Mechatronics versus Robotics

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1.1 Mechatronics: definitions and evolution

The name *mechatronics* was coined in 1969 (40 years ago!) by Ko Kikuchi, who subsequently become President of Yaskawa Electric Corporation [10], [32]. The word is composed of “mecha” from mechanism, i.e., machines that move (or mechanics), and “tronics” from electronics, and reflects the original idea at the basis of this discipline, i.e., the integration of electrical and mechanical systems into a single device.

The spread of this term has been growing in the years, and different definitions have been given, each time adding something and/or underlining some aspect not previously highlighted. The analysis of the various definitions through years can help to well understand how mechatronics was considered at the beginning and what it represents nowadays.

In [6] mechatronics is defined as the "integration of electronics, control engineering, and mechanical engineering", thus recognizing the fundamental role of control in joining electronics and mechanics. An *official* definition was given in mid 90's by a technical committee of the International Federation for the Theory of Machines and Mechanism: "Mechatronics is the synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes" [10]. The key point in such a definition was the concept of *synergistic combination*, distinguishing mechatronics from the classical *concurrent engineering* approach, in which groups of the same project team work separately, sharing the overall obtained results, but only partially the specific design decisions during the project development.

Subsequent definitions in late 90's put in evidence the goal of designing "*improved* products and processes" [5], thanks to the synergistic use of the different mechatronics components, and of achieving an "*optimal design* of electromechanical products" [48], recognizing at the same time the role of other disciplines beyond electronics, control engineering and mechanical engineering, like computer engineering and communication/information engineering.

At the beginning of the 21st century mechatronics has already a well defined and marked identity, as an ever-growing engineering and science discipline, thanks to the continuous advancement in enabling technologies, such as multi-sensor fusion, motion devices, very large integrated circuits, microprocessors and microcontrollers, system and computational intelligence software and techniques [29]. The importance of sensors and of communication capabilities for mechatronic systems has grown steadily: currently, an intelligent mechatronic system is supported by various sensing devices, and it can be of micro/nano size, as well as highly integrated in a multi-system overall architecture.

1.2 Mechatronics versus robotics

What is the difference between mechatronics and robotics? A robot is commonly considered as a typical mechatronic system, which integrates software, control, electronics and mechanical designs in a synergistic manner. Robotics can be considered as a part of mechatronics, i.e., all robots are mechatronic systems but not all mechatronic systems are robots. In [15], Fukuda and Arakawa highlighted how autonomy and self-decision making represent the key points to classify systems in the fields of mechatronics and robotics. All machines that do not have any kind of autonomy in their behavior, because they simple *automatically* act according to the inputs they receive (directly or indirectly) from the humans, are strictly pure mechatronic systems. All the robots (manipulators, mobile robots, etc.) instead have a certain degree of autonomy, and hence they can be considered as special mechatronic systems, which can be classified both in the mechatronics and in the robotics fields. If a robot has also a proper self-decision making function, allowing it to autonomously determine its behavior, it is then classified into the fields of robotics only: according to [15], it is then something more than a pure mechatronic system.

Such a classification is not (and cannot) be really so rigid, because the level of autonomy of a mechatronic system or a robot could be very different. In [33], it is said that "the main difference is inputs are *provided* to mechatronics systems whereas robotics systems *acquire* inputs by their own".

The capability of a robot of acquiring inputs by its own is strongly related to its *awareness* of what it is happening around it. Sensors and information from the environment can be used by a robot not only to automatically act according to the way it has been programmed, but also to vary its behavior in autonomous manner.

The industrial robots have generally a quite limited (or null) awareness of the events occurring in the surrounding environment, so that they can be considered as standard examples of good mechatronic systems. On the contrary, the last generations of robots, devoted to various, not strictly industrial applications, are characterized by an ever-growing level of autonomy, and of awareness of the environment. Examples are given by service robots, underwater and aerial robots, and biologically inspired robots; all these kinds of robots exploit various technologies beyond mechatronics, e.g., automotive issues, smart machine technology, software and communication structures.

1.3 Mechatronics and robotics: new research trends and challenges

As mentioned in the previous sections, drawing a sharp border between mechatronics and robotics is impossible, as they share many technologies and objectives. A mechatronic system makes use of sensors, actuators and controllers, like a basic robots equipment. They usually have a specific task to accomplish and this is performed in a known and fixed scenario. Advanced robots, on the other hand, usually plan their actions by combining an assigned functional task with the knowledge about the environment in which they operate. By using a simplified approach, advanced robots could be defined as mechatronic devices governed by a "smart brain", placed at a higher hierarchical level. This definition, however, does not cover some new mechatronic devices, used in tight interaction with humans, such as an active rehabilitation orthosis. For such type of devices, user safety is the primary issue.

Clearly, for the achievement of an intrinsically safe behavior, the use of smart control strategy (the above mentioned “smart brain”) is not enough and the use of actuators that will never harm the user (even in case of control failure) is mandatory. This simple example tells how it is difficult to characterize new research trends and challenges exclusively pertaining to mechatronics or robotics. Having this in mind, in the following, we will present what we consider the “hot topics” in both fields, with attention to new fields of application, new challenges to the research communities and new technologies available. The next subsections will follow the reminder of the book, in which researchers from different institutions will provide their view on specific subjects.

1.3.1 Advanced Actuators for Mechatronics

Actuators are building blocks of any mechatronic system. Such systems, however, have a huge application span, ranging from low–cost, consumer applications to high end, high precision industrial manufacturing equipment. Actuators have to provide the driving force to a mechanism which, in turn, has to perform some actions or movements. The technologies available to produce such driving forces are quite varied. We can have traditional electromagnetic actuators, piezoelectric, capacitive, pneumatic, hydraulic etc. Each of them has different peculiarities in terms of range of force generated, speed of response and accuracy. In addition to the actuator itself, reduction gears, recirculating ball screws etc. are often used to convert the actuator output, in order to be coupled to the mechanical load. Such fixtures are usually introducing friction and backlash, thus reducing the level of precision achievable. The solution to this problem has been addressed by either designing new actuators [14], or by introducing sophisticated modeling and compensation of the non–idealities introduced by the motion transmission device [41]. The design of new actuators can follow different paths, driven by the specific needs of the application. In high precision applications, the use of a secondary actuator, placed in series to a primary one, is an effective way to obtain at the same time large motion spans and high accuracy. This solution, at first introduced in consumer products like Hard Disk Drives (see [31]), is now being utilized in manufacturing plants, when a single actuator cannot achieve at the same time the prescribed range of motion and accuracy (e.g. [9]). The use of multiple extra actuators, however, requires the development of new control strategies, to cope with the diverse interaction that may arise, compared to standard systems with a single actuator [56]. Two degrees of freedom actuators can also be designed in order to combine two motions, like the roto–translational direct drive motor the presented in [51]. Actuators can be also tailored to the specific application and they can be designed either to move along a specific path in space (see the half-circle-shaped tubular permanent magnet motor presented in [35]) or to provide a variable compliance, in order to increase the safety of all mechatronic devices that directly interact with the user [44]. Finally, among all possible actuator technologies available for a mechatronic application, the designer must account for the cost/performance trade–off. For some inexpensive, ultra–low–cost applications as those for consumer devices, a new type of actuators makes use of Shape Memory Alloy (SMA) wires, which contract and relax according to their operating temperature [30]. Their response time is in the order of tens to hundreds of milliseconds, but they can be profitably used in many mechatronic applications, thanks also to their self-sensing capabilities [4].

Among all the possible directions mentioned above, we will deepen the main issues arising in the realization of a high–end industrial manufacturing system. For the achievement of the highest performance, accurate modeling and compensation of the non–idealities of the transmission gears is mandatory. Additionally, multiple–stage actuation is becoming the "mantra" for the high–end designer, as it allows to cope with the usual conflicting specifications of large motion spans and ultra–high accuracy. Both concepts will be developed by Prof. Iwasaki of the Nagoya Institute of Technology (Japan).

1.3.2 Advanced Sensors for Mechatronics

Like actuators, sensors are needed in all mechatronic systems, in order to guarantee the achievement of the desired performance, in spite of all disturbances and uncertainties. Indeed, there are numerous references on traditional sensors for mechatronic systems (see for instance [39]), mainly aimed at the description of standard sensor technologies and their use in measuring some quantity to be controlled. The technology advancements and the manufacturing cost reduction, however, have opened new perspectives in the use of sensors in mechatronic systems. This is the case, for instance, of MEMS sensors [47]. Thanks to the push coming from the consumer electronics world, the once expensive accelerometers and gyroscopes have evolved into ultra-small (2x2x1 mm) and low cost (less than 1 USD) commodities, which can be placed virtually everywhere in a mechatronic system, to better monitor and/or control it. Of course, the use of additional sensors to achieve higher control performances requires smarter designs and better understanding of the underlying system dynamics. Applications of MEMS sensors in the control of mechatronic devices can be found in the area of vibration control, where they can be used to sense the oscillations of the mechanical load, due to flexible couplings between actuator and load (e.g. [3]). The same sensors can be also used to measure and compensate torque/force ripples caused by the actuator non–idealities, thus allowing a better overall performance [2].

In addition to classical sensors, capable of measuring a single process variable, we see a growing number of applications in which the state of the process to be controlled and, possibly, its colocation w.r.t. the operating scenario are determined by properly fusing measurements from different sensors. This is not only the case of autonomous vehicles [23] but it refers also to floor-cleaning robots, smartphones, inertially stabilized cameras etc. In this scenario, humans make their appearance as sources of disturbances (e.g. obstacles to be avoided) or like partners to collaborate with (e.g. in assistive mechatronic devices). This deep interaction between mechatronic devices and humans requires specific sensors and this subject is tackled by Prof. Murakami of the Keio University (Japan) and his collaborators, who will deepen some aspects on the use of vision systems and other sensors (tactile, Brain–to–Computer Interfaces etc.) for the implementation of safe and reliable interaction of humans with mechatronic devices, like an active wheelchair.

1.3.3 Model Based Control Techniques for Mechatronics

Control is what ties together mechanisms, actuators and sensors, in order to perform an assigned task with a prescribed degree of accuracy, speed and robustness, all in spite of the possible disturbances. Usual designs rely on feedback to synthesize the proper command for the actuator, and this per se requires an accurate tailoring of the control around the nominal plant, its possible variations and the disturbances acting on the system. The simple mathematical modeling of the plant is no longer sufficient in this scenario and new techniques and procedures have been developed through the years, aimed at identifying not only a linear approximation of the process to be controlled, but also all disturbances and non linearities affecting it [45], [50], [21] . But feedback control of a mechatronic device relies on a measurement of errors between target and actual motion and this, unfortunately, tells us that with this approach it is almost impossible to achieve a null error by relying exclusively on feedback. The usual practice, in this scenario, is to add some feedforward action, as it is typically done in CNC when implementing the tracking of a trajectory. In advanced, ultra–high precision control, the use of feedforward is gaining more and more support, thanks to the development of very accurate models for all system components. A notable area in which the demanded performance is at the highest level is the photolithography in integrated circuit manufacturing. Here, the most advanced control techniques have been developed and the most relevant results (applicable in many other highly demanding mechatronic applications) will be presented by Prof. Omen and Prof. Steinbuch of the Eindhoven University of Technology (The Netherlands).

1.3.4 Control and Manipulation

Traditional definition of Robotics deals with articulated, multi d.o.f. mechanisms, capable of manipulating objects and tools along a desired path, in terms of position and orientation. On this subject, numerous publications and books are available, dealing with standard motion control, force control, visual feedback, etc. [11], [46], [20]. The most recent trends and challenges are oriented toward new robotics applications, requiring advanced manipulation capabilities and possible collaborations with the human operator, so that the most classical approaches in the fields of task space control, robot compliance behavior, and force and interaction control need to be revised, e.g. including joint trajectory generation to create compliant motion for manipulators [24], developing new solutions for task space control guaranteeing a compliant behavior for possible redundant degrees of freedom [42], or exploiting force control and optimized motion planning to achieve autonomous manipulation capabilities [40]. In the first chapter entirely devoted to Robotics, Prof. Siciliano and Prof. Villani of the University of Napoli (Italy) will survey the motion control problem as the basis for more advanced algorithms. Particular attention will be devoted to manipulators having non negligible joint elasticity, as well as to redundant robotic systems, exploiting a large number of degrees of freedom to simultaneously execute multiple tasks. Several applications, both in industrial and service robotics, require the physical interaction of the robot manipulator with the environment, or possibly with the human operator. Since the pure motion control strategies are not suitable for handling such situations, the main interaction control approaches will be also addressed in the same chapter, which will be completed by a discussion about future directions in robot control, including a list of recommended readings for a deeper analysis.

1.3.5 Navigation, Environment Description and Map Building

Mobile robots, introduced several decades ago [17], have evolved from simple “devices on wheels”, with very simple reaction control (e.g. aimed at implementing simple collision avoidance), to very complex systems, with a rich set of sensors and actuators, under the control of sophisticated software, which allows the robot to autonomously move in an unknown environment. Halfway between fully autonomous mobile robots and simple reacting mechanisms, we can find Automatic Guided Vehicles (AGVs), which are nowadays profitably deployed in many industrial scenarios [52]. Most of them navigate the environment by following some magnetic or optical reference, placed under or over the floor. This, however, makes any modification of the paths a little bit hard and there are also problems in dealing with turnarounds in case of unexpected obstacles on the path. So, even in industry, there is a lot of interest for those technologies developed in the field of totally autonomous mobile robots, which do not make use of special guiding infrastructure to reach the final target position. In this regard, critical for the completion of the tasks assigned to a mobile robot, is its ability to detect its current position w.r.t. the environment in which it moves and w.r.t. to the final goal. Additionally, the capability of finding a way to reach the final goal is also necessary [49]. Prof. Castellanos of the University of Saragozza (Spain) and his collaborators will illustrate the most recent advancements in the area of mobile robot navigation, starting from the above–mentioned basic issues and getting to the so–called SLAM or Simultaneous–Localization–And–Mapping.

1.3.6 Path Planning and Collision Avoidance

In the previous subsection, we mention the need for modern mobile robots to localize themselves in an unknown environment and to find their way to the final goal. This goal–reaching feature is also present in standard industrial robotics, where, however, the operating scenario is slightly different compared to that of mobile robots. For instance, in an industrial robotic cell, the manipulator is an articulated mechanisms, for which the computation of possible collisions with the obstacles in the workspace is by far more complicated than in the case of box–shaped mobile robots. Additionally, path planning is no longer merely done by constructing a path from starting to end position, composed by lines and circular arcs [27], but it takes advantage of the availability of high computational power to use more complicated curves definitions, like high order polynomials and NURBS [37]. Planning can be done also by taking into account additional objectives, like the minimization of time or energy consumption [53], even by exploiting the redundancy of the manipulator, when available [16]. Eventually, the trajectory planning can also consider dynamic aspects such as the structural flexibility of the manipulator and, in turn, design a trajectory that does not excite the structural modes, or produce a null residual vibration of the end effector at final target position (or while following a desired path) [55]. Prof. Müller of the Johannes Kepler University (Austria) and his collaborators will present the most recent advancements in the field of optimal path planning and collision avoidance, both dealing with standard and redundant robots, and investigating methods to incorporate the existence of obstacles in the robot workspace in the path optimization problem.

1.3.7 Robot Programming

In the early age of industrial robotics, programming was restricted to the construction of a list of actions to be performed by a single manipulator, possibly interfaced with some sensors and coordinated with other manipulators, placed in the same production line [36]. In all robotics textbooks, a little portion was devoted to programming and usually the subject was treated as something handled by robot manufacturers, who developed proprietary programming languages (e.g. VAL by PUMA). Each manufacturer also developed closed ecosystems, in which only the proprietary peripherals (like vision systems) could be seamlessly integrated into the robotic cell. Programming, in such scenario, was an art, mastered by few experts, with a deep understanding of the architecture of the robotic system (i.e. the mechanical device, its sensors, the controlling unit and all the peripherals) and adding some new features (e.g. by using the readings of new sensors) was extremely difficult. Since such early stage, robot programming has evolved in many directions, in order to cope with the request of creating new robotic equipments, possibly composed by multiple robotic devices and sensors, manufactured by different companies or developed ad–hoc. With the emerging needs for new and complex robotic equipments, their programming becomes more and more a team work, with parallel development of different functionalities. Both academia and industry have tried to respond to such requests for a unique digital industrial platform for robotics. The present scenario is rather vast; the chapter authored by Prof. Schlegel and his collaborators of the Technische Hochschule Ulm (Germany) will investigate the most advanced solutions nowadays available for robot programming, explaining the step change from framework-specific programming to technology-agnostic modeling, separation of roles and composition. Eclipse-based open-source tooling with repositories of software components and robotic applications is accessible to make first own steps.

1.3.8 Network Robotics

Recently, there has been a growing interest and research activity on cooperative control and motion coordination of multiple robots. Such interest is mainly due to the growing possibilities enabled by robotic networks, not only in the monitoring of natural phenomena and the enhancement of human capabilities in hazardous and unknown environments, but also in the industrial scenario, where a team of networked robots can be used to flexibly implement a production cycle [8]. In this scenario, the coordination between robots becomes a key issue to exploit as much as possible the potentialities of a team cooperatively carrying out a common task. Multi-robot coordination addresses several issues, e.g. centralized and decentralized control, formation control [1], consensus networks [34], coordinated trajectory tracking, communication infrastructures and resources (heavily exploited by the most recent *cloud robotics* solutions [25]). Prof. Melchiorri of the University of Bologna (Italy) and his collaborators from University of Reggio Emilia and Modena (Italy) will consider a team of mobile robots, equipped with general purpose tools and coordinated along complex trajectories, to be employed as an automated solution for highly flexible and variable production scenarios. In particular, the multi-robot system is partitioned in two groups: one of independent robots (acting as supervisors and defining the production cycle) and the other one composed by dependent robots, actually provided by tools and acting as workers.

1.3.9 Intelligent, Adaptive Humanoids for Human Assistance

Humanoid robots, for long time present only in sci-fi movies and novels and, more recently, as expensive demonstrators of technological achievements [19], are now making their actual appearance in real–world applications, where they are promising to bring a new form of bilateral and assistive interaction with humans. The envisioned applications of humanoid robots are countless and they all have in common the fact that this type of robots will closely interact with humans in the same places where they live and work. Such environments, indeed, have stairs, doors, windows etc. and are full of different objects to be grasped, manipulated and moved around. Humanoid robots represent a great challenge for both science and technology, as their realization requires a deep understanding of essential aspects of biomechanics (at least those needed for the replication of some human ability, like walking, stair climbing, object grasping, perception etc. [22]) and the deployment (and sometimes the development) of many different technologies for sensing and actuation [12]. Additionally, as humans, it is expected that humanoid robots will interact with their world in an adaptive way, learning by experience. The state of the art and the most recent achievements in this research area of robotics will be investigated by Prof. Caldwell and his collaborators of the Italian Institute of Technology, with particular focus on the COMAN humanoid robot developed at IIT.

1.3.10 Advanced Sensors and Vision Systems

The most recent research results in machine vision and advanced sensors are leading to significant improvements in various fields, and in particular in for the autonomous vehicles navigation, with several applications form robotics to space exploration [28]. Autonomous navigation can be achieved giving the robot the capability of planning a global path toward the target position [54], [13], of locating itself with respect to certain benchmarks (or with respect to a given map), and of recognizing obstacles that must be avoided [49]. Such capabilities require the fusion of data coming from different types of sensors (e.g. vision sensors, omnidirectional cameras, laser range finders, GPS), whose characteristics and performances must be exploited in a robust manner, taking into account the environment conditions in which the autonomous agent has to move [38], [43]. For example the environment could be indoor or outdoor, static or dynamic, structured or unstructured, described by means of landmarks or by an occupancy grid map.

Prof. Kang-Hyun Jo from University of Ulsan (Korea) and his collaborator from Quang Binh University (Vietnam) will survey the main issues of visual odometry (such as the extraction and matching of feature descriptors, and the estimation of the robot rotation by using an omnidirectional vision system), as well as some advanced sensors successfully employed for autonomous navigation, like laser range finders and GPS, providing general guidelines for sensor fusion.

1.3.11 Human–robot interaction

A strong Human-Robot Interaction (HRI) requires that humans and robots share similar sensing capabilities. The haptic sense in particular allows humans to recognize various physical characteristics of an object simply touching it. The “real-haptics” technology allows the reconstruction of the haptic sense, and can lead to a new generation of robots, ready for a more complete interaction with humans in various fields, from daily life to medical and rehabilitation robotics [7], [18]. Moreover, a smooth and compliant manipulation capability can be exploited in the Robot Learning from Demonstration framework, for the development of teaching interfaces that allow to change the robot stiffness by physically interacting with it [26].

The potentialities of real haptics as a new way to interact with robots are discussed by Prof. Kohuei Ohnishi from Keio University (Japan) in the last chapter, which provides an introduction to the basic principles of the feedback of the tactile sensation between the robot and the human together with some experimental examples.

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