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Causal Links and Informational Links in the Structure of Technical Systems

Vlad TĂMAȘ [1], Vistrian MĂTIEȘ [1]

[1]*Department of Mechatronics, Technical University of Cluj-Napoca, Cluj-Napoca, Romania*

Abstract: *This paper presents details on the concept of links, in the consecrated approach of the classical mechanics as well as the openness due to mechatronics, by bringing to the foreground the material and energy of the information component. Mechatronics, the 21st century technology and smart machine science, operates with the triad: matter-energy-information. Dualism: energy flow - informational flow is the defining characteristic of any mechatronic system. Based on the analysis of the general structure of a mechatronic system and the structure of a smart machine, the concepts are explained and exemplified: information links, information carriers, information kinematic couplings and information kinematic chains. Examples from the field of actuators and mechanisms are analyzed. The proposed approaches bring new openings in technology, science as well as in education.*

Keywords: smart city, mechatronics, cyber-physical systems, internet of things

1. INTORDUCTION

From the perspective of classical mechanics, the movement of a system of N material points is defined if, at any given time t, the vectors $\vec{r}_n$ and $\dot{\vec{r}}_n n = 1,2,\ldots,N)$ positions and velocities are known [20]. If the mechanical system is free, $\vec{r}_n$ and $\dot{\vec{r}}_n$ can take any value. In most cases, however, there are system constraints, which limits its movement. These limitations require restrictions on the $\vec{r}_n$ and $\dot{\vec{r}}_n$ vectors, meaning that they are no longer independent variables. In these situations, it is said that the system is subject to constraints and that there is a set of relations that mathematically express the constraints imposed. This means that certain points of the system are required to be fixed or to remain permanently in mechanical contact with a surface or a curve.

The constraints can be bilateral, if these relations are equal or unilateral, if the constraints are expressed through inequalities. In general, the equation of a bilateral connection is expressed in under the following form [20]:

$$f(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N, \dot{\vec{r}}_1, \dot{\vec{r}}_2, \ldots, \dot{\vec{r}}_N; t) = 0 \quad (1)$$

The above equation describes a nonholomic constraint, since it depends on velocities. In case the velocity does not appear, the constraints are called holonomic.

If a system has constraints, its equation of motion is no longer in the form:

$$m_n \ddot{\vec{r}}_n = \vec{F}_n(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N, \dot{\vec{r}}_1, \dot{\vec{r}}_2, \ldots, \dot{\vec{r}}_N; t), \quad n = 1,2,\ldots,N \quad (2)$$

where $\vec{F}_n$represents the force acting on the particle $n$due to the other particles of the system and the external field. The main reason why the movement of the constraint system does not respect the relation (2) is that the forces $\vec{F}_n$ are not causally determined by the constraints. As a result, the existence of the constraints requires the extension of the equation (2) so that the new relation also includes the additional forces $\vec{R}_n$, due to the constraints. Thus, equation (2) becomes:

$$m_n \ddot{\vec{r}}_n = \vec{F}_n + \vec{R}_n, n = 1,2,\ldots,N \quad (3)$$

In conclusion, on a mechanical system, two types of forces do act: the known forces $\vec{F}_n$ and the connection forces $\vec{R}_n$, which can generally be determined only after the movement is known [20]. A useful perspective is the following: on the system act the applied forces which are known and the constraint forces, which are not known initially, but can be determined. According to the axiom of constraints, the constraints to which a system is subjected can be suppressed and replaced with connection forces, thus have the sameeffects on the system as the constraints suppressed [20]. Thus, the constraint system can be treated as a free mechanical system, that issubject to a set of forces that includes both applied and connection forces. Obviously, the balance of the system requires that the result of all these forces is null:

$$\vec{F}_n + \vec{R}_n = 0 \quad (4)$$

One of the most useful results of the analytical mechanics regarding the properties of the connection forces is the D'Alembert principle, according to which, in the case of perfectly holomic constraints, the mechanical work of the bonding forces at a virtual displacement of the system is null:

$$\sum_{i=1}^{N} \vec{R}_n \cdot \delta\vec{r}_n = 0 \qquad (5)$$

According to this perspective on the concept of connections, the constraints imposed to the system needs only material and energetic support. Also, in the classical theory of control mechanisms, the kinematic coupler represents the mobile, direct connection between two kinematic elements, which aims to limit the relative freedom of movement between them and the transmission of movement from one element to another. Therefore, in the classical approach, the transmission of movement from one cinematic element to another takes place only directly, which implies the existence of direct contact, matter-matter and the energy exchange between the two kinematic elements.

The development of mechatronics brings in the foreground the information component [6]. The mechatronic word, patented by Yaskawa Electric Concern in Japan in 1970, was used to describe the technological fusion of three major engineering fields: mechanical engineering - electrical engineering, electronics, telecommunications - control theory and information technology. Mechatronics was born as a technology and, quickly became a philosophy (the philosophy of integration), the science of smart machines, respectively, the environment for smart education and organizational learning, in the knowledge-based society. The technological development in the 21st century is based on the triad: Advanced Mechatronics (backbone) - Cyber-physical systems (CPS) and Internet of Things (IoT). The technological triad mentioned is the foundation of Industry 4.0 concept [3], [8], [18].

In mechatronics, information is a key component in relation to mater and energy [6], [8], [15]. This position of the information is motivated by the Japanese through the following [6]: the information ensures the fulfillment of the spiritual needs of the human being and, at the same time, ensures the increase of the newly added value of all things. Promoting information connections in the structure of technical systems ensures flexibility and reconfigurability. Information is the expression of the non-uniformity of the distribution of material and energy in time and space. As the transmission of information requires small amounts of material and energy, the functional performances of the technical systems increase. For engineering practice, mechatronics marked the jump from traditional, sequential engineering to parallel / concurrent engineering. Thus, the concept of integrated design / control design was developed.

Therefore, in the case of mechatronic systems, the connection between two kinematic elements can be mediated by information. In these cases, we can talk about cinematic informational couplings, which provide information connections between the kinematic elements, mediated by the information carriers. If several movable elements are connected by means of information, kinematic couplings, an information kinematic chain is formed.

Thus, from mechatronics point of view, the kinematic coupling can be defined as the totality of the interaction modalities between two rigid kinematic elements [9]. According to this definition, the interaction of the kinematic elements can be achieved otherwise than through direct mechanical contact, namely through the information carriers. If the role of the information carriers is played by fields (electrical, magnetic, etc.), we can speak of information fields.

Through the integrated approach of the triad: information-energy-matter, mechatronics has opened up unanticipated horizons in all fields of activity. These openings for the technological field are explained below.

2. THE HARDWARE STRUCTURE OF A MECATHRONIC SYSTEM

Generally, a mechatronic system comprises the following modules [8], [9], [15] (*Fig-1*): the task scheduling system, composed of microprocessors and microcontrollers, which generates the movements and sequences arising from the transmitted requirements or commands; the sequence and movement controller, responsible for comparing the imposed parameters with those of the movement and for making the necessary corrections; the power amplifier, which amplifies the signal, to be in accordance with the actuator requirements; the actuator, which transforms the corrected signal into an appropriate signal for the technological process; mechanical mechanisms and transmissions, which adapt the actuator parameters to the process-specific requirements; sensors, which process information related to process parameters, then transmit signals to the controller; the signal conditioning device (consisting of amplifiers, filters, etc.), which processes the signals so that they can be picked up by the controller.

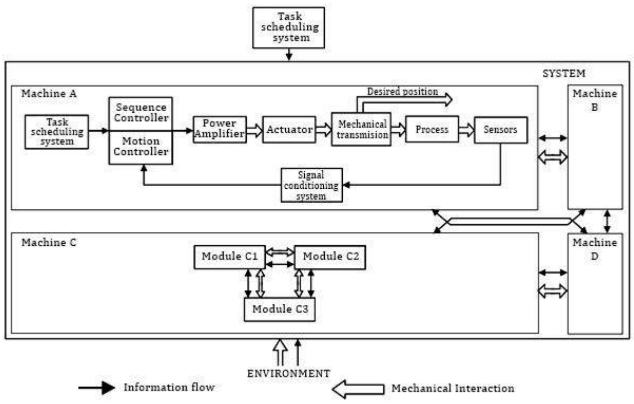

Fig-1: The Hardware structure of a mechatronic system

Analyzing the block diagram of a mechatronic system we notice the dualism: energy flow - informational flow.

The materialization of the dualism energy flow - informational flow results more explicitly by analyzing the basic functions of an intelligent machine.

3. BASIC FUNCTIONS OF A SMART MACHINE

Each smart machine consists of three basic subsystems (Fig-2) [1], [2], [8], [9]. The border between the functions of these subsystems is impossible to trace, as these functions are not necessarily fulfilled by different physical components.

First, a smart machine must have both sensory properties as well as the ability to interpret the sensations. Therefore, the first subsystem of a machine equipped with intelligence must be that of perception, responsible for collecting, storing, processing and distributing information about the state of the machine and its external environment. The perception function is performed through sensors and converters (devices that transform a physical input unit into an electrical output physical unit, intended for further processing), as well as data acquisition systems (systems through which information, taken from the converters, they are processed so that they can be picked up by the controller). The main difference between a sensor and a converter is that the converter is an elementary device that, without elements of signal processing, only performing its conversion, while the sensor can respond to other functions [8], [9].

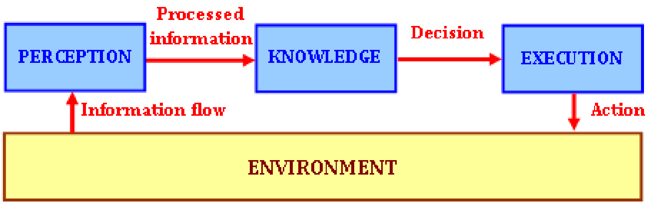

Fig-2: Basic subsystems of a smart machine

Some sensors contain, as a part of them, signal conditioning systems, or even microprocessors to perform different smart functions even at the sensor level (digital signal processing, error correction in the detection process, self-calibration and self-testing if the equipment has anomalies in operation, etc.) [8], [9]. The rapid development of microelectronics, micromechanics, integrated optics and other high-level technologies has allowed miniaturization of sensor elements (called "microsensors"), as well as the physical integration of several functions and signal processing elements on the same substrate. These represent the components of the microsystems, meaning those systems that have at least one component performed by one of the known micro technologies, several functions being fulfilled on a reduced physical space. The recent trend is that as many elements are incorporated into one body, smart sensors have been constructed that contain other sensors, coupled together, to measure as many different physical quantities as possible [8].

The second subsystem is the one that performs the function of knowledge, which consists in evaluating the information acquired through perception and making decisions in order to plan the actions of the machine. The physical component with an essential role in this process is the controller (microprocessor).

The execution subsystem, the third subsystem of a smart machine, is responsible for initiating, controlling and completing the actions of the machine, based on the information received from the other two subsystems. The physical elements through which the execution function is performed are the actuators.

4. INFORMATION CARRIERS

An essential feature of the information is that it can exist only as a form of manifestation of the matter-energy couple. Therefore, as any transmission of information involves a material and energetic transfer, the transfer of information needs support, that is, information carriers. The electric field, the magnetic field, the electromagnetic radiation (in particular the photons), the electric charges, the crystalline lattice atoms of a solid or the molecules of a liquid or a gas are some examples of information carriers. The physical quantitiesused for mathematical modeling of the information transmission process are specific to the nature of the information carriers involved in this process.

Depending on the nature of the energy that facilitates the transmission of information, there are six types of information carriers [1], [8] which have the appropriate physical quantities (Fig-3):

• Radiant type - electromagnetic radiation (physical quantities specific to electromagnetic oscillations are used: radiation intensity, frequency, phase, polarization).

• Mechanical - the transfer is made through mechanical energy, so it is worked with physical quantities such as: position, speed, force, dimensions (length, thickness) etc.

• Thermal - parameters specific to thermal phenomena are involved: temperature, heat, entropy.

• Electrical - electric energy facilitates the transmission of information, so it is called electricity voltage, electric intensity, electrical resistance, electric capacity, etc.

• Magnetically - physical quantities appear regarding processes in which the main role is magnetic energy:

magnetic field induction and intensity, magnetic flux, magnetic permeability, etc.

• Chemical: they appear especially in the processes that take place at the level of the internal structure of matter, so the main parameters involved are those related to the crystalline structure, states of aggregation, the movement of molecules in liquids or gases, etc.

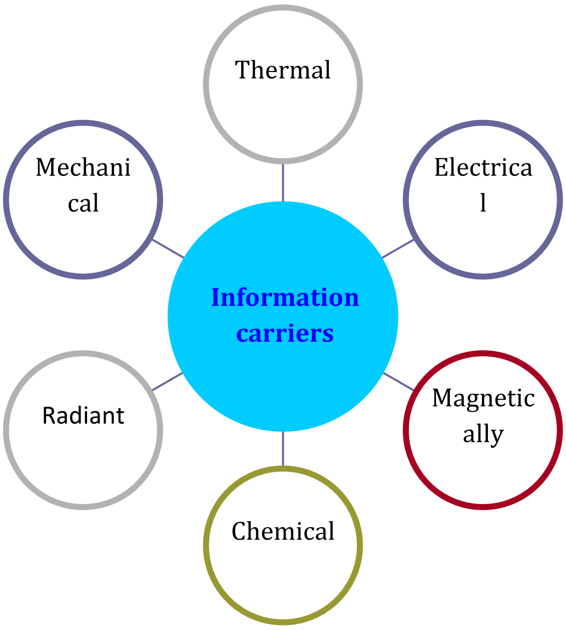

Fig-3: Information carriers

In general, in a complex process of transmitting information, more information carriers are involved, which transfer their information from one to another. Thus, the sensors, for example, take the information from the outside through one or more information carriers (Fig-4).

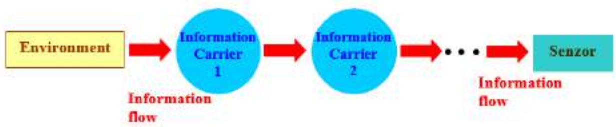

Fig-4: Information transmission from the environment through sensors and through information carriers

In conclusion, the sensors, the actuators, as well as the devices for conditioning the signals are components with an important role in making the connections between the modules of a mechatronic system, mediating the transmission of the information between them. On the other hand, these components represent key physical elements in terms of the materialization of the principles, laws and phenomena of physics in the form of applications in technology that respond to high demands.

In the following sections, representative examples of informational cinematic couplings as well as informational kinematic chains are analyzed.

5. LORENTZ ACTUATOR - INFORMATION CINEMATIC COUPLE

The Lorentz Actuator [8], [9] is a representative example of a kinematic couple, whose action does not take place through the direct mechanical contact, but is due to the interaction between the magnetic field and the electric current.

Lorentz actuators can be seen as an electro-mechanical system formed by integrating three subsystems: the electrical circuit, the magnetic circuit and the mechanical subassembly. From a structural point of view, the Lorentz actuator consists of two modules (Figure 5): the inductor and the mobile assembly. The inductor is composed of a permanent magnet (cylindrical in shape) fixed to the base plate, polar parts and a core. The movable assembly consists of a coil fixed on a roller frame.

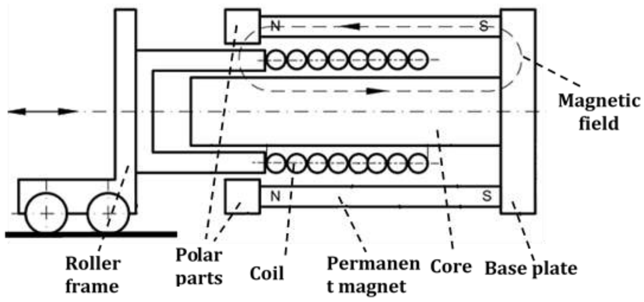

Fig-5: Lorentz actuator

The translational motion of the actuator is the consequence of the force with which the magnetic field acts on the electrons moving through the conducting coils of the coil. This force, called the Lorentz force, is the force acting generally on any charge particle q, which moves at speed $\vec{v}$ in an induction magnetic field $\vec{B}$:

$$\vec{f_L} = q(\vec{v} \times \vec{B}) \tag{6}$$

If we delimit an infinitesimal element, of length dl, from a conductor through an electric current having intensity I, in that element there is an electrical charge:

$$dq = I \cdot dt \tag{7}$$

moving with speed

$$\vec{v} = \frac{d\vec{l}}{dt} \tag{8}$$

In the expression above we considered that the vector $d\vec{l}$ is oriented in the sense of the current intensity and has the module equal to dl.

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As a consequence, the electromagnetic force acts on the element $d\vec{l}$ in the conductor (Fig-6):

$$d\vec{F}_{em} = dq \cdot \vec{v} \times \vec{B} = I \cdot dt \cdot \vec{v} \times \vec{B} \quad (9)$$

meaning:

$$d\vec{F}_{em} = I \cdot d\vec{l} \times \vec{B} \quad (10)$$

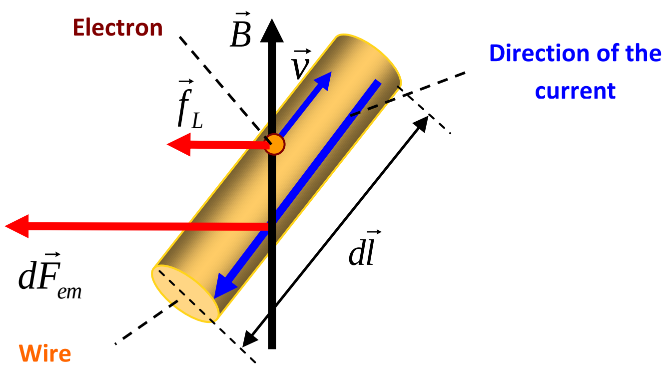

Fig-6: Lorentz force and electromagnetic force

Since the direction of the magnetic field is perpendicular to the direction of the intensity of the electric current, the force acting on each element $d\vec{l}$ of each coil winding is oriented horizontally (Fig-7) and has the value:

$$dF = B \cdot I \cdot dl \quad (11)$$

A total electromagnetic force obtained by integrating all these elemental forces will act on the actuator coil. This force is oriented horizontally, and its direction can be left or right depending on the direction of the current through the windings of the coil.

The value of the force that determines the displacement of the mobile assembly of the Lorentz actuator is:

$$F = N \cdot I \cdot B \cdot L \quad (12)$$

where N represents the number of windings of the coil portion exposed to the action of the magnetic field, I is the intensity of the electric current established by the coil, B is the induction of the magnetic field (produced by the permanent magnet) and L is the length of the circumference of the winding.

Obviously, the coil moves between the polar parts and the core only if it is powered by an electrical source, the direction of its movement it is depending on the direction of the electric current. The Lorentz actuator is one of the subsystems integrated in the structure of smart translation units, along with sensors, microcontrollers and other electronic components.

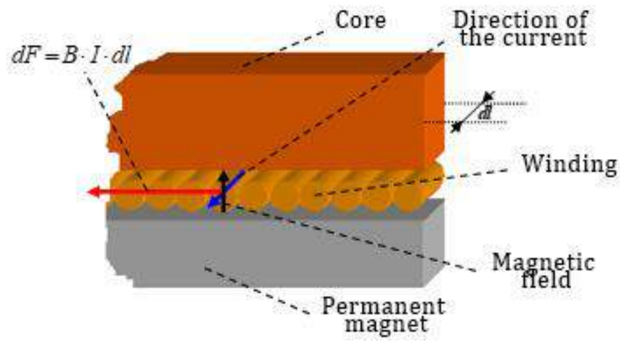

Fig-7: Cross section through the magnet, coil and core of the Lorentz actuator

From the perspective of the proposed approach, the main characteristic of the Lorentz actuator is that the displacement of the mobile assembly takes place in the absence of any mechanical contact between the kinematic elements [9], this being exclusively determined by the interaction between the magnetic field and the electric charges moving through the windings of the coil. Therefore, the Lorentz actuator is a special type of kinematic couple, in which the informational bound between the kinematic elements is realized through information carriers which, in this case, are the electric charges and the magnetic field. The magnetic field represents the energy support for the transmission of information to the electric charges, on which the Lorentz force acts. Therefore, we can speak of the Lorentz actuator as an information kinematic couple: between the kinematic elements of the actuator the connection is first of an informational nature, this mediating the transmission of the remote interaction through fields and not through mechanical contact.

6. INFORMATION KINEMATIC CHAINS IN THE STRUCTURE OF MECHANISMS

The information kinematic chain is a set of hardware and software components that collect, transmit, process, store and use the information received from the sensors to control the mechanisms, machines, processes etc. In their structure it integrates sensors, suitable electronic components as well as specific software

The simplest planar mechanisms that allow this approach are the five-element mechanisms. The two motor elements can perform rotational and/or translation movements.

Unlike hybrid mechanisms, in this case for coordinating the movements of the two elements, it is necessary to introduce a trajectory generator. It, based on the motion parameters imposed on the point P(x, y), determines and correlates the laws of motion of the two motor elements. The information received from

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the trajectory generator is used by the two controllers to control the actuators.

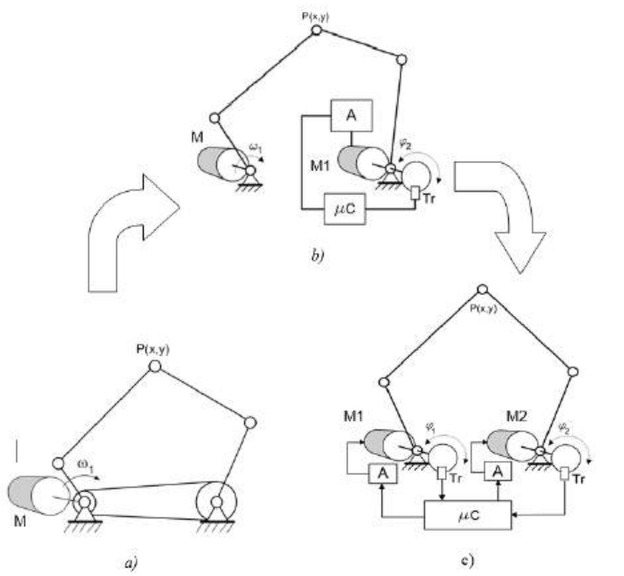
The evolution from the traditional mechanisms to the mechanisms for mechatronics is shown in Fig-8 [9], [16].

In the case of mechanisms with two degrees of mobility, in the traditional approach presented in Fig-8 a, the two drive elements are connected by means of a transmission through the belt, chain or gear wheels operated at constant speed, by an electric motor. Changing the trajectory of characteristic point P is possible only by modifying the transmission ratio.

The next stage is the hybrid mechanisms (Fig-8b) in which one of the motor elements is actuated by means of a DC motor. With the help of a converter, information on the parameters of the movement can be collected thus creating a closed-loop control system. The path generated by the main drive motor can therefore be changed. Depending on the configuration of the mechanism, adjustable oscillations or strokes can be obtained for the driven element.

If the motion parameters are controlled for each motor element separately, the characteristic point P can theoretically occupy any position in the working space of the mechanism (Fig-8 c). With the same mechanical structure, a very wide range of trajectories can be obtained.

This implies an efficient control and correlation of the movement parameters for the two motor elements through a kinematic information chain. In this case, the performance of the mechanism depends largely on the mode of action and the performances of the control algorithm.



A- Amplifier, Tr- Converter, µC – micro-controller, M – Motor, M1,M2 – DC motors

Fig-8: Evolution from traditional mechanisms to mechatronics

7. CONCLUSIONS

The evolution in the development of the society is closely related to the evolution in the development of technology. The following are relevant in this regard: Stone technology - mechatronic technology. Mechatronics is 21st century technology. Triad: advanced mechatronics-cyber-physical systems (CPS) and Internet of Things (IoT), is the foundation of Industry 4.0.

The 9th decade of the XX century, was marked by the mechatronic revolution, which determined the leap from the information society to the knowledge society. Mechatronics, the science of intelligent machines, operates with the triad: matter-energy-information. Information is the key component compared to material and energy. This position of the information is motivated by the Japanese through the following arguments: the information ensures the fulfillment of the spiritual needs of the human being and, at the same time, ensures the increase of the newly added value of all things. Promoting information bonds in the structure of technical systems ensures flexibility and reconfigurability. Information is the expression of the non-uniformity of the distribution of material and energy in time and space. As the transmission of information requires small amounts of material and energy, the functional performances of the technical systems increase. For engineering practice, mechatronics marked the jump from traditional, sequential engineering to parallel / concurrent engineering. Thus, the concept of integrated design/control for the design of systems was developed.

By making smart products, the resources of material and energy are conserved. It follows that mechatronics is a non-dissipative and less polluting technology. The emphases in the specialized literature point out that mechatronics has opened up unusable horizons in all fields of activity, due to the stimulation of the synergy effect. For the technological field, the details of the present work on the concepts of: information links, information carriers, information kinematic couplings and information kinematic chains are also relevant. For the development of educational technologies, the facilities for understanding the integration-complexification process in nature and technology are important. In this context, it is understood that qualitative and quantitative evaluation of information integrated into the structure of intelligent products and systems is of particular importance in education and research.

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