Mechatronic Machine Elements: On Their Relevance in Cyber-Physical Systems

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Abstract. This paper discusses the appearance of mechatronic machine elements (MME) in the greater context of cyber-physical systems (CPS). For this purpose it establishes classifications for CPS. Three groups of MME are identified, characterized and illustrated with examples. Regarding the advantages of MME, the text explains how they allow for new functions in mechanical systems and how they help to reduce the development effort for complex products. As desirable characteristics for MME in general are identified independent communication abilities, "plug-and-play" integration in networks and mechanics and the preprocessing of sensor data on the element itself. CPS with specifically designed MME can further become a valuable tool in product development for information collection.

Keywords: Cyber-Physical Systems, Mechatronics, Machine Elements, Product Development.

1 Introduction

In 2006 a group of computer scientists opened a new research field under the term *Cyber-Physical Systems* (CPS), which was coined by Helen Gill [1]. Expressing the new understanding of embedded systems in the context of the interaction of computers with physical processes, it is an indicator of an ongoing development in engineering and computer science. At first mechanical products were enhanced with electronics and programmable computing units, what climaxed in the 1990ies in the rise of the field of mechatronics. Now networking is being added to the physical systems. Embedded and remote computers are being connected within a single machine and over large distances as to collectively gather and exchange data about the physical world. This new stage in integrating engineering disciplines requires new questions to be asked and new vocabulary to be developed.

Lee and Seshia [1] define CPS as follows: "A cyber-physical system is an integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa."

Of course, many of the arising issues like network security, the computational handling of concurring events, and so on, are mainly to be discussed and solved by computer scientists. When it comes however to the contact point between the "cyber" and

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the "physical", there are also issues in the mechanical engineering field that are well worth to be considered in the wider context of CPS. This also becomes clear from a position paper where Tabuada [2] presents a vision of a programmable sports car, able to emulate an arbitrary driving experience. The much one can argue about the technical feasibility of such a system, it is clear that developing such a system would necessitate new mechatronic solutions.

One of the issues to be considered in this new context are machine elements. Most machine elements used today are well understood and applied for decades. Recent developments mostly concern increase in robustness, miniaturization or better precision. However, over the past twenty years a development has gained momentum, which is about to revolutionize the way, complex mechatronic products are designed. Even more this development will make new mechatronic designs possible. It is about the increasingly tight integration of sensing, actuating and even computing and networking functions with conventional machine elements, resulting in what the authors call *Mechatronic Machine Elements* (MME). Why this expression has been chosen is explained in section 4.

An ideal MME the authors define as an element which has a mechanical function, is either able to generate and communicate information or to apply received information to a mechanical system, and is an independent instance in a data network. As an *element* is understood a small assembly of components which cannot be divided into subassemblies while any of its main functions is maintained.

The advent of MME is interpreted as the result of a technology push and a market pull. The advances in mechatronics push the development as they allow for an every tighter and more miniaturized integration of functions. At the same time the technical systems are increasingly dependent on comprehensive information about the state and condition of subsystems and its environment (i.e. they are developing towards every more complex CPS). This results in a pull for more mechatronic solutions and deeper mechatronic integration to extract information from and apply control to the inmost parts of the subsystems.

This paper aims at discussing the observed trend towards mechatronic machine elements in the context of cyber-physical systems, to set up a rough classification of different types of CPS and to illustrate three groups of MME. It further outlines how CPS in general and MME in particular can improve not only marketable products but also the process of developing them. Section 2 describes the initial observation of the trend towards MME which is then put into the context of CPS in section 3. In section 4 general considerations and examples of three distinct groups of MME are presented. Section 5 gives an outlook how CPS can be beneficially applied also in product development. The last section presents the conclusions.

2 Observation of Dissolving Borders

Starting from the 1960s with fast advances, first in electronics and subsequently in computing, machines and mechanical devices became more and more integrated with electronics and software. While devices and machines, mechatronic on a product level, for a long time could be clearly divided into mechanical and electronic components, a second step of integration is taking place at the moment on a machine element level. Traditional borders are dissolving and we can observe both: There are conventional machine elements enhanced in their capabilities by adding electronics to them and there are novel machine elements that were developed as mechatronic elements from scratch and did not exist before.

Good examples for the first are roller bearings. Probably already known in the ancient world was their sole purpose to support a rotating axis with little friction. In a recent patent [3] a roller bearing was presented that integrates an angular encoder in a cost and space saving way into the bearing ring. Machine element and sensor are inseparably merged to a MME.

A bit more difficult to classify as machine elements are active magnetic bearings [4]. They are rather complex systems by themselves. But looking at their function within a system they clearly serve as machine elements and they are elements from the perspective that their core function cannot be achieved when removing parts of it. Active magnetic bearings can be regarded as the first MME that were not conventional machine elements enhanced with mechatronic features, but mechatronic from the core.

3 The Web Reaching into Devices

The observed development of appearing mechatronic machine elements the authors would like to consider in the context of Cyber-Physical Systems. To date, many of the CPS discussed in the computer science community, which is primarily researching in this topic, are networks of independent devices or plants. An example are Advanced Electric Power Grids [5]. In such a network, instances like power plants, energy storages, control computers and consumers are connected on different levels in digital, physical or often both ways. These instances can in general be produced, installed and connected to the network independently. For the network existing outside the single products, this type of CPS shall be referred to as *External Network CPS*.

The great interest of automotive and aerospace companies in CPS topics leads us to a second type of CPS [6]. External network CPS like smart power grids are a web of things[1] with the things being plants and devices. Modern cars and airplanes are things containing an own web inside them. Their subsystems are mechanically connected and digitally linked to each other. The subsystems are controlled by electronic control units (ECU), e.g. to decide on the activation of the airbags, which are networked together. The single subsystems are still an assembly of mechanical parts, sensors, electronics and actuators, often provided by different suppliers and as individual elements. This type will be further referred to as *Internal System Network CPS*.

With the emergence of mechatronic machine elements the web is beginning to reach even further down, into the element level. The angular decoder-integrated roller bearing, described above, or seals equipped with sensors for condition monitoring [8] are machine elements, also able to generate information. It is a small step to MME

[1] The use of the term *web of things* is inspired by, but not necessarily identical to its use by Guinard and Trifa [7]. It is meant in this context as a network digitally connecting physical objects in its widest sense.

acting as independent instances in a computer network, able to communicate over standard bus protocols. Similarly, but the other way round, work machine elements receiving commands or information out of a bus environment, processing and applying it to actively adapt their properties according to the information. When in a CPS not only subsystems but even machine elements are digitally connected and act and communicate independently, the authors call that an *Internal Element Network CPS* (see Fig. 1).

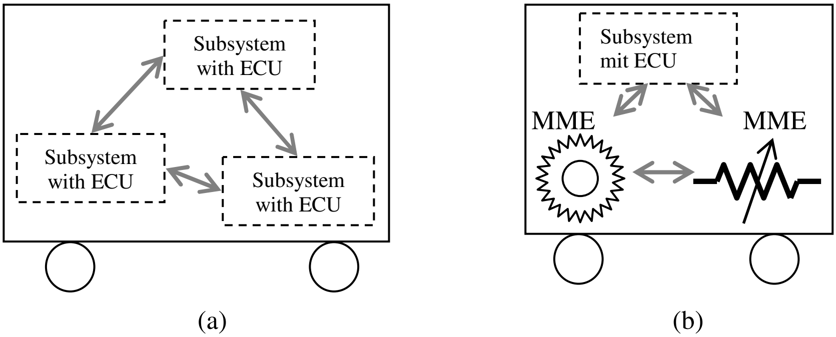

Fig. 1. Principle of an internal systems network CPS (a) and an internal element network CPS (b). The network nodes in (a) are subsystems, complex themselves, whereas in (b) the network reaches down to a machine element level.

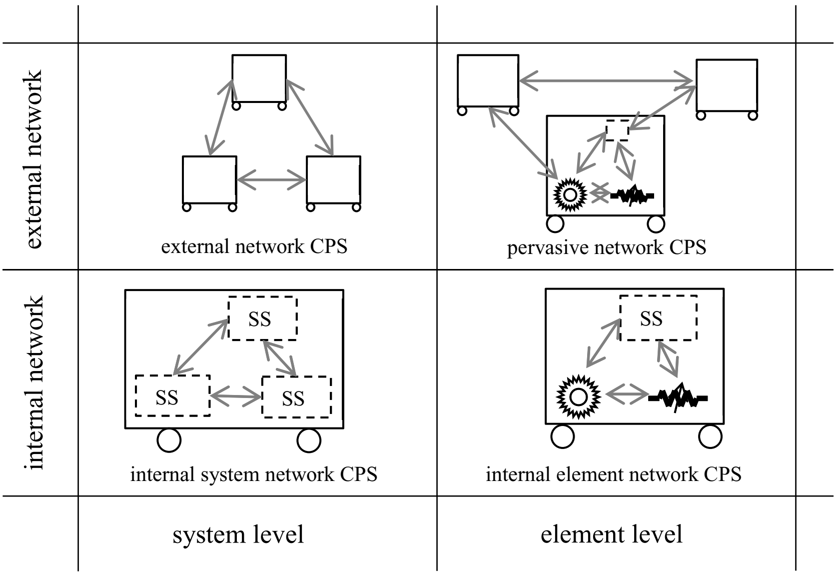

Fig. 2. Overview of the classification of cyber-physical systems used in this paper

This still being rather a vision than an observable development, it can even be imagined CPS, at the same time reaching down to an element level inside one machine and out to other devices. Imagine the timing belt of your car detecting a precarious wear on its own, before breaking. Through the internal element network of the car, the information will be transmitted to a mobile communication interface. From there a message is sent through external networks to your smartphone. The smartphone then helps you to schedule an appointment at a garage and sends a specific message to the spare part ordering system of your garage of choice. This type of CPS combining internal element networks and external networks shall be referred to as *Pervasive Network CPS.*

4 Mechatronic Machine Elements

4.1 Discussion of the Term

The term *mechatronic machine element* seems to have rarely been used to date. A Google search for the precise expression produces in September 2012 four hits. One of them leads to the encoder integrated bearing described in section 2. In the only publication found, using the term[9], it does not play a major role, nor is it defined.

The term was chosen for the following reasons: The part *machine element* refers first to the similar role these items have within a mechatronic product to conventional machine elements, especially in terms of mechanical function. Secondly it stresses out the element character as being a small integral assembly which only develops usefulness when all parts are contained. *Mechatronic* brings in the combination of mechanics, electronics and digital computing.

4.2 Standard Solutions Reduce Design Effort

As briefly mentioned above, typical CPS products which contain Internal System Networks are automotive vehicles and airplanes. These highly complex systems are developed by huge design teams. The high development efforts can be afforded due to the large number of vehicles produced or the high price paid for an airplane. Other products, as medical rehabilitation devices for example, are too specific to be produced in hundreds of thousands and cannot cost millions of euros, neither. In consequence the development effort has to be kept comparably low. Thus the cyber-physical integration is often minimal, although it might be highly desirable that they exchange more information with other devices and adjust better to the current task.

So we can see on one side the trend towards CPS and on the other side products for which the development effort to design complex internal system network CPS cannot be afforded. Here MME may close the gap. Having – in future – at hand a wide range of MME, which work plug-and-play in a bus system and can be selected and mechanically integrated by the development engineers as easily as today a gear box, this will enable also small teams to develop sophisticated CPS.

A similar development already took place in electronics a few years ago, looking at digital camera sensors for example, or GPS modules. In 1990 GPS receivers were bulky devices and due to their price only used professionally. Ten years later, GPS navigation devices were already handy and wide spread for navigation in cars or outdoor sports. Today the small size and cheap price of a GPS module makes them enhance devices like mobile phones and digital cameras with secondary functionality. But it also contributes to their broad application that developers do not need to understand the whole GPS technique anymore. It is enough for them to know the physical interface of the module and the *processed* digital values that it gives out.

(a) (b) (c)

Fig. 3. Historical development of GPS receivers, from bulky positioning devices (a) over smart navigation devices with map functions (b) to small modules integrated into smart phones (c)

From the example above can be deduced that mechatronic machine elements should have the following traits in order to have a great impact on future product development. Of course they should have reasonable costs and a compact design. Then they should process as much information as possible directly on the element. Thus the amount of data transmitted is reduced, and the transmitted data can more easily be interpreted by the integrating development engineers. For easy network integration it is important that the elements communicate according to an appropriate standard. Also regarding their mechanical design MME should follow general standards.

Three groups of MME, where important developments are going on, are examined more closely in the next three subsections. The examples given may not be MME exactly as defined above but they illustrate the key characteristics of each group.

4.3 Sensor-Integrated Machine Elements

An example of the group of MME which the authors call *Sensor-Integrated Machine Elements* is the roller bearing including an angular encoder, described in section 2 [3]. That this is truly one element can be seen from the fact that the angular structure detected by the transducer is manufactured into a bearing ring. Thus sensor and machine element are inseparable. While here the advantage of the fusion lies mainly in cost and space saving, sensor-integrated machine elements can offer more.

Dickerhof [10] showed in his research that it is possible to detect dry running and rib contact running of roller bearings through ultrasound analysis. Thus impending failure can be detected before it occurs. This detection is generally desired for roller bearings, as both, failure and unnecessarily early replacement is often very costly. So the demand for standard elements combining bearing and ultrasound analysis is given.

Now, from an ultrasound measurement the data flow is obviously large while one only needs one single value: okay or not okay. The analysis to get to this value requires considerable knowledge of the physical system, i.e. the spectrum of vibrations occurring in "healthy" and "unhealthy" bearings. Therefore it is useful that the manufacturer implements the raw data processing directly on the machine element, which then sends to other systems only the relevant okay/not okay status. Thereby it requires only minimum communication bandwidth.

Another advantage of sensor-integrated machine elements is also illustrated by Dickerhof's research. It is that damages on bearing races can be detected already from low impact energies, i.e. at low speed or with small damage, when the vibration is measured directly at the bearing. Often only a very tight sensor-mechanical integration regarding space and component parts leads to sufficient signal quality to extract relevant information from the system.

4.4 Semi-Actuators

A second group of MME is referred to as *Semi-Actuators*. While the main function of an actuator is to transform a certain form of energy into mechanical energy, the main function of a semi-actuator is mechanically passive. However, a semi-actuator can adjust the properties of its main function actively. Thus semi-actuators have generally the properties that they add degrees of freedom to the system, consume little energy and require often not so fast control cycles as principal actuators.

An example for this type of MME comes from robotics, where there is a lot of research going on in the field of variable impedance joints. The DLR VS-Joint [11] is a passive spring joint that produces in both directions forces towards a neutral position. Through an actuated spindle the pretension of the springs can be adjusted in order to change the joint stiffness. So this actuator does not actuate the joints but just influences the way the links are passively coupled through the joint.

Novel semi-actuators have the potential to make completely new mechanical solutions possible.

4.5 Sensor-Actuator Fusion

A third group of MME are *Sensor-Actuator Fusions*. Similar to sensor-integrated machine elements sensor function is deeply integrated into another element – here into an actuator. One motivation is again to save space. Another reason for such elements is to measure directly at the "hotspot of action". As an actuator by definition produces a change to a system, one often wants to measure the effects of it. On the one hand the measurement of the resulting effects of an actuator input is usually the most relevant the closest to their source, i.e. the actuator itself. On the other hand, as certain sensors are often deployed together with an actuator in a system, it can be very useful to develop and distribute them as a single element.

One example for a sensor-actuator fusion element is a self-sensing short stroke linear drive, developed for a force feedback keyboard [12]. It uses the identical hardware to produce force and to sense position. The position is derived from the damping of electric oscillations in the system, which is proportional to the position of the ferromagnetic core in the coil. A second example pointing in the direction of a sensor-actuator fusion is a highly integrated light-weight robot actuator [13]. Here the motor and sensors are still separable, but designed for a tight spatial integration. One cylindrical assembly contains a hollow shaft motor, motor and joint position sensors, torque sensors, a brake, a gear, plus ring shaped electronics boards.

5 Outlook: Insights for Product Development

So far cyber-physical systems are mainly discussed as marketable products or networks of such. The value of the intense exchange of data lies in operation states and services which are specifically optimized to the current situation, thanks to more situation awareness of the machines. Or, in another case, the value can be to free the human user from the task of acquiring, processing and deciding upon data. But CPS can also play an important role in the development process of products which are themselves low mechatronic.

To design good products, engineers need correct and precise specifications regarding the application of a product. CPS can provide information from prototypes in field testing in real time around the globe. This can be for example data on the frequency and duration of usage or the ambient temperature and humidity in the place of application. Much more powerful becomes the database if it provides information on the dynamics of the product in interaction with the user and the application.

As an example can serve the testing of hand-held power tools. Small units integrated in the prototypes record the operation of the switch and measured accelerations and temperatures. The data is sent via GSM network to the R&D headquarters of the company. It should be noted that relevant accelerations are to be measured at the force bearing structures inside the device and not at the housing. Additionally, not to alter the dynamics significantly, the data acquisition unit has to be light compared to the mass of the product.

With the need to measure relevant properties deep in the core structure of the prototype, this example again indicates the usefulness of mechatronic machine elements. New solutions should be actively sought for MME specifically designed to collect data for design purposes. The authors think for example of sensor-integrated machine elements, which are in the end product exchanged for conventional machine elements to save costs.

6 Conclusions

This paper in the first place documents the observation of first mechatronic machine elements being developed. This observation is brought into context of a general trend towards cyber-physical systems in engineering.

A major contribution is the introduction of a nomenclature for both, categorizing observed MME and existing or envisioned CPS. Four types of CPS are identified and named external network CPS, internal system network CPS, internal element network CPS and pervasive network CPS. Three groups of MME are identified so far. They are sensor-integrated machine elements, semi-actuators and sensor-actuator fusions (see Table 1). These groups are characterized and illustrated with examples.

Table 1. Comparison of the three proposed types of mechatronic machine elements

MME type	**Short description**	**Add mechan-ical energy**	**Change mechanical properties**	**Sensor output**
Sensor-integrated machine element	Passive machine element with deeply integrated sensing capability			X
Semi-actuator	Basically passive mechanical beha-viour, which is actively adjustable		X	
Sensor-actuator fusion	Deep integration of actuator and sensor functions into single element	X	X	X

While the emergence of MME is a consequence of the increasing integration of mechanics, sensing, computation and networking, they are at the same time a prerequisite for types of CPS that reach deeply into the machines, namely internal element network CPS and pervasive network CPS. Advantages of MME are most obviously saving space and better data quality, as they can sense very close to the source of measured effects. But they can also reduce the development effort to design complex products as they provide already more functionality, coordinately engineered and readily integrated in one element. Some MME also create mechanical functionality which can only be achieved through a mechatronic solution.

It is argued that for a broad success of MME it is crucial that they simplify further the work of the engineers deploying them in products they build. Therefore MME should follow mechanical and communication standards. For sensing MME it is important to implement as much preprocessing as possible on the element itself in order to boil down the data to the relevant information. This helps the deploying engineers in understanding and using the transmitted data, and it also helps to reduce the required bandwidth of the network.

In an outlook there is a great potential identified for building CPS not only as marketable products but also as a tool for gathering information in the product development process. It is suggested to develop MME specifically for this purpose to make best use of this potential.

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