Trends in Mechatronic Engineering and Education

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Abstract

This paper outlines the emergence of mechatronic engineering as a distinct professional activity and area of study. Current and future trends in mechatronic engineering and the educational needs of its practitioners are discussed.

Keywords: mechatronics, engineering education.

1. The Importance of Technological Innovation for Economic Progress

Over the past 50 years, technological innovation (see Figure 1) has accounted for over one-third of the growth of the largest economy, the USA, in the world. The pace of innovation around the developed world is increasing dramatically in recent years owing to technological developments in communications, computerization, the Internet, etc., and the resulting globalization of markets and the global distribution of the processes of new product realization (concept development, design, prototyping, manufacture, and servicing).

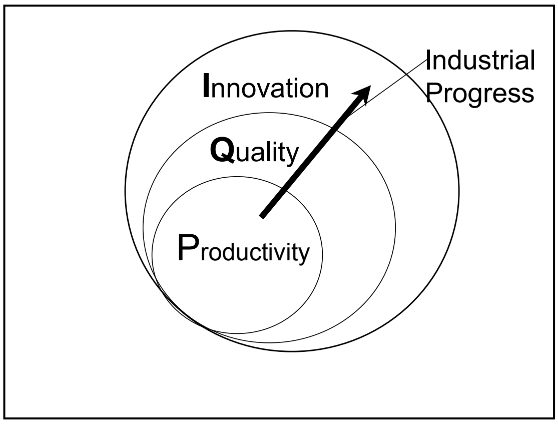

Figure 1 P→Q→I Competitive Strategies

Some are genuinely concerned (to the extent of being frightened) with the increasing pace of innovation. For instance, as suggested by von Braun [1] "[s]uppliers of new products replacing previous ones should bear in mind that they are also reducing, or even destroying, the assets of customers, either their own or some other supplier's. This "creative destruction" is perhaps not exactly what Schumpeter [2, 3] had in mind when he was extolling the virtues of innovation at the beginning of this century." However, the majority opines that innovation, when taken in its broadest sense, can become the force that could "liberate humanity in general from the preventable evil called poverty [4]". In any case, it is generally accepted that we cannot ignore the onward march of technological innovation.

Innovation may be defined as "new ways of delivering customer value [5]." Often the outcome of innovation appears in the form of a new process, product, or service. However, in many cases, the development of new services is a consequence of the availability of new processes and products—e.g. the development of the Internet has resulted in a radical expansion and transformation of service industry). The new services become part of "an emerging industrial value-adding structure that supplies functionality around a new basic technology system [6]."

While a corporation is passing through the stage of competing mainly on the basis of superior productivity (functional capability/input) and quality, the focus is on process innovation (in addition to strategic issues related to organization, human resource development, marketing, etc.). However, as the corporation forges ahead towards competing on the basis of innovation, more attention needs to be paid to product innovation.

2. Changes in the Nature of Technological Processes and Products

The left side of Figure 2 shows the changing nature of technological processes and products. In the era prior to the invention of the electromagnetic induction dynamo (1830-40) by Michael Faraday, all 'machines' (technological processes and products) were mechanical (M) in nature, i.e., composed essentially of mechanical units. Since mechanical units exhibit large inertia, machines of this era tended to be large, cumbersome, slow, 'uni-functional' and 'non-user friendly (difficult to control and maintain)'. However, it sufficed for the innovators of such machines to be well versed in mechanical sciences and arts.

By the late 19th century, since electrical (E1) energy can be transmitted and transformed much more easily than mechanical energy, the energy receiving and manipulating units within machines (technological processes and products) started to be replaced by functionally comparable electric units. As a result, machines became more compact, controllable and user-friendly.

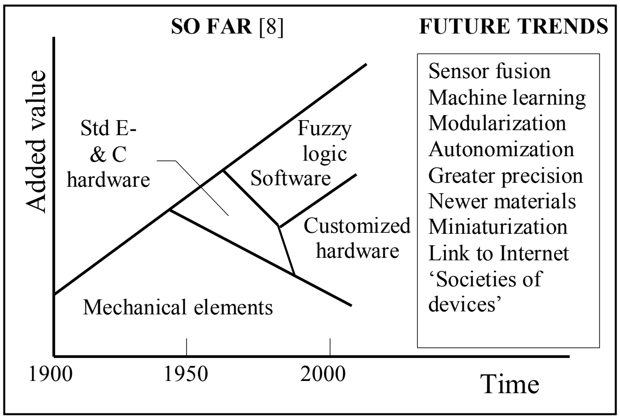

Figure 2 Trends in mechatronic engineering

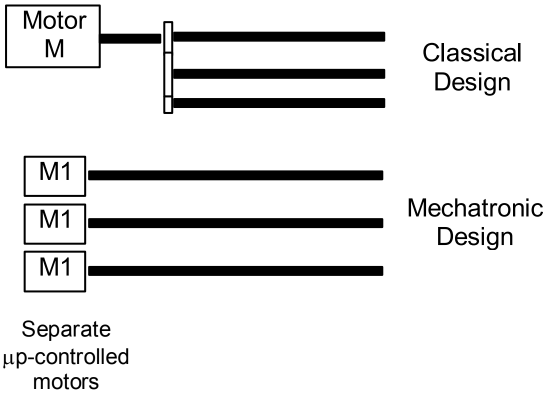

Figure 3 Classical and mechatronic speed control (after [8])

A technological transformation occurred with the advent of analog electronic (E2) valves in the earlier half of the last century. This transformation accelerated after the 1950s owing to the development of transistors, digital electronics and power electronics (E3). Wherever possible, electrical functional units were replaced by such electronic units so as to attain several orders superior performance in terms of size, controllability and user-friendliness. The synergistic combination of E1, E2, and E3 technologies may be collectively referred to as E technologies (electrical/electronic technologies).

The second half of the last century saw dramatic changes in technological processes and products owing to the rapid extension of earlier successes in electronic technologies towards the development of a bewildering array of digital computational units (computers): general purpose integrated chips (IC), application specific ICs (ASIC), microprocessors (μp), etc. These functional units are now so small in size (miniaturized) that they can be embedded within the functional units. Such units will be referred to as belonging to C technology in the rest of this paper. Figure 3 provides an example of the impact of such developments on engineering equipment. Indeed much of the recent progress in industrial automation (in particular, with regard to FMS: flexible manufacturing systems [13]) owes a lot to the emergence of mechatronic engineering.

3. The Emergence of Mechatronic Engineering

The synergistic combination of M, E, and C technologies eventually led to processes and products that could not even be contemplated before [7-12] while attaining unprecedented levels of performance (sees Tables 1 and 2).

Table 1 Some types of mechatronic products (adapted from Dinsdale [7-10])

TYPE	EXAMPLES
Transducers and measuring instrumentation	Ultrasonic receiver Electronic scale
Processing machines	Turning and machining centers Bonding machines Robots
Industrial handlers	Robots Component insertion machines
Drive mechanisms	CD players Printers Disk drives
Interface devices	Keyboards

Table 2 Benefits of mechatronic engineering (adapted from Dinsdale [7-10])

BENEFIT	EXAMPLES
Faster response time	Servo-motion controller Camera
Better wear and tear characteristics	Electronic ignition
Miniaturization potential	Camcorder
Easier maintenance and spare part replacement	Washing machine
Memory and intelligence capabilities	Programmable sequence controllers
Shortened set up time	Computer numerical control (CNC) machines
Data processing and automation	CNC machines

User friendliness	Photocopier
Enhanced accuracy	Electronic calipers

Many modern products use embedded computers (computer-on-a-chip) to provide hitherto unattained functionalities exclusively through mechanical means. One may also exploit the ability of a computer to be programmed at will to add new functionalities. For instance, we can create 'smart' products by programming the computer on the basis of fuzzy logic, or by making the computer behave like an artificial neural net (ANN). Thus computer technology offers an opportunity for endless product innovation. Mechatronic egineering is the emerging discipline that supports the development of this class of technological processes and products.

Although USA and Europe had contributed significantly to the development of M, E, and C technologies described above, it was Japan that had first recognized the strategic importance of mechatronics as a distinct discipline. Indeed, much of Japan's economic success since the 1970s seems to be linked to its mastery of mechatronic engineering [14, 15]. However, soon, the concept of mechatronic engineering [16] spread to many other parts of the world. For instance, in Denmark, a full PhD project was devoted to the development of a theoretical approach to mechatronic design [17]. By the 1990s, several mechatronic courses/programs within and outside departments mechanical engineering programs started appearing worldwide: e.g., Australia [18], Hong Kong [19, 20], Mainland China [21], and UK [22,23]. In Singapore, mechatronics is even introduced at the secondary school level [24]. In Russia, mechatronics courses are introduced within aeronautic engineering programs [25]. Chronologically, the first full-length mechatronic programs to be offered within the Asia-Pacific region was that [19, 20] launched (under the leadership of the first author) in 1989 at City University of Hong Kong (then City Polytechnic of Hong Kong). More recently, mechatronic engineering undergraduate programs have been launched at two engineering colleges in Andhra Pradesh, India. These represent the first ever mechatronic education ventures in India.

The proliferation of mechatronic engineering programs in universities worldwide, in turn, is leading to a deeper understanding of the specific nature [26] of mechatronic engineering, how it could be taught more effectively [27-34], and the software tools needed for mechatronic design and its teaching [35].

4 What is Mechatronic Engineering? What it is not?

Since mechatronic engineering is an emerging discipline, it is not surprising that its definition is still under development. Among the more popular definitions is the one composed by the Industrial Research and Development Advisory Committee of the European Community: Mechatronics is "*a synergistic combination of precision mechanical engineering, electronic* [read computer] *control and systems thinking in the design of products and manufacturing processes* [8]."

While the above definition seems to be acceptable in the short term, several simplistic views or, even, misconceptions continue to prevail. Two examples are:

- Mechatronics is "*the application of microelectronics in mechanical engineering*" (the original definition suggested by MITI of Japan).

- Mechatronics is "*a combination of mechanical engineering, electronic control and systems engineering in the design of products and processes*."

While these views are acceptable from a limited viewpoint, it is useful to clarify and/or elaborate upon them.

$$M + E + C \neq \text{Mechatronics}$$
$$M \cup E \cup C \neq \text{Mechatronics}$$
$$M \cap E \cap C \neq \text{Mechatronics}$$

What Mechatronics IS NOT

$$S\overrightarrow{(M,E,C)} \Rightarrow \text{Mechanical Goal}$$

What Mechatronics IS

Figure 4 What mechatronic engineering IS and what it IS NOT

Mechatronics does not warrant recognition as a distinct discipline if it were to be viewed merely as a summation, union or intersection of mechanical, electronic and computer principles (see upper part of Figure 4). The lower part of the figure illustrates a more useful view. Three essential features of this view are worthy of note:

i. There must always be a design goal that is mechanical in nature. Hence, designing a voltmeter is not a mechatronic activity although the casing of the voltmeter is mechanical in nature. The mechatronic activity needed is dictated by this 'mechanical' goal. This goal is often expressed as a set of performance variables that need to be controlled (constrained within limits or optimized). Hence control engineering (especially, motion control) is central to mechatronic engineering.

ii. The design solution is invariably a system. A system is a set of interacting elements satisfying a specified goal. In the case of a mechatronic solution, the elements can be of mechanical, electronic (including electrical elements and computational elements), or software types. The interactions (signals passed) can be of analog (continuous) or digital (intermittent).

iii. Mechatronics is NOT about finding ANY solution to the given problem. Its aim is to produce a *competitive* solution. Typically, there exist a range of solutions to a given design problem. Often, a purely mechanical solution is feasible. If this is the 'best' solution, it does not fall within the domain of mechatronics. Mechatronic design invariably involves tradeoffs between the advantages of alternative mechanical, electronic, and software solutions at the sub-unit level. Experience shows that an M-solution is usually inferior to a competing E-solution which; in turn, is inferior to a C-solution (Note that M-elements have large inertia, electrons have very little, and 'bits' none.). Hence, the hallmark of mechatronic engineering is the conscious effort to progressively substitute M-solutions by E-solutions and, in turn, E-solutions by C-solutions. This notion is signified by the 'arrow' capping (M,E,C) in the lower part of Figure 4.

4. What Professional Roles Do Mechatronic Engineers Fulfill and What Knowledge and Skills Do they Need?

Technological process or product design in a modern context is usually a group activity that involves the communications among electrical, electronic, materials, mechanical, manufacturing, and other types of scientists and engineers. Usually, the team members are specialists in their respective disciplines/professions. Conventionally, such teams have been coordinated by one of the specialists with broad experience. This suffices as long the design problem is conventional. However, if the design is to be innovative, the design team needs to explore totally new avenues that involve tradeoffs amongst competing M, E, and C solutions. The competitive strength of the team then lies not so much on how elegant the individual M/E/C solutions are but in how elegantly they have been 'balanced' and integrated. Unfortunately, by virtue of their specialist training, many M, E, or C professionals do not possess the breadth of knowledge required for performing this 'balancing' act. This missing link is expected to be provided by mechatronic engineering professionals.

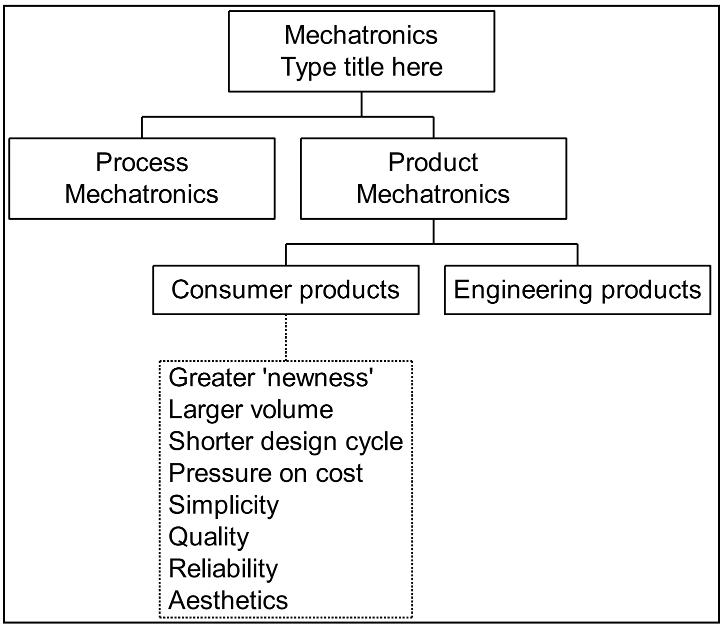

Figure 5 The scope of mechatronic engineering

i. From the industrial viewpoint, a mechatronic engineer should be particularly useful in Product mechatronics, i.e., the design of mechatronic products; and

ii. Process mechatronics, i.e., the utilization, and maintenance of mechatronics process equipment—mainly in the manufacturing industry [20] (see Figure 5).

Product mechatronics could be further divided into [20]:

- Consumer products that tend to be mass-produced, have shorter life cycles, and have greater pressures on cost, and greater requirements in terms of aesthetics, and
- Engineering products that tend to be technogically more complex;

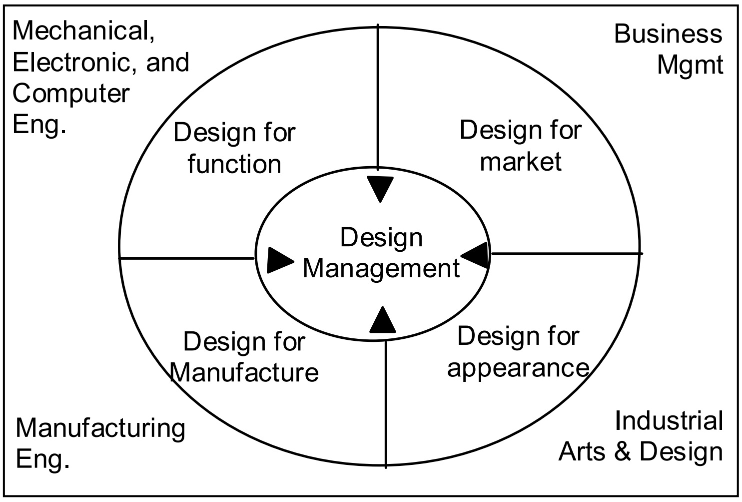

Figure 6 The Role of Design Management [36]

Hence, in addition to a critical understanding of mechanical, electronic, and computer sciences needed while designing for function, mechatronic engineers coordinating consumer product design need to have a broad understanding design for market, manufacture (DFM), and appearance that fall under the domains of business management, manufacturing engineering, and industrial arts and design respectively (see Figure (6). Design management is the process of bringing these diverse issues together.

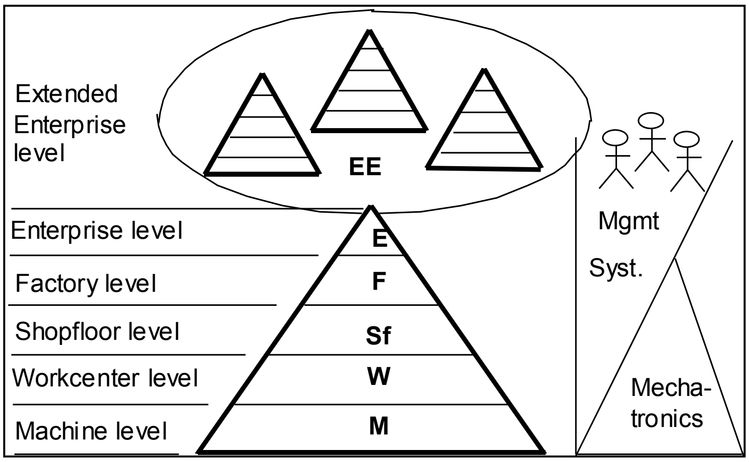

Figure 7 Contemporary industrial structure

Since a mechatronic engineer is expected to take up the role of coordinating teams designing technological processes and products, her/his domain of technical interest within a corporation mainly straddles the machine, workcenter, shopfloor, and factory levels (see Figure 7). If the corporation is competing mainly on the basis of innovation, design becomes a strategic activity. In such a case, the mechatronic design coordinator should be able to communicate effectively with people in the marketing department as well as those at the strategic level.

In corporations operating on the global arena, usually, geographically distributed teams collaborate in design by communicating through broadband systems and the increasingly ubiquitous Internet. This approach enables teams to engage in design round-the-clock so as to cope with ever decreasing design lead times. In recent times, a host of software tools that facilitate collaborative design by geographically separated designers and for pooling their knowledge (Knowledge Management—KM) are becoming available. Mechatronic engineers need to learn to utilize these tools

5. Mechtronic Education

Section 3 has already drawn attention to a range of educational initiatives focusing on mechatronics. Following these developments, several pedagogic principles of specific relevance to mechatronic education have emerged.

It was noted in [20] that mechatronic design

- "is a complex and open ended activity requiring refinement of creativity and experience through application;
- is often a group activity in industrial practice;
- is a combination of art and science;
- requires a broad overview of market needs and business goals, and manufacturing technology."

These considerations had led the designers of the BEng Mechatronic Engineering program of City University of Hong Kong to adopt the following curricular strategy [20]:

- "While the Japanese view of the mechatronic engineer as a mechanical engineer whose education is broadened to include microprocessors, electronics, actuators and control is broadly valid, as far as possible, avoid biasing the students towards a specific discipline—i.e., emphasize and interdisciplinary approach.
- Develop the mechanical and electronic design aspects systematically while providing a broad understanding of computers to enable their effective utilization in design.

- Recognize that control engineering (especially motion control) is a core activity.
- Develop a broad understanding of the interactions [among] design, manufacturing and design management.
- Take advantage of computer aided design and analysis (CAE) software in order to enable students to undertake more substantial design tasks.
- Develop the skills in technical communication required by all engineers."

An outline of the curricular structure following the above principles is illustrated in Figure 8. Note that a team-based design (and make) project (undertaken over three semesters) is at the very center of the curriculum.

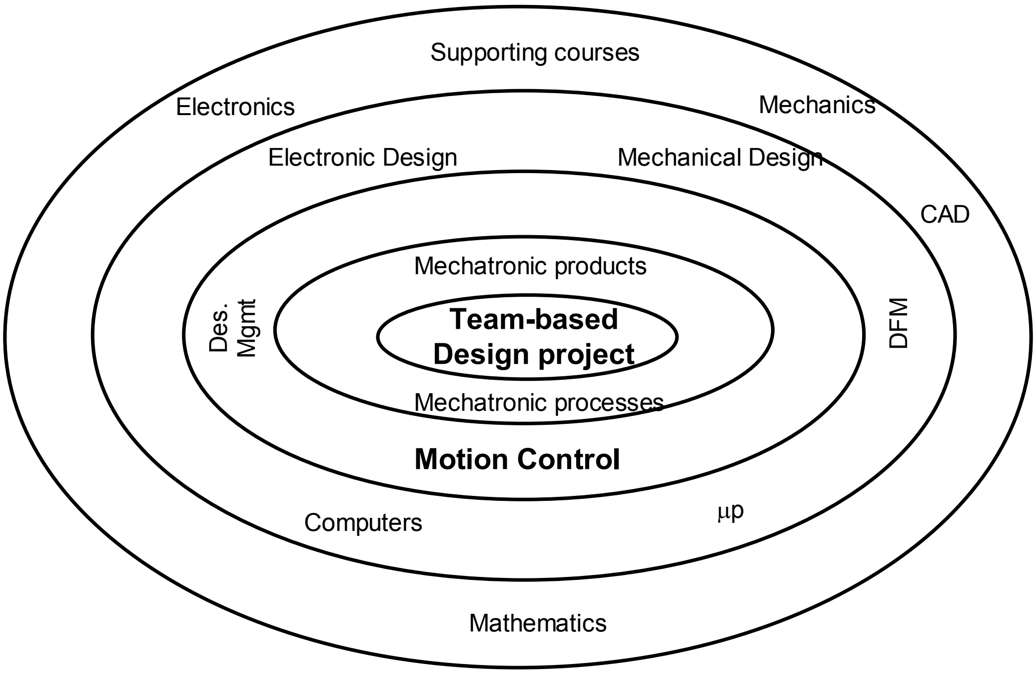

Figure 8 BEng. Mechatronic Eng. at City U of Hong Kong (2000)

Milne *et al* [22] note that the core disciplines of mechatronics (mechanics, electronics, and computing) are usually taught separately in different engineering departments in a "bottom-up" manner from fundamental principles and concepts. In contrast, they suggest that mechatronics "requires a systems-thinking attitude where consideration is given to the overall objective rather than individual components, which is evidently "top-down". Therefore, special attention has to be paid to mechatronics education [37]."

Team-based projects can be used to achieve experience-based learning of group goals, individual accountability, equal opportunities for success, team competition, task specialization, and adaptation to individual needs [37, 38].

It is useful to make team-based projects industrially relevant. Provided that sufficient resources are available, robotics can be used a potent arena for mechatronic projects undertaken even by undergraduate students. Projects aiming to develop robots capable of cleaning glass window panes in high rise buildings, filling automobile petrol tanks, playing table-soccer, cleaning floors in hospitals, and vacuum cleaning in homes are amongst the project undertaken by teams consisting 3 to 5 undergraduate mechatronic students at the City University of Hong Kong. Likewise, groups working under the supervision of the first author have worked on a robotic home kitchen system, a 4-axis

CNC turning/milling center, and a smart shopping cart using radio frequency identification chips to replace bar code reading technologies currently in use in super markets worldwide. Note that, contrary to popular opinion, the scope of mechatronics extends well beyond robotics.

6. Future Trends in Mechatronic Engineering

By definition*,* automation is the replacement of human labor. And technology is (just) a bag of tools that come in the form of hardware and/or software. A tool is something that assists in performing existing tasks better or enables new tasks to be performed. In other words, it somehow replaces human labor, i.e., automates the task. Thus progress in technology (through mechatronics, or otherwise) is synonymous to automation.

Human activity can be broadly divided into two categories: individual or collective (social). Individual activities may be purely mental or combined with physical activity. Irrespective of whether it is reflexive or reflective [39], any human physical act requires effort at five levels:

(i) Setting the goal (a purely mental activity).

(ii) Sensing the environment through the five sensory organs—eyes, ears, skin, tongue, and nose.

(iii) Communicating the sensory signals to the central neural processor called the brain.

(iv) Fusing the signals to recognize patterns of interest and output the command signals to human limbs.

(v) Performing the physical task using limbs (actuators).

A remarkable human ability is to *learn* from the results obtained from past acts so as to perform better when executing similar tasks in the future. This learning ability provides human beings with the ability to act as autonomous units. A further ability lies in communicating with other human beings so as to undertake collective tasks.

The above description of human abilities provides a basis for understanding and trends in mechatronics (see the right side of Figure 2). Note that task (v)—actuation, task (ii)—(signal communication), and task (iv)—(signal processing and decision making) have already been enabled (at least in part) by M, E, and C technologies respectively.

<u>Sensing and sensor fusion</u> (task ii) will be the next capability to be acquired by mechatronic systems. Already, many mechatronic units possess rudimentary sensing abilities. For instance, modern air conditioning units are able to sense air temperature and humidity through separate sensors and fuse the signals through fuzzy logic reasoning. Likewise, sensors in the form of transducers have long been used to enable feedback control in machines. However, there is still a long way to go. Sensors produce copious amounts of data that need to be digested to discover patterns of interest before control can be effected through the ‘actuators’. Advances in high-speed microcomputers and signal processing algorithms (such as those based on wavelet theory) have now opened the door for the exploitation of sensors exploiting a wide range of physical, chemical and, even, biological phenomena. While actuators are limited in variety, the variety of possible sensors is almost unlimited. For instance cutting forces in CNC machining and its consequences (e.g., tool fracture) can today be monitored and controlled using commercially available devices capable of sensing

machining noise, machine vibrations, acoustic emission, drive motor current [40], etc. Future mechatronic engineers will have to possess deeper understanding of natural sciences so as to cope with the growing variety of sensors. And they will have to learn to fuse these sensors using such emerging techniques as fuzzy logic reasoning and artificial neural nets (ANN).

Machine learning: Intelligence means adapting to the environment and improving performance over time [41]. Within the domain of mechatronic engineering, "there has been considerable interest in learning through the use of ANN and fuzzy logic for applications in control and robotics, autonomous guided vehicles (AGV), etc., that require mainly reflective intelligence when performed by human operators and tasks, such as machine diagnostics, requiring combinations of reflexive intelligence and low level reflective intelligence [39]." This interest will continue well into the future.

Autonomization refers to the development of the ability to survive and perform robustly while the external environment changes. With progress in sensor and learning technologies, tomorrow's mechatronic devices can be expected to become progressively more autonomous. They will be able to reset their local goals autonomously under changing external environments so as to meet the broad system-level goals set by human beings.

Modularization will be a consequence of autonomization. Mechatronic sub-units will come in modular form, i.e., with all the abilities required for local goal setting, control, and learning encapsulated within the sub-unit. Thus, in time, every mechatronic sub-unit will be self-contained and intelligent. To the mechatronic engineer, they will appear as black boxes. All (s)he has to do is to choose the right combination of sub-units and build the desired system

Miniaturization refers to the trend towards mechatronic units of significantly smaller size. Progress in precision engineering, newer materials (composites, diamond coatings, etc.), and nano-technologies will contribute to this development

Links to the Internet: The Internet will become ubiquitous within the mechatronic world. Every autonomous mechatronic unit will be connected via broadband and satellite networks to the rest of the world. Each mechatronic device will be able to access the information and knowledge base available on the Internet so as to optimize its own performance. At the same time, it will be able to communicate its operational status to remote monitors. For instance, one would be able to query from one's office the refrigerator at home about its contents and receive a fairly accurate answer. Likewise, one can query a pillbox how many pills are remaining!

Societies of devices: The metaphor of *society* is very similar to that used by Minsky in his book 'The Society of Mind [42]'. He says: "[M]ind is made up of many smaller processes. These we'll call *agents*. Each mental agent by itself can only do simple things that need no mind or thought at all. Yet when we join these agents and societies—in certain special ways—this leads to true intelligence." Once a mechatronic device has become autonomous, locally intelligent, and able to communicate extensively via the Internet, it can join 'societies' of devices with a common purpose or interest.

The implications of meachatronic devices developing social relationships with other devices and human beings can be bewildering. Quoting from [39]: *"[I]magine that you are walking through a production facility. Your guide points to a* [mechatronic] *work center and says "He is a baby. He still has to a lot to learn." He then walks to another and says "Ah! This guy is the smartest. He knows what he is doing. He is* *correct 80% of the time."”* Note that, while we had started this article with an implicit image of mechatronic devices as being inanimate, we are ending with a very animate (live) image.

Future mechatronic engineers will have to learn to cope with the immense technological changes described above. Let us hope that educators of mechatronic engineers will keep up.

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