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# BIOLOGICAL STRUCTURES AND TECHNICAL DESIGN
## - A BIO-MIMETIC APPROACH

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## ABSTRACT

Development and improvement of technical devices occur in a synectic manner by transferring principles of living systems, like organisms including the human body, reactions of bio-molecules or even supra-organismic phenomena, into technical design. Besides this, the process can have also the aim to pattern technical processes on organismic systems. This paper is a digest of the theoretical work on this topic, according to the tasks on different technical developments and their didactics. It includes citations of the main communications concerning the results of the application in design of micromechanical systems, the research of biocompatible materials and bio-inspired motion systems.

***Index Terms -*** Bionics, biomimetics, specifics of bio-systems, systematical transfer, mechatronic systems, design concepts of biomimetic material, muscle-like actuators, strategies of development of sensors.

## 1. INTRODUCTION

The historically well-founded strategy of biological inspiration of the process of technical development (the term “bionics” was at first published by Col. STEELE in 1960, but the method was invented in the renaissance, especially by Maestro LEONARDO) is more than ever a concept well acceptable for most engineers. Everyone plans to do so, but only a few at last really do. Mechatronics - as distinguished science subject still in the explanatory stage – can be much more open to bionic influences than traditional domains of science since by integration unconventional technologies, new materials and designs it likewise particularly requires integrative thinking. To control the effects of the complexity of products like those emergent (not being based on the single element) and non-intentional functions (risks and side effects) increasingly requires the knowledge of the nonlinear behaviour of such highly complex systems like they are investigated in biology. The effects of handling of matter, energy and information are also interesting for the design of technical micro systems which integrate components directing the flow of such general quantities in bio-systems.

About the conceptual term “biomimetics” going out, this interdisciplinary system-approach is more than just a copy of nature, but should draw analogies, problems and applications, that are driven by engineering sciences. This assumes the finding of morphological, structural and functional analogies between biological and technical systems (Fig. 1).

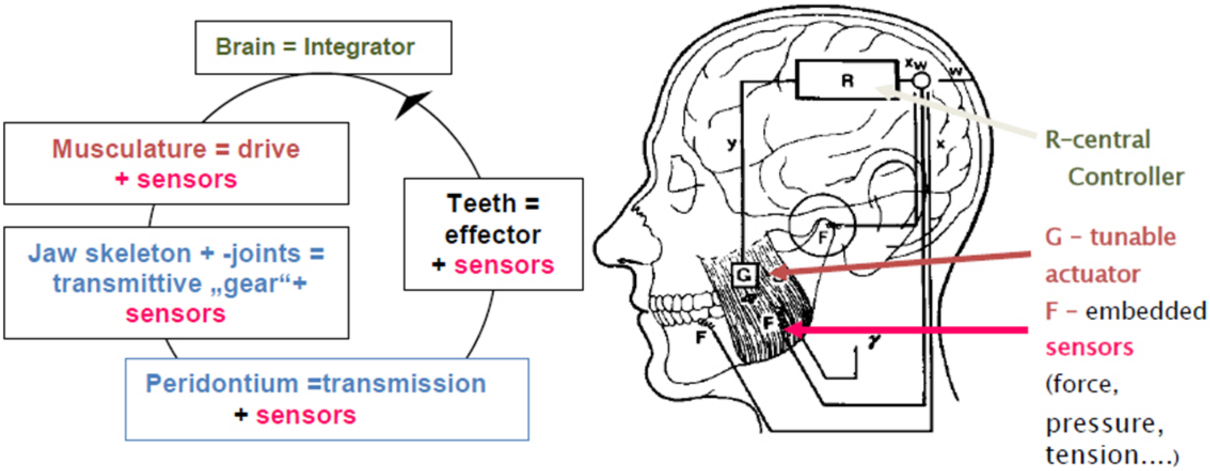


**Fig. 1**: The chewing apparatus – a bio-mecha-“tronic” system (“Orofacial system” according SCHUMACHER)

## 2. ORGANISMS AND MACHINES – TWO DIFFERENT WORLDS

The basic understanding for a profound comparison of common characteristics and differences between organisms and machines is a condition of derivation of objectively reasonable analogies between the phenomena of living nature and various technical problems. This can occur with the criteria of the general system theory according to BERTALANFFY [1].
There are different ways to convey beneficial proceedings in biomimetic solutions. The classic way is to choose a singular biological species as a paragon for specific presentation of a technical problem. The conceptual orientated bionics can broaden the space of solutions through formulation and implementation of a design principle without drawing an analogy between two particular objects (Fig. 2).

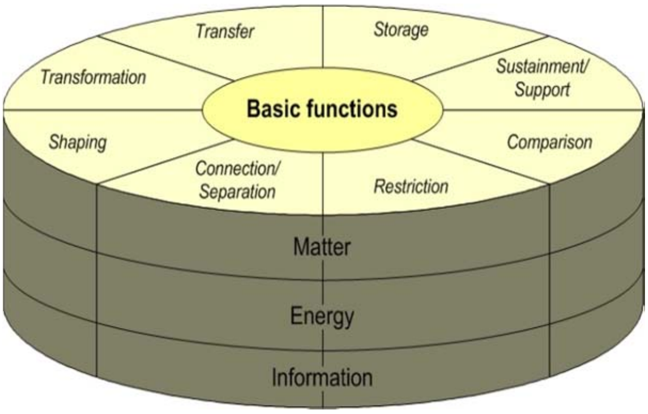


**Fig. 2**: Organisms own the complete set-up of the life-maintaining functions, but not as clear separable modules. Each component in this hierarchy is fulfilling a complex of tasks, but in a gradually manner. The correlation of modules (structure, function) in an organism and a machine requires a high level of abstraction. "*Every component of the organism is as much of an organism as every other part."* (cit. Barbara MCCLINTOCK – Nobel-Prize 1983)

This includes the supplementary principles of the integration resp. differentiation of functions, the configuration of the material with intrinsic functions at the location of performance this function and the ubiquitous dynamic features of structures.

During the developmental process of complex technical systems, evolutionary trends are also of interest. The enkaptic implementation of actuators and sensors illustrate through the current technical developmental stages the tendency of an increasing complexity in biomimetic orientated comparison.

For a bio-inspired design of motion systems, mechatronics is the method of choice. This strategy of modeling corresponds well to the concepts of biomimetics. Modularization should be accepted as a concession of man's difficulties to differentiate the terms "complex" from "complicated" – and to the fact, that animals regenerate by histogenesis, and engineers by assembling of exchangeable modules.

Modern micro system technologies enables through an increasing degree of structural and functional integration, compatible to biological systems, the transfer of these concepts into industrial production [2].

The interpretation of found biological phenomena occurs under using terms and concepts of the technical knowledge. This creative process may be supported by data and knowledge bases, to the systematically abstract the generation of ideas.

Systematic construction and design in Germany have a tradition of more than half a century. The field of bionics (or biomimetics) exists for about the same period. The work approach, however, is rather unsystematic from an engineer's point of view. Ilmenau, as a place with a tradition in both fields from the beginnings of the two methodologies, seems a right place to bring biologists and engineers together in their scientific approaches closer than before. We proposed a structured "Bionic Algorithm". The diagram (Fig. 3) not only illustrates the sequence and order of tasks to be fulfilled, but also states logical interdependencies.

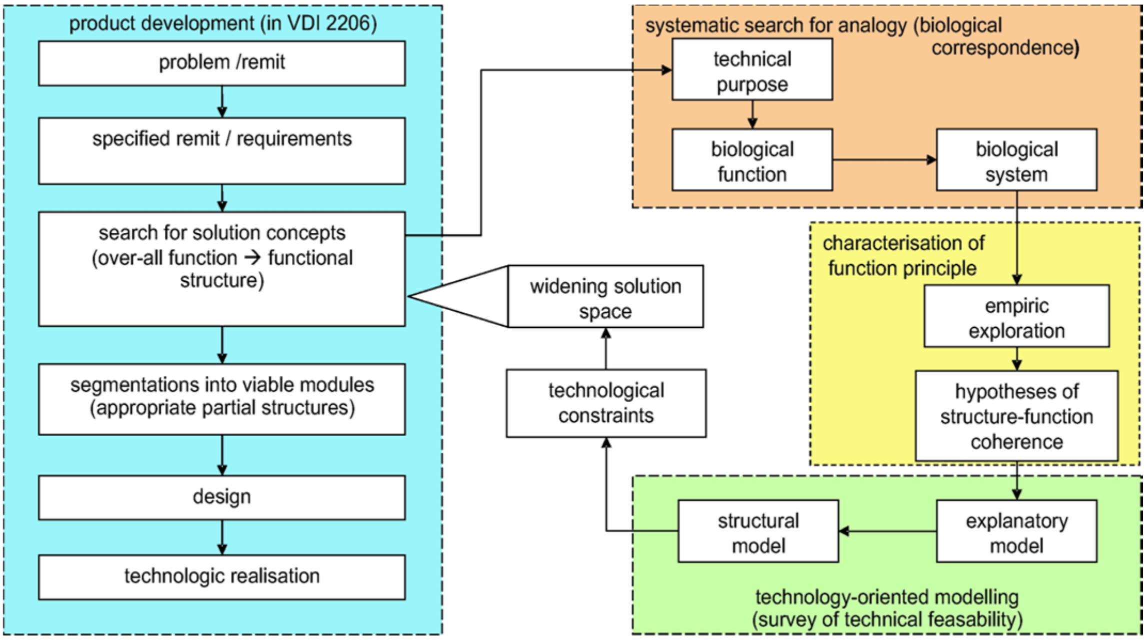


**Fig. 3**: A heuristic trail for the systematic search of structural and functional analogies according to the methods of design in engineers science (see the guidelines to the draft of mechatronics) [3].

**Captions** for Fig. 3**:**
What means “analogy”? – the step of “inspiration”:
make accessible bio-medical knowledge to engineers, to identify biological paragons and functional-structural solutions embodied by them, to synectically propose alternate solutions.

- has to be drawn between a technical demand (goal-directed “task“) and biological functions sustaining the survival of a biological system (in nature “goals” and “tasks” do not exist).
- may be based on different levels of abstractions, from copies of nature (“biomimetics“) to transfer of principles into quite different technical purposes (“bionics” in sensu strictu).

What are „biological paragons“ ?

- complete ecological (supra-organismic) systems.
- Complete organisms(animals, plants, protists… – the “organismic approach”)
- organs and cells (always multifunctional!) and biomolecules
- processes of development
- processes of material, information, energy transfer

The ubiquitary step of modelization is including:

- increasing the level of abstraction by leaving out features which are irrelevant for the technical purpose.
- interpreting biological phenomena using technical terms and symbols

The domain of “Technical biology” results explanatory models:

- experimental test of functional-structural relations hypothesised for the bio-system.

The biomimetic transfer used models for design:

- constructive realisation under the restriction of user demands, based on technological possibilities.

The common aim is the extension of space of solutions:

- to conquer paradigms („always did it this way ...“),
- to create completely new ideas derived from other areas of knowledge, under the motivation of “synectics”, a common term in construction theory,

But here are boundary conditions and need a critical check of transferability, referring to criteria of geometric similarity, availability of other types of materials, and a different “production” processes.

In case of tentative drafts, motion machines that follow organismic construction principles with the purpose of developing ‚smart‘ systems, perhaps even robots, that substitute for the restoration of failing physical functions of humans insert mechatronics into the human body or other living beings. Keeping the organismic construction principles in mind when drafting motion machines with the purpose of developing ‚smart' systems, perhaps even robots, that substitute failing physical functions of the human body with mechatronics for the purpose of restoration, could evolve.

The unique feature, in comparison to these different areas of objects, could be that both of them consist of a mechanical framework to transform a specific type of energy into mechanical work and their directed transfer to an effector location to couple out forces and displacements, controlled by information processing of external and internal states. This corresponds with the paradigm of motion systems according to the concept of a complete mechatronic structure (Fig. 4). Further applicable system-features in this confrontation are the internal structure in the sense of the topology of enclosed elements, the consistency of the system boundary, the fulfillment of a whole function or the ability in the self-preservation and adaptation in a different degree.

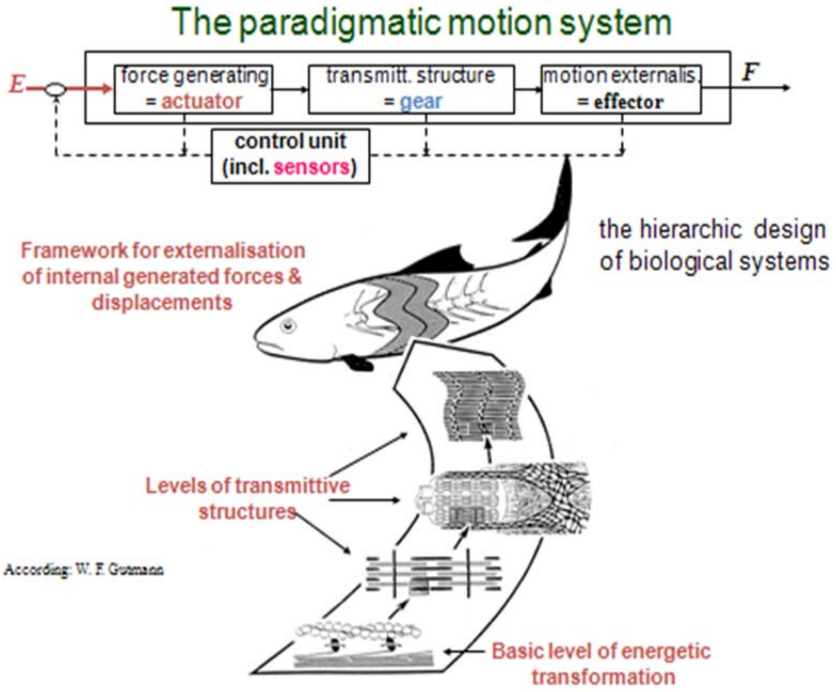
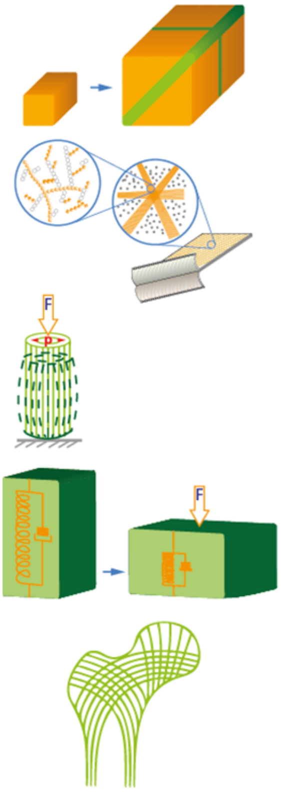


**Fig. 4**: "Meet on a high abstractive level" – the explanation of organismic "construction" [4], containing the iterative structures of force-generation and transmission.

All living beings consist of a common substrate (the proteins) caused by the development of a single cell and exists in substantially coherency. The structural components, the organs, are not distinctly separable, however build-up hierarchically. Also the structures of transmission for mechanical energy are integrated in iterative enkaptic levels, starting at the molecular level of transformation of chemical energy.
The common compliance of their body depends on an adjustable degree of stiffness, differentiated in the locations of fulfilling mechanical functions. The framework of such motion systems esp. animals, shows an adaptable outline (the contour), controlled by internal fluid pressure and muscular traction. The, fuzzy' geometry of the interacting components is compensated by a woven hierarchy of control.

Compliant mechanisms work by flexing all or some of their parts to transfer motion, force, or energy and, therefore, they are considered to be sophisticated flexible materials. In difference to their traditional rigid-body counterparts compliant mechanisms do not contain moving parts which work together in order to carry out a function (Fig. 5). Compliant mechanisms are made from one piece. This makes them ideal candidates for use as miniaturized components in mechatronic devices. The application of textile materials and techniques in compliant mechanisms is the objective of ongoing research [5].



**Theses of the analogies concerning the substrates**

- Biological structures with mechanical functions are organized hierarchically and consist of materials with gradual moduli depending on location and direction of the load-input.
- The compliance is fulfilling the kinematic reaction, depending on internal structures.
- In each level of hierarchy actuatoric and sensory components are included in the matrices of the substrate.
- Induced by the complex 3-dimensional orientation of the fibers, resp. macromolecules in the composite force-guiding paths are guided across the whole body.
- The fulfilling of mechanical function of each part is depending on the external contour as well as the internal texture, with several inhomogeneity´s in geometry, concentration and stereo chemistry.
- Implantable materials are coherently and optimally integrative into human tissue, if mechanical conditions and chemical characteristics of the surfaces are bio-compatible.

**Fig. 5**: Some remarks to the features of biogenic material in comparison to man-made composites (i.g. fabrics) – finding an interdisciplinary language [Graphics: D. VOGES].

In contrast, machines are assembled from pre-casted components (i. g. the modules for actuation, for transmission of energy and information and the process control) with a discrete functionality, made from different materials and having an exactly defined geometry. The accuracy of the parts is a requirement for fulfilling the anticipated main function and the designer has anticipated the use (internal function) of these parts within the entire system.

## 3. THE DOMINANT BIOLOGICAL DRIVE PRINCIPLE

It is the conversion of chemical into mechanical energy on the molecular level. The contraction of a muscle produces a translational movement being conducted and transformed by, e.g. a skeleton. This principle has some significant similarities compared to the design of microsystems [6]**:**

- longitudinal motion is preferred for compliant kinematical structures of monolithic micro-mechanisms,
- the intrinsic flexibility tolerates perturbing forces in the case of blocking actuators are located near to the effectors,
- the motion is similar concerning the complexity, sensitivity, gentle and powerful movement the variation of the muscle stiffness with muscle force.

The arrangement in biological muscles is an extremely hierarchical one (Fig 6). All the numerous force-generating elements are mechanically coupled with the next higher unit. The sub-units of the iterative structure are: macromolecules, sarkomers, fibrils, fibres, bundles of fibres, and individual muscles. The result of this connection and the simultaneous series-parallel attachment of the elements is the multiplication of the power parameters. The total force and displacement reach macroscopic values.

The fibres of the skeletal muscles of vertebrates in the first approach are binary functioning elements with different mechanical characteristics. On demand the working muscle switches fibre groups on and off, as the several fibre groups have to relax during the overall stimulation. The total muscle is a movement generator, if the fibres with large displacement ranges are predominantly energised. The result of an excitation of the force generating kind of fibres is the function of the muscle with a dynamic effect on the complete system. In contrast to the muscle, technical actuators are capable of resetting itself automatically, without antagonists shows the comparison of biological and technical structures for force generation in the main levels of hierarchy with specific properties depending on the dimension. In general, a muscle is put on one level with a homogeneous drive module, whereas this approach, however, includes the interlaced hierarchy of force-generating elements that are linked in a mechanically 3-dimensional and cybernetic variable mode.

The technomorphic structure of a muscle shows the model consisting of damping and spring elements with adjustable characteristics, the contractile element which generates the mechanical power, and the inertial mass of muscle. It shows that the muscular drive is capable of generating velocity as well as force at low velocity and low antagonistic force, respectively.

The constituents of the muscular drive carrying out several tasks, a differentiation of the single elements and their assignment to the constituents is hardly possible. These models are often confined to an exact imitation of the transient response, with the real drive being considered as a black box. The artificial machine to be developed is expected to supply a transient response comparable with muscular drives rather than to imitate the identical structure of the muscle.

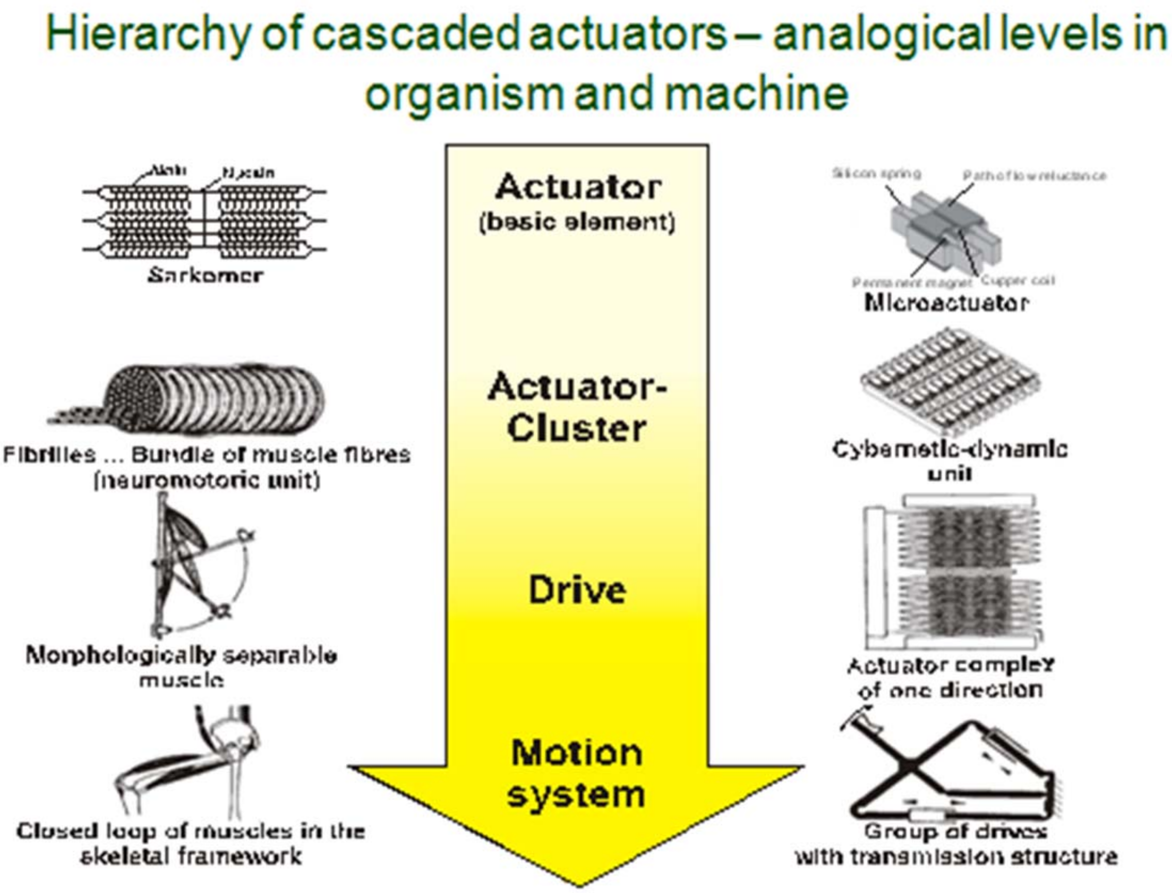


**Fig. 6**: An example for the transformation of the principle of musculature onto an array of micro-drives.

### 3.1 Advantages to be expected by cascaded micro-drives

The simulation of the transient response results in a source of force and velocity as well. As a result, there is the powerful delicateness of muscular drives creating the lithe and fluent motions typical for organisms. Other advantages and qualitatively new properties of the overall system may result from the interaction of a plurality of simply operating micro-drives with variable rules of combination which cannot be derived from the sum of properties of the single drives.

The technical interesting properties can be as follows:

- jerk- and thrust-less execution of sophisticated movements,
- execution of movements with a higher degree of freedom with tuneable stiffness of joints by the contraction of a pair of drives in an antagonistic arrangement,
- optimal generation of force and velocity in a duplicate drive design via independent adjustability of output parameters,
- the probability of malfunctions of the system in case of failures of single elements is reduced by the reliable redundancy of power by means of concatenation of all elements,
- creation of a “mechanically active space“ by means of 3-dimensional cascading of co-operating multi-axial translational actuators with differentiated wiring,
- active damping and retardation of movements and, if required, reduction of the degree of freedom of joints [6].

### 3.2 The electro-mechano-active polymers as bio-mimetic actuators

Electroactive polymers [EAP´s] have emerged in recent years with great potential to enable unique mechanisms that can emulate biological systems. Much more research and development work still needs to be done before EAP`s become the actuators of the first choice. The development of an effective infrastructure for this field is critical to the commercial availability of robust actuation materials for practical applications. The recent emergence of EAP materials with large displacement response changed the paradigm of these materials and their potential capability. The most important characteristic of EAP`s is their operational similarity to natural muscles. Biologically inspired robots can be made highly manoeuvrable, noiseless and agile, with various including insect-like shapes. Unique robotic components and miniaturised devices are being explored, where EAP serve as actuator to enable new capabilities.

## 4. SOLUTIONS OF SENSING PROBLEMS TO BE EXPECTED IN THE NON-NERVOUS STRUCTURES

Micro sensors for mechanical parameters need supporting structures in their periphery for serving contact and tolerance to the complex physical environment. The robustness of sensor housing is an essential condition for interaction with unexpected loads. While the signal transducing and signal processing in adaptive machines (e.g. Robots) are highly sophisticated, the sensor periphery (stimulus leading apparatus) in animals holds a pool of inspirations for the instrumentation of robots.

Relevant characteristics of biological sensors:

- they are very small and have a high degree of functional integration (“multi-channel”)
- they are outstandingly sensitive and selective
- they commonly have a number of sensory elements induce functional security (redundancy)
- they are highly adaptive = the range of dynamics is tunable (off-set)
- mostly fast and enabling efficient analysis & processing
- and finally, caused by an active sensor-periphery, they are able to permanent re-calibration
- and includes a mechanical coupling between signal transducing structure and the environment.

What is common to all sensing organs is the signal processing? Each receptor cell transforms the specific stimulus energy, e.g. chemical or mechanical energy, into an electrical-chemical membrane potential. Through this action potential the signal is coded by frequency modulation. Therefore the highest diversity among biological sensors can be found in their non-nervous structures. That‘s why we focus on the “stimulus conducting apparatus” (Fig. 7). This concept includes all structures which take part in transmission of the signal bearing energy to the receptor cells [7].

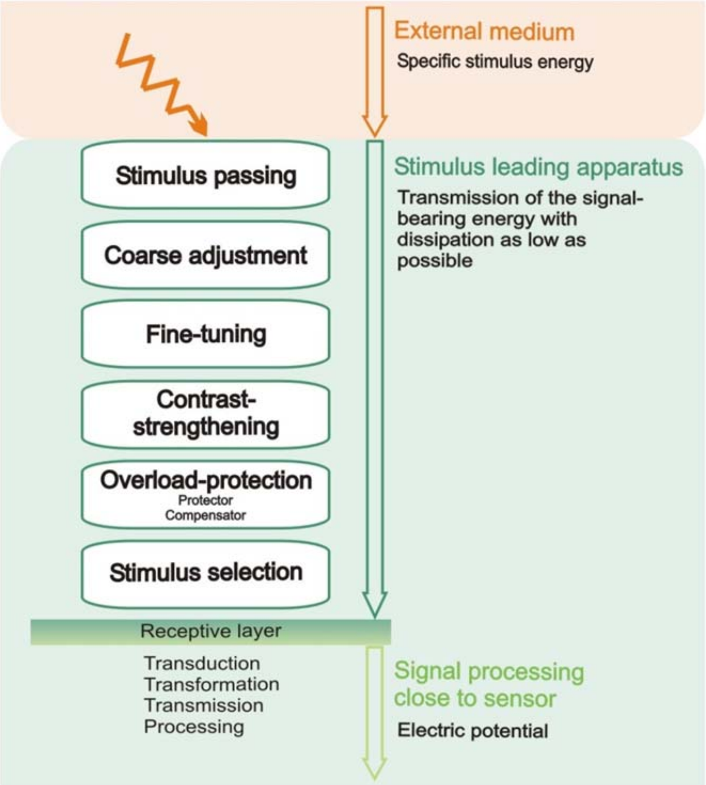


**Fig. 7**: Sensor-strategies in the living nature – the highest diversity among biological sensors can be found in their auxiliary non-nervous structures.

In the different sensing organs of animals a lot of varying structures are involved in this transmission process. But we identified six discrete functions which are fundamental for contact to the environment and protection of the system. The morphological correlates for these functions take part in transmitting the relevant stimulus information to the receptor cells with a low dissipation and they prepare an optimal signal processing. Independently from the specific sensor task we define different principles concerning the design and arrangement of sensor complexes. Especially in adaptive machines and autonomous robots these principles are useful in interaction with the environment. Therefore they should be involved in the mechatronical draft.

## 5. FINAL REMARKS

The development of bio-systems has no anticipated aim, but evolves by spontaneous self-organisation. The dynamically stabilized structure is in permanent rebuilding at the molecular level. Such features allow the processes of maintenance, reconstruction and self-repair. Nevertheless, this causes a high degree of adaptability, while technical structures exist in a static equilibrium and decay, attrition and corrosion are irreversible. The final function of living systems is the self-maintainability of the body-structures in a permanent exchange with their environment and the quasi-identical transfer of the “construction draft” (the genome). In contrast, the aim of man-made objects, like machines are the doings of physical work for an external purpose, defined by the engineers. The cooperation with the possibilities of the intervention in bio-systems, like the genom-technology and the nano-technology, will have far-reaching consequences, almost as the use of the nuclear research in the last decades.

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