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Mechatronics - An Education Approach towards Product Engineering

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Abstract: This paper shows that Mechatronics is more than just combining mechanical, electrical and information processing elements. Although state of the art control engineering works from a systems point of view, it becomes evident that mechatronics design is much more than understanding interacting phenomena of the different building elements, transferring these phenomena into abstract models and manipulating control algorithms. Three distinguishing properties of mechatronic systems are addressed: the turn towards (consumer) end-products, the use of advanced in-situ technologies to build compact and smart products and the co-operative design approach, where all system building elements are subject to design freedom. From these properties the demand for a new engineering paradigm "design to market" is derived. In this sense mechatronics has to be understood more generally as a product engineering task. Some key educational elements for academic curricula are proposed to form beside sound domain specific knowledge also the required concurrent design and co-operative engineering skills as well as the skills to think in product and market categories. A sample implementation for a mechatronics curriculum at Technische Universität Dresden is given.

1. MECHATRONIC SYSTEMS

Although mechatronics is already known for 30 years (Harashima, et.al. 1996), it is interesting to observe, that the mechatronics community is still looking today for a concise and comprehensive definition of what "mechatronics" really means. Starting from the first understanding as "synergistic use of integrated mechanical and electronic systems" the definitions have moved in the meantime as far as to the "synergetic integration of *physical* systems with information technology and complex decision making in the design, manufacture and operation of *industrial products and processes*" (Tomizuka, 2000). The latter definition shows clearly the turn of the scope of interest from technical *systems* towards *products*, with all their peculiarities concerning development, production, marketing as well as the handling qualities for their "operators". But nevertheless this most actual definition seems *not at all appropriate*, because it is *too comprehensive* in terms of *target products*. It does not state any restrictions to the addressed target "physical systems, industrial products and processes". This definition would allow also to include application areas like process engineering, power plants, and even telecommunication, navigation (e.g. road vehicle route guidance). These applications have "product properties" as mechatronic products have, but they are of completely different nature in terms of the involved physical systems.
Therefore it is recommended for sake of clarity to *restrict* mechatronics clearly to those target applications where the *mechanical* building blocks of an "integrated mechanical, electronic, information processing system" play the *major role*.

In this sense mechatronics can be defined in two stages:

Mechatronic System :=

... *realizes* a mechanical oriented product task (“generation of controlled motion under consideration of heterogeneous constraints”)
... *consists of* tightly coupled mechanical and other physical processes
... *uses* as realizing technologies highly integrated electro-mechanical components with distinct embedded real-time information processing and decision making functions

Mechatronics :=

... *engineering approach* which supports the development of *mechatronic systems* towards competitive products using scientific methods.

2. MECHATRONICS FROM THE CONTROL ENGINEERS PERSPECTIVE

If a control engineer looks at a typical mechatronic system (Figure 1) consisting of a mechanical plant, hydraulic actuators, piezoelectric sensors and a micro-controller with the control and decision algorithms software, he could answer rather seriously: " Mechatronics ? Oh, that's really nothing new for a control engineer ! We do this job for controlling mechanical systems already for decades: *given the plant* we have to select the *appropriate* sensors and actuators, we have to design the *appropriate* control and decision algorithms as well as the *appropriate* human-machine interfaces".

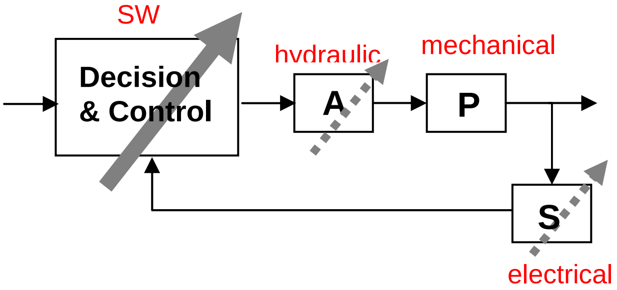

Fig.1 Mechatronic System from the Control Engineers Point of View

This is completely true and it works only, because interdisciplinary thinking by a thorough modeling and physical understanding of all participating elements is applied. Moreover it should be emphasized that the same *state of the art* engineering tasks are being performed in any other automation application areas like process control or industrial automation.
So what is new then with mechatronic systems ?

3. NEW ASPECTS ON MECHATRONIC PRODUCTS

A second and more detailed glance on what we understand today under a mechatronic system reveals the following *three distinguishing properties* with regard to other controlled and automated systems (Figure 2).

(A) End-user products

Mechatronic systems tend since the beginning when the synonym "mechatronics" was created towards "products" rather than pure (high-)tech systems. This means that they are devoted more and more for direct use of the *end customer* on *consumer* and *mass markets* (e.g. automotive, CD-players) or on *high end markets* (e.g. medicine, prosthetics). These products have a high degree of direct involvement and interaction with the operator, who is normally not a technician and not interested at all to know what technology is behind. The ultimate reason for a customer to buy such a product is that it must show clear *benefits* to him, i.e. "the product must solve distinct customer problems at a fair price". As a consequence these technical systems have to be developed with respect to (economic) market rules, where economic success and customer satisfaction (i.e. product benefits) top the pure technical performance.

(B) In-situ technologies, smartness, compactness

Mechatronic products use today advanced *in-situ technologies* for sensing, information processing and actuation. With these micro- and nano-technologies it is possible to sense and act at any location within a mechanical structure where it is needed. This results in products, which are extremely *smart* in their behavior and which can be kept nevertheless *compact* in terms of size, mass and power demands.

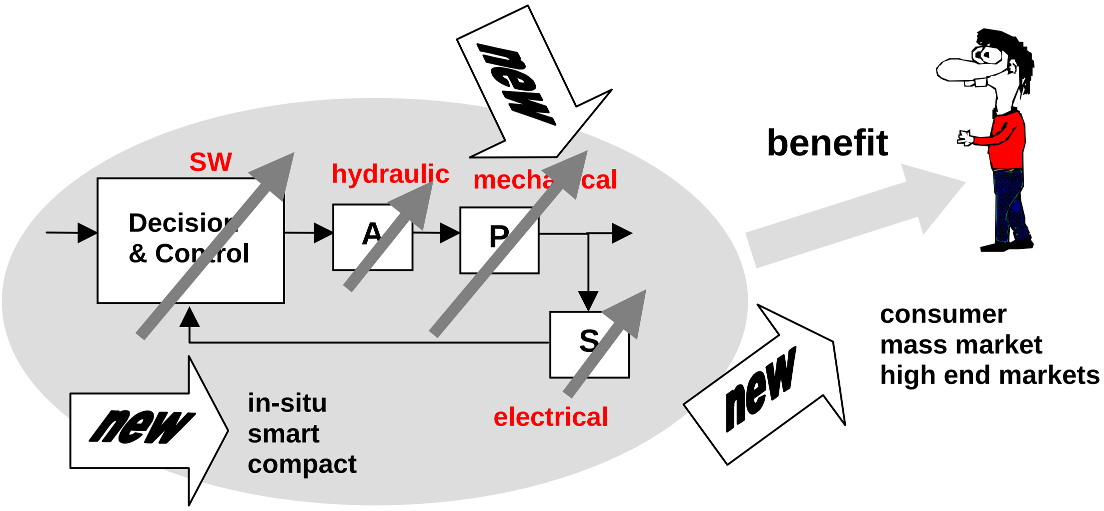

Fig. 2 Mechatronic Product View

(C) Design freedom for all building elements

Smartness and compactness of mechatronic products can be realized only if *all* building elements are subject to a well balanced *design freedom*. In particular the *(mechanical) plant* is no more fixed and "given", but it has to be traded always against all possible and appropriate design solutions of sensors, actors and control algorithms (e.g. smart structures). The mechanical design does no more govern the overall system layout, any building element must be open to design variations and only a co-operative design process for all building blocks will result in a well behaving and competitive product.

4. PRODUCT ENGINEERING - HITTING THE BIG PICTURE

The three distinguishing properties of mechatronic systems as outlined in the previous chapter provide a good basis to understand why mechatronics is difficult, non-trivial and challenging (but not at all new !).

Property (A) demands for a clear distinction between a "mechatronic *system*" and a "mechatronic *product*". It shows that the required contents and performances of the mechatronic system have to be derived carefully from the customer's needs (requirements analysis). The mechatronic product has to show clear *benefits* to the customer, i.e. "it must solve distinct customer problems at a fair price". Thus the conventional design paradigms "design to performance" or even "design to cost" have to be substituted by ***"design to market"***. The latter means, that the top level design objective is to develop a technical system, which implements *the adequate technology with the best ratio of performance vs. effort* (Janschek, 1999a).

The engineering approach "design to market" has therefore to combine the design constraints "technical performances" with "economic effort" (cost) and adding the additional constraint "economic success". Only such a complete view can avoid the design of unsuccessful high-tech products, like the mechatronic mouse-trap (Roddeck, 1997), which uses unbalanced high-tech elements to substitute conventional, "old-fashioned" but nevertheless well-doing and cheap problem solutions (mechanical mouse trap).

Properties (B) and (C) demand for the famous and frequently quoted "*system approach*", "*thinking in systems*" or "*multi-disciplinary engineering*", where the interacting phenomena of the building elements are more important than the inherent and encapsulated phenomena. Understanding of what is an interacting phenomenon and what is not needs a thorough understanding of the nature of *all* building elements (knowledge of one element would not enable to deduce how and in what sense the other element would interact with it).

It should be noted that this is *not at all new* in engineering industry. *Systems engineering* in the sense as described above is a well established engineering approach in *aerospace* industry for a long time. Moreover aerospace systems are true mechatronic systems in the sense defined in chapter 1, because they have to fulfil motion related product tasks and they combine mechanical, electrical and information processing elements. The main difference to "industrial" mechatronic systems however is given by the fact, that aerospace systems (aircraft, rockets, missiles, spacecraft) are much more *large scale* and high-end products in terms of functionality and cost. As a consequence the underlying industrial structures operate in some niche areas and so this engineering approach did not become common practice in a wide area so far.

Industrial mechatronic products are in some way even more challenging than aerospace ones, because they are mostly not devoted to well defined high-end niche markets as aerospace products, but they have to compete rather on highly competitive mass markets. These products are faced there with demanding economic constraints such as short innovation cycles and as short as possible time to market. In such a way industrial mechatronic systems show in a much more concise way the need to go beyond a pure "thinking in systems" towards a "*thinking in products*". As a consequence the "design to market" paradigm becomes the ultimate focus of the mechatronics engineering task. Thus the systems engineering approach has to be extended to a tough *product engineering*, which implements and adopts the appropriate scientific methods to allow a thinking in product and market categories.

5. KEY EDUCATIONAL ELEMENTS

The specific nature of mechatronic systems and the increasing importance of mechatronic products on the markets need an adaptation of the traditional academic engineering curricula. The proposed mechatronics educational approach is derived from the following two theses:

Thesis 1: *"Mechatronics is an engineering approach rather than a science".*

Thesis 2: *"The main objective of engineering is to build competitive products using scientific methods".*

An appropriate educational approach has to combine a balanced mix of well established scientific domains with (new) specific educational elements to cope with the relevant product engineering skills.

This basic education model consists of three pillars (Figure 3):

- *Sound domain specific scientific knowledge*
- *Concurrent design and co-operative engineering skills*
- *Thinking in product and market categories.*

A brief description of these pillars is given in the following.

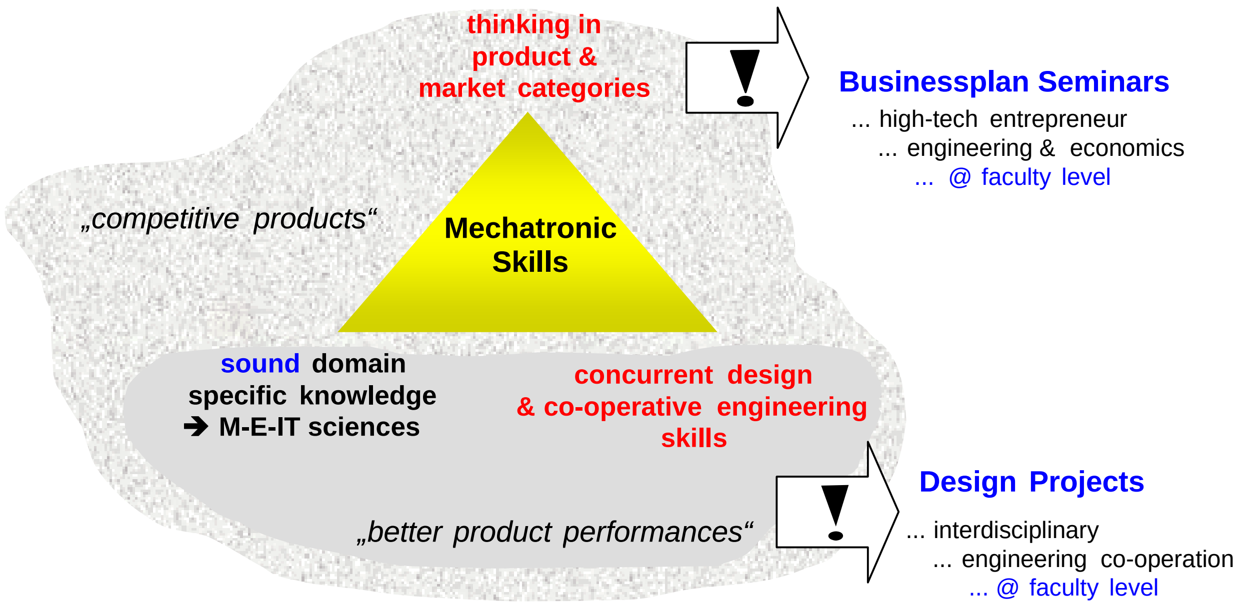

Fig. 3 Mechatronics Educational Approach

Sound domain specific scientific knowledge

That mechatronics is not a new *science* should have become evident from the previous chapters. A mechatronic design composes different self-standing technologies in the most appropriate way to form added-value products. This requires to have available a sound knowledge and understanding of the basic physical phenomena of all involved elements. Therefore a balanced *mechanical* (M) and *electrical* (E) engineering curriculum has to be supplemented by *embedded information processing* (EIP) skills. What "balance " means in the particular case depends on the background and capabilities of the specific academic institution. Some general considerations may help for some guidance in the particular case.

It is important to understand, that it will never be possible to get an equally deep knowledge in all three domains (M, E, EIP). As target physical systems are the subject of interest it is mandatory to develop the curriculum from either the mechanical or electrical engineering domain (and not from IT) with their associated physics oriented theories and scientific methods. Embedded information processing always has to be treated as a supplementary skill. Emphasis has to be put on system theoretic methods, in particular automation and control methods, as well as on modern system design methodologies which support a structured requirements engineering.

The main area of *"new" scientific methods* (to be developed by research and made available at the education level) is seen in *domain overlapping* methods and tools for modeling, analysis and simulation, in order to improve the handling of heterogeneous physical systems within a common abstract and formal framework.

Concurrent design and co-operative engineering skills

A clear distinction should be made between the *co-operative* engineering process (i.e. the creative process, when a team of different skilled engineers is developing a joint product) and the *concurrent* design skills of any team member. A comparison with a sports example shall make transparent what is meant.

A winning football (soccer) team consists of team members who are all basically skilled to play football (· mechatronics). The joint objective of the team is to win the game (· develop a mechatronic product) and can be achieved only by close *co-operation*, whereby any single team member supplements the others. On the other hand it is essential that some specialization within the team takes place, such as specially skilled forwards and backs (· mechanical, electrical, information technology engineers). But to be able to outwit the opponent (·overcome the "done as usual" design inertia) with unconventional actions (· innovative system layouts), it is necessary that any team member has *concurrent* football skills, i.e. a back must be able to score a goal as well as a forward must be able to defend the own goal area.

This means for mechatronics, that the control engineer has to have enough mechanical design skills, to be able to make a creative design proposal by his own for a certain constructive variant for a smart structure, which allows to use a simple and robust control law. A mechanical engineer on the other hand should be able to invent a more simple robot joint by proposing a certain local feedback solution. Nevertheless the detailed design of the different building elements will be performed by that team member, who is adequately specialized and skilled.

These concurrent design and co-operative engineering skills can be trained only through *practical experience* ("learning by doing").

The best way to do this are *design projects* for real and *complete mechatronic systems* which cover all of their inherent peculiarities. Within such projects the students will experience what steps are necessary to come up with a design solution, which provides appropriate good system performances.

It is important to note, that "good" projects are not only characterized by challenging technical and scientific contents, but they need also a good and open minded co-operation between the different participating academic departments. This is an equivalent situation as in industrial organizations, but usually more difficult to implement at academia due to the self-determination nature and organization independence of university departments.

Thinking in product and market categories

The ultimate aim of mechatronic education is the *"product and market minded engineer"*, who is skilled to think in product and market categories as well as in standard engineering categories. This is the much more difficult task for teaching (academia) and learning (student), because it crosses the engineering domain and enters the economic domain.

Due to the today's situation that an ever increasing volume of knowledge has to be conveyed within a limited volume of education time, it is generally difficult to implement appropriate academic curricula that allow the students to "understand the big picture" (Lee and Messerschmidt, 1998).

The *big picture of product engineering* is to understand how customer needs can be translated into technical requirements, how a (high-) tech product acts on the market, what quantitative effort is necessary to produce the product and what earned value actually can be received. Some of these skills can be trained at course level, e.g. system & product design, but practical experience ("learning by doing") shortens considerably the learning effort in this area. We have gained extraordinary positive experience with one-semester *business-plan seminars*, where the students have to establish a complete business-plan for a concrete mechatronic product (Janschek, 1998b). In these seminars the students are forced to go beyond the pure technical level, they have to view their mechatronic system mainly from the market point of view, they have to make up their mind on what are the outstanding competitive properties of their product and so forth. By such a complete analysis the students are able to detect early eventual weak product properties like the mechatronic mouse-trap (Roddeck, 1997).

As the engineering students will not have the capacity to acquire the complete economic knowledge of an economist, we are operating these seminars with *mixed teams* of *engineering* and *economy science students*. This gives an ideal constellation for all participants, because it prepares perfectly for the real world situation. As an important spin-off of this type of seminar it has worked out that we can find easily potential entrepreneurs (two students are currently founding their own enterprises with venture-capital). It should be noted for completeness, that for this educational element inter-department co-operation is as much essential (and as much difficult to implement) as for the engineering design projects.

6. THE DRESDEN MECHATRONICS MODEL

At *Technische Universität Dresden* an international two years *Master Course of Electrical Engineering* with a *specialization in mechatronics* is currently offered (http://www.et.tu-dresden.de/). Although the course is administrated by the Department of Electrical Engineering, the curriculum is jointly organized with the Departments of Mechanical Engineering and Traffic Sciences.

In addition to this a *new* self-standing five years *diploma course Mechatronics* (➔Diplomingenieur Mechatronics) is currently prepared to start in *autumn 2001*. This new diploma course is *jointly* organized and administrated by the Departments of Electrical Engineering, Mechanical Engineering and Traffic Sciences and it implements the main ideas given in this paper. The undergraduate curriculum (two years) comprises courses in mathematics and physics (30%), information technology (13%), mechanical engineering (23%), electrical engineering (24%) and system theory (10%).

The subsequent two years graduate course is based on a balanced set of compulsory courses (30%) comprising basic scientific M-E-EIP methods and offers a further optional *specialization* in scientific *engineering domain areas* (M-E-EIP-Automatic Control, 45%) as well as in target *application areas* (25%), e.g. automotive, robotics, aerospace, manufacturing.

All laboratory courses at graduate level are thematically directed towards mechatronic system aspects and they are jointly organized by the relevant departments. A product design project (as outlined in chapter 5) is mandatory. The graduate course is complemented by a six month industrial internship and a six month master thesis.

7. CONCLUSIONS

This paper discussed the view on mechatronics as a product engineering discipline and gave some ideas on relevant educational elements for academic curricula. Although mechatronic design paradigms are in principle not new for automatic control engineers, it has been pointed out that some particular engineering elements distinguish the design of mechatronic systems: "design to market" paradigm, integrated design solutions by use of advanced micro- and nano-technologies and consequent design freedom for all system building elements (no system component is a-priori fixed, every building element has to be traded against any others). The academic curricula to be offered to mechatronic students are not determined by new science areas and theories, but rather by a pragmatic and balanced mix of existing scientific methods and new courses which train the design and engineering skills in terms of product development. As these curricula cross the well established boundaries of academic departments, the successful implementation of "well performing" curricula depends much on the willingness and open mind of the different participating scientific communities.

A quick implementation of the appropriate academic structures seems to be important, because mechatronics could serve as a good reference model for the anticipated next generations of *integrated technologies* such as *biotronic* systems. These technologies will include additional biological building elements (e.g. Bashir et.al., 2000), what brings new challenges, because it needs a crossing and co-operation of new scientific domain boundaries.

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