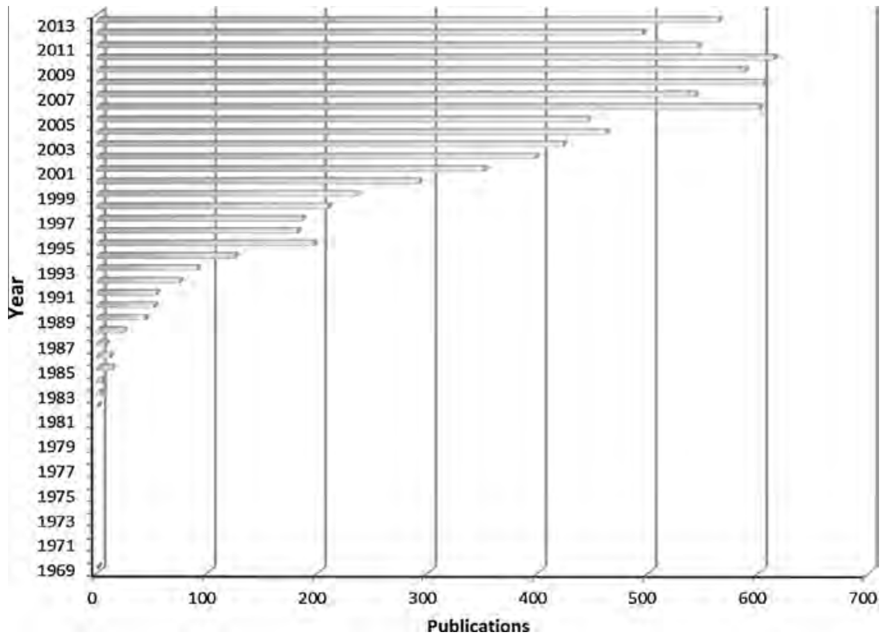


Fig. 1. The results of a search on *Google Scholar* for articles with either or both of '*mechatronic*' or '*mechatronics*' in their title in the period 1969–2013.

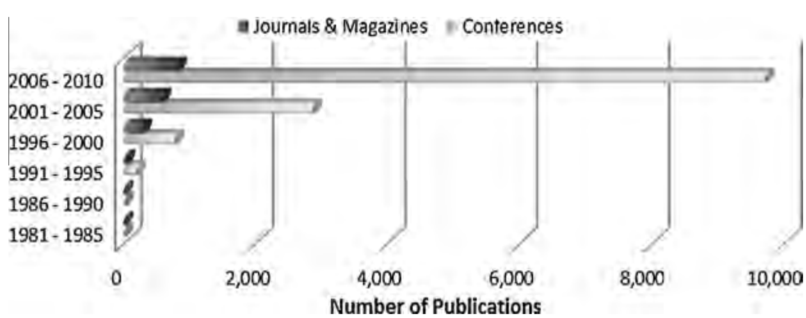


Fig. 2. The results of a search using *Web of Knowledge* and *IEEE Xplore* for articles with either or both of '*mechatronic*' or '*mechatronics*' as a keyword in the abstract in the period 1981–2010.

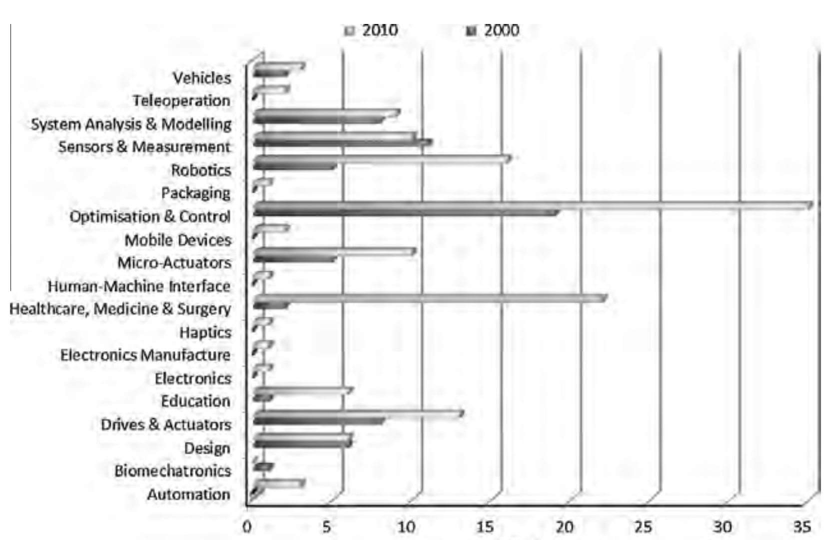


Fig. 3. Mechatronics subject areas derived from a keyword search using *Web of Knowledge* and *IEEE Xplore* for the years 2000 and 2010.

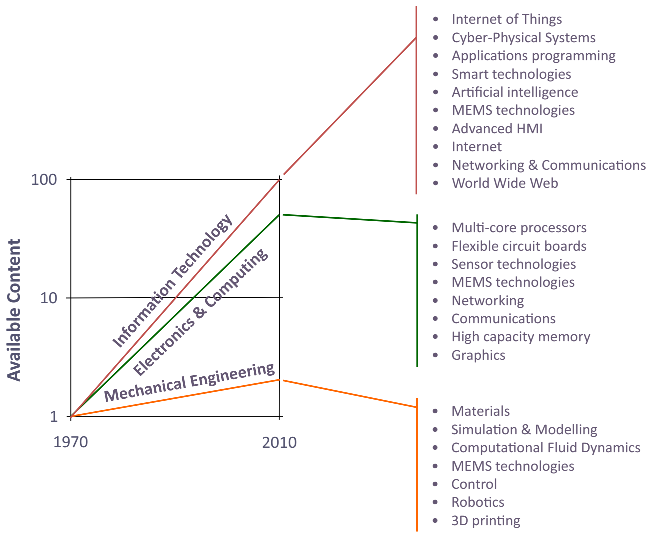


Fig. 4. Development and diversification of core mechatronics technologies in the period 1970–2010.

two leading technologies of their era, the Apollo control and guidance computer from 1969 and the iPad *Air* from 2013 as shown in Table 1.

Perhaps more importantly for the future of mechatronics, recent years have seen a shift from systems based around the interconnection of physical components in which transmitted data has been used to facilitate control, as for instance in the case of the simplified model of a mechatronic system or sub-system shown in Fig. 5, to systems in which information is at the heart of the system and serviced by smart objects as suggested by Fig. 6.

An underlying concept of such cloud based or *Internet of Things* system models [11–22] is that of treating information as a commodity whose value is determined by user or system need or context, allowing for negotiation between system components as required. In illustration, consider the following:

An individual has a meeting for which she is required to catch an earlier train than normal. She therefore sets her alarm clock accordingly. This is detected by the heating system which autonomously determines the time at which it should come on, and for which rooms, utilising reference data from external sensors and the local weather station.

During the night, a road traffic incident occurs and the normal route to the station starts to experience significant delays. This is detected from real-time information transmitted by road users, and the alarm clock and heating system autonomously adjust themselves to an earlier time. A new route avoiding the incident is loaded into the navigation system in the car.

On waking, there is a text message waiting explaining why the alarm time has been reset and providing an update on the traffic situation.

Here, the information regarding the traffic situation has been given both context and value by the user imposed criteria of the imperative that they catch the early train.

The rate and extent of developments in these areas may be seen in Figs. 7 and 8 showing the increase in the number of publications using *Internet of Things* in the title and the rate of increase of use of internet connected devices and the ubiquity of wireless services [23].

It is here suggested that this shift in emphasis in the way that systems are designed and configured is going to impact on the way that mechatronics is viewed and considered, and hence in the way that systems are designed and implemented. The paper

Table 1
Comparison between Apollo guidance computer and iPad Air.

Apollo guidance computer	
Invented by	MIT Instrumentation Laboratory
Manufacturer	Raytheon
Introduced	August 1966
Discontinued	July 1975
Type	Avionics Guidance Computer
Processor	Discrete IC Resistor-Transistor Logic (RTL) based
Frequency	2.048 MHz
Memory	16-bit wordlength, 2048 words RAM (magnetic core memory) 36,864 words ROM (core rope memory)
Ports	Display & Keyboard (DSKY) Inertial Measurement Unit (IMU) Hand Controller Rendezvous Radar (CM) Landing Radar (LM) Telemetry Receiver Engine Command Reaction Control System
Power	55 W
Weight	70 lb (32 kg)
Dimensions	24 × 12.5 × 6.5 in. (610 × 320 × 170 mm)
iPad Air	
Type	Tablet computer
Power	Built-in rechargeable Li-Po battery 8827 mA h, 3.7 V, 32.4 W h (117 kJ)
System-on-chip	Apple A7 with 64-bit architecture and Apple M7 motion co-processor
CPU	1.4 GHz dual-core
Memory	1 GB RAM
Storage	16, 32, 64 or 128 GB flash memory
Display	9.7 in (250 mm) 2048 × 1536 px colour IGZO display (264 ppi) with a 4:3 aspect ratio Oleophobic coating
Input	Multi-Touch Screen Headset Controls M7 Motion Co-Processor Proximity & Ambient Light Sensors 3-axis Accelerometer 3-axis Gyroscope Digital Compass Dual Microphone
Camera	Front:1.2 MP, 720p HD Rear:5.0 MP AF, iSight with Five Element Lens, Hybrid IR filter, video stabilisation, face detection, HDR, $f/2.4$ aperture
Connectivity	Wi-Fi and Wi-Fi + Cellular
Dimensions	240 × 169.5 × 7.5 mm (9.4 × 6.67 × 0.3 inches)
Weight	Wi-Fi:469 g (1.034 lb) Wi-Fi + Cellular:478 g (1.054 lb)

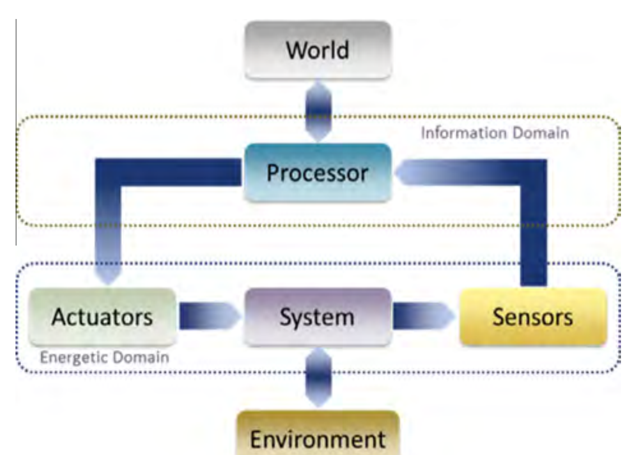


Fig. 5. A conceptual model of a conventional mechatronic system.

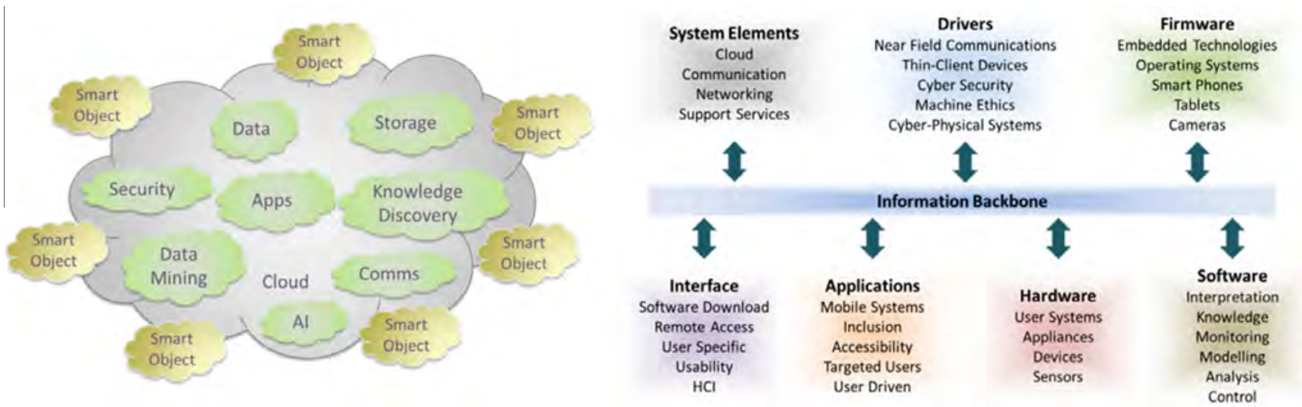


Fig. 6. Cloud based systems, or the *Internet of Things.*

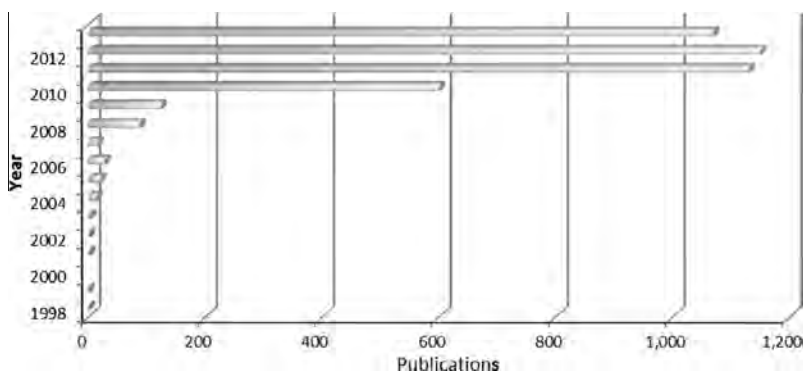


Fig. 7. Results of a search on *Google Scholar* for publications using *Internet of Things.*

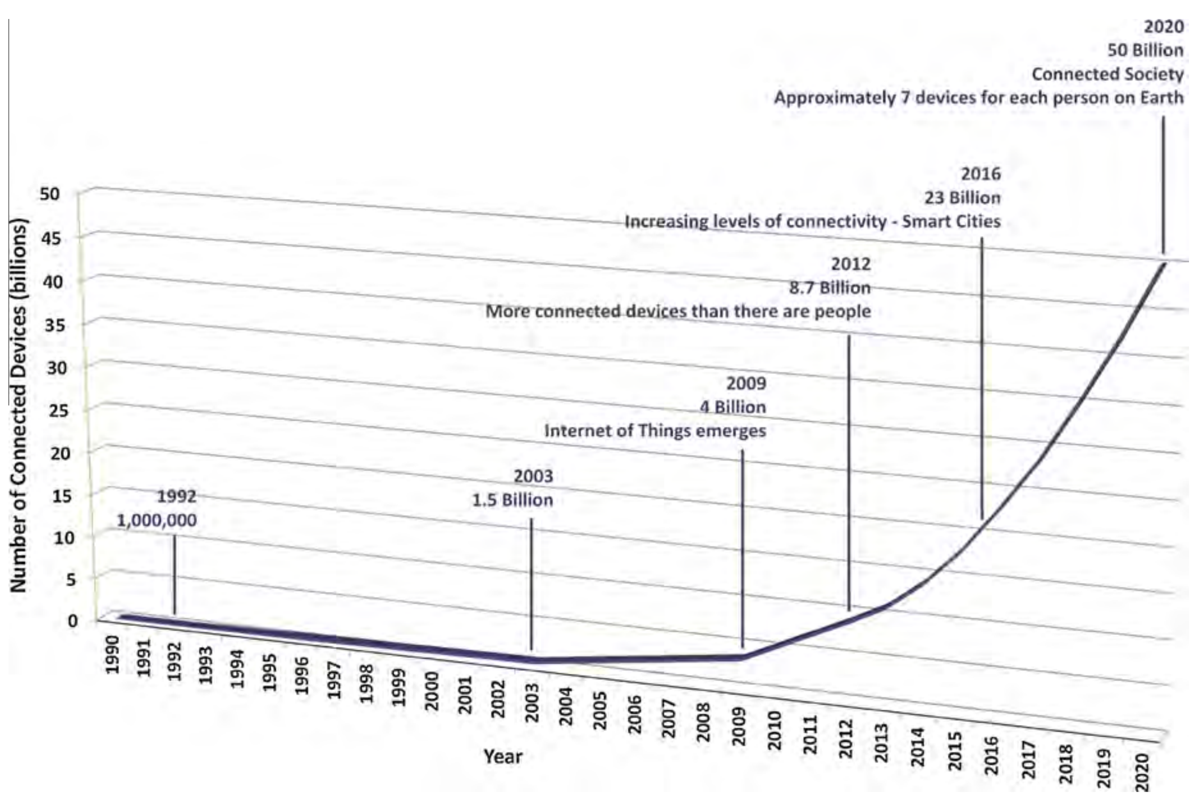


Fig. 8. Growth in connectivity.

uses current research by the authors in areas such as systems and design, components and devices, security and digital forensics and sustainable systems together with a commercial prospective to consider the future prospects for mechatronics in light of developments such as the *Internet of Things*.

2. Impact of the *Internet of Things*

The model of the *Internet of Things* (IoT) used here is essentially that of Fig. 6 in which information that resides in the cloud is autonomously accessed and utilised by smart objects connected to the cloud via the internet. The cloud also contains, and supports access to, a range of services and facilities which can be drawn upon on demand by a cloud client in the form of a connected smart object. These cloud based artefacts are summarised in Fig. 9.

The IoT cloud itself can also be considered at a number of levels. For instance, consider the environment of a house as represented by Fig. 10(a) in which the basic physical components are linked to a range of activities, systems and artefacts. In Fig. 10(b), this is shown reconfigured to create a local cloud environment encompassing the house along with external services and provisions, which may themselves be cloud based or oriented. Finally in Fig. 10(c) the interconnection of a number of house clouds with shared services to form a smart grid which can itself be considered as a local cloud, again serviced by external cloud based entities.

Referring once again to Fig. 6, the smart objects used to service the cloud, and to provide the underlying connectivity of the *Internet of Things* range from devices such as smart phones and tablets to artefacts such as appliances and vehicles and components such as sensors and actuators. Configuration of the resulting system is then supported by the applications (Software as a Service (SaaS)), platform (Platform as a Service (PAAS)) and infrastructure (Infrastructure as a Service (IaaS)) components of Fig. 9 and a combination of person-to-person (P2P), machine-to-person (M2P) and machine-to-machine (M2M) communication as per Fig. 11 [24–29].

This allows for a range of configurable devices to be readily connected via the internet to create customised information based systems, reconfigurable in relation to need. This is further supported by the availability of technologies such as the Arduino and Raspberry Pi computers and configurable components such as the Ninja Blocks concept.

Integrating the above with the structure of Fig. 10, then functionality can be considered in relation to a series of layers or levels as follows:

Layer 1	Embedded and networked sensors and actuators supporting the development of context aware devices.
Layer 2	Data capture, processing, storage and analysis, including aspects of data mining and knowledge discovery, at a local level to service local systems and provide enhanced responses to time-critical and context dependent data. In the context of Fig. 10, this would be in relation to both the house and the local cloud components.
Layer 3	Central data systems including advanced computing, storage and analysis processes to support both the creation of new knowledge and its transfer between and among systems, as for instance in healthcare. In the context of 10, this is associated with both the local cloud and the external cloud based systems and has links into Big Data structures and concepts.
There is also the potential to consider a further, integrating, level which encloses the previous 3 levels, namely:	
Layer 4	The user driven development of new and innovative applications and services.

These relationships may then be expressed by Fig. 12.

2.1. Challenges for the Internet of Things

In its report "*A roadmap for interdisciplinary research on the Internet of Things*" [30], the '*Internet of Things Special Interest Group*' of the Technology Strategy Board in the UK identified key areas for research as set out in Table 2.

It is perhaps interesting to note that the emphasis in Table 2 is not on the nature of the technologies associated with the IoT, but the ways in which those technologies is used in relation to and support of individual users. Where technology is concerned, the

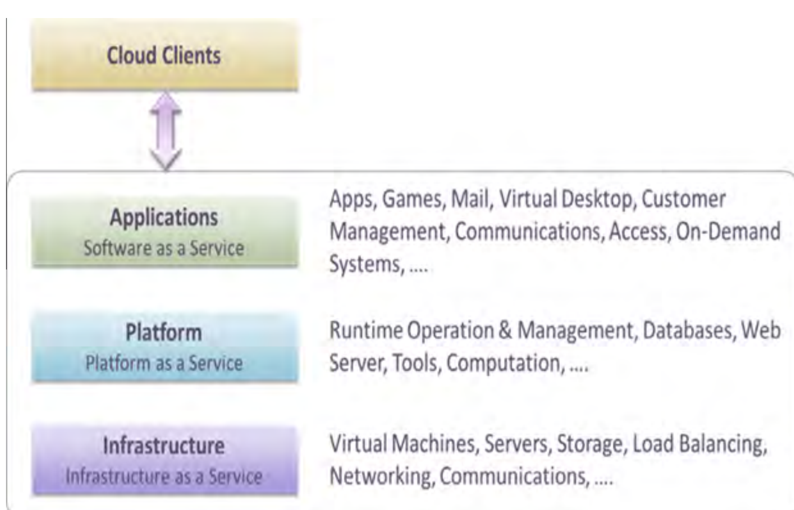
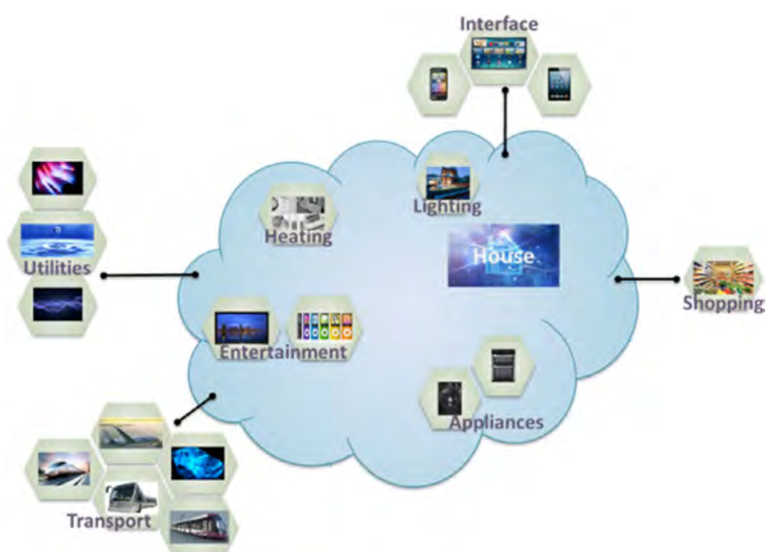
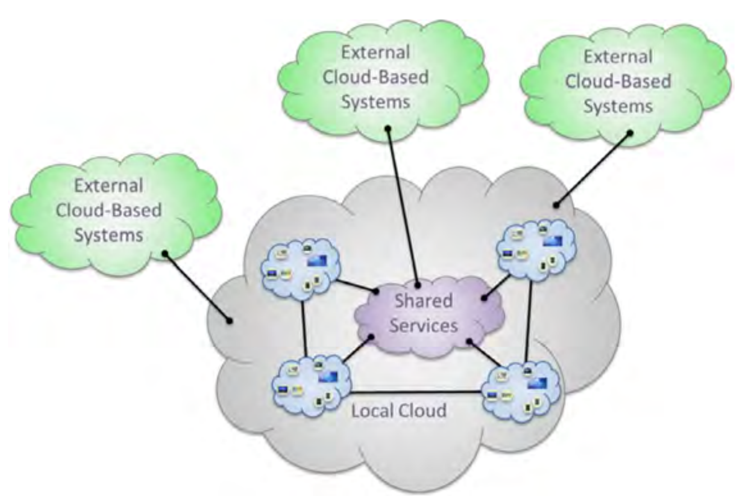


Fig. 9. Cloud based artefacts, services and infrastructure.

(a) Basic, non-Cloud configuration



(b) The house as a Cloud



(c) Integrated, and multi-layered cloud environment incorporating smart grid concepts

Fig. 10. Layered cloud architecture.

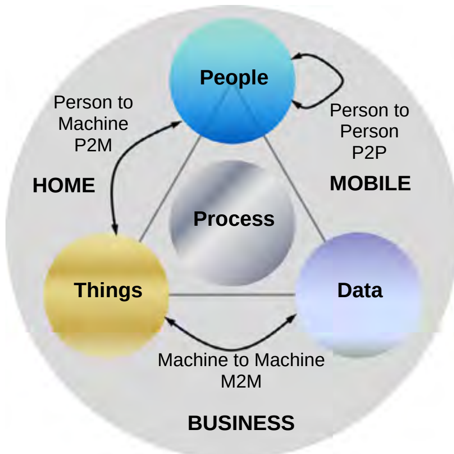


Fig. 11. *Internet of Things* connectivity.

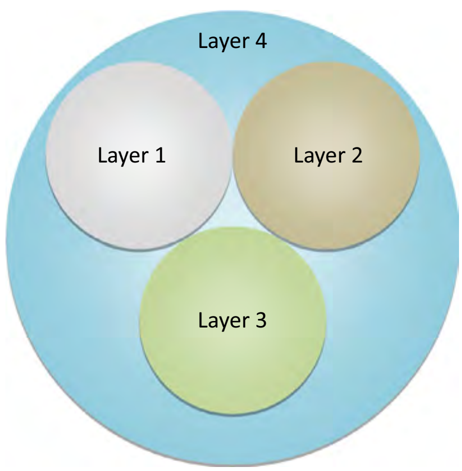


Fig. 12. Functionality within the *Internet of Things*.

emphasis is on operation as part of an interconnected network of devices and the means by which this is achieved.

In relation to the economics of the IoT, in 2013 CISCO suggested [31,32] that there is in excess of $14 trillion of value at stake globally over the coming decade and that this can be primarily accessed by a company:

- Capturing new value by connecting the unconnected.

  and

- Gaining competitive advantage by taking market share from other companies less able to transform and capitalise on the *Internet of Things*[1] market transition.

Elsewhere, Fleisch [33] has suggested the set of relationships of Table 3.

2.2. A role for mechatronics?

Referring to Figs. 5, 6 and 9 along with Figs. 13 and 14, it is argued that many of the smart components associated with the *Internet of Things* will be essentially mechatronic in nature, and that the hierarchical structures associated with Fig. 5 in particular remain valid. However, that is not to suggest that little will need to change in relation to the perception or perspectives of mechatronics as currently assumed. Indeed it is more likely that there will need to be significant changes to the way mechatronic, and related, systems are designed and configured, and it is these considerations that then form the basis of the discussion in the following sections.

3. Challenges facing mechatronics

3.1. System design and complexity

The ability to handle increasing complexity while managing the transfer of functionality, particularly from the mechanical domain to the information technology and electronics domains, has long been an issue facing system designers [34–36]. As technology has evolved, along with the ability to create increasing volumes of information, the challenges for designers have increased, requiring the wider communication and integration of knowledge and understanding across and between individuals. Further, as has been identified in the previous sections, the nature of systems is also changing with devices, the smart objects and mechatronic artefacts of Fig. 14, now actively seeking out information from within the cloud in order to enable them to complete their tasks [37].

Consider the participatory system shown in Fig. 15 in which the system is essentially defined by the user through the selection and specification of appropriate components which then use context based information, supported by user feedback, to establish the desired outputs [38–51].

Consider now the issues associated with the implementation of a telecare system intended to provide medical information on the status of an individual to facilitate pre-emptive interventions to provide additional support in response to changing need. This has been the subject of research for nearly 20 years, yet the goal of providing systems of the desired capability still seems relatively remote, despite advances in sensor technologies and information processing over that period [52].

Key technical problems in both instances are those associated with the ability to configure the system to the individual and to integrate data over large numbers of individuals to establish generic patterns of behaviour indicative of changes in need. As an aside, personal privacy laws may well have acted as inhibitors on the implementation of many potential developments in this area by making it difficult to assign responsibilities within the context of the system and its operation.

In relation to the ability to match the system to the individual and their environment, the individual sensors around which the system is configured are in the context of Figs. 14 and 15 smart objects configured for data capture which must be positioned appropriately within the environment to ensure their efficacy. Thus the system designer needs to be able to quickly and easily define that environment to allow the system to identify the correct locations for the sensors, and to build appropriate and necessary logic to deal with factors such as erroneous or illegal overlapping detection zones.

Further, there is the requirement that the local system autonomously learns about the individual and their behaviour, and adjusts its responses accordingly. This includes the ability to take account of and accommodate influential external factors such as the weather, including seasonal variations, favoured television and radio programmes and visitors. This suggests that approaches structured around learning strategies, and ontological processes, are likely to be necessary to manage system control and configuration during the utilisation phase of the system.

Next, in order to facilitate the ability of a network of such systems to improve their performance by interchanging information

[1] CISCO actually refer to the *Internet of Everything*!

Table 2
Potential research areas within the *Internet of Things* (after Tafazolli [30]).

Topic						
Governance	Ethical implications	Accountability & liability	Regulatory & standards issues	Digital life & death	Ownership & intellectual property rights	Aligning local, national, regional & global practices & policies
Business	Ecosystems	Value chains, their dynamics	How to create & monetise value	How to measure value		
People	Education	User engagement in design	Understanding attitudes, opinions & behaviours towards the IoT	Impacts on working life	Impacts on everyday life in the household and public space	
Trust	Empowering users & establishment of trust in mechanisms	Privacy & data protection	Safety & protection of the public	Reliability & dependability		
Data	Storage, discovery & federation	Efficient transition between machine & user understandable data	Integrity & quality	Scalable & extensible semantics & ontology	Variable grade security	
Devices & Connectivity	Addressable & seamless connectivity over internet protocols	Networks, devices & repeaters	Mobility & network federation	Energy-efficient operation & energy harvesting	Self-management, reconfiguration, organisation & healing	

Table 3
Value drivers associated with the *Internet of Things* (adapted from Fleisch [33]).

Value driver	Business value	Consumer value	Applications
Manual proximity trigger	Increased transaction speed, accuracy and performance	Increased speed & convenience	• Self-check out • Access control
Automatic proximity trigger	Reduced fraud, process and labour costs Highly granular data for process improvement	Increased convenience	• Asset tracking • Theft prevention in stock taking
Automatic sensor trigger	Increased process efficiency and effectiveness Further improvements in data granularity for process improvement	Increased quality of products & services	• Production monitoring • Condition monitoring • Compliance monitoring • Smart metering
Product security	Reduction in fraud Increased consumer trust	New trust related services	• Anti-counterfeiting • Proof-of-origin • Access control
User feedback	Processes become more accurate, flexible and faster Identification of contacts	Increased convenience Individualised information	• Quality status monitoring • Production monitoring & control • Enhanced systems • Guides • Tagging • Maintenance record
Advanced (mind-changing) feedback	Enables new product features Alignment of business goals Active selection of customers	Improved quality of life and responsibility of actions	• Healthcare • Energy management • Accident recorders • Smart metering

between and among individual systems, and learning from the outcomes, there is a need to introduce rapid data mining and knowledge discovery approaches that support the creation of new knowledge which can be integrated to improve the original systems. Emphasis is thus less on the system components, which would be selected from those available, than on the underlying information infrastructure around which the system is configured, and its means of access, interpretation and analysis. For the designer, this suggests a function-based approach to system design, with components, be they hardware, software or firmware, chosen appropriately to provide the requisite service and functionality [53,54].

In relation to mechatronics, this means that there is a need to provide an increasing range of function based smart devices and components capable of being modified and integrated within a range of systems along with more conventional mechatronics elements. Thus, a modern vehicle contains a number of identifiably mechatronic sub-systems ranging from drive-train management to smart lights and auto-parking systems. These are then integrated into a systems package providing driver information and support, and including monitoring features such as driver alertness and pre-collision detection. Information from individual vehicles, for instance on road and traffic conditions, can then be integrated through the use of vehicle-to-vehicle and other communications to support new and novel approaches to traffic management and control. Indeed, it is not impossible to envisage the vehicle itself organising servicing based on the monitoring of component and other performance, and integrating this with 3D printing, perhaps integrating both mechanical and electrical components and functionality, for parts production at the level of the service provider [55,56].

The challenge for the mechatronics designer is therefore that of extending the underlying design principles of mechatronics, and in particular those associated with the transfer of functionality, to a point where integration at the system level is facilitated. One way that this might be achieved is through the embedding of context awareness and self-knowledge at the level of the device so that its system level role can be established (semi-) autonomously

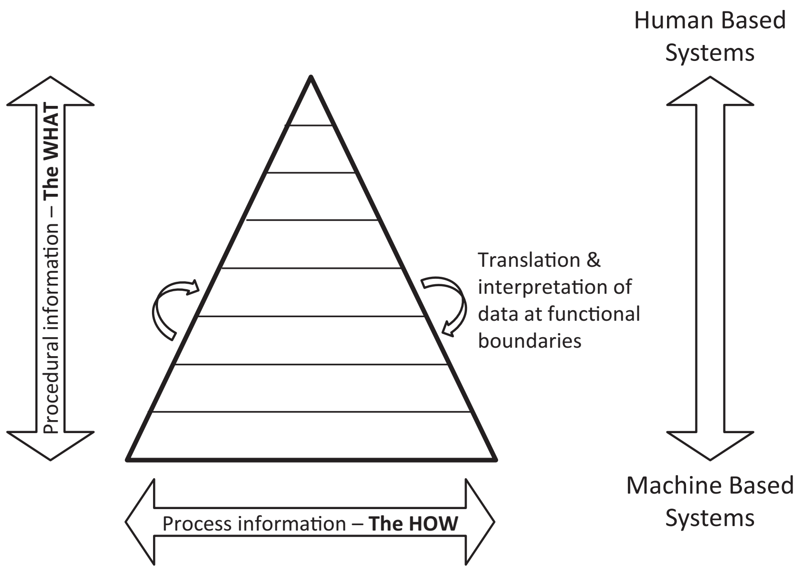


Fig. 13. System configurations.

Fig. 14. Cloud based system configuration.

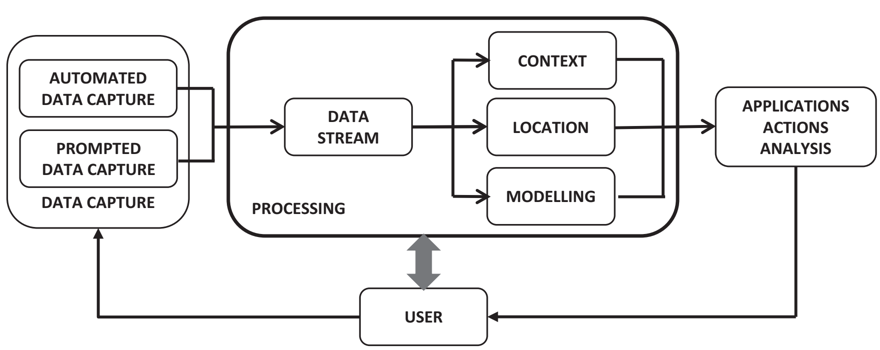


Fig. 15. Participatory system.

once it identifies itself to the system. The system can then itself adapt to the performance provided by the device, supporting interchangeability and rapid reconfiguration.

3.2. Technology

As suggested by Fig. 4, the major advances over the lifetime of the mechatronics concept have been in relation to the ability to access, transmit and process data in increasing volumes at increasing speeds [57–59]. This has in turn been associated with the development of technologies such as the mobile phone, which itself can be increasingly considered as a multi-function system, and accessible computing power such as is provided by component devices such as the Arduino [60], Raspberry Pi [61,62] and Ninja Blocks [63–65], each of which can be configured to provide a range of functions at both the device and systems levels. The introduction

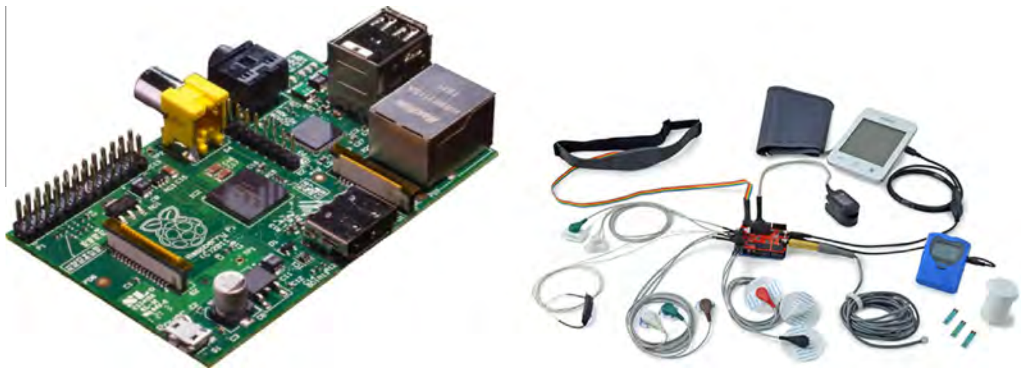


Fig. 16. Raspberry Pi e-Health kit showing a range of connectable sensors and devices.

of these and other mechatronic smart components has in turn been facilitated by continuing developments in sensors and sensor technologies [66,67].

3.2.1. Digital first responder

One element of current research in this area attempts to use the low cost and useable processing of the Raspberry Pi as digital first responder for disaster or remote care scenarios [67]. In remote areas, such as Africa and Asia, health care workers are often not able to gain access to patients quickly due to the large distances between the villages [68–74]. Once they do arrive on the scene, there is normally no record of the patient's condition due to a lack of monitoring and recording equipment. Similarly, in scenarios involving major incidents such as a train crash or natural disaster, the number of available heath care personnel may well be significantly reduced as a result of commonly used triage procedures which require such personnel to stay with injured patients until further help arrives.

It is possible to connect a number of health sensors; including pulse, blood oxygen, temperature and respiration sensors, to a Raspberry Pi or similar device [75,76]. This then allows the host device to act as a recording hub to track and record a patient's vital signs. Additionally, the host can be equipped with communication technology such as a GPRS modem allowing the recorded data to be transmitted to appropriate health care personnel or to a temporary monitoring station. The location of the patient can also be tracked with the addition of a GPS receiver. Not only can such a system be used to monitor patients remotely, using the processing power of the host, it can also be used to generate alerts based on the patient's condition or automatically update the triage status. Due to the inexpensive nature and open architecture of the hardware, multiple devices can be easily distributed with little replacement cost [77–80]. Fig. 16 then shows an e-Health kit as associated with the Raspberry Pi [81].

The Raspberry Pi has also been used to acquire data from pressure sensors attached to a bed or a chair when it has sufficient processing power to analyse these data using machine based intelligence to make predictions about user activities. In the chair scenario it has been able to discriminate between activities such as sleeping, reading, typing and watching television. This has applications in care of the elderly, where the system could flag up anomalous behaviour, alert carers, or interact with other devices to alter the ambient environment. When monitoring a bed in a hospital environment, the system could be used to alert nurses to inactivity that might lead to the onset of pressure sores.[2]

[2] It is important to note that the Raspberry Pi is not essential to any of these examples, any low-cost, low power device with similar capabilities in terms of size, power requirements, cpu power, interfacing and WiFi connectivity could be used in its place.

3.3. User interaction

As systems increasingly interact with users at a variety of levels, there is a requirement to develop a wider range of flexible and user oriented interfaces which adapt to user need and capabilities [82,83]. This often implies the need to introduce new and different ways of conveying information. For instance in e-Health systems the use of touch screens and '*pointing*', supported by intelligent responses, enables the patient to readily convey indications of and location for symptoms using a mobile device, while the incorporation of sensors enables the same device as a monitoring and reporting tool.

Historically, these devices would have been created as proprietary pieces of hardware each performing a specific function or allowing set forms of interaction using a user interface designed by the manufacturer. The high definition display, processing power and sensor environments available in modern smart phones and tablets allow for the development of much more flexible passive and active interactions running on a common hardware platform. For example, accelerometers were originally included in mobile devices to allow the screen position to be rotated depending on the detected device orientation. The same technology can be used actively by the user to determine their speed in a moving vehicle, or passively by an application monitoring their activity level.

Mobile devices also offer the user the opportunity to customise their interactions. The two largest mobile platforms (Google Android and Apple iOS) now allow voice access to common commands across the applications on the device. The multi-touch screen technology allows the user to create custom gestures enabling applications to be controlled with gestures intuitive to the user. The latest devices are able to detect near-touch or "*finger hover*" over the touch screen giving another dimension for display interaction.

Not only have mobile devices became interactive devices in themselves they are now being utilised as connection hubs for a wide range of other devices. Devices such as Fitbit [84,85] and the Jawbone UP [86,87] are wearable technologies used to allow users to monitor and record their activity levels during exercise and sleep. These devices have no display and no direct connection to the internet, the user can only access the information stored by using the companion app on a tethered mobile device [88–90].

More recently "*Smart*" watches, such as the Galaxy *Gear* and the *Pebble* [64,91] have emerged on the market. These devices act similarly to small phones, having touch screens, displaying notifications and can be used to make and answer text messages and phone calls. However these devices have no communication capability of their own apart from a simple Bluetooth tether to a parent mobile device. Both the *Pebble* and the Galaxy *Gear* allow for users to install a wide range of apps to create a custom display and interaction environment [64,92,93].

Indeed, it could be argued that there is a tendency towards a '*gadget culture*' [94] based around a combination of mechatronic and other smart objects and the availability of a range of cloud based software, applications and services (Fig. 9) to support use and user interaction. It is however interesting to note that adoption of advanced technologies is not always guaranteed, as for instance in the case of *Google Glass* where despite there being significant interest in relation to applications in areas such as medicine [95,96], development is currently on hold.

3.4. Cyber-physical systems

The concept of cyber-physical systems as bringing together systems technologies with the *Internet of Things*, and hence mechatronics, has emerged in recent years in relation to a wide range of systems applications. The emphasis on such systems is generally on the interaction between devices, as for instance in the case of swarm robots, and shared sensory and other data between numbers of devices. In the context of the paper, cyber-physical systems are therefore an extension of the underlying interaction between mechatronic smart devices and components and the IoT [97–102].

3.5. Security

As issues such as those that have been associated with the operation of internet systems such as eBay [103] show, CyberSecurity remains an ongoing problem despite progress in secure communications [104] and storage [105] of data. The open architectures of the *Internet of Things*, as typified by Figs. 6 and 10, can serve to exacerbate the problem. A brief consideration of the Stuxnet incident [106], although not the first cyber-attack on a physical system, serves to illustrate the issues.

The Stuxnet attack was an attempt by person or persons unknown to delay the Iranian nuclear programme. It intended, and to a degree succeeded, to damage the centrifuges used in the enrichment of uranium by removing the speed limit setting in their SCADA control system, resulting in an over-speed and mechanical/electrical damage. The following, admittedly hypothetical, route by which the attack took place may have involved placing some malware carrying malicious code onto a USB "*pendrive*" which was then found, carried into the plant and inserted into a staff computer on the plant network by a member of staff curious to see what it contained. The computers controlling the centrifuges were attached to the same network and the malware was able to copy itself there. Once there, the final step was from the PC into the SCADA hardware. Although unintentional, the design of the networked system mimics an open IoT architecture in several points:

(a) Everything was connected – The staff PC was on the same network as the control PC.
(b) Data was allowed to flow freely (unchecked) through that network.
(c) The mechatronic element (SCADA) had no security facilities, or at least they were not being fully used.
(d) The prime concern of the human element of the systems was not security.

The attack did not just target the lack of security in SCADA/mechatronic centrifuge hardware, it exploited the fact that the plant system as whole was a hybrid (which had probably evolved rather than being designed that way) consisting of SCADA, IP networks and "*sneaker-net*" (manually carrying data on physical devices) to transfer information. The Stuxnet attack was thus able to exploited vulnerabilities in various pieces of software in order to reach its target.

The lesson to be learned here is that the security of mechatronics and the IoT cannot be considered in isolation, rather the system must be considered as a whole including SCADA, IP and human aspects.

Whilst it is difficult to be certain about particular and specific vulnerabilities in the Stuxnet case, certain categories of vulnerabilities exist (e.g. buffer overuns, memory corruption vulnerabilities) [107]. If such categories are known and understood, why do they continue to create problems? One possibility is that security is often not the prime concern of those building software and systems – they just want it to work.

Secure communications and data storage require the use of strong cryptographic techniques which are often computationally intensive. The use of bounds checking to avoid buffer overun can impose a time overhead in a real-time system which a small microcontroller will struggle to meet. In the case of the limited capability devices that typify the IoT (limited memory, processing power etc.) adding security can prove to be such a burden that it is largely overlooked [108–110].

Some of these problems can be addressed. Better training of systems engineers to have security as a concern equally waited with functionality would help as would the use of modern languages with implicit bounds checking, but as Software Engineers have found, there is no magic bullet [111]. Instead, a better way to look at the problem is as an arms race – with those creating systems constantly trying to find and fix any flaws more rapidly than those who would exploit them. A systems development lifecycle which includes an explicit security testing phase with knowledge of discovered vulnerabilities being fed back into the development of an improved version would be a first step to formalising the treatment of cybersecurity in the development for IoT systems.

Such a lifecycle could of course be applicable in the development of traditional systems. The IoT architecture however poses some challenges of its own, in particular, the openness of the architecture with data flowing freely "*on-demand*" from sensors to consumers via a "*backplane*", as suggested by Fig. 15. The problem is one of context coupled with the traditional security concerns of identity, access control and trust [112,113].

The following scenario may act as an exemplar. A worn sensor measures blood-pressure as part of a health monitoring system. Most of the time, the user wishes this data to remain private as knowledge of an underlying health condition could result in detrimental consequences such as refusal of insurance cover. However, during a medical emergency, the user will be less concerned about such an issue and more worried that medical staff can rapidly diagnose any problem. From this, it can be seen that the rules governing which data needs to be accessible to which party at which time vary with purpose and circumstance.

The problem of actually keeping data secure can be addressed via encryption and key-sharing (provided the underlying infrastructure has the processing power to cope) but the problem of identifying to whom access should be granted in what circumstances remains an open problem. In such an open system there are many elements which may or may not be worthy of trust – users, data, sensors, the underlying hardware itself. The fields of context-aware computing [89] and trust-models [114] have looked to address these issues. One possible approach is to make the data itself active (in the manner of mobile agent systems [115]) and responsible for decisions. Data encrypted and encapsulated in an agent which can travel over the backplane and which has the necessary code to make decisions as to whether or not to provide a decrypted representation of itself may be a useful abstraction. In this sense, such an agent is truly representing the interests of the data's owner.

The Internet was never designed to be secure and subsequent attempts to layer security on top of it have shown how difficult this is. The *Internet of Things* represents a second chance to "*do the right thing*" and treat security as a first class consideration.

3.6. Education

As has been argued above, the world is changing to one of interconnected smart devices or objects embedded in the environment, and both engineering and information technology (IT) are thus increasingly focussed on the means to provide the bridges between the virtual, or information oriented, world and the physical world. With its emphasis on achieving design synergy through systems integration and the transfer of functionality, mechatronics has a role to play in the development of the necessary technologies, methods and means, which must in turn be reflected in the design of the next generations of mechatronics, and other, undergraduate and postgraduate programmes.

When undergraduate and, subsequently postgraduate, programmes in mechatronics began to be introduced in the mid-1980s, there tended to be an emphasis on the application of microprocessor based controllers to achieve enhanced functionality in relation to a wide range of products, processes and systems. Such systems ranged from domestic appliances, such as washing machines, through manufacturing technologies and robotics to engineering components, such as smart valves and pumps. This was backed up by research into the design of mechatronics products and the means of achieving an effective integration of the core technologies [1,6–8,116].

As mechatronics continued to develop, so did the interest in developing mechatronics education programmes, as for instance can be seen from the results of a short search using the term '*Mechatronic Education*' on the *Web of Knowledge* and *IEEE Xplore* publication databases,[3] the results of which are presented in Fig. 17.

Along with the increasing number of mechatronics courses and programmes, the underlying concept of mechatronics has expanded to encompass a greater, and increasing, diversity of applications along with issues of design and systems integration. This has in turn resulted in their being a continuing and ongoing debate as to the nature and standing of mechatronics as an engineering discipline and of its role within the engineering design process in particular.

With respect to mechatronics course development, the inherent ambiguity over what constitutes mechatronics has resulted in a wide range and variety of course forms and formats structured around achieving core competences in the primary domains whilst introducing concepts of systems, integration, transfer of functionality and synergy. It is suggested that major components of diversity of course development include:

- The nature and challenges of mechatronics as both an academic and an engineering discipline [1,6–9,116–122].
- The importance and role of engineering design within mechatronics [5,6,116–118,123,124].
- The linked issues of course development and the embedding of mechatronics as an academic discipline within courses [121,125–128,130–134].
- The development and implementation of methods and means of embedding all aspects of system level and other integration within an academic programme in Mechatronics [117,130–133,135].

It can of course be argued that these components can be supplemented by others, and indeed it is in the nature of mechatronics both as a subject and a discipline that it encourages and supports such debate.

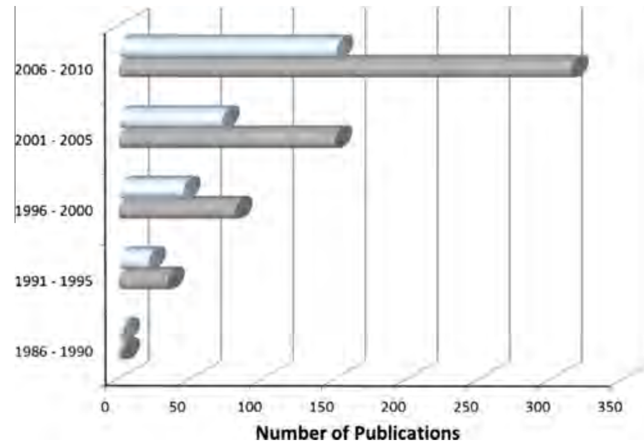


Fig. 17. Literature search on *Web of Knowledge* and *IEEE Xplore* databases using the search term '*Mechatronics Education*'.

This combination of breadth and flexibility has resulted in the development and implementation of a wide and varying range courses structured to accommodate local requirements and conditions. Thus a course developed and delivered in, say, Detroit [136], is likely to differ significantly from one put in place in Singapore [137]. Both, however, have entirely legitimate claims and arguments to be considered as representative mechatronics programmes.

Notwithstanding this difference in emphasis, each individual course will in general seek to conform to the requirement of achieving appropriate levels of integration and understanding between the core disciplines, with the emphasis then being that which is appropriate to the overall requirements of the course.

Based on a review of course documents and programmes encompassing Europe, the USA and Canada, Africa, the Far East and Australasia, applications areas identified as being incorporated into a diverse range of mechatronics programmes are as set out in Table 4 [120].

A key element of course development in recent years has been the inclusion of significant a design-based component into

Table 4
Mechatronics applications areas.

• Automation and robotics
• Automotive engineering
• Computer aided & integrated manufacturing systems
• Computer Numerically Controlled machines
• Consumer products
• Control engineering
• Diagnostic, reliability, and control systems techniques
• Engineering design
• Engineering and manufacturing systems
• Expert systems
• Games technologies
• Health technologies and systems
• Industrial engineering
• Machine vision
• Manufacturing technologies
• Mechatronics systems
• Medical technologies and systems
• Packaging technologies
• Power production & generation
• Sensing and control systems
• Servo-mechanisms and control
• Space technologies
• Structural dynamics
• Systems engineering
• Transportation and vehicular systems

[3] The searches are intended to be indicative rather than comprehensive, hence the restricted choice of search terms.

mechatronics programmes, often through the medium of project based working [118,122,126–130,133,138,139].

The paper therefore sets out below some of the issues that the authors believe to be associated with achieving an effective mechatronics programme which balances the requirements for technical integration with the need to encourage an innovative and inventive approach to design by students. It would seem also prudent to ensure mechatronic students have considerable Information Technology (IT) and computer knowledge at levels beyond those of the user, particularly as if problems occurs within the cloud, they will be increasingly difficult to detect and correct. Also, as many users work on the same problem without a common understanding there is a real possibility that a "*Tower of Babel*" situation will arise without strict version and change control.

Returning to the results of the search shown in Fig. 17, if the search is adjusted to (*Mechatronics Education* AND *Design*), 292 of the 581 papers originally identified are returned. If these 291 papers are then considered in relation to the major components of mechatronics education put forward earlier, the results are then as shown in Fig. 18 where *Unclassified* is used to refer to all falling outside any of the other 4 categories.

In considering the requirements of a mechatronics course with engineering design at its core, the requirement remains that of balancing the engineering and IT content within a design focus that supports both individual and group working. The latter is especially important for mechatronics, which sits at a confluence of very diverse technical domains, and thus any one person is unlikely to be a master of all of the technical skills required to build a successful device. In industry, most graduates will be expected to work in a team and so ought to experience the realities of such co-operative work in their programmes.

Key elements within this are the need to support communication between members of the group, for instance through computer-based communications structured around the use of digital libraries [135,140], and to expose students, both individually and as members of a group, to the design process from concept development to implementation [141]. Intrinsic to this is the need to ensure that, particularly in a cross- and inter-disciplinary environment, issues of potential misunderstanding through different and differing use of terminology is avoided [142].

Further, it has been suggested elsewhere [120] that design strategies can be categorised in relation to two broad approaches; theoretical and pragmatic. In practice, these extremes do not exist in isolation, but co-exist along a continuum within the design process. What is perhaps of more significance in relation to course design is that students, inevitably, lack the range of experience associated with established experts in the field.

Taking the view that innovation is about the generation of new and novel ideas and concepts, the aim of a mechatronics programme must be to ensure that throughout the course students have the opportunity, and the confidence, to challenge existing concepts and precepts, to be willing to take risks and to think radically about the ways of doing things, particularly at the interface between the virtual and physical worlds.

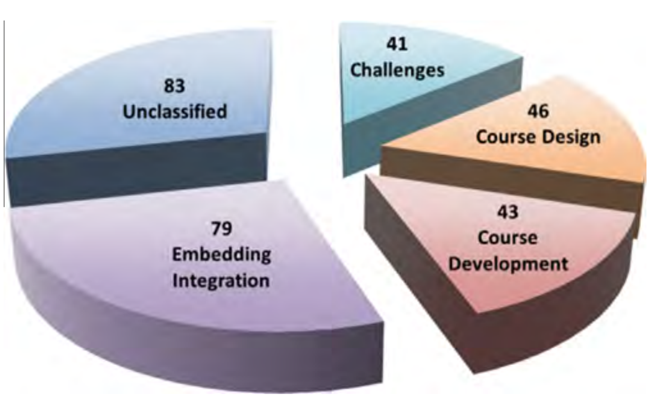


Fig. 18. Classification of papers from Fig. 17.

However, in 1998 John Prados of the University of Tennessee [143] suggested that engineering graduates were perceived by industry as having a range of weaknesses including:

- Technical arrogance.
- Lack of design capability or creativity.
- Lack of appreciation for considering alternatives.
- Lack of appreciation for variation.
- Poor overall perception of the project.
- Narrow view of engineering and related disciplines.
- Weak communication skills.
- Little skill or experience in working in teams.

In developing innovative thinking and approaches by students, all of the above issues need to be considered, some of which may well, however, be in conflict with the administrative requirements associated with grading and the ability to differentiate between individual students in assessment schemes [144–149]. For instance, an assessment scheme may be predicated on a process of grading activities against a series of attainments in which failure to achieve an outcome is seen as a negative. However, in the innovative process, the failure of a concept or idea is a major factor in that process, provided that lessons are learned from such failures.

In terms of encouraging an innovative approach to design problems in which the aim is encouraging students to bring forward new and novel ideas, there is a need to create an environment where trying and failing is not considered as a failure in relation to a student's ability to progress or pass the course or module. This means that students are then free to put forward ideas and pursue options in an environment in which the emphasis is on trying and not on failing, i.e.:

"*Try and fail, but don't fail to try*"[4]

However, students often focus on the requirements necessary to achieve a particular grade, which in turn tends to lead them to be conservative in their approach as they attempt to ensure that they achieve the necessary marks for the target grade. Indeed, it is not unknown for students to attempt to guess the preferred solution to a design challenge and then attempt to reverse engineer their design process to ensure that they arrive at the "*correct*" answer. This conservatism then runs contrary to the requirement to encourage innovation at the expense of an occasional failure to achieve set goals. Thus, insistence on the allocation of a grade, and of differentiating between students, can have a negative impact on the level of innovation.

Next generation mechatronics oriented courses will face the challenge of maintaining the linkage between the core disciplines while simultaneously introducing new and novel technologies into the course structure. Thus, students need to consider, and be exposed to, the impact of operating strategies based around, for instance, gesture. Such systems are likely to increasingly focus on the user with the underlying technology becoming increasingly invisible to the user.

Indeed, over the history of mechatronics to date, it has been the increasing availability of low cost computing power, and the associated software, that has generally been the driver behind much of the observed innovation. With an increasing emphasis on the end-user, this may well shift to a position in which the

[4] Attributed to Stephen Kaggawa.

engineering aspects of the system take the predominant role, with the software then acting to provide the link with the user. It is also likely that the Internet, in the form of the *Internet of Things* [11–14,150], will play an increasing role in providing the user with the means of operating and managing a wide range of systems, many of which will be mechatronic in nature, all of which must be accommodated to a greater or lesser degree within the course structure and curriculum.

Engineering design is a major element of mechatronics and can form the unifying theme throughout such courses. However, the requirement to encourage innovation is often in conflict with the requirements of '*academic quality*' and of the need to assign grades to all forms of student based activity, even when doing so encourages a conservative approach to design. Instead, the aim should be to encourage innovation, and even failure, in order to reward students for the adoption of an innovative and a novel approach.

It is suggested that one possible way of accomplishing this is to simplify the criteria or measures of success as much as possible – ideally to a single such metric, e.g. the fastest or the lightest. It is also suggested that all mechatronics programmes focus not only on the development of working solutions, but also on how the solutions fit within the wider environment of their use, including their users.

3.7. Industry

The complex nature of modern industrial systems provides the perfect environment for an *Internet of Things* approach to manufacturing and innovation [151–158], and this is already starting to happen in sectors such as:

- Advanced manufacturing.
- Bio-Pharmaceuticals.
- Medical Devices.

The geographically distributed nature of many modern manufacturing operations has made it essential to develop internal networks to control and optimise production, with logistics planning and automated quality control systems as key foundations [159,160]. This in turn has led to an aggregation of data that is now being employed to optimise all steps of the process to ensure higher quality goods are manufactured at lower cost. The advent of 3-D or additive printing technology is taking this a step further with new product innovations based on a combination of data mining strategies to define new products and the flexibility of manufacture provided. The following illustrative example is drawn from the bio-pharmaceuticals industry and encompasses issues of ethics, security and user interaction as well as technical issues associated with the *Internet of Things*.

In the Pharmaceutical and Medical sectors, the development of an internal IoT approach is driven more by regulatory needs and a drive to lower the cost of innovation as personalised medicine, based around Point of Care (PoC) diagnostic systems, starts to become a medium term technological reality, allowing drugs to be targeted at the correct patient cohorts. The development of such PoC diagnostic devices has become a major focus for research funding, as evidenced by the EU *Horizon 2020* programs in Europe [161] and National Institutes of Health [162] funded programmes driving both academic and commercial research in the US, and relies on the ability to create intelligent systems that themselves increasingly rely on a combination of interconnected sensor systems and the data mining of both analytical and epidemiological data stored in the cloud.

The regulatory need to monitor and measure pharmaceutical products throughout the discovery/development/clinical trials and production processes has created massive data bases of internal information that are now being mined to optimise production processes as well as identify potential new applications for existing drugs, while the wider biotechnology research industry has broadened the reach of these data bases into new areas of disease research as *Big Pharma* focuses more resource on buying up novel treatments and companies than on internal R&D.

The growth in personalised medicine that sprang from the Human Genome project has also created a paradigm shift in both drug discovery research and diagnostics, with high throughput screening systems and sophisticated sensors capable of detecting single molecules combining with bioinformatics software approaches to unravel complex disease pathways. Problems associated with balancing the cost of medicines against the relatively small markets for the highly targeted therapies under development is driving an *Internet of Things* approach to R&D to drive down discovery costs in particular.

Coupled with this is the realisation that early detection in cancers and degenerative diseases are crucial in reducing the overall cost of healthcare, which in turn requires diagnostic systems to be developed that can detect pre-cursor bio-markers rather than look for cellular damage. Such systems need to be portable so that they can be used in clinics by skilled medical technicians rather than analysts, or in some cases by the patient themselves, and capable of analysing for many bio-markers present in femtomol concentrations at the same time, then reporting the results as a simple diagnostic parameter within a few hours with minimal error rates to prevent false positives & negatives from affecting the subsequent patient care.

A big concern here revolves around the medical ethics of allowing patients "instant" access to potentially life changing information before it has been contextualized by medical professionals, i.e. would you want true Point of Care (PoC) systems (e.g. glucose monitors, pregnancy tests) available to the general public where cancer detection is the aim? How to build ethics into IoT systems is probably the trickiest issue to overcome in medicine, since there is a strong lobby that free access to one's own data is sacrosanct, even when such access could have harmful side effects.

To gain maximum benefit from these approaches using a true IoT approach rather than internal sources of data and measurement arrays, it will be necessary at some point for corporations and academic research organizations to generalise and share the data collected from both processes and people, and as always the main restrictions on accomplishing this goal are more to do with regulation, commercial advantage, and personal privacy than technology. Before the true potential of personalised medicine and Point of Care diagnostics can be felt, it is going to be necessary to find solutions to a series of issues, only one of which can be classed as technical:

> *Prediction reliability* – with all data mining approaches to controlling a process, there needs to be careful consideration given to how well a given model can predict outcomes based as they currently are on human based logical assumptions that frame the problem to be solved. Many data mining algorithms in use today suffer from an overall lack of broad based data and full understanding of all the factors involved, largely because commercial concerns restrict data sharing between competing organizations and, in some cases, it can be financially advantageous for a computer based system to drive the process towards particular outcomes rather than identify the unconstrained outcome that would have happened through human interactions. This is most evident in the Financial Services sector where markets have become very much more volatile since trading became automated.

In the medical field, this issue becomes dominant since diagnosis and treatment are so closely interrelated and errors potentially fatal. False positives and negatives have to be eliminated in an ideal system, and unlike in financial markets, it is not possible to drive towards a desired rather than actual answer.

Data security/privacy – how to protect an individuals' records from unauthorized use by government, employers, insurance companies and so forth, while at the same time giving sufficient detail within the cloud based data sources for intelligent systems to utilise.

Intellectual Property – most research based companies are valued on the basis of the knowledge they control, and mechanisms will need to be devised that allow sharing of knowledge between organizations through an IoT that either does not compromise the intrinsic value of an individual entity to private investors or creates new co-operative funding mechanisms that allow cloud partnerships to be developed between contributing researchers.

Regulation – industry is increasingly having to operate within a framework of International regulations created by politicians for safety, environmental, moral, financial or security reasons, and any broad based IoT solution to industrial problems will need to take this into account. This is of particular importance in the medical sector where success of a drug depends on the operation of the Food and Drug Administration (FDA) regulatory framework, itself based on previous precedence and demonstrated improvement over current medicines and a "*guarantee*" of safety. With clinical trials and regulatory approval potentially taking several years, and costing several £100 million, systems need to be robust enough to prevent the manipulation of algorithms that can predict desired outcomes in ways that contain the potential for future legal liabilities.

For example, International Widgets Inc (IW) comes up with a way to use remote 3-D printing to manufacture its products and sets up an on-line service for customers around the world to buy its widget as a software download for the customer to print locally. If IW is physically based in, say, the US, and the customer is in an unfriendly state, such a transaction can take a few seconds to complete but would potentially fall foul of Government sanctions, compromise state security, avoid customs duties and other taxes, and be part of a bigger process to produce a noxious chemical that created health and environmental problems – how do you handle such situations within the current legal frameworks?

What the wider IoT supposes is that clients will access and pay for systems as a service and populate their facility with private data. The assurance of confidentiality will be thus be paramount, especially at the global level where unscrupulous hackers seek free access. As internet services become more and more ubiquitous, affluent nations and citizens will rush to become participants, creating another version of the digital divide. If sectors of the citizenry are excluded, then the IoT will really only service users who can afford to buy in.

Notwithstanding the above, it is likely that many IoT services will be transparent and free, so general use in all internet-enabled countries will be widespread and will hopefully improve efficiency and availability of quality of life services.

From the above it is apparent that the IoT is likely to impact across a range of industries. Thus in manufacturing, the ability to provide and access real-time information is supporting a shift towards manufacturing on demand with automatic scheduling supported by knowledge of machine utilisation and availability along with active stock control and management [154,163,164]. Other areas where the IoT is likely to have a significant impact include logistics [165,166,93] and energy [167–169]. In each case there will be a need to service the underlying information through the increased use of mechatronic smart objects [170].

4. Conclusions

Since its introduction, the concept of what constitutes a mechatronic system has been subject to a continuous process of revision and debate as a result in developments in technologies and the concept of what constitutes a system. While this has resulted in a degree of diversification in the ways in which mechatronics is perceived, and in particular on mechatronics education, the underlying precepts of the transfer of functionality from the mechanical domain to the electronics and information domains have been maintained.

The recent development of the *Internet of Things* is forcing mechatronics designers, practitioners and educators to further review the ways in which mechatronic systems and components are perceived, designed and manufactured. In particular, the role of mechatronic smart objects as part of an IoT based system in which the structure is defined by context is resulting in an increased and increasing emphasis on issues such as machine ethics, user interaction, complexity and context as well as with issues of data and individual security. This is in turn driving forward innovative approaches to design and education to meet the challenges being presented.

The paper sets out some of the issues associated with these changes along with thoughts as to how these are to be met. It is also suggested that the mechatronics concept has both value and merit within this changing functional environment, in particular in relation to the function and operation of an increasingly broad, and user oriented, range of smart objects.

The future, though challenging, is thus still seen as requiring mechatronics thinking.

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