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SCALABILITY OF MECHATRONIC SYSTEMS

M. Neumann and T. Sadek

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1. Introduction

Both, the growing demand for customer specific products as well as the associated effort of a product's manufacturers to fulfil different customer requests in an appropriate manner lead to a steady growing variety of products and decreasing number of variants at the same time. The increasing expenses connected with these aspects are encountered in the areas of construction and production by means of type series development as well as modular design. At the same time, especially new trends in the fields of medicine, micro as well as nano technology lead to new requirements in the case of miniaturization of technical systems. Therewith, they extend the products' demanded spectrum with respect to size according to the specific scale. Affected are especially mechatronic systems which can be characterized by a synergetic integration of the domains mechanical, electronic as well as software engineering.

Until now, the investigation of mechatronic systems with regard to analysis and synthesis with respect to scaling and scalability only takes place in an inadequate manner. A further development beyond the borders of type series development and modular design of methodological approaches in the case of mechatronic systems' scaling which would follow the described trend for miniaturization does not exist. Aim of a today's efficient product development must it be to transfer design knowledge by means of system scaling taking into consideration the integrative interrelations of the involved mechatronic domains.

2. Differentiation of the term „scaling“

In its original context, the term "scaling" is used to describe a certain change in size of objects. Scaling is often associated with mathematics and a geometrical change in size supported by an arbitrary scale. Over the years, the term scaling was carried forward into different technical areas, therefore leading to an extended comprehension of the term "scaling" itself. Some views upon "scaling of technical systems" have proven their worth in industrial appliance and are therefore selected for further discussion.

2.1 Scaling in mechanical engineering

In order to allow for spatial scaling and to rationalize the construction-/ production-complexity of products in mechanical engineering, type series have been developed. A product out of the same type class differs in its size, but it fulfills the same function, applies the same solution concept and uses the same manufacturing techniques. Based upon an elementary design, adjacent scaled designs are derived with the help of similarity laws [Katt 1967],[BaWeDo 1973]. Therefore, a product class offers economical advantages as well as a higher product quality compared to regular product designs, since it allows an almost loss-free transfer of development-knowledge with regard to adjacent designs.

In context of a “product class”, the term “similarity” implies a constant relation of at least one physical term between the elementary and the adjacent designs [Katt 1967]. As an example, geometrical similarity connotes a constant relation of all geometrical variables of elementary and adjacent designs. Furthermore, the term “specific similarity” means a constant relation of various basic proportions. Some of the most important elementary similarity rules and derived combined specific similarities are shown in table 1. Please note that table 1 is supposed to give an overview only and that it needs to be adjusted to the actual application.

Table 1. Fundamental and specific similarities [Katt 1967]

Fundamental similarities			Specific similarities		
similarity	fundamental unit	ratios	similarity	fundamental units	ratios
geometric similarity	lengths	$\varphi_L = L_1/L_0$	static similarity	lengths, forces	φ_L, φ_F
similarity of forces	forces	$\varphi_F = F_1/F_0$	kinematic similarity	lengths, time	φ_F, φ_t
similarity of time	time	$\varphi_t = t_1/t_0$	dynamic similarity	lengths, forces, time	$\varphi_L, \varphi_F, \varphi_t$
similarity of temperature	temperatures	$\varphi_\vartheta = \vartheta_1/\vartheta_0$	thermal similarity	lengths, time, temperatures	$\varphi_L, \varphi_t, \varphi_\vartheta$
electrical similarity	electric charge	$\varphi_Q = Q_1/Q_0$	thermodynamic similarity	lengths, forces, time, temperatures	$\varphi_L, \varphi_F, \varphi_t, \varphi_\vartheta$
photometric similarity	intensity of light	$\varphi_B = B_1/B_0$	thermoelectric similarity	lengths, time, electric charges, temperatures	$\varphi_L, \varphi_t, \varphi_B, \varphi_\vartheta$

A “complete similarity” between two physical actions means that all characteristic values of elementary and adjacent designs react to their individual constant relation. For technical and economical reasons, it is mostly not reasonable to achieve “complete similarity” of technical products. In this case, one relation of a characteristic value differs with regard to the overall constant relation of the specific value class. Compared to the original system, the scaled system then shows a “partial” or “incomplete similarity”.In order to scale a product class in different degrees of size, decimal-geometrical preferred numbers have proven to be a practical solution.

2.2 Scaling in IT Engineering

The common perception of the scalability in information technologies (IT) is that it is a measure of the adaptability of an IT system to the growing work load (e.g. Liu 2009]). According to this definition, the demand on the resources of scalable IT systems or software applications grows proportionally to the required performance. The performance requirements put on the IT system can become higher through, for example, increased volumes of processed data or increases numbers of the participating members in a network or bus system. A software application with optimal scaling properties requires twofold on the resources for the twofold increase in performance, or the twofold increase of the resources leads to the halving of the computing time for the same performance. Therewith, the essential feature of the classical definition of the scalability in IT is that the increasing work load is inevitably followed by the expansion of the system through the additional resources and not through the extensive changes to the application itself.

2.3 Scaling in electrical engineering

In electrical engineering, the term scalability is related to the size variation of the electronic parts. As in the classical mechanical engineering, the scaling is carried out in accordance with the similarity theory [SeSmit 2003]. The particular significance of the “scaling down” has been achieved through the introduction of the semiconductors, which allowed a high level of the miniaturization of the electronic parts. The rapid development of the miniaturized electronic parts took place in the 20th century. The most important development of this technology is materialized in the integrated circuits. Within a few decades, the minimal structural sizes could be further 50-fold reduced. At the same time, the surface of the chip could be about 170-fold increased and the “packing efficiency” could be 100-fold raised.

Therewith, the total number of the transistors in a chip could be 50 000 000-fold increased. The fundamental basis of this development is the scalability of the transistors [Pagel 2001].

2.4 Domain-independent definition of the scaling

As shown in sections 2.1 and 2.3, the interpretation of the notion of scaling or scalability in terms of different domains relevant for the mechatronic systems is very versatile and complex and different definitions target different aspects of the components of a mechatronic system. However, for the scaling of the mechatronic systems, a consistent and uniform definition of the scaling is needed. A general definition of the term scaling has to result from the main purpose of the scaling task. The primary goal of the scaling can be certainly traced back to the required changes of the system properties, so that the scaling can be achieved through the adjustment of a known solution subject to certain scaling rules in defined increments. A standardized and integrated definition may be obtained through the notion of the scaling as an adjustment of the system properties to a scale under the consideration of certain rules. The entities and specifications of the scale depend on the task and are for each application individually determined. For example, in case of a required miniaturization, the geometry of the system can determine the primary scaling parameters. In this case, the scale is geometrical. Considering a pump as another example, the gradation of the flow rate is decisive, hence, the scale is to be configured as a capacity scale. The general comprehension of scaling in the information technologies is included in the given definition as well. In this case scale must be considered as a measurement of the necessary computing time of a software application to varying computing power requirements of a given system. Additionally, a functional based point of view is included in the idea of scaling. Systems that are functional scable allow an adjustment of its functional range to varying requirements. This interpretation of scaling also confirms to the given definition of scaling. In the case of functional scaling the scale can been seen as a measure for a system's functional expandability. The more the scale is diversified and the smaller it is staggered the more can the system be adapted to a specific application. With respect to this interpretation also modular design can be defined as scalable systems. Whereas type series enable a geometric size scaling without changing the initial system's functional principles, modular design combines different components to achieve overall systems with similar geometric values but different overall functions [Kohlhase 1997]. The classification of components of a modular design can be achieved by means of numerous criteria. In literature often the classification by Pahl&Beitz is used differentiating components according to "Must-Have-Blocks" and "May-Have-Blocks" [PaBei 1997]. Must-Have-Blocks are elements which have to appear in each product of a modular design to achieve the main function of the system. May-Have-Blocks are optional elements which can be used to increase or adapt a product's function range. In this sense, that scaling of a product with respect to its modular design can be achieved by extension and reduction of a basic system by means of May-Have-Blocks.

The enhancement of the idea of scaling by a functional point of view suggests the expansion of interpretation of scaling with regard to software technology. While in the information technology scaling has always only be interpreted as the ratio of necessary computing power and available computing power scaling should include the possibility of increasing and decreasing functions within the software. By this the scalability of the software can be described as the effort to adapt the software to varying requirements. This common interpretation includes the former definition.

Until today modular design has been limited to a system's hardware. This view is steadily expanded to a modularization of software and control. The aim of modular software architectures and control systems is to solve different tasks with low costs of work and to find simple ways to react on varying requirements associated with a function. The benefit in working costs results due the reusing and rearranging of software modules which simply can adapt to the new requirements. So redundancies by creating software code can be highly minimized. In this way the development of flexible software and control techniques and the partitioning of independent software blocks comes in the fore with modular design of software and control structures other domains like the information technology is entering the use of modular design.

Figure 1 illustrates, which consequences with respect to scaling mechatronic systems can be derived at system level taking into regard the afore mentioned superpositioned view. According to this scaling mechatronic systems can occur either as a change of geometric dimensions or a change of systems input an output quantities or as a change of its functional range. While geometric scaling ist restricted to the systems hardware both other kinds of scaling can be applied to each mechatronic domain.

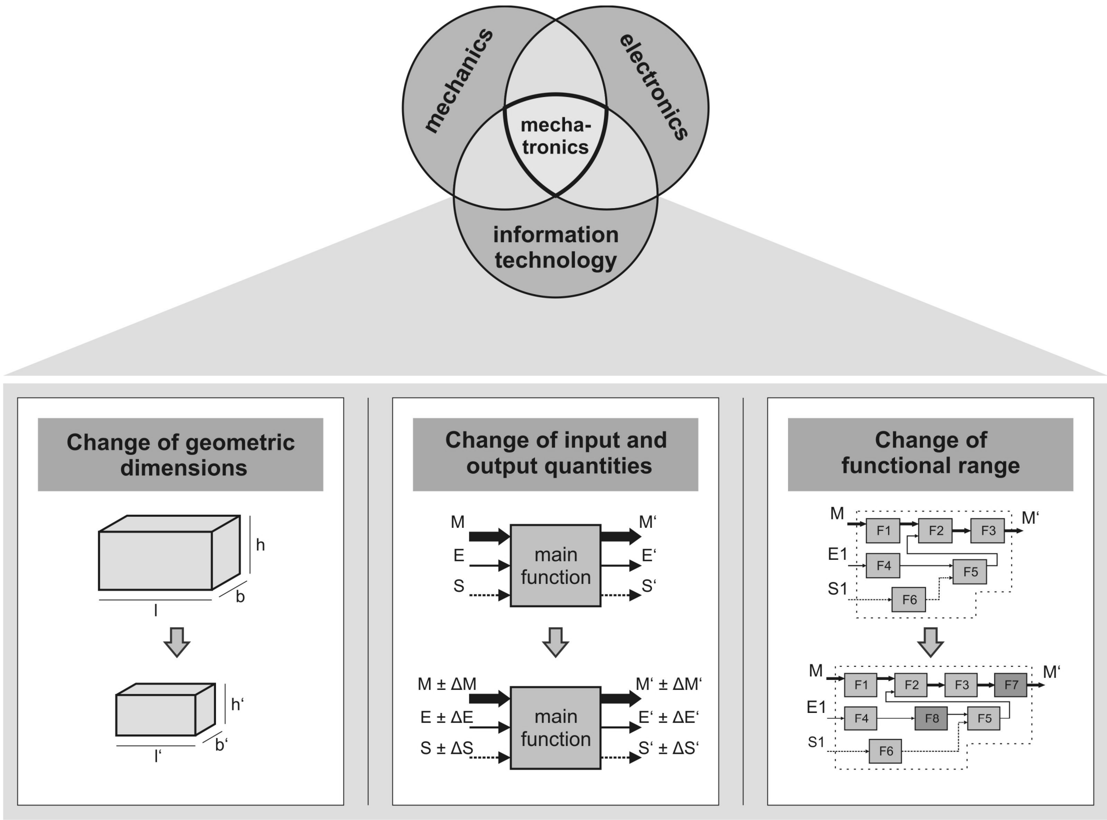

Figure 1. Solution space for scalability

3. Effects due to scaling

Development engineers responsible for scaled mechatronic systems are highly challenged by the already in chapter 2 defined and described different forms of scaling as well as the high degree of interdisciplinarity of mechatronic products. Scaling aspects connected with either classical mechanical, electrical or software engineering could so far be managed predominantly domain specific. With regard of mechatronic systems these aspects now occur in combination and have to be coped with by means of a domain integrating approach. For this, a common understanding related to the occurring effects and interdependencies as well as resulting consequences due to scaling of mechatronic systems has to be elaborated.

3.1 Interdependencies

When considering the development of type series as an established method for scaling of mechanical products already obvious interdependencies between the individual system components can be recognized. These interdependencies can be mathematically formulated in form of similarity ratios. Just to be able to make reliable statements with respect to the scalability of a system by means of similarity ratios it is an essential precondition to have a complete understanding of the initial system's physical characteristics. This aspect especially refers to the identification of basic, from each other independent influencing quantities as well as their separation from insignificant factors [Pagel 2001]. Besides of the proved similarity ratios with regard of type series there exist further interdependencies according to the enhanced understanding of scaling of mechatronic systems. These especially originate from a system's scaling on a functional level. In this sense, functional interconnections as well as interdependencies between function fulfilling components have to be increasingly taken into consideration if a system is not only changed by its geometric size and scaled with respect to its input and output quantities but also changed with regard to its functional spectrum. One example for this aspect is a mechatronic system's extension by means of additional sensory. An appropriate extension simultaneously demands for an adequate adaptation of the system's control and implementation. Beside the knowledge about interdependencies of elements within the same abstraction-level the identification of interdependencies between different abstraction-levels (figure 2) is necessary as well to estimate the consequences of the scaling. In the sense of an extended understanding of scaling of mechatronic systems especially those interdependencies which are not adequately considered or even misinterpreted can lead to far-reaching problems with respect to scaling.

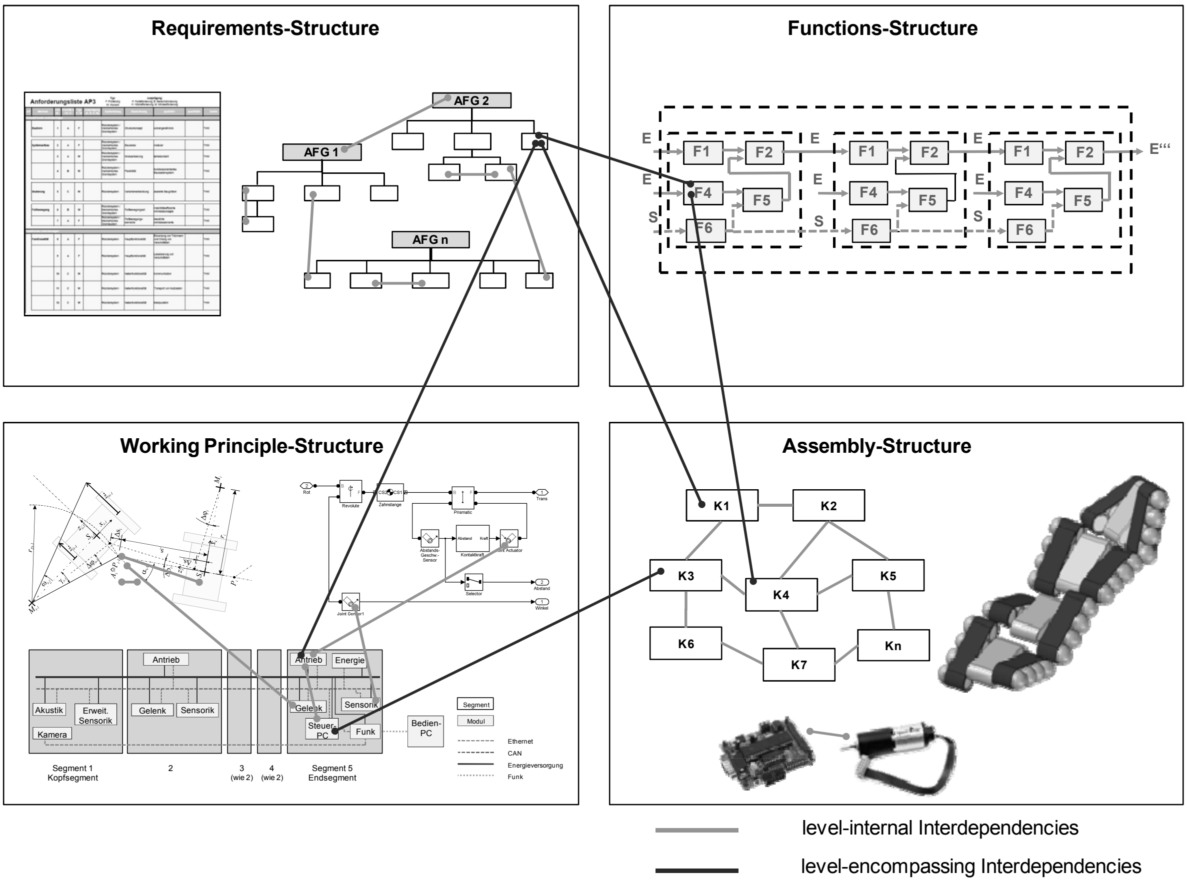

Figure 2. Interdependencies within and between different abstraction-levels

3.2 Divergent effects of physical working-principles due to scaling

In the course of a significant change of size of a technical system often unexpected effects occur which apparently contradict with gained experience. Effects which are dominant at macro level can lose impact with increasing miniaturization or even become irrelevant. Other effects, in turn, can be effectively used not until dealing with a system's micro level. One example for this circumstance is electro-static force having, from experience, no significant impact at macro level but a dominant one at micro level. Contrary, both, gravitational as well as inertia forces being dominant at macro level lose relevance with increased miniaturization. Though macro and micro level are subject to the same physical laws a pure scaled downsizing of an existent system does not consequently lead to desired properties of a target system [Pagel 2001], [UchGin 2003]. As a conclusion, the reason for this is not a change of physical laws of individual working principles but a change in ratio of different effects interdependent with each other. It can be recognized that a system runs the risk of losing harmony between the ratios of effects in the course of a system's scaling process due to an increasing number of working principles combined within an overall concept as well as due to an increasing number of involved disciplines. As a consequence, the transformation of an initial system to a scaled target system must always happen under consideration of all relevant similarity ratios associated with the partial solutions at hand. Divergent effects of physical working principles resulting from a geometric scaling have to be identified already in the early phases of a development process. This is due to the fact that these effects otherwise could endanger a scaled overall system's functional compliance. In early development phases "counteractions" can be initiated in time allowing e.g. the consideration of a possible change of used working principle.

3.3 Domain specific and domain integrating interdependencies between system elements

The integration of mechanical and electronic system elements as well as elements associated with software engineering in minimal space in the sense of mechatronics can lead to problems connected with undesirable interdependencies and disturbance quantities between the given system elements. These interdependencies cannot be neglected due to their increasing relevance in the course of an increasing miniaturization. Therefore, in the case of miniaturized mechatronic systems interdependencies themselves can gain a functional character or relevance, respectively. As a consequence, the overall function of a miniaturized mechatronic system can be often recognized as being more than just the sum of the individual sub-functions. Interdependencies can occur, both, between system elements of an equivalent domain as well as between system elements which can be assigned to different domains. Therefore, interdependencies can e.g. occur between pure mechanical components. Further on, loss in momentum because of bearing mechanism as well as toothwork cannot be neglected in the case of electro-dynamic gear-box motors with respect to a specific size if e.g. a motor has been miniaturized by multiple of its initial size. As a consequence, according effects have to be captured already during a system's conceptualization just to be counteracted by adequate solutions like e.g. improved toothing geometry and bearing as well as an optional change of working principle.

A representative example with respect of interdependencies between system elements assigned to different domains is the electro-magnetic effect. Coming back to the already above given example, electro-magnetic effects are generated by an electro-dynamic actuator and can exert disturbances on a system's signal processing with respect to the system's increasing spatial miniaturization. As a consequence, undesirable electro-magnetic interdependencies can lead to significant drawbacks of a system's functionality or even cause a system's breakdown and malfunction, respectively.

4. Methodical development of scalable mechatronic systems

Because of an increasing cost pressure and higher customer requirements the development process of mechatronic products is often based on well known approved solutions. The development of type series follows this approach by using similarity laws to generate designs with staggered geometric or physical values referencing to the basic design. Contrary to this a construction kit allows to customize the functionality of a product to special customer requirements by a flexible combination of fully developed construction blocks. As shown in chapter 3 the scalability of technical systems is limited to a specific range, in which the functionality of the system can be ensured. Beyond these limits the functionality of the system may not be kept up by the cosen technology. The range in which the required functionality of the system can be achieved can be ascribed to the diverging impacts of the working principles caused to the scaling. In addition the possible range of scaling is influenced by negative effects due to the interdependencies between the subsystems. Often the effects of these interdependencies are not known or the interdependencies themselves are not noticed. Therefore the scaling process on a mechatronic system frequently provides no useable solution. Especially the significant miniaturization of mechatronic systems demonstrates that the direct scaling just by using the geometric similarity generally do not provide useable solutions. Significant miniaturized technical systems are therefor often not the result of a methodic or structured development process, but are based on intuitive ideas that are realized in lots of unnecessary and cost intensive iteration cycles.

To sustain the requirements of the market even in the future, it seems necessary to expand the ranges of conventional type series and construction kits.

4.1 Partitioning of scalable mechatronic systems

On the one hand the scaling of a mechatronic system becomes more complicated if the complexity of the system increases. This effect occurs if the amount of interdisciplinarity and the number of integrated mechatronic components increases. On the other hand exactly this interdisciplinary and the diversity of components offer new potential for the partitioning of mechatronic systems. The simultaneous appearance of mechanics, electronics an software technology offers numerous options for the variation of the domain structure. Generally many functions of a mechatronic system may be solved by more than one of the different domains. Regarding to scalable mechatronic systems the question comes up, how the domain allocation of a mechatronic system can change its scaling-attributes to extend the technical limits of type series.
In [Jansen 2006] Jansen makes a distinction between functional and spatial partitioning of mechatronic systems. As defined by Jansen, functional partitioning describes the assignment of single functions or groups of functions to a specific domain without consideration of the spatial structure. The spatial partitioning contains the spatial structure of mechanical system components among special consideration of the applied domain.

Scaling by domain-allocation on the example of a digital camera

The following example of a digital camera shows the remarkable relevance of the partitioning of scalable mechatronic systems. Therefor figure 3 displays the simplified functional structure of a digital compact camera. In the represented camera the incoming light ist projected on the CCD-array by a zoom lens.

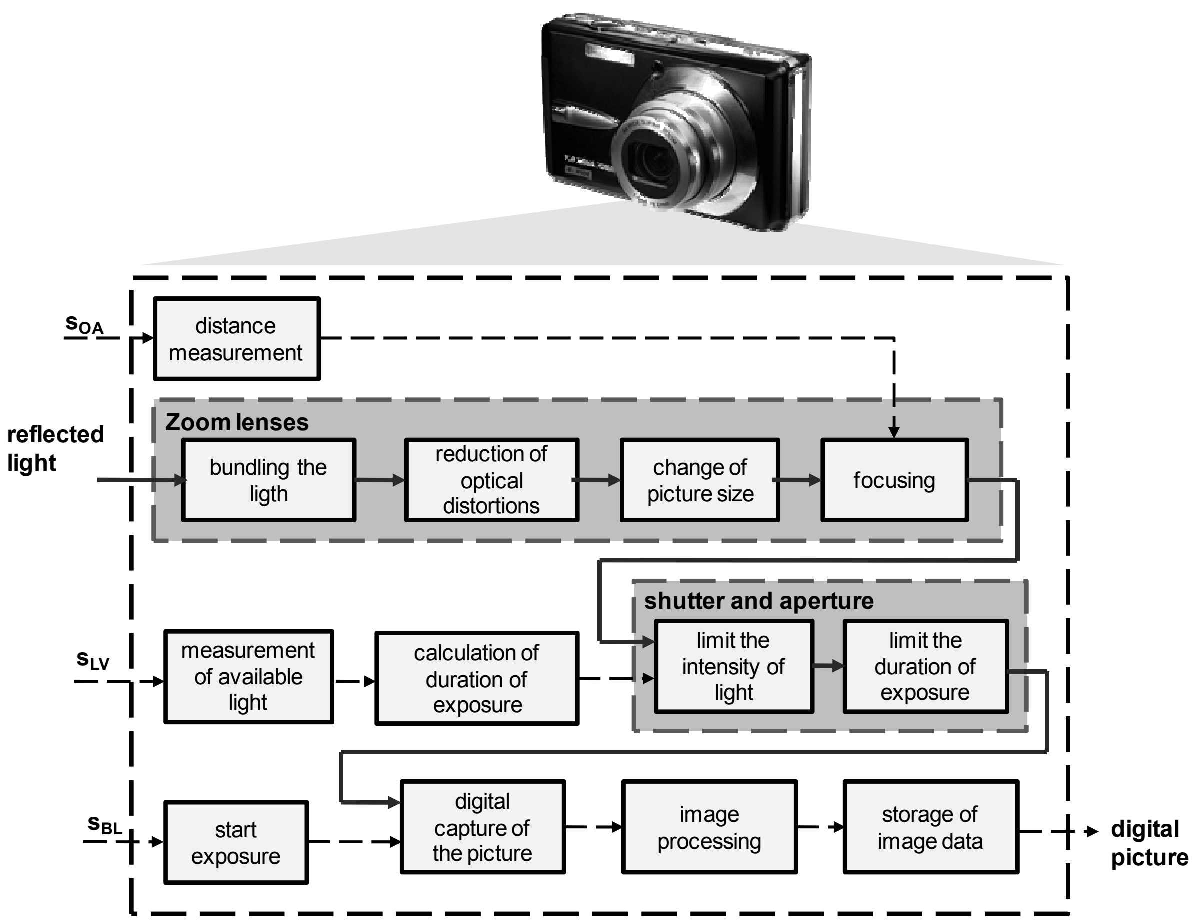

Figure 3. Functional structure of a digital camera

The exposure time and the aperture are automatically adjusted to the external conditions by measuring the lighting conditions. The analog signals at the CCD-array are digitalized and preprocessed by the internal data processing. In fact, the dimensions of the camera are mainly dictated by the mechanical components of the system. Among the camera body especially the zoom lens, the aperture and the shutter define the construction space of the system. Normally the zoom lens consists of a system with different lenses and an electrodynamic drive to control the autofocus of the camera. With respect to a wide zoom range and a high opitical quality over the whole CCD-array a lot of lenses have to be integrated in the zoom lens which makes the lens one of the largest components of the camera.

If the camera needs to be miniaturized to integrate it for example in a cell phone it ist obvious that simply minimizing the geometric dimensions of all system components does not lead to usable results due to the existence of technological restrictions and economic inefficiency. A reduction of the number of single lenses in the zoom lens would obviously simplify the miniaturization of the system. On slightly penalties on the optical quality of the zoom lens it is possible to decrease the number of lenses by a domain specific reallocation of the lens functions. In this case some lenses can be passed from the zoom lens if the zoom function is realized by a digital zoom. In the same way optical distortions can be reduced in the step of data processing, which makes a further reduction of single lenses possible. The relocation of a system function from the photomechanical domain into the information technology advances the process of scaling the system. If scaling effects constrain the miniaturization of the aperture or the shutter the reallocation of their functions into other domains can also produce relief. An active LCD-panel, that is mounted in front of the CCD-sensor , for example should be able to replace the shutter and the aperture. Such an optimization in partitioning and scaling can also be performed on the CCD-Sensor itself. To keep the resolution of the sensor it is necessary to reduce the dimensions of the pixels and the distance between the pixels of the CCD-Sensor. The appearance of an optical noise is a direct annoying effect as a result of this scaling of the CCD-Sensor an the increament of opical pixel density. The reason of this noise is a smaller capacity of the pixels due to the smaller area what results in a higher sensibility for aberrations. Micro lenses on each pixel are added to limit this effet. In this case the data processing offers options to optimize the system behavior as well by analyzing and optimizing numerical algorithms. Thru this the micro lenses could be substituted or the possibility of scaling the CCD-array and the the resolution of the sensor may be further increased.

4.2 Requirements for a scaling method

The given example “digital camera” makes clear in how far the limits with respect to scaling of mechatronic systems can be shifted by means of domain allocation. Just to be able to reasonably deploy a partitioning methodology in the sense of development of scalable mechatronic systems this methodology must consider, both, the requirements as well as the special character of scaled mechatronic systems and additionally be domain integrative applicable. The provision of an adequate tool for system scaling support requires the development of a procedural model, a suitable modeling approach as well as the formulation of methodical supportive blocks. These aspects have to be harmonized with each other in the sense of an integrative overall concept. The methodical supportive blocks have the purpose to assist a development engineer in the course of the development process under consideration of different levels of concretization. The assistance is associated with the processing of data and information deposited within a concept model.

An appropriate scaling methodology must support the scaling of an already existing initial system in a top down scaling process as well as the conceptualization of product lines with reliable scaling properties in a bottom up approach. An adequate modeling approach must be able to generate transparency with regard to occurring scaling effects as well as interdependencies between system components and the involved domains with the aim to be able to evaluate the limits of scalability of technical systems already in the early development phases. Basic requirements for an integrated scaling methodology for mechatronic systems are summarized in figure 4.

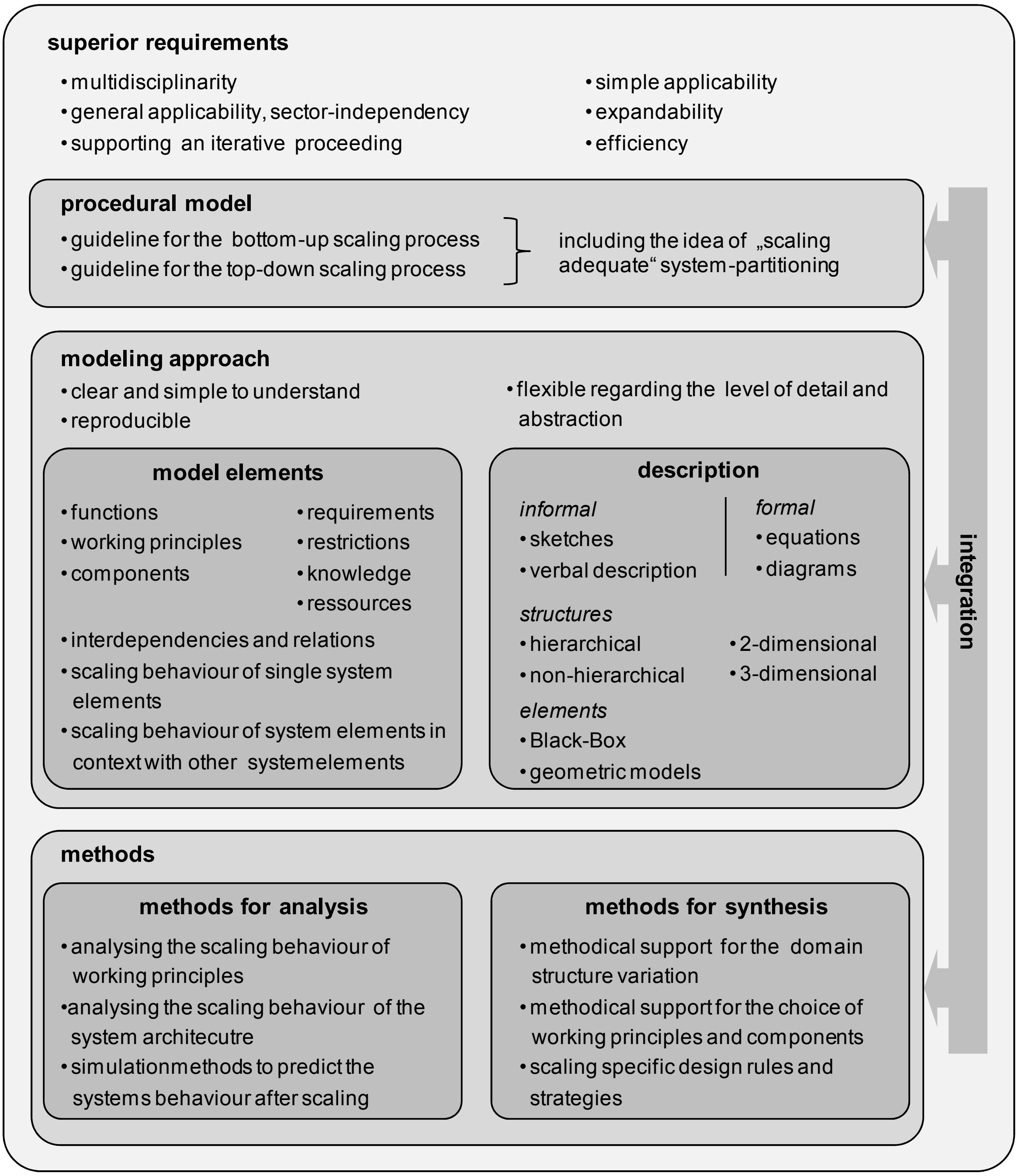

Figure 4. Requirements for a scaling methology for mechatronic systems

5. Conclusion and outlook

The paper at hand states that an efficient development of customer specific products can be achieved by means of scaling of already existing systems. For this purpose, the term scaling of mechatronic systems has been defined as a domain integrative adaptation of system properties according to a give scale with regard of specific laws and ratios, respectively. Therefore, a distinction has been introduced differentiating between spatial and functional scaling as well as the change of a system's input and output quantities. The need for a domain integrative scaling approach has been highlighted by means of an analysis of occurring effects as well as problems and disturbances associated with the scaling of mechatronic systems with regard of the given scaling differentiation and the derived scaling limits. The described scaling approach has the aim to support a development engineer in form of provision scaling methods and demand-oriented process models. In this sense, the partitioning of mechatronic systems with regard of scaling aspects has turned out to be an adequate approach. For further research and development of a methodology for scaling mechatronic systems the following question will be of interest:

- What are the importance and impacts of system scaling with regard to the properties of a scaled system under consideration of a product's requirements? What are the significant aspects for the definition of limits of technical systems' scalability? How far can an initial system be scaled by means of a classic type series?
- How far can the properties of a scaled system be optimized by means of an efficient allocation of available resources of mechatronic sub-components? Thus, can the limits of a classic type series be extended if the system's structure is kept unchanged?
- How far can a domain integrative approach increase the scalability of a system already during the early phases of development? Which predefinitions according to this can be made in early and late phases of a development process?

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Dipl.-Ing. Marc Neumann
Ruhr-University Bochum, Institute Product and Service Engineering
Telephone: 0049/234/3224055
Email: Neumann@lmk.rub.de