8 Mechanical Connections, Mechatronics and Adaptronics

In this chapter three classes of generic solution are presented in a systematic way. Because of their overriding importance in mechanical design, mechanical connections are the first class to be discussed. The other two classes are mechatronic and adaptronic systems. These allow the realisation of new functions and improved performance using novel approaches through the integration of mechanical, electronic and software elements, and are thus changing the traditional field of mechanical engineering. Even though these developments may seem utopian or too expensive in some of the more traditional areas, their increased application will make them cheaper and more common. Automotive technology has already embraced Mechatronics and Adaptronics and their solutions will be transferred to other areas of mechanical engineering, or at least influence them.

It is only possible for mechanical designers to adopt these new types of solutions and exploit their potential if they work in interdisciplinary teams (see Section 4.3). Such teamwork can only be fruitful when all members of the team are fully knowledgeable in their own fields while at the same time possessing a shared knowledge with the other members in order to understand each other and work together effectively and efficiently [8.22].

8.1 Mechanical Connections

Assemblies and components, whether mechanical or electrical, are connected to each other in order to fulfil particular functions. The type of connection determines its basic behaviour and its application the success of a solution. Connections can be divided into those that result in a *fixed arrangement* of the components relative to one another and those that result in a *moveable arrangement*.

Connections with moveable arrangements are joints with different degrees of freedom. This could, for example, be pin joints with one rotational degree of freedom, translating joints on a square profile with only one translational degree of freedom, and ball joints with three rotational degrees of freedom [8.6]. Roth developed a matrix in which, for every possible joint, the free and restricted movements are shown in order to support a search for possible solutions [8.25].

The following sections describe the functions, working principles and some embodiments of the different types of connection for fixed arrangements.

8.1.1 Generic Functions and General Behaviour

Functions (Figure 8.1)
Connections serve to transfer forces, moments and movements between components having a clearly defined fixed arrangement. They might fulfil the following additional functions:

- taking up relative movements that are not in the loading direction
- sealing against fluids
- insulating or transmitting thermal and electrical energy.

General Behaviour
The working surface pairs at the interface are subjected to loading during the assembly process, which can produce preloading and residual stresses, or loading during operation.

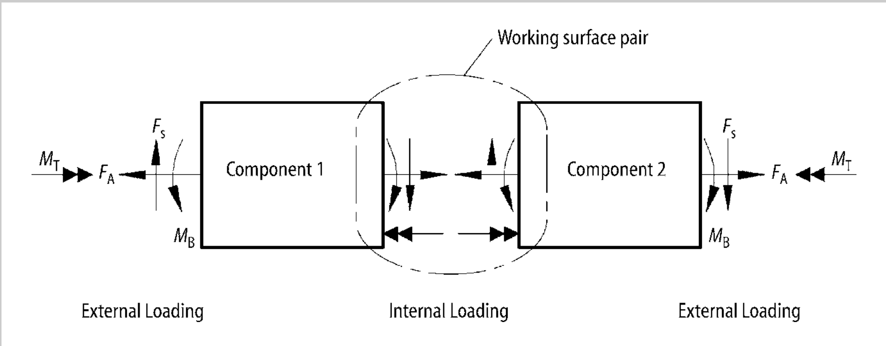

Figure 8.1. External loading and internal loading of the working surfaces of two components. F_A axial load; F_S shear load; M_B bending moment; M_T torsional moment

8.1.2 Material Connections

Working Principle (Figure 8.2)
A material connection is the result of joining components, either directly or by using additional material, utilising molecular and adhesive forces over the working surface area. These connections transmit axial and shear forces as well as bending and torsional moments.

Structural Characteristics

- form, position, size and number of mating surfaces
- stresses in the connection after production (residual stresses) and in operation
- component materials and additional materials involved
- production and operational temperatures.

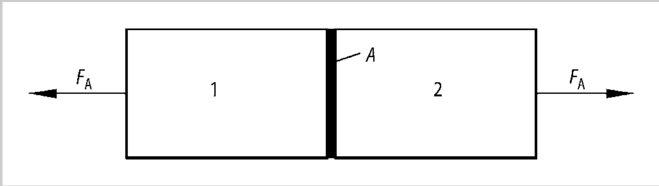

Figure 8.2. Material connection between two components subject to uniaxial loading. A working surface area, F_A axial force

Main Properties

- precise position maintained
- cannot be disconnected
- can break or deform if overloaded.

Embodiments (Figure 8.3)

- welded connections [8.5, 8.7, 8.21, 8.26, 8.27]
- soldered connections [8.6, 8.7, 8.35]
- adhesive connections [8.7, 8.15].

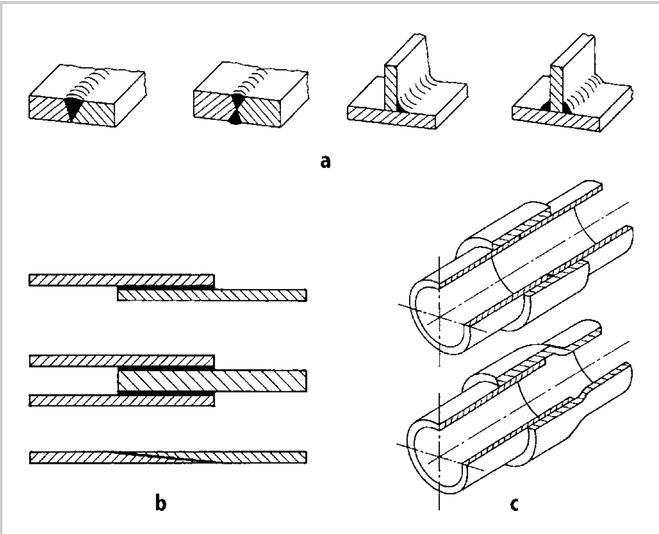

Figure 8.3. Types of material connection (selection). **a** welded connections, **b** adhesive connections, **c** soldered connections

8.1.3 Form Connections

Working Principle (Figure 8.4)
A form connection is realised by normal forces between the working surfaces of the components, which produce a surface pressure p and result in stresses at

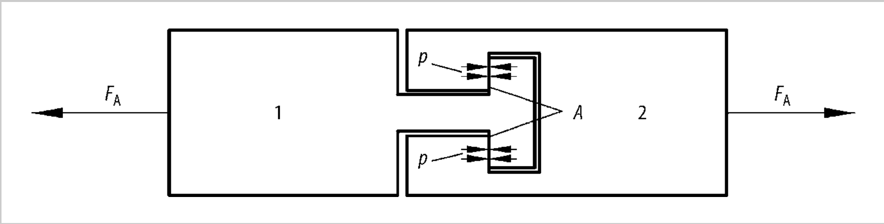

Figure 8.4. Form connection between two components subject to uniaxial loading. *A* loaded working surface area, F_A axial loading, *p* surface pressure

the mating surfaces according to Hooke's law. The pairs of working surfaces that are under pressure also fulfil additional functions such as sealing, insulating and transmitting.

Structural Characteristics

- form, position, size and number of mating surfaces (including form connection elements)
- forceflow in the connection zone
- load distribution (pressure distribution) on the form connection elements
- load distribution variations caused by material combinations involving different Young's moduli
- stiffnesses of components and form connection elements
- stresses and stress concentrations in the connection zone surrounding the working surfaces
- preloading possibilities
- arrangement of tolerances to avoid double fits
- assembly and disassembly possibilities
- loosening potential during operation and preventative measures.

Main Properties

- precise position maintained
- can be disconnected
- can break or deform if overloaded.

Embodiments (Figure 8.5)

- wedged, bolted, pinned and riveted connections [8.7]
- shaft-hub connections [8.20]
- locating elements [8.7]
- snapping, clamping and drawing connections [8.7].

The riveted connection shown in Figure 8.5a is not a pure form connection. The riveting process also causes a friction force connection between the riveted com-

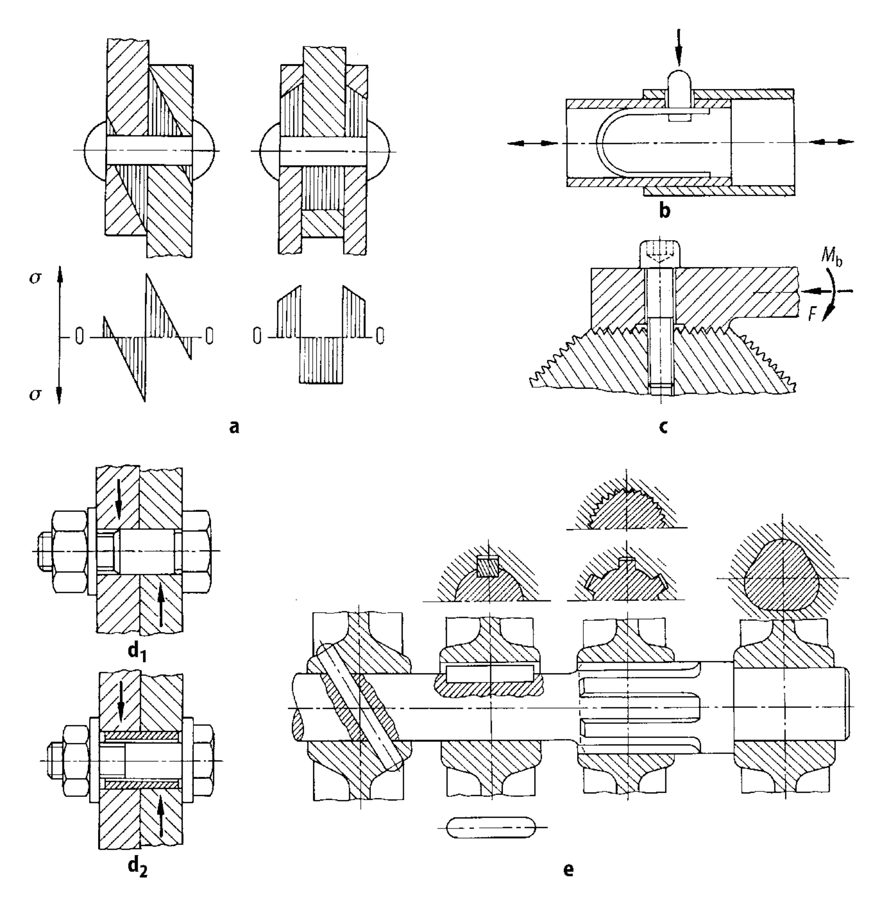

Figure 8.5. Types of form connection (selection). **a** riveted connections (disconnection difficult), **b** snap connection, **c** preloaded spline connection, $\mathbf{d}_1$ shear-loaded bolted connection with fitted bolt, $\mathbf{d}_2$ with shear sleeve, **e** shaft-hub form connections

ponents. How much of the transmitted force is taken up by the form connection and how much by friction cannot be determined because of the lack of clarity of the final forceflow distribution. Nevertheless, riveted connections are frequently used in structures because they do not loosen. They are also used in composite constructions of metal and plastics to avoid peeling when adhesive connections are subject to bending.

8.1.4 Force Connections

General Behaviour

A force connection is realised by forces between the working surfaces of the components. Force connections can be classified by the origin of the forces, i.e. physical effects involved.

1. Friction Force Connections

Working Principle (Figure 8.6)
A friction force connection is realised by friction forces F_F acting on the working surfaces. These are produced in response to normal forces F_N utilising Coulomb's law of friction $F_F = \mu_S \cdot F_N$. Only forces smaller than the friction force, i.e. $F \leq F_F$, can be transmitted.

Structural Characteristics

- static coefficient of friction (the main parameter that depends on the material combination)
- normal forces
- surface pressures on the working surfaces
- number of working surface pairs and distribution of the normal forces
- stiffnesses of the components and preloading elements
- relative deformations of the components during assembly and operation (friction corrosion zones, see Section 7.4.1)
- assembly and disassembly possibilities
- loosening potential during operation and preventative measures.

Main Properties

- precise position retained as long as $F_A \leq F_F = \mu_S \cdot F_N$
- can be disconnected
- relative movement (slipping) when overloaded, i.e. $F_A \geq F_F = \mu_S \cdot F_N$. Danger of fretting due to large surface pressures and of overheating in the case of continuous slipping.

Embodiments (Figure 8.7)

- shaft-hub interference connections with or without elastic inserts [8.20].
- bolted connections [8.33, 8.34]

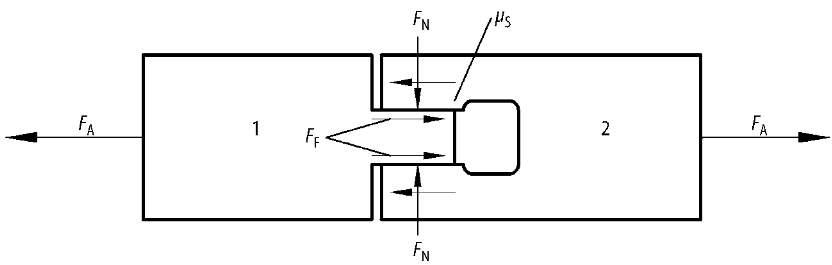

Figure 8.6. Friction force connection between two components subject to uniaxial loading. F_A axial force, F_F friction force, F_N normal force, μ_S static coefficient of friction

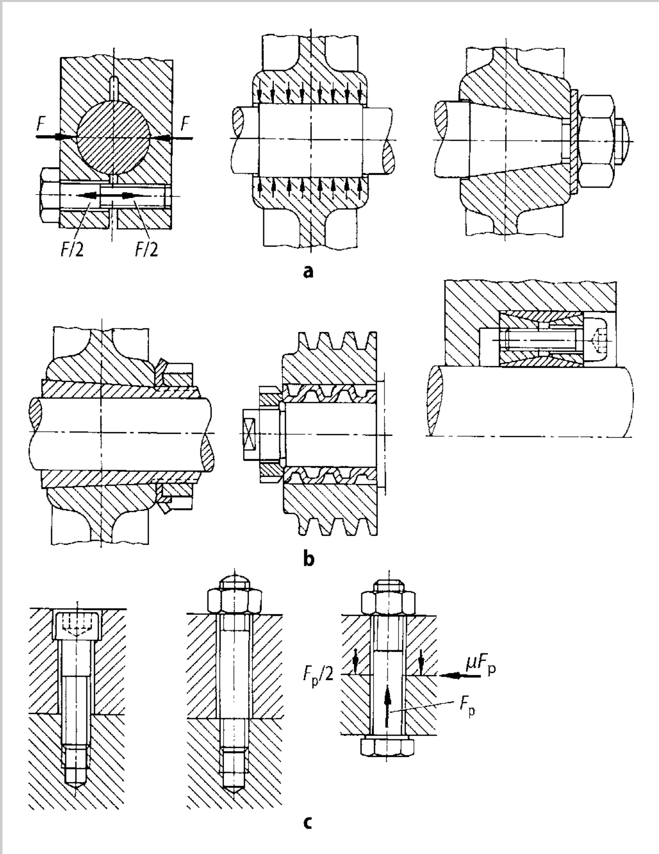

Figure 8.7. Types of friction force connection (selection). **a** shaft-hub interference connections without elastic inserts, **b** shaft-hub interference connections with elastic inserts, **c** preloaded bolted connections

2. Force Field Connections

Working Principle

A force field connection is realised by utilising force fields such magnetic force fields, hydrostatic or aerostatic pressure force fields and viscous force fields.

Structural Characteristics

- force field required
- external energy source or viscous medium
- sealing and shielding.

Main Properties

- force-displacement relationship (often stiff behaviour)
- can be disconnected

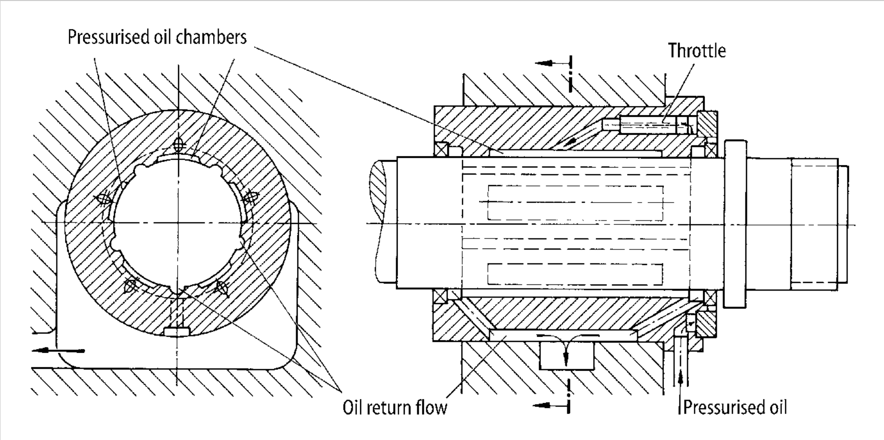

Figure 8.8. Example of a hydrostatic bearing

- in the case of overloading movement occurs until a stop is reached (usually resulting in a form connection with loss of original functionality).

Embodiments

- hydrostatic or aerostatic bearings, see Figure 8.8
- hydrostatic couplings
- magnetic bearing and closures, see Figure 8.9.

3. Elastic Force Connections

Working Principle

An elastic force connection is realised by the forces generated using elastic elements that act as energy stores when they deform. The forces of the inserted elastic elements determine the position and dynamic behaviour of the components to be connected.

Structural Characteristics

- elastic elements
- embodiment of the elastic elements within their elastic limits
- hysteresis characteristics of elastic elements, e.g. metallic springs have very low internal losses whereas rubber springs have higher losses
- durability
- possibility of introducing damping elements.

Main Properties

- force-displacement relationship
- energy storage capability through deformation work

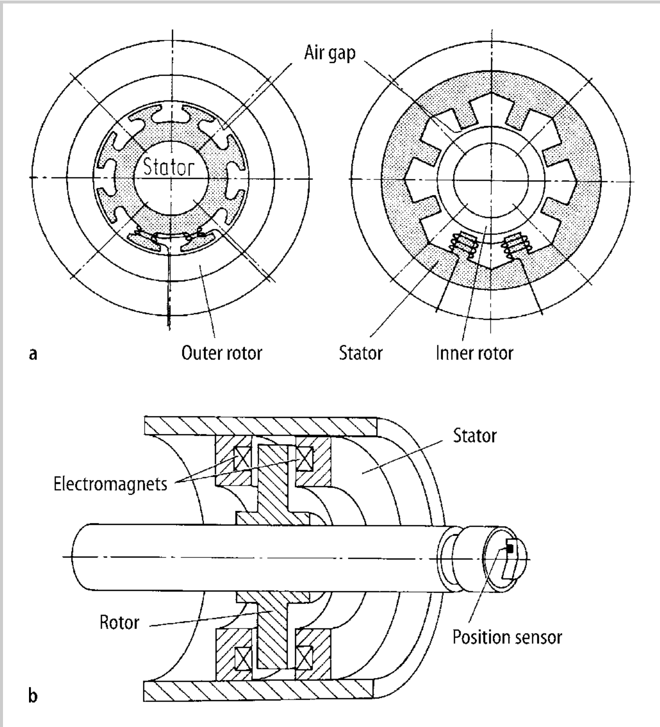

Figure 8.9. Types of magnetic bearing [8.1]. **a** radial bearing, **b** axial bearing

- sensitivity to vibrations, but with damping possibilities
- can be disconnected
- in the case of overloading movement occurs until a stop is reached (usually resulting in a form connection or compacting, such as coil binding in compression springs (see Figure 7.58), with resulting loss of elastic properties).

Embodiments

- flexible spring elements in couplings and bearings, see Figure 7.144
- elastic supports, see Figure 7.27
- elastic inserts for damping impacts [8.10, 8.12, 8.13].

8.1.5 Applications

Material connections are preferably used to:

- take up multiaxial as well as dynamic loads
- maintain relative position
- realise an economic fixed arrangement of components of the same material group

- allow easy repair through welding, soldering and gluing
- seal connected areas
- allow the use of standardised components and semi-finished materials.

Form connections are preferably used to:

- allow frequent and easy disassembly
- permit unambiguous positioning of components
- take up relatively large forces
- connect components from different material groups.

Friction force connections are preferably used to:

- allow easy and economic connection, including parts from different material groups
- permit slip when subjected to excessive loading
- set relative position of connected components
- allow components to be easily disconnected.

Force field connections are preferably used to:

- realise a connection without physical contact between components
- reduce friction losses
- control precise positioning in space
- influence dynamic behaviour.

Elastic force connections are preferably used to:

- store energy
- take up impact loads
- influence dynamic behaviour, along with damping elements where appropriate
- balance out relative movements
- balance out tolerance and dimensional differences.

8.2 Mechatronics

8.2.1 General Architecture and Terminology

The term mechatronics is made up from mechanics and electronics. By including information technology, mechatronics integrates these three fields to provide opportunities for novel solutions for products, and for their production and assembly processes, see Figure 8.10 and [8.19]. Compared to conventional systems, mechatronics permits functionality to be extended, and allows certain functions to be realised for the first time.

Mechatronic solutions are basically structured as shown in Figure 8.11. The *basic system* can be mechanical, electro-mechanical, hydraulic or pneumatic, with energy, material and signal flows. The overall function aims to fulfil a complex task. Sensors capture specific characteristic status data of the basic system. These data are then transferred to a computer system for processing, and, based on the results, actuators are instructed to perform in a pre-specified ways on the basic system. Energy has to be supplied to the computer, sensors and actuators. Humans can intervene, if necessary, to override the system.

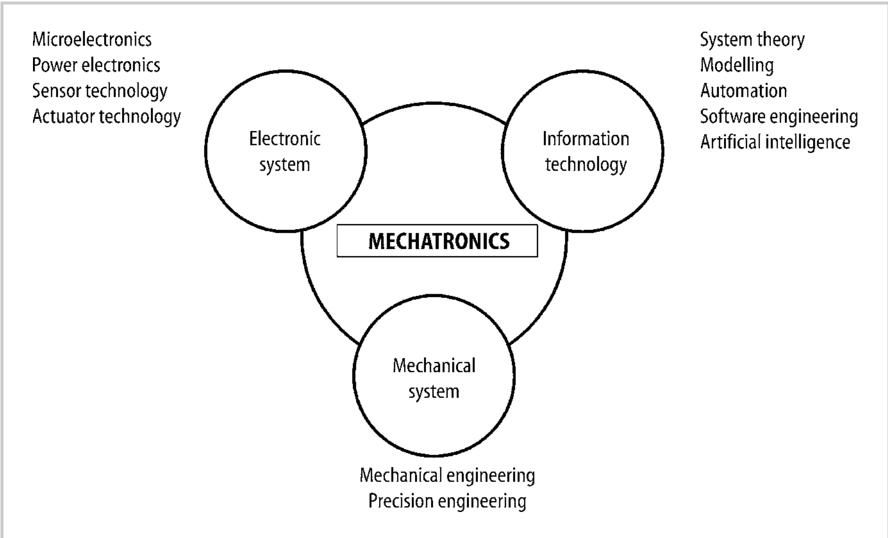

Figure 8.10. Mechatronics. Integration of the fields of mechanical engineering, electronics and information technology, after [8.19]

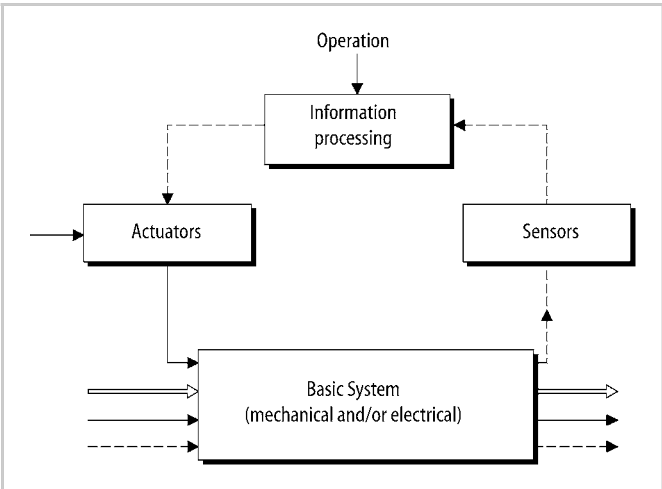

Figure 8.11. Basis structure of a mechatronic system, after [8.19]

The possibility now exists to physically integrate sensors, actuators and the data processing into the basic system, i.e. to create self-contained subsystems that require little space and are positioned at their working locations. Even when these components are only partially integrated, the term mechatronic solution is used. Increasing miniaturisation opens the way to microsystem technology and further utilisation opportunities. A draft VDI Guideline 2206 [8.32] has been published about mechatronics and its development methods.

8.2.2 Goals and Limitations

The goals of mechatronic development are to:

- realise new functions
- improve the behaviour of systems through monitoring and control without external intervention
- extend application boundaries
- realise automatic system monitoring and fault diagnosis
- achieve physical integration within a small space
- develop mechatronic subsystems as building blocks or assemblies that can be independently tested and added to existing systems
- improve operational safety.

The limitations of mechatronic solutions include:

- damage to the electronic components in the case of high surrounding temperatures or when subjected to mechanical loads, e.g. vibrations – in such cases these components cannot be integrated
- repairs are often impossible or uneconomic, requiring the replacement either of the whole mechatronic system or a major part of it
- the cost/benefit ratio is not always in line with current market economics because certain sensors, actuators or the whole system are still too expensive.

8.2.3 Development of Mechatronic Solutions

The development of mechatronic systems requires a holistic and interdisciplinary approach. It is not possible to differentiate clearly the domains and disciplines involved, nor is this desirable because the boundaries are fluid. Team members should be drawn from mechanical engineering, electronics, control, software and the relevant production disciplines. See Section 4.3 for guidance on setting up and running such teams.

The complexity and interdisciplinary nature of the process requires a systematic approach, such as the one described in this book. However, it must be applied with greater flexibility and consideration of the knowledge and terminology of the various disciplines involved.

First of all a requirements list has to be prepared (see Section 5.2) from which the necessary functions and a preliminary function structure can be derived (see Section 6.3). The starting point is the basic architecture shown in Figure 8.11. The discussion and abstract description of the subfunctions that have to be fulfilled is particularly useful in an interdisciplinary team. This helps to identify, elaborate and communicate the intentions, goals and objectives, as well as possible initial solutions. Function structures, even if they are incomplete, support the clear definition of the interfaces in the overall system. This permits the definition of independent subtasks and their allocation to the individual disciplines involved.

All the participating experts can then take responsibility for their tasks and undertake a systematic search for solutions (see Sections 4.2 and 6.4). Because of the different disciplines, the size and duration of their tasks will differ, requiring continuous coordination and adjustment of the schedule by the project manager. The solution will progress from a rough structure to a detailed embodiment through many iterative steps, similar to, but more flexible, than the methodology presented in Section 7.1. Isermann [8.19] describes the detailed steps of a mechatronic development process. Recommendations on sensors and actuators can be found in [8.19, 8.31].

An effective development process comprises an early assessment of the partial solutions using the selection and evaluation procedures discussed in Section 3.3. Every solution variant of the basic system affects the development of the sensors, actuators and the software and vice versa.

8.2.4 Examples

Early examples of mechatronic systems can be found in precision engineering and include automatic cameras and electronic office equipment. Pioneering mechatronic applications in the area of mechanical engineering can be found in the automotive industry. Antilocking braking systems (ABS), for example, are mechatronic systems that measure wheel speeds and control the braking forces to prevent the wheels locking. Such control minimises the braking distance whatever the road conditions. A further development of ABS is electronic brake distribution (EBD) to avoid the car spinning if skidding does occur by controlling the individual brakes to maintain the dynamics within preset limits. Automatic gearboxes are also controlled more and more through integrated electronic elements.

The following examples, some of which are still under development, show the possibilities that could be realised when demand exists and economic conditions are favourable.

Example 1: Friction Coupling

In a large research project on integrated mechanical and electronic systems, a standard clutch was fitted with piezo actuators. When the clutch is engaged, the actuators reduce the clutch force from its maximum value by following a specific characteristic line so that the clutching process is completed in about 0.4 s. The aim is for the clutch to follow a characteristic that at the start of engagement provides a higher coupling moment than at the end, rather than the conventional constant moment (see Figure 8.12). Following this characteristic, the maximum temperature in the friction pads, which is exponentially responsible for wear, can be reduced by up to 30%, depending on the Fourier number, see Table 9.2. Figure 8.13 shows the rotational speed, the coupling moment, the temperature and the power losses of a clutching process for a Fourier number = 1. The reduction of the maximum friction temperature is largest when the Fourier number is small, i.e. the clutch wall thickness into which the heat flows is large.

Temperature sensors in the clutch wall measure the temperature and select an appropriate clutch characteristic using, in this case, an external computer to control the piezo actuators. In addition, the rising characteristic of the clutch moment can be controlled such that the time to rise is at least as long as the period of the lowest torsional natural frequency of the systems that are coupled. This results in minimum shaft torsional vibration during the clutching process [8.14].

Example 2: Self-Reinforcing Automobile Brake

In Section 7.4.3 a type of self-reinforcing brake is discussed, which, however, can lock up. A self-weakening configuration would be preferred, provided that appropriate brake force reinforcement can be supplied. Using mechatronics brakes can

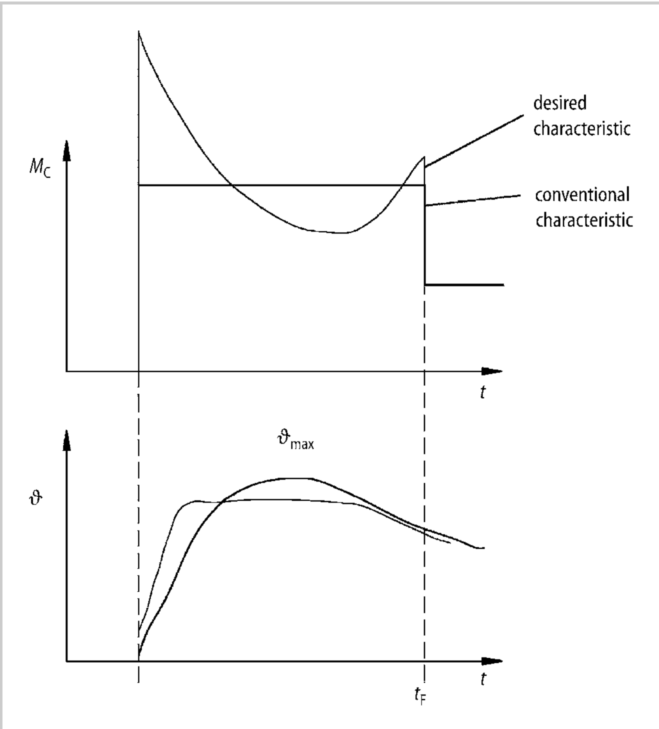

Figure 8.12. Principle correlation between coupling moment M_C, friction temperature ϑ_{max} and synchronisation point t_S, after [8.14]

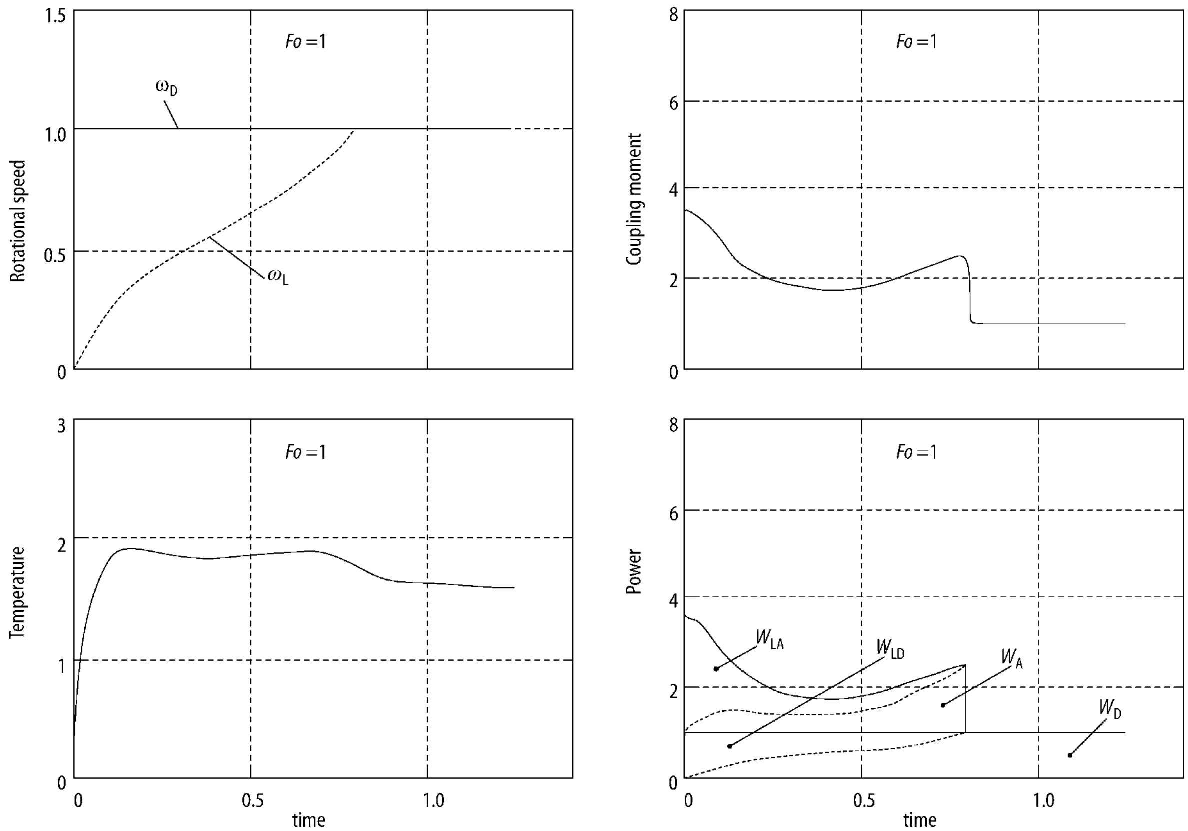

Figure 8.13. Characteristics of rotational speed, coupling moment, friction temperature and power against time for a Fourier number $Fo = 1$ (normalised values), after [8.14]

be realised that automatically provide brake force reinforcement (self-reinforcing brakes) thus saving activation energy.

New automobile concepts are tending to abandon central hydraulic systems in favour of electrical systems. This affects the braking system of an automobile. Given the overall energy availability, these systems should be as efficient as possible.

In the research project mentioned in Example 1, Breuer and Semsch [8.11] developed a self-reinforcing disc brake. This brake provides a controlled constant force and avoids self-locking [8.3, 8.28, 8.29]. Figure 8.14 shows the basic principle of the brake wedge on the brake disc. The brake force in this system would, after the activation force is applied, increase progressively until the brake locks, depending on the coefficient of friction of the brake pad. The introduction of a mechatronic solution, however, prevents the brake locking. Figure 8.15 shows the basic configuration of the new disc brake. The activation force is introduced by an electric motor with a gearbox via a lead screw. The wedge angle has been chosen such that self-loosening is always possible while at the same time providing a substantial reinforcement of the braking force.

The braking force is measured by a sensor. It would be possible to measure the normal force acting on the brake pad, but this has the disadvantage that it does not include the coefficient of friction of the pad. It would be better to measure the braking moment on the brake disc. The best solution is to measure the delay behaviour, because this also includes the coefficient of friction of the tyre. This is possible because of promising developments in tyre sensors that indicate coefficients of friction between tyre and road [8.3]. Where the sensor will be placed or whether the braking force can be measured indirectly using other available data depends on the specific electronic concepts of the automobile, e.g. making use of the ABS system. A computer controls the activation force based on the measured braking force and brake behaviour in such a way that in every wheel the required self-reinforcing braking force can be realised with relatively little energy.

The energy requirements remain within limits thanks to self-reinforcement; the brake can be ventilated at any time; and changing clearances caused by wear and thermal influences can be balanced out automatically. A version of this brake was constructed and tested in an automobile under real conditions.

Example 3: Chassis Support

In automobiles, wheels are mounted using a spring-damper system. In general, the spring and damper properties cannot be altered and are preset based on the typical operation of the automobile. The loading, the road conditions and driving behaviour influence the required spring-damper behaviour. To achieve a comfortable ride in every situation, mechatronic solutions can be used that automatically adapt the spring stiffness and damping characteristic, as well the chassis level for road clearance and roll control. To achieve this, a piston subjected to oil pressure is located in the spring leg. This is connected via a membrane with controllable air pressure that can alter the spring stiffness and length. The damper subsystem is fitted with bypasses whose cross-sections are controlled by magnetic valves to increase or decrease the damping. Sensors continuously measure the behaviour

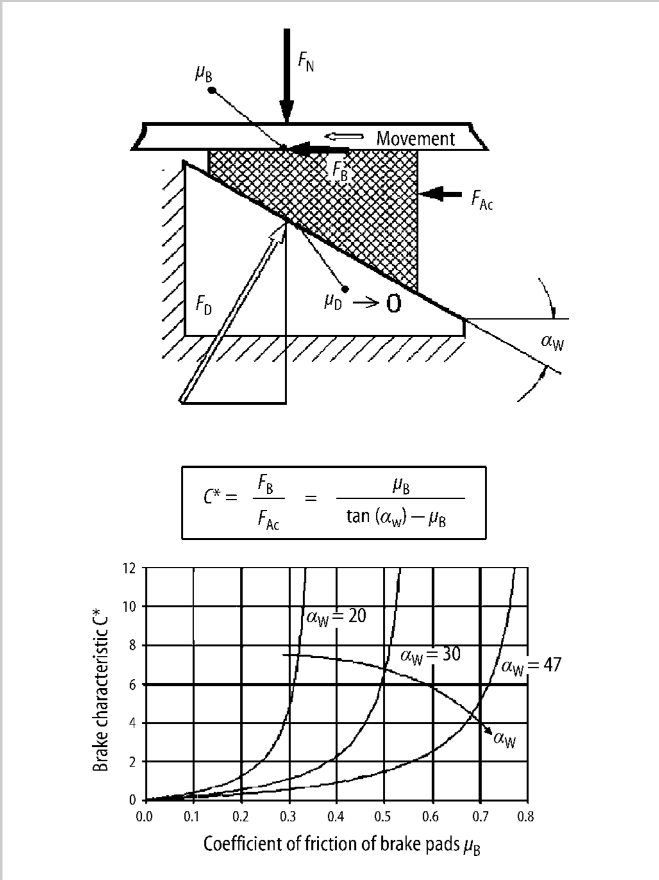

Figure 8.14. Self-reinforcing wedge on a disc brake; brake characteristic C^* = braking force F_B/activation force F_{Ac}, after [8.28, 8.29]

of the vehicle while being driven and while stationary. A processor regulates and controls the optimum spring stiffness and damping for every driving condition and adjusts the level of the chassis in accordance with the loading. The processor is connected to a diagnostic system that not only identifies the driving conditions but also faults in the measurement and regulation system itself. In the case of disturbances, the system settings go back to normal and the driver is informed [8.4].

Example 4: Self-Regulating Magnetic Bearing

Figure 8.9 shows radial and axial bearings as examples of magnetic force field connections. Magnetic bearings with active field magnets can be used as actuators as well as sensors. In combination with a digital control system, the stationary bearing position and dynamic behaviour of the shaft can be influenced. This allows new functions to be realised as demonstrated by Nordmann [8.30].

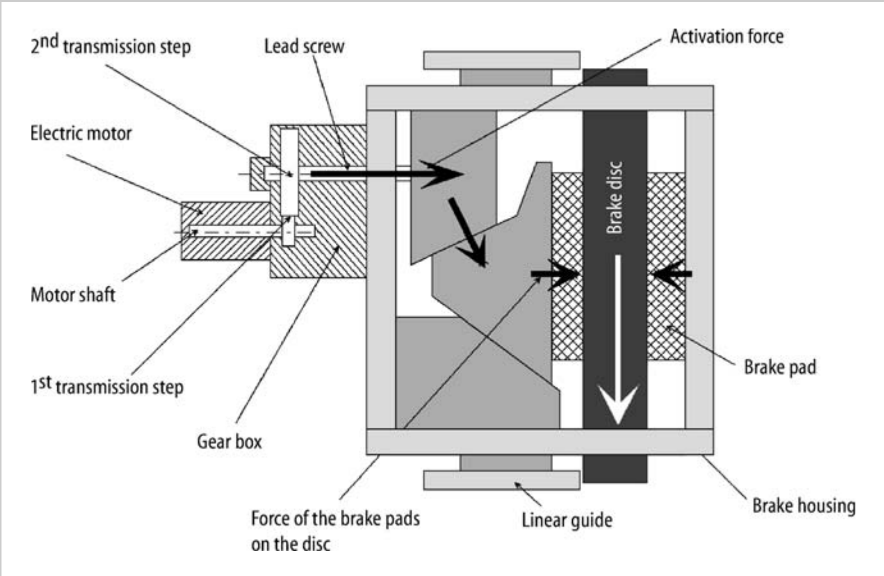

Figure 8.15. Basic configuration of the self-reinforcing disc brake, after [8.28, 8.29]

We will use a grinding drive unit for the precision grinding of small holes [8.30] as an example. Figure 8.16 shows the configuration of this unit. The grinding shaft, which is overhung from the bearings, rotates at over 100 000 rev/min. The workpiece to be ground can rotate at up to 3 600 rev/min. The grinding shaft is supported by two electromagnetic radial bearings. The axial force is taken up by an electromagnetic axial bearing. By using electromagnetic regulation it is possible to improve the grinding process by oscillating the grinding cylinder axially by a few micrometres. The normal grinding force deforms, in particular, the overhanging section of the shaft. This deformation gives the inner grinding surfaces a more or less conical shape. This phenomenon can be controlled by automatically angling the axis of the grinding shaft depending on the magnitude of the normal force. Errors in the true running of the workpiece can be corrected by a high frequency bearing control of the shaft. These measures provide for high precision and a correctly ground cylindrical surface.

Disturbances caused by unbalanced forces and abnormal grinding forces from the wear or breakage of the grinding tool produce reactions in the magnetic fields of the bearings. These can be measured and compared with a digital model in the system and immediately corrected, at least to a certain extent. If specific limiting values are exceeded, then the grinding operation is terminated.

Monitored magnetic bearings coupled with mechatronics make possible the diagnosis of failures in the rotor systems of turbines, compressors etc. Figure 8.17 shows how to build an overall model for a failure diagnosis system according to [8.2]. The rotor system is modelled in such a way that its dynamic properties are captured. Displacement sensors, e.g. on the bearings, measure the instantaneous rotor behaviour, which can change due to disturbances in the fluidic system, in the

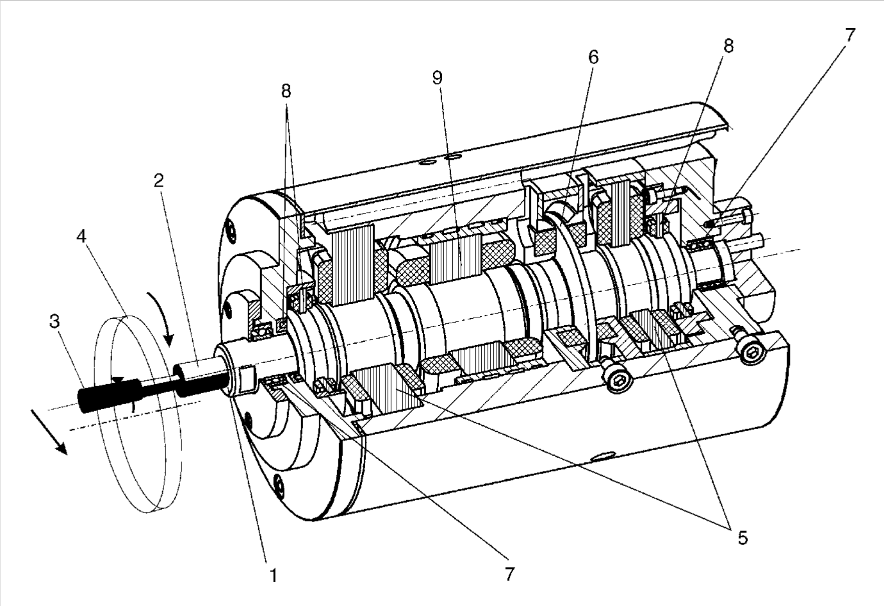

Figure 8.16. Grinding drive unit with electromagnetic radial and axial bearings. *1* grinding shaft, *2* tool, *3* grinding cylinder, *4* tools, *5* radial magnetic bearing, *6* axial magnetic bearing, *7* auxiliary bearing, *8* displacement sensors, *9* drive motor

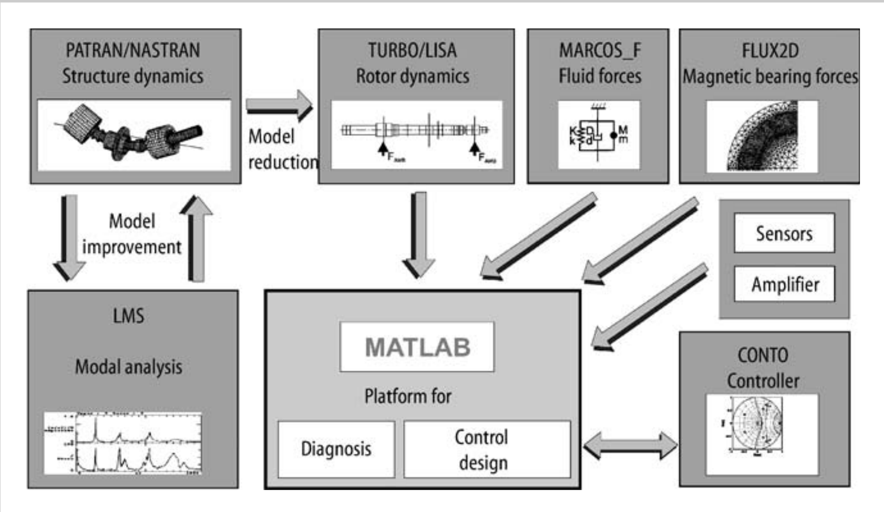

Figure 8.17. Building an overall model of a rotor system for failure diagnosis, after [8.2]

bearing system and in the rotor itself, e.g. sudden unbalanced forces caused by blade failure. The changes in the behaviour are measured and identified using the signals from the magnetic bearing sensors. Different situations give different characteristic signatures and these are analysed, the fault identified, and the appropriate measures applied.

8.3 Adaptronics

8.3.1 Fundamentals and Terminology

The term adaptronics is made up from adaptive structures and electronics. Hanselka [8.16–8.18] defines adaptronics as integrating mechanical engineering structures with the possibilities offered by electrical and electronic technology supported by control and information technology. Other authors, such as Elspass and Flemming [8.8], call these types of solution structronics and some consider adaptronics to be part of mechatronics.

The aim is to develop construction structures that continuously fulfil their tasks by actively adapting themselves to disturbances and to changes in loading and required functionality. Using adaptronics allows the construction structure to be directly influenced because the actuators and sensors are integrated in the structure as multifunctional materials. These sensors and actuators are positioned in the forceflow and via the processor react, signal, regulate and hence control the structure, which can therefore be seen as an active composite construction.

In Section 7.4.3 the principle of self-help is described. This principle refers to pure mechanical structures that through careful design can have self-reinforcing, self-balancing and self-protecting properties. The introduction of adaptronics widens and considerably improves the potential performance of these structures by incorporating the actuators and sensors as load-carrying parts, i.e. they continuously participate and do so in a coordinated way.

Compared to the concept of mechatronics (see Section 8.2), the following characteristic differences exist:

- the structure always has active material parts
- actuators can act as sensors and vice versa
- the system always contains a dynamic model of the structure that adapts, based on signals from sensors, to changes of the real structure and controls this structure through the actuators
- the reactions in the model and in the control system always take place in real time.

Multifunctional materials that can be used are: piezo ceramics, shape memory alloys, PVDF fluorothermoplastics (as films or foils), optical glass fibres, and multifunctional composites such as fibre-reinforced glued layers with embedded piezo ceramics. Piezo actuators can be produced in a multitude of shapes so that they can be integrated into a structure in the most effective way [8.8, 8.16]. Figure 8.18 shows some of the available shapes. For a stacked piezo actuator the main extension direction is in the direction of the stack, whereas for a plane one the main extension direction is parallel to the plane. Embedded in structures these actuators can provide regulated and controlled extensions. Such actuators can, for example, lengthen a bar as if tension had been applied to it. When placed pairwise in the outer surfaces of a fibre composite plate, bending effects can be produced. Configured at 45° to the main axis they are able to initiate torsional deformations.

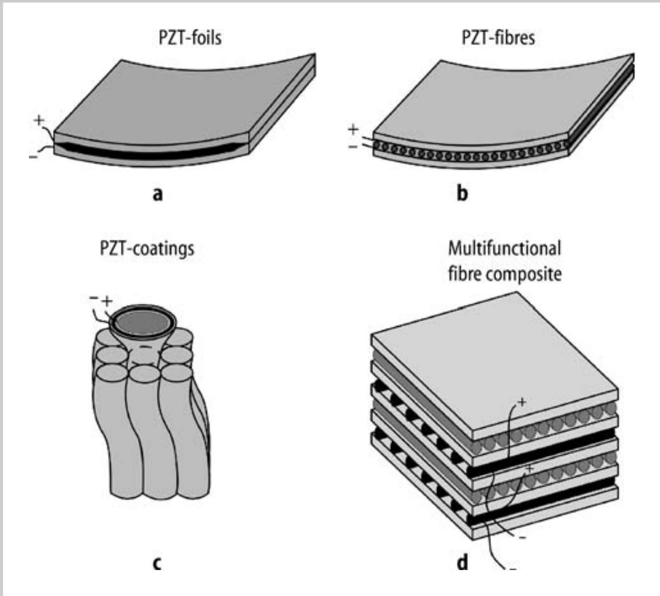

Figure 8.18. Shapes of piezo actuators as **a** foils, **b** fibres, **c** coatings and **d** integrated as a multifunctional fiber composite, after [8.16]

The general architecture of adaptronic solutions is shown in Figure 8.19. The active structure is essentially a fibre reinforced composite plate that can be complemented by a sandwich or hybrid structure. Sensors and actuators are embedded using material connections between the laminate layers of fibres and the matrix material. When a disturbance or change is sensed, signals from the sensors are sent to the computer model that simulates the structure. Depending on the goal, the control system is activated. Guided by the model, it sends correcting signals to the actuators of the structure. The structure then moves into a new state in line with the one defined by the model. This fast real-time control allows continuous adaption.

The applications described here may be considered utopian, unnecessary or too expensive given the current state of technology. However, the possibilities are fascinating and the examples that follow provide useful suggestions to trigger novel ideas for hitherto conventional areas.

8.3.2 Goals and Limitations

The goals of adaptronic systems are to:

- return a structure to its original state by undoing the effects of loads, temperatures and disturbances
- suppress actively vibration and noise
- change actively the embodiment
- realise structures with infinitely large stiffness at discrete positions

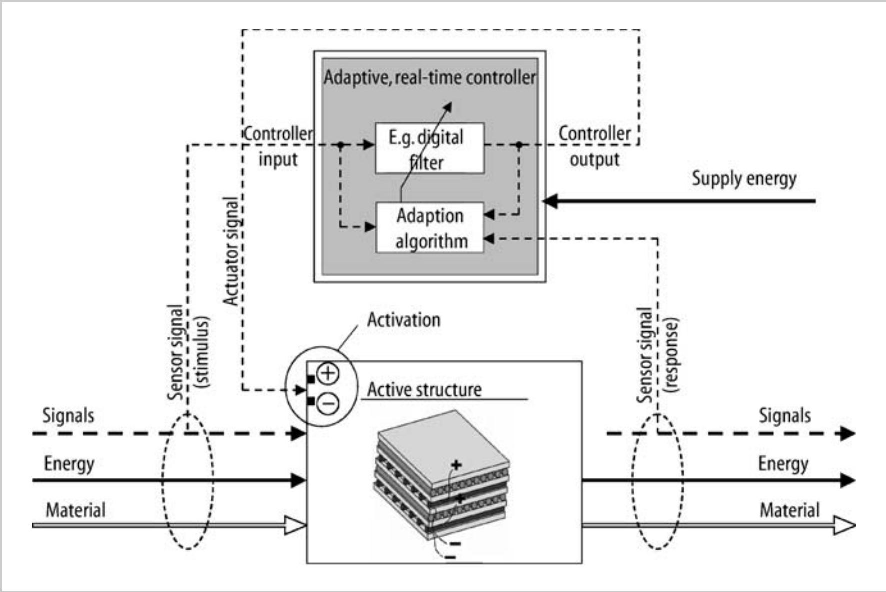

Figure 8.19. General architecture of adaptronic systems, after Hanselka [8.16]

- change actively the position
- identify damage in composites.

The limitations of adaptronics include:

- construction effort is comparatively high
- forces or movements initiated by the actuators are small
- costs for the sensors and actuators are high
- full theoretical understanding and modelling of the control process might not be possible because of the complexity
- improvements offered seem unnecessary, i.e. the cost/benefit ratio is not yet convincing.

Further research and development will overcome these limitations and extend the boundaries.

8.3.3 Development of Adaptronic Solutions

What has been said for the development of mechantronic solutions (see Section 8.2.3) applies equally to the development of adaptronic solutions. Theoretical understanding and appropriate mathematical modelling of the structures, their intelligent configuration and embodiment, and the optimal placement of sensors and actuators are essential. The development of such structures also requires a systematic approach and teamwork involving different disciplines.

8.3.4 Examples

Example 1: Non-Deforming Beams

Beam-like components subjected to external loads perpendicular to their main axes deform by bending. Adaptronic solutions can prevent this. Depending on the number and placement of piezo surface actuators, the bending can be reduced to zero at one or more discrete positions along the beam, even with differing loads. Bending due to the self-weight of a component can be compensated for in the same way. Figure 8.20 shows a beam and its deformation in a conventional arrangement and in an arrangement with embedded piezo actuators. The latter results in zero bending deformation at discrete positions [8.17]. To calculate the required "counter deformation" a model of the structure and the loading has to be built and the appropriate formulae established. Such compensation possibilities

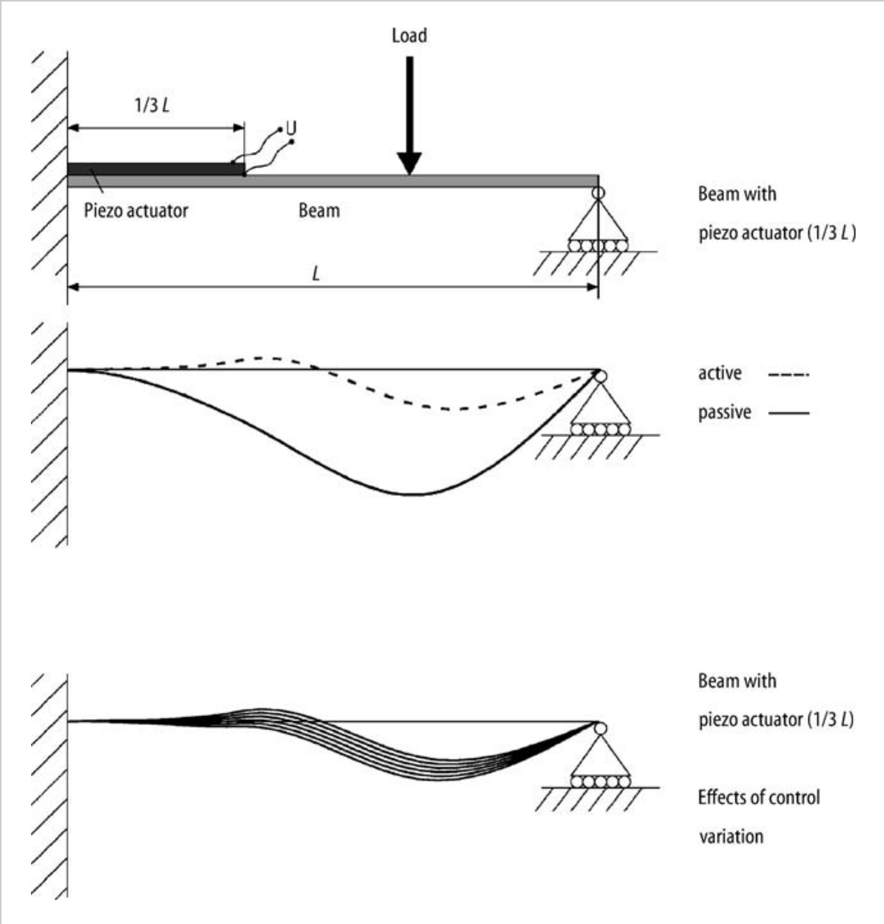

Figure 8.20. Beam with active reduction of its bending deformation, after [8.17]

are of importance for robot technology, high-precision measuring instruments, and minimal invasive surgery technology.

Example 2: Self-Correcting Antenna Reflectors

In the aerospace industry and for high-precision mirror systems, the exact shape of the reflectors is crucial. This can be realised using adaptronics. Elspass, Flemming and Paradies [8.9, 8.23] give an example for the continuous adaption of a reflector surface to compensate for the Earth's gravity. The reflector surface, see Figure 8.21, has a double wall filled with foam. The outer layers of this sandwich structure are fitted with sensors and actuators in a star-shaped arrangement. The actua-

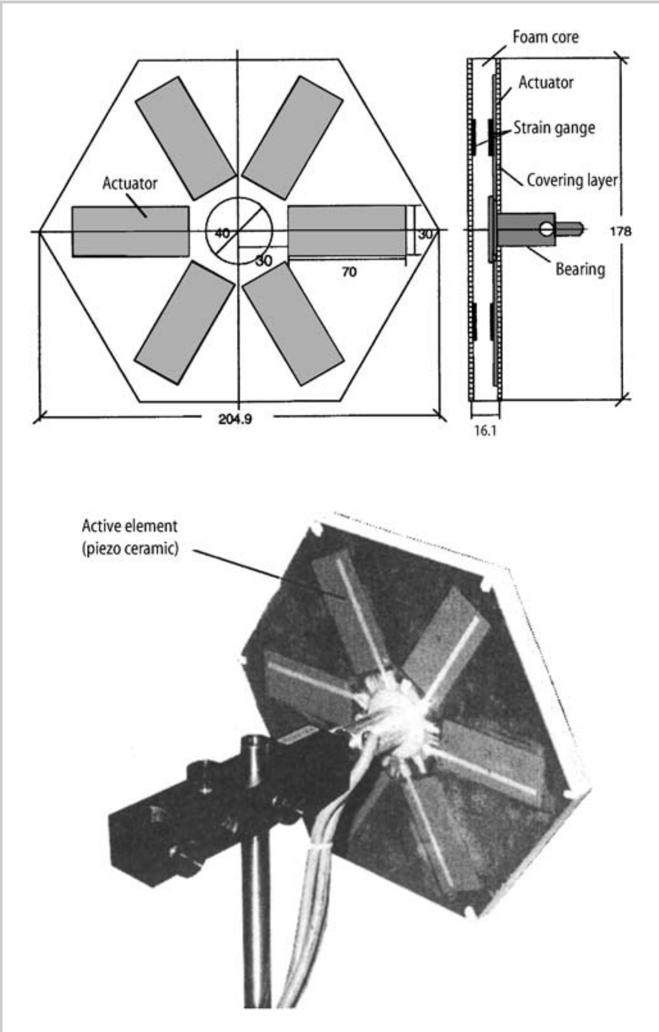

Figure 8.21. Detailed arrangement of a parabolic reflector with active sandwich structures and integration of piezo actuators, after [8.8, 8.9, 8.23]

tors are used to actively counteract the deformations caused by external effects or by the structure itself. This also allows the initiation of a deformation that is more parabolic or ellipsoidic. This principle of adaptive self-correction was used in the Hubble telescope to compensate for errors and to focus the antennae reflectors.

Example 3: Low vibration vehicle body shells

In the automobile industry there are several possible applications to improve the characteristics of body shells. Large thin-walled surfaces tend to vibrate and cause drumming. This can be counteracted by fitting piezo actuators in selected areas in order to actively reduce the vibrations, see Figure 8.22.

Such surfaces can also be used to prevent noise transmission. The surfaces are excited by piezo actuators in anti-phase to the noise vibrations thus compensating for the noise. The ride inside the vehicle thus becomes much quieter [8.8, 8.16, 8.18, 8.24].

Extending piezo actuators can be fitted in the forceflow paths of connecting and stiffening elements of a car body shell to compensate for deformations. In particular, torsional piezo actuators can be used to compensate for torsional deformations during operation. In the case of a crash, deformations that take place in opposing directions can be introduced to channel the flows of energy such that the crash deformations follow the desired paths.

Figure 8.22. Active body shell, after [8.15, 8.17]