Chapter 1

Interdisciplinary Mechatronics Engineering Science and the Evolution of Human Friendly and Adaptive Mechatronics

Mechatronics represents a unifying interdisciplinary and intelligent engineering science paradigm [HAB 07]. It describes the synergy of education in science and technology, knowledge, learning, thinking, a way of working, practices and professional skills. Interdisciplinary mechatronics is regarded as a philosophy that supports new ways of thinking, innovations and novel possibilties and new design methodologies that aim to achieve optimum functional synergy. Interdisciplinary mechatronics is supported by a strong engineering science foundation beyond the traditional disciplinary boundaries and features open-ending learning chains with ability to fuse new knowledge and experiences through lifelong learning process. Mechatronics engineering is about mastering a multitude of disciplines, technologies and their interaction, whereas mechatronic science is about invention and the development of new theories, models, concepts and tools in response to the needs evolving from interacting scientific disciplines. This philosophy has led to the development of new products, processes and systems that exhibit quality performance, such as reliability, precision, smartness, flexibility,

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adaptability, robustness and economical features. Human adaptive and friendly mechatronics (HAFM) represents the new era of mechatronics [HAB 07, HAB 08a, HAB 08b, HAB 12].

The evolution of interdisciplinary mechatronics and the growth of interest in this field triggered a need to have a quality of engineers whose education and training enables them to operate in an interdisciplinary environment. This demanded further the development of an efficient curriculum structure of a mechatronics engineering degree program designed to provide in-depth interdisciplinary knowledge and to focus on individual and team-based learning through a problem and project-based learning approach to fulfill the challenges of modern technology and innovation [HAB 08a].

1.1. Introduction

The new frontiers of engineering have a significant impact on engineering practices, and the formal boundaries among traditional engineering disciplines have become fuzzy following the advent of reliable integrated circuits, sensor technologies, computers and software engineering [HAB 06]. To meet the challenges of the new frontiers of engineering sciences and the needs of the 21st Century, it is important to educate engineers to think across multiple disciplines. Many of the new frontiers involve a high degree of interdisciplinarity and require a strong engineering science foundation.

Mechatronics has come to mean the synergy and the interdisciplinarity of engineering science that successfully fuses (but not limited to) mechanics, electrical, electronics, informatics and intelligent systems, control systems and advance modeling, optics, systems engineering, artificial intelligence, intelligent computer control, precision engineering, virtualization and virtual environments into a unified framework that enhances the design of products and manufacturing of processes. The synergy in mechatronics engineering creative design and development enables a higher level of productivity, precise performance, smart and high functionality, precision, robustness, power efficiency, application flexibility and modularity, improved quality and reliability, intelligence, maintainability, efficiency, energy and environmental consideration, better spatial integration of subsystems (embodied systems), miniaturization, and embed lifecycle design considerations. In addition, it contributes to shorten development time, to deal flexibly with complexity and to adopt cost-effective approaches for a wide range of intelligent products and applications. It is important to note that the mechatronics concept is not just about achieving technological and knowledge synergy but it also involves aspects of organization, training, management (projects, products, market demands and administration) and sustainable development. Mechatronics systems, processes and products enable the implementation of a scalable architecture in which functional elements are equipped with local control, diagnostics and communication features. The design of mechatronical systems must ensure an effective transfer of complexity between individual technologies, both for individual elements within the system and for the system as a whole. The adoption of such a synergized, inter- or transdisciplinary approach to engineering design implies a greater understanding of the design process [HAB 07].

The term “mechatronics” was first coined by Tetsuro Mori, CEO and president of Seibu Electric and Machinery Co Ltd. in 1969 when he worked for the Yaskawa Electric Corporation in Kitakyushu, Japan [KYU 96]. “Mechatronics” was used in his proposal to describe a new technology focus to produce new electromechanical machine tools that unites mechanisms and electronics while supported by semiconductor power devices and CPUs. “Mechatronics” has, since then, taken on a wider meaning than the traditional term of electromechanics. Figure 1.1 shows the evolution of mechatronics as a technology, practices, a concept and an engineering science discipline. In addition, mechatronics is now widely used to describe a philosophy in engineering and not just the technology itself [HAB 07].

During the early 1970s, mechatronics was simple and focused mostly on servo technology used in products with electronically controlled mechanisms, such as automatic door openers, vending machines and auto-focus cameras. At this stage, Mechatronics products were simple in implementation and encompassed the early use of advanced control methods, while the applied technologies were developed individually and independently of each other. With the development of ever more sophisticated technologies, the technical know-how has become a primary competitive factor, and efficient technology management were extremely important to keep track of the fast development in a large number of fields. The introduction of microprocessors in the mid-1970s has produced an explosion in the development of new products that incorporate the technologies associated with mechanical engineering, electronics and information processing. Hence, there has been an increasing need for a new approach to engineering. During the late 1960s and 1970s, the term “system engineering” came into widespread usage and the design methods used in mechatronics are derived substantially from the techniques involved by system engineers [TRE 03]. System engineers were the first to deal with the complex issues raised by interactions between software, mechanical engineering and electronics.

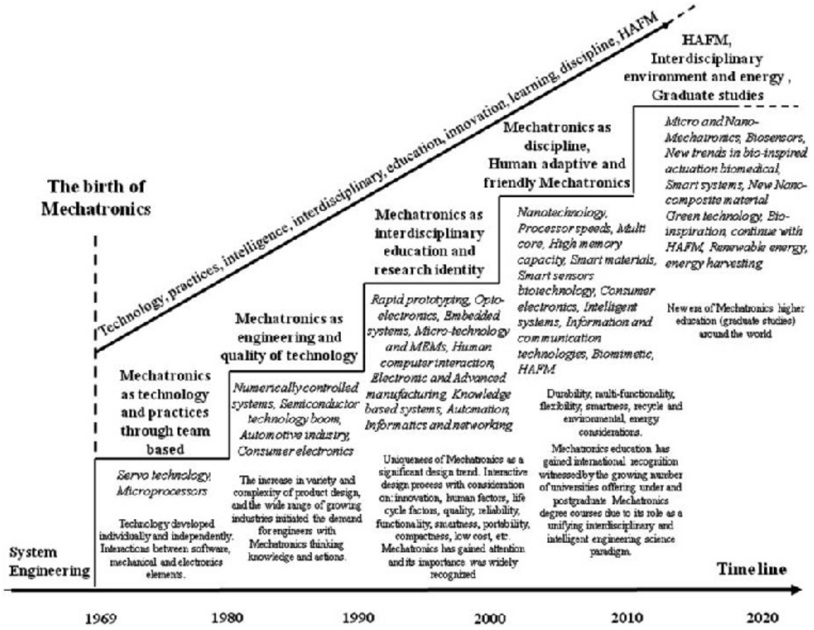


Figure 1.1. *Evolution of mechatronics as an interdisciplinary engineering science field. Adopted and modified from [HAB 07]*

Mechatronics emerged in Japan to describe the Japanese practices of using fully integrated teams of product designers with other members that represent engineers with traditional engineering backgrounds, manufacturing staff, purchasing and marketing personnel, etc. Such approach facilitates the development of a practical base approach supported by traditional theory to cover the key areas of practical design. In addition, mechatronics at this stage reflects the way people work to design and implement high performance, simple and reliable solutions. Nevertheless, most engineers working in teams rely on people outside their circle for implementing the technical solutions.

This demands spending much of their time on communication and the coordination of activities, and organizing technical solutions rather than implementing them. Mechatronics evolves as a design philosophy and a methodology used to optimize the design process, raises synergy and provides catalytic effect for discovering new and simpler solutions to traditionally complex problems. Such methodology is a collection of practices, procedures and rules used by those who work in a particular branch of knowledge or discipline.

In the 1980s, mechatronics came to mean engineering and technology. The advances in digital electronics have enabled the possibility to invent, create and improve systems that rely on mechanical components to perform their intended actions. A synergistic integration of different technologies started taking place, a notable example being in optoelectronics. During this stage, the codesign concept of hardware/software has been developed and used. The development of mechatronics technology was initially driven by the explosive trend in automation within the automobile industry and the increased use of electronic content in vehicles and the enhanced features of the control systems via software. Other contributing industries include industrial machinery and numerically controlled systems, product integration and manufacturing in consumer electronics and the semiconductor industry. During the second half of the 1980s, the mechatronics quality product lifecycle started to be compressed dramatically in which new technology has to be developed, manufactured and introduced to the marketplace, in a cost effective manner and quickly ahead of the competition, as early market entry for the product provides a critical competitive edge.

The enormous increases in variety and complexity of product design and the wide range of growing industries initiated the demand for engineers with mechatronical thinking, knowledge and actions; engineers who are comfortable in making the necessary decisions among a wide range of alternative approaches based on given design constraints. Such demand eventually guided universities toward creating dedicated degree programs for mechatronics. Such programs aim to develop an interdisciplinary way of thinking and practices to problem solving where the most effective engineering solution can be reached without bias from any given traditional engineering discipline. The question was how to develop an engineering curriculum and teach such a different philosophy within traditional engineering disciplines.

By the 1990s, mechatronics came to mean education and research identity as it emerged as an important engineering discipline. The most notable features at this stage are the increased use of smart functions in mechatronical products and systems, miniaturization of the product, enhanced human–computer interaction and shortening the development cycle time by adopting the use of virtual prototyping and computer simulation. Closely related topics of development during the 1990s were: rapid prototyping; human–computer interaction; optoelectronics, electronic manufacturing and packaging; microelectromechanical systems; advanced manufacturing technology for polymer composite structures; knowledge-based systems; material handling technologies; etc. Furthermore, a new breed of intelligent components and systems start to emerge that combine an optimum blend of all available technologies featured by innovation, better quality, high reliability, better performance, compactness, and low cost. In addition, the consideration of the human factor during the design process led to ease of product use, safety and increased benefits for the end user. The advances of miniaturization technology led to the further development of microelectromechanical devices such as sensors and actuators and thereafter, the evolution of more sophisticated sensors and servomotors with built-in intelligence supported by local computer-based signal processing and control functions. Microprocessors embedded into mechanical systems led to size and efficiency gains with the birth of anti-lock brakes and electronic engine controls. Embedded systems and real-time software engineering was also accomplished through various types of embedded microcontrollers, which are an indispensable component of modern mechatronics systems.

The 1990s highlights the beginning of new era that merges, innovatively, mechatronics with modern communication and information technologies. These technologies were added to yield intelligent products that are portable, mobile and could be connected in large networks. This development made functions such as the remote operation of robots, home appliances, manufacturing, biomedical devices and health facilities possible. Furthermore, fundamental and applied developments in mini-, micro- and nanoscale electromechanics (especially microscale electromechanical systems (MEMS) and micro-opto-electromechanical systems (MOEMS)), control, informatics and power electronics have motivated and accelerated such growth and have found a wide range of applications. MEMS, such as the tiny silicon accelerometers that trigger automotive air bags, and other electronic engine controls are examples of the latter. After the mid-1990s, mechatronics has been widely recognized and has received wide attention due to its role and importance.

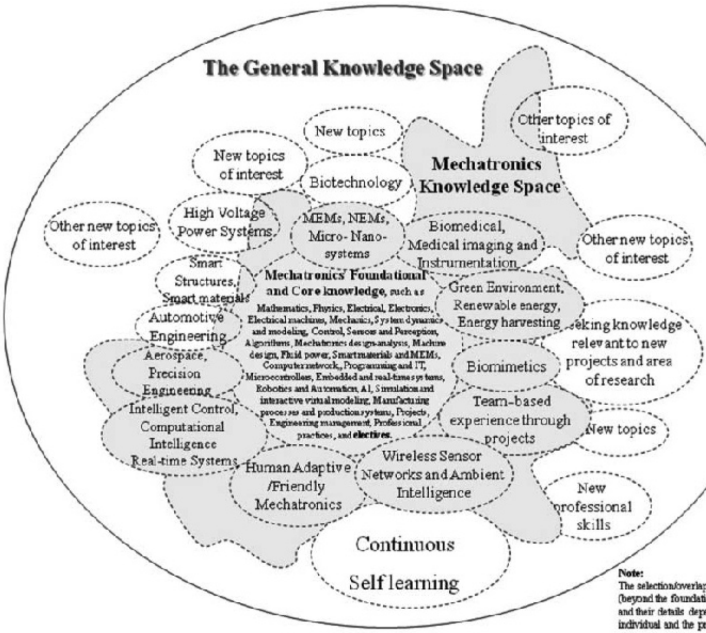
Since 2000, processor speeds, multi-core processors, advancements in building high memory capacity, smart sensors, the new era of micro- and nano-mechatronics predicated the boom in embedded and smart systems, such as in-car navigation systems, network-based audiovisual consumer electronic products, biomedical technologies as well as passive and active safety systems and more. The additional important trends are the increasing role of nanotechnology, and the incorporation of living and non-living molecules into processes and products, given their value in improving strength, appearance, durability, recycle and other functions.

Since the mid-2000s, HAFM represents the new era of mechatronics, which provides new methodologies and tools to design and to build new human-oriented machines and systems, featured by harmony and coexistence with its human user. HAFM allows creating, designing and support of new concepts for realizing intelligent human-oriented machines that coordinate and cooperate intelligently with their human users while understanding their status and surrounding situations through their interactive dynamic models supported by selected parameter constraints [HAB 12].

The interdisciplinary mechatronics engineering science field has experienced phenomenal growth since starting more than 42 years ago due to multidimensional advances in technology and methodology. Today, the term “mechatronics” encompasses a large array of technologies and it represents most of the research issues of modern design. The mechatronics design methodology is not only concerned with producing high-quality products, but maintaining these products as well. This area is referred to as lifecycle design which supports the knowledge-intensive engineering activities from initial conception to product disposal. The lifecycle design factors include delivery, reliability, maintainability, efficiency, serviceability, upgradeability, energy consumption and disposability (environmentally friendly) resulting in products that are designed from conception to retirement. Interdisciplinary mechatronics focuses on continuous individual self-learning, and team-based learning through a problem and project-based approach to fulfill the challenges of modern technology and the demand for innovation.

Modern engineering encompasses diverse interdisciplinary areas and interdisciplinary mechatronics engineering science has become and remains a significant design trend, which influences the nature of the product development process and technological changes, both in effect as well as pace. Yet, mechatronics was slow to gain industrial and academic acceptance, but this starts to change from early 2000, as witnessed by the growing number of universities offering undergraduate and postgraduate mechatronics degree courses. Mechatronics has gained tremendous international attention and its teaching is becoming important, becoming widely and globally implemented. It has yet to be universally adopted as an engineering science discipline. Hence, it is important for both industry and academic institutions to work together in order to tune the required infrastructures that provide mechatronics engineers with essential interdisciplinary knowledge, practices and skills [HAB 06, HAB 07].

Interdisciplinary mechatronics engineering science focuses on continuous individual self-learning, and team-based learning through a problem and project-based approach to fulfill the challenges of modern technology and the demand for innovation. Figure 1.2 introduces the paradigm of the knowledge space describing a mechatronics engineering science discipline that reflects the authors understanding of the mechatronics knowledge space.



Note:
The selection/overlapping of specialized topics (beyond the foundational and core knowledge), and their details depend on the interest of each individual and the professicnal needs of the relevant carrier.

Figure 1.2. *General and the mechatronics knowledge space paradigm. Adopted and modified from [HAB 07]*

1.2. Synergetic thinking, learning and innovation in mechatronics design

Mechatronics evolved into a philosophy supporting a new way of thinking and innovations in engineering science practices and design. It focuses on the learning process linked with actions rather than teaching. Thinking is a skill that can be developed and leads to effective learning. It is important to prepare students, engineers and members of research teams to engage in thinking and in knowing how to conduct an inquiry, how to listen and evaluate the opinions of others and how to compare alternatives. It is critical for successful thinking to associate two contradictory behaviors that should be separated in time: the aspiration and imagination to develop new ideas and how to argue these ideas to reach the best conclusion. This helps to organize thinking as a methodology and techniques to reach certain goals through a systematic use of thinking tools, clear awareness of the need for reflective thinking, self-evaluation of thinking, designing thinking tasks and methods to implement these tasks [HAB 07, HAB 08a, HAB 08b, HAB 12].

Interdisciplinary mechatronics engineering science is a challenging field that contributes to improve methodologies of the design process, aiming to achieve better efficiency, energy savings, ease of use and contributing human factors from the viewpoint of system integration. Mechatronics engineering is about mastering a multitude of disciplines, technologies and their interaction, whereas mechatronic science is about invention and development of new theories, models, concepts and tools in response to needs evolving from interacting scientific disciplines.

Imparting a synergetic and creative thinking through a problem-solving approach within the design process of mechatronical projects and systems requires not only changing the teaching methods and academic environment, but also adopting new assessment methods [MIO 98, WOL 89]. This component of the evaluation determines the degree to which the “across the curriculum, industrially relevant” approach to mechatronics is implemented, and maps each part of the design and implementation of a project activity on specified student learning outcomes.

These aspects of learning contribute to create challenges, curiosity, imagination and success in studying science and technology. It is evident that there is a role for science and technology education, as they remain a crucial part of general education [GAR 97]. Infusing creative thinking skills into the design process during project-based learning may provide a rich learning environment that contributes not only to the development of thinking skills but also to a better understanding of the discipline under study. The mechatronics engineering science curriculum suggests that educators create rich learning environments filled with real-world applications. The assessment processes of learning outcomes in a rich learning environment has an important impact on the learning process.

It is important for the student to study and apply lateral thinking tools in order to deal with different alternatives, consider multiple factors, and to refrain from premature judgments on ideas. Lateral thinking refers to discovering new directions of thinking in the quest for a wealth of ideas through brainstorming. In addition, students should use vertical thinking tools in order to shortlist the best solutions, document their design process and then go through the details of implementation, testing and evaluation. Vertical thinking deals with the development of ideas' details and checks them against objective criteria. To be able to use both effectively, one must appreciate their differences. During the work on a technological project, lateral thinking initiates the learning process while students seek alternatives and examine different solutions through brainstorming [WAK 97, HAB 07]. Vertical thinking is essential at the stage of choosing a solution and developing it. Vertical thinking and lateral thinking complement each other, and both are the essential elements of creative thinking [DEB 86, HAB 08]. Lateral thinking is a central, but not singular, component of creative thinking.

Researchers, designers and commercial developers are now employing a wide range of advanced computing techniques that are capable of enhancing the working environment of designers and empowering engineers in their work [REI 99]. Some important elements of engineering informatics are explicit representations of physical and abstract components, symbolic and numerical process models, graphical user interfaces, large-scale databases and interactivity. The processing of information consists of low-level and high-level feedback control, supervision and diagnosis, and general process management. With the aid of the knowledge base and inference mechanisms, mechatronics systems with increasing intelligence are developed [ISE 97].

In mechatronics, software and sensory information represent vital dynamic elements that contribute to optimize capabilities, enhance smartness and improve flexibility of targeted systems through the design process. The capabilities of mechatronics systems are increasingly a function of their control software, and computational capabilities and limitations must be considered at every stage of design development and implementation. The software in mechatronics systems is made up of information, fused with methods and algorithms which make it possible to facilitate decision and action support, and the building of associated intelligent functionalities. Information fusion can take place at different levels of abstraction in a system and at each subsystem as necessary. The resulting decision or action is in some sense better, qualitatively or quantitatively. In addition, utilizing the Internet and fusing mechatronics with information networks is supporting global connectivity and enabling people and systems to act and operate beyond the constraints of time and space. Just as the Internet induces us to think of information as a flow with a plurality of contexts, research on the network similarly forces us to think of science as a dynamic enterprise with a plurality of referents. Practicing interdisciplinarity means taking advantage of this plurality and guaranteeing the diffusion of ideas and the mobility of concepts [DAS 01, GAR 04, HAB 08a, HAB 12, HEW 96, REI 99].

For the purpose of avoiding unexpected trouble of a generalized design process, students/engineers/researchers should integrate the knowledge of the various disciplines, and learn the applicable standards and rules, as well as the underlying scientific principles and economic concepts with the necessary project management skill. Project-based learning in technology encourages students/engineers/researchers to work in teams where they can combine hands-on activities and project-based learning that could be used as a tool to develop students' competencies by working on integrated projects [BAR 02].

1.3. Human adaptive and friendly mechatronics

The evolution of mechatronics provides new methodologies and tools to design and build new machines and systems for safety, security and dependability. The main goals of modern technologies are to provide smart living and a clean environment that reduces operational stress, facilitates intelligent human life and to assist human well being while enhancing skills and maximizing performance. The increased functionality and smartness means the ability of products to identify and respond to changes in the human environment and to user's needs; that is to have intelligent machines that can be seen as a partner rather than just a tool. Hence, a key topic in the new mechatronics era is the design of human-oriented machines that implies intelligent and cooperative coexistence (beyond time and physical constraints) between technical and biological systems (human) within their natural environment.

A human and a machine may either share the same natural environment or be located at a different environment. If it's the latter case, it should be supported by mutual awareness to create a natural and mutual perception as they are located within the same natural environment. Machines can overcome situations that could not be foreseen by the machine at the design stage in an autonomous way and up to a certain degree of complexity, while in critical situations it is necessary to facilitate, intelligently, the interaction with the human user/operator [HAB 12, SCH 96]. Mechatronics will meet science to enhance human knowledge, skills, intelligence and performance through the harmony of coexistence, and will help elderly/handicapped people to lead their lives safely and securely supported by modern science and technology. However, the design of human-oriented machines should bring no mental and psychological stress to its user. This will lead us to have a human-friendly and environmentally conscious mechatronic technology that coordinates work and cooperates with human beings. It appears natural to design machines that can cooperate in an intelligent way with their human users, thus enabling humans to make best use of the machines capabilities while it protects itself from any misuse or critical situations. Such human-oriented machinery will have novel features in their behavior relevant to the level of interaction with humans [HAB 06, HAB 07, HAB 12, HAR 05, SCH 96]. This implies that the enabling mechatronics systems have to understand human behavior and interact intelligently, adaptively, seamlessly and mutually for the sake to optimize the performance and both sides of the interaction should have the ability to assume the initiative within a task. Human-oriented machines should be able to adapt according to the competence of the human user and the capacity of adaptation may be related to the level of mental workload, and this implies that such machines have the ability to recognize a human's performance within the process. This can be achieved by using new methods and techniques with learning and adaptive properties that reflect the complexity of the working environment and the design requirements for the interactive cooperation between man and machine.

Robust HAFM systems adapt themselves to the skill level or dexterity of a human under various environments which aims to improve the user's skill, and assist the human–machine interaction to achieve the best performance. This includes not only assisting the control action, but also providing proper data and knowledge for understanding the situation and giving better decisions. Humans can improve the skill elements of their actions based on interactive signals that yield to change within skill parameters. Figure 1.3 shows the concept of HAFM [HAB 12].

To fulfill this reliably, it requires the following:

1) to model human and machine dynamics with special consideration on variable constraints;

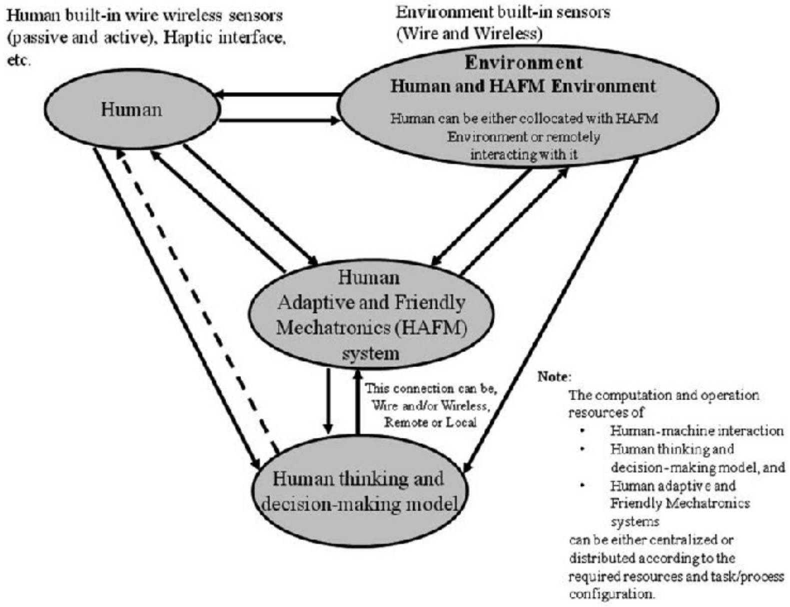
2) to model the psychophysical characteristics of a human user/operator;

3) to model the required operation based on the demand for essential skills, knowledge and quality decisions;

4) The mechatronic system has to understand cognitive human behaviors, and extend assistance to the human by providing information that helps to understand the situation, which leads to the making of quality decisions and achieves a high level of coordination;

5) to enable dynamic interaction between such mechatronical systems and humans. Aspects that have to be considered in designing such interactive and cooperative machines are: work psychology, safety, ergonomics, control architecture, control modules, etc.;

6) that safety should be assured throughout the coupling and interactive relation between a human and machine with the capability to resolve urgent and critical situations.



Note:
The computation and operation resources of

- Human-machine interaction
- Human thinking and decision-making model, and
- Human adaptive and Friendly Mechatronics systems

can be either centralized or distributed according to the required resources and task/process configuration.

Figure 1.3. *Conceptual diagram of human adaptive and friendly mechatronics. Adopted and modified from [HAB 07]*

There are number of criteria for how functions and authority are assigned to the human and machine depending on the versatility of the human and the consistency of the machine. These criteria may include techniques such as: leftover (with a high degree of automation the tasks, which cannot be automated are left over to the human), economic (for each partial task the cheapest solution is chosen), comparison (the task is allocated to the side who performs best) and complementary (assume that both sides have different capabilities, which complement each other) [HAB 07, SCH 96]. Understanding these criteria may help to develop intelligent tools that can assist human operators/users by giving them natural operational feelings. This needs to have physical symmetrical interaction between both sides mediated by common tools/modules, which includes their dynamical and behavioral/functional models, and is supported by sensory information reflecting each side's activities, and their local environments. Both sides may be located at the same local environment or located at completely different environments. Ambient intelligence, biologically inspired technology (Biomimetics), information and communication technologies, intelligent control and smart materials represent good candidates to facilitate the evolution of HAFM.

1.4. Conclusions

Mechatronics has opened up enormous technological possibilities that would never be possible to achieve or foresee by adopting a traditional single disciplinary or classical subsystem-based approach. Mechatronics has proven itself as a unifying interdisciplinary and intelligent engineering science paradigm as it is opening up new horizons and a bright future in all fields due to the stimulation of synergy, fusion and interdisciplinarity. This insight naturally lends itself to the concept of total quality that focuses on thinking, learning and innovation. HAFM represents the evolution of mechatronics into a new era that aims to provide new methodologies and tools to design and to build new human-oriented machines and systems characterized by harmony and coexistence with its human user. HAFM contributes to the change in the interactive relation between human and computerized systems, such as machines in order to find out the best solution to problems, maximize efficiency to achieve common goals and provide a good level of adaptation with some degree of autonomy for the machine side.

Mechatronics has gained tremendous international attention and its teaching is becoming important, and widely and globally implemented. The industry is now demanding engineers with a great, detailed and wide range of interdisciplinary knowledge, properly trained and supported by concurrent practices through a problem- and project-based curriculum to meet the challenges of interdisciplinary demand. To prepare capable mechatronics engineers, mechatronics curriculums and degree programs should feature a major design component through creative and innovative learning processes and balanced by basic and applied mechatronic theory. Accordingly, there is a need from the mechatronics community to focus their efforts on sustaining the progressive evolution of mechatronics as an engineering science discipline by strengthening its core pillars: interdisciplinarity, learning and thinking, knowledge fusion, problem- and project-based innovation, and skill building. In addition, mechatronics engineers and practitioners should always be associated with lifelong learning, and the capability to engage challenging problems and complex tasks with initiative.

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