DESIGN, MODELING AND FUNCTIONALITY ALLOCATION IN MECHATRONIC PRODUCTION SYSTEMS

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Abstract
This paper reviews current developments in mechatronic systems for metal cutting and forming machine tools. The integration of mechatronic modules to the machine tool and their interaction with manufacturing processes are presented. Sample mechatronic components for precision positioning and compensation of static, dynamic and thermal errors are presented as examples. The effect of modular integration of mechatronic systems on the reconfigurability and reliability of the machine tools is discussed along with intervention strategies during machine tool operations. The performance and functionality aspects are discussed through active and passive intervention methods. A special emphasis was placed on active and passive damping of vibrations through piezo, magnetic, and electro-hydraulic actuators. The modular integration of mechatronic components into the machine tool's structure, electronic unit, and CNC software system is presented. The paper concludes with the current research challenges required to expand the application of mechatronics in machine tools and manufacturing systems.

Keywords:
MECHATRONIC SYSTEMS; MACHINE TOOLS; INTEGRATION

1 INTRODUCTION

The technological transformation of the information society is associated with considerable changes in the demands on machine tools, requiring new solutions for the inherent conflict in design between precision and productivity [1, 2, 3]. Future performance requirements of machine tools will be characterized by trends in microsystems technology and nanotechnology. Beginning with today's mechatronic products, such as fuel injectors with piezo actuators or micro-structured biosensors, increasing integration of mechanical, biological, and electronic subsystems into a single product is discernible, accompanied by the necessary adjustment to the relevant structural dimensions. For mechanical manufacturing, this results in constantly growing demands for precision in machine tools. The scientific and technical challenge does not lie entirely in the capability to produce mechanical structures with ever greater precision, but also mass produced workpieces at reasonable production costs. The concrete demands identified from surveys of customers and manufacturers in this respect [2] are:

- An increase in availability as a result of prescient maintenance; status and process monitoring; intelligent maintenance; diagnostic functions.
- Highly economic manufacturing (life-cycle costs) as a result of function-oriented design; improved performance due to dynamics, flexibility as a result of reconfigurability.

These factors are of necessity associated with:

- A high level of standardization and modularization: interfaces, technology modules, independent functional assemblies.
- Efficient control systems.

In recent decades, mechatronics has become established as a developmental method for such systems. Today it constitutes the key discipline in production technology. For the further development of the mechatronic system "machine tool" it makes sense to adhere to a hierarchical conceptual framework:

1.1 Machine Tools as Mechatronic Systems

Component sensors and the lowest possible number of additional sensors capture an image of process and machine that approximates to reality. With the support of models, the intrinsic drives of the machine tool are used by the control system to correct processing errors. The primary application for which this is suitable today involves quasi-static error sources, such as thermally determined displacements or calibration of machines. However, the comprehensive data from the sensors also provide initiatives for increasing the reliability and availability of the machine tool. The increasing importance of solutions of this kind is a consequence of the high speed of development of CNC-technology. They are strongly influenced by design and system integration.

1.2 Machine Tool's Mechatronic Components

These include in particular the main and feed drives. Past research work has concentrated on this system level and has already been analyzed and published in detail. These components and their integration in terms of information technology define the capability of the actuator and the bandwidth of the solution initiatives in system level 1. Major progress can therefore be expected as a result of optimum system integration.

1.3 Integration of Additional Mechatronic Solutions into Machine Tool Components

The aim of intervention in this system level is to improve machine tool malfunctions by means of autonomous components which either act directly as ancillary drives to compensate for dimensional errors near to the source of the interference, or to improve the behavior of the controlled process of the basic structure of a machine tool component for the higher-level control system. The advantage of this kind of system intervention lies in a design which is optimally adapted to the local problem and the consequent removal of restrictions with regard to the bandwidth of malfunctions to be compensated. As Plug & Play modules, such solutions are interesting for the implementation of reconfigurability.

In relation to the overall function of the machine tool, the above system levels, which are not independent, have both a specific suitability for use and, at the present time, different levels of advancement in application. The optimum effect can therefore only be achieved by thorough system integration concepts, which take into account both the mechanical involvement and the signal and energy flows, but above all the architecture of the data processing.

2 DESIGN PROCESS

Mechatronic systems are complex systems whose solution field is interdisciplinary. They show a greater functional density and closer of function than traditional mechanical and electrical systems. In their design, therefore, the functional aspect is clearly at the forefront compared with the purely mechanical/geometrical aspect. The mechatronic initiative results in a dramatically enlarged range of approach and conversely in a dramatic increase in system complexity. Controlling the latter is a pure bottom-up initiative, i.e. the integration of separately developed and optimized assemblies is no longer viable.

Conventional design process:	**Additional requirements:**
• sequential work flow of different domains	• cross-domain functionality of working principles
• clearly defined specifications for each development step	• immediate introduction of new materials and working principles
• long-term defined interface between engineering fields	• close relations between domain specific simulations
• usually superposition possible	• non-linear effects (no superposition)
→ **low design flexibility domain oriented design**	→ **high design flexibility function oriented design**

Fig. 1. Engineering process requirements for the design of mechatronic systems.

Instead, a prior top-down design is needed, i.e. the design of a gross structure from which, by means of division into functional elements and an increase in the level of detailing, individual elements can be specified more accurately. A transition to bottom-up design is required as a subsequent iterative step towards system optimization. In summary, a higher flexibility for a product-oriented design process is needed. This leads to additional requirements for the design of mechatronic systems (Fig. 1). The underlying process for designing mechatronic systems, and the associated system support is shown using VDI 2206. Nevertheless it has been shown in design research, that a generally applicable stringent process cannot exist, and that the flow diagrams have more of the character of a guideline [5, 8, 9, 10].

The V-model envisages a macrocycle, which is based on the requirements of the product development, provides for the system design which is subsequently transferred to the now parallelized domain design. This is followed by integration, resulting in a (virtual) prototype, and the verification and validation of the system design. This cycle can be repeated several times in order to achieve a greater level of maturity through iteration.

The design cycle is flanked by modeling and simulation. The virtual prototype of a mechatronic system includes the mechanical system, the electric or hydraulic system, and the information system. In the model, the mechanical and the electrical domains are coupled by the physical properties of the sensor-actuator-unit to a virtual prototype (Fig. 2). The complex model firstly allows the optimization of the complete system (topology and parameters, including sensor/actuator positioning). Secondly, it makes possible the examination of the state dependent instabilities (parameter excited vibrations, chatter, instabilities of control loop). Thirdly, we get a “red line” for the calibrating strategy.

The design of mechatronic systems is iterative, because the challenge is to seek a system that has specific properties. However, all simulation-supported methods initially require a system, the properties of which can then be predicted. For them, the design task is an inverse problem.

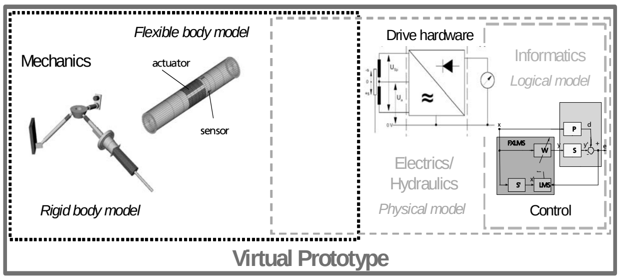

Fig. 2: General aim of mechatronic simulation: Virtual Prototype.

3 FUNCTIONALITY ALLOCATION BY MECHATRONICS

The extension of functionalities by the mechatronic approach often leads to increasing complexity of the system. Therefore, the functionality allocation by mechatronics has to be a strongly problem oriented development task. This normally causes influences on system’s behavior by revisions in the component level. Following, different options for intervention are discussed by means of concrete solutions for machine tool components.

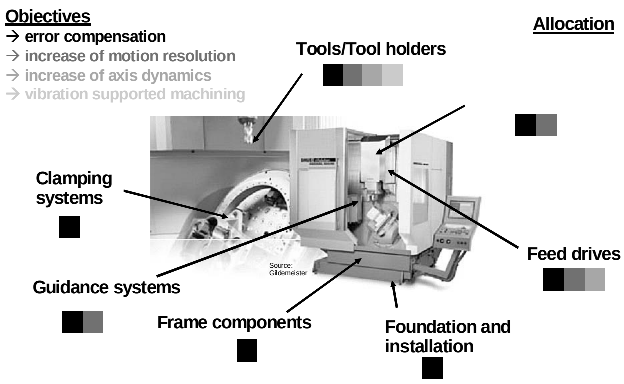

Fig. 3: Functionality allocation by mechatronic systems for machine tools.

3.1 Feed Drives

Feed drives are the central elements of machine tools. Solutions for increasing the axial dynamic stiffness of screw drives are presented in [11] and [12]. Autonomically acting compensating units are described, which are configured between spindle nut and slide. This allows compensation for vibrations in the drive train for which the bandwidth of the feed drive is inadequate. The solution proposed in [11] uses piezo actuators integrated into the compensation unit via solid flexures (Fig. 4). Piezo fiber sensors serve as vibration sensors.

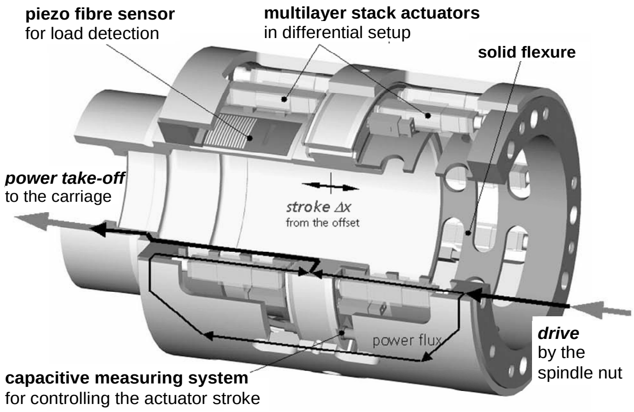

Fig. 4: Axial vibration compensation unit [11].

An approach, which in principle can achieve maximum bandwidths on the tool and workpiece respectively, and which is similar to the solutions already described for increasing positioning accuracy, is to use superposed NC-axes. It is also based on the combination of drives and kinematics with markedly differing characteristics, [13] and [14]. Superimposing of large axes with low dynamics and as well short as high-dynamic axes (working in the same direction) results in a hierarchical division of the overall dynamics on several functional levels, [15], [16], (cf. Fig. 5).

The overall dynamics (actual values) are obtained from the individual dynamics working in the same direction. The highest possible overall dynamics can usually only be locally achieved. For example, roughing operations are carried out globally by moving the slow axes. Finishing operations take place locally by moving the fast axes in conjunction with positioning movements of the slow axes.

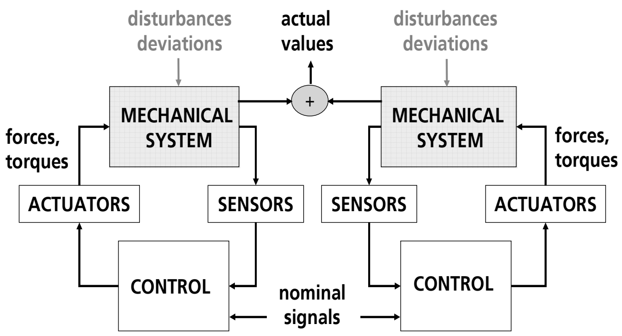

Fig. 5: Principle of superposed axes.

3.2 Guidances

In conjunction with drive systems, guideways constitute the interfaces between frame components that move relative to one another. Extreme demands are made on them regarding freedom from constraint (low friction), uniform movement and guidance precision, stiffness and damping characteristics. Damping in guideways plays an essential role in the system damping of the machine. Approaches and solutions for active guidances are especially known for

- Hydrostatic guide systems, e.g. [17]
- Magnetic guide systems, e.g. [18]
- Aerostatic guide systems, e.g. [19]

There are essentially two methods of realizing active bearings or guideways explained on aerostatic bearings (AAB). First principle is the air-film-thickness feedback method (Fig. 6 a). The second one is the bearing pressure feedback method (Fig. 6 b). At method (a), changes in the air film thickness are detected and electric signals are sent to actuators for controlling the flow resistance, thus keeping the gap height constant [19]. This approach is very accurate; however it is complex and expensive. At method (b), the pressure change on the surface of the bearing controls the opening of the active restrictor. A disadvantage of this approach is that the film thickness on the bearing surface is not measured directly. However, this method needs no electrical supply, and hence it is possible to incorporate the active restrictor within the aerostatic bearing, [19]. In [20], the use of (a) for linear guide systems and (b) for rotary guide systems is proposed.

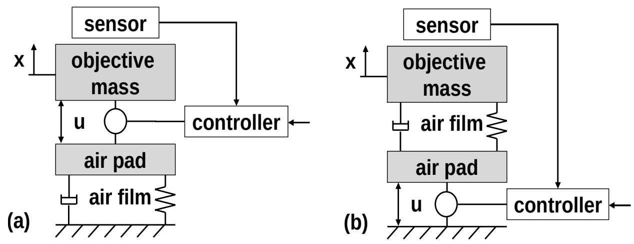

Fig. 6: Types of AAB after [19] and [20].

3.3 Frames

Frame components are crucial for static and thermal machine stiffness because of their frequently high elastic and thermal effective lengths. (Quasi-)static deformations can however be compensated by calibration or model-based solutions (in the case of existing corresponding NC-axes). Often such compensation is impossible, due to non-existing NC-axes or insufficient bandwidth of the axes. In these cases, integration of additional mechatronic systems is a useful approach to improve stiffness and/ or damping properties.

Solutions for structurally integrated actuator systems are known from parallel kinematics. Stiffness properties of the structure shown in Fig. 7 are unfavorable, due to the torsionally loaded struts.

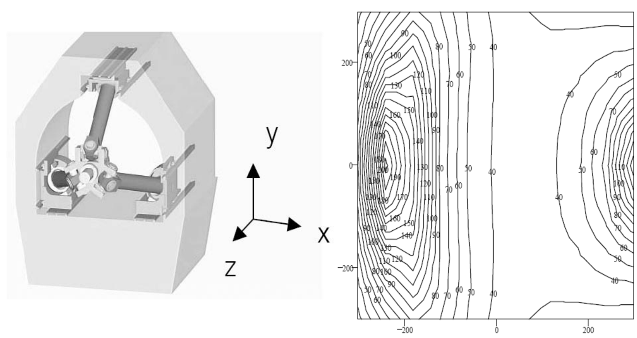

Fig. 7: Stiffness distribution of a Tripod-structure; stiffness in X-direction of the X-Y-level.

Because of the often clearly defined strut loads and the simple strut structures, these provide, in contrast to the often complex frame topologies of serial kinematics, favorable conditions for the integration of additional compensation actuator systems. With parallel kinematics, there is also a greater need for strategic vibration suppression, because struts are more susceptible to vibration. For struts with torsional load, a structurally integrated unit with piezo actuators is described in [22]. A strain gauge is used as a sensor. This permits compensation for static deformations and vibrations of up to 300 Hz. The sensor-actuator unit is shown in Fig 8.

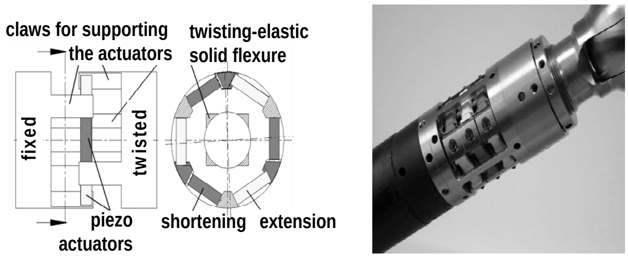

Fig. 8: Unit for compensation of torsional strut deformations.

Mere feed-forward control of disturbance is a simply to realize technique, and offers the maximum possible dynamic reserves. With it, however, compensations of the piezoactoric countermovements as well as the material-based piezoelectric effects (hysteresis and drift) are not possible. Hence, accuracy of torsional movements is limited. Undesirable effects can be compensated as far as possible by sensory registration and control of the piezoactoric movements.

Experimental results in principle prove the applicability of this procedure. By means of an experimental adaptive test strut, sevenfold increase of the torsional stiffness in comparison to a conventional strut could be reached with the simple control concept of feed-forward control of disturbance; 40-fold increase was achieved in consideration of the actuator's state within the control algorithm, see Fig. 9 (left).

In the theoretical case of infinitely high effective torsional stiffness, stiffness of the exemplary Tripod-structure might be increase in X-Y-direction from 28 N/µm to 410 N/µm, as shown by the resulting stiffness distribution in Fig. 9 (right). Simultaneously, natural frequency would rise from 20 Hz to more than 100 Hz.

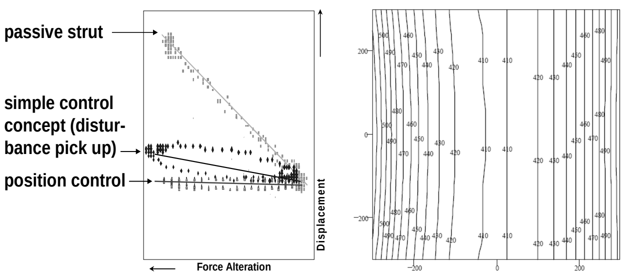

Fig. 9: Stiffness of an active strut (left); stiffness distribution in X-direction of the Tripod's X-Y-level in the case of infinitely high effective torsional stiffness of the struts (right).

The example represented in this paper shows the feasibility to significantly improve machine tools' system properties by adaptronic components. Its application in such structures, the external constrains of which limit the margin for passive optimization, is especially obviously.

3.4 Main Drives

A fundamental distinction can be drawn with regard to the active damping of main spindles between two variants of the active bearing. The first variant exerts forces on, or shifts the motionless component of an existing roller bearing, sliding bearing or aerostatic bearing, or is based, especially in the case of magnetic and hydrostatic bearings, on the control of the bearing gap. This is known as active bearing support and integrates the actuator system into the flow of force of the passive spindle bearing.

The functional approach is of the same kind like the principles used for guidance systems. The second variant is used for preference at locations where there are large amplitudes, by integrating additional active bearing points between, or adjacent to existing bearing points (ancillary bearings). The actuators are integrated in parallel with the force flow of the passive spindle bearing.

3.5 Forming Machine Tools

Due to the growing contraction of process chains, forming technologies become more and more important. Analogously to cutting machine tools, approaches and solutions for active improvement of their functionalities were developed for forming machine tools, too (Fig. 10).

The most relevant activities can be summarized as follows:

- Multipoint drawing technology [25][27]
- Redundant drive structures [23]
- Compensation of frame deformations [24].
- Active damping of ram vibrations [26]
- Parallel holding (bed, ram) [25][28]
- Vibration superposition in the forming process [29]

Especially directly process influencing techniques like multipoint drawing technology or superposition of vibrations expanded process limits in recent years. Publication [30] gives a comprehensive overview on the field of mechatronic systems for forming machine tools.

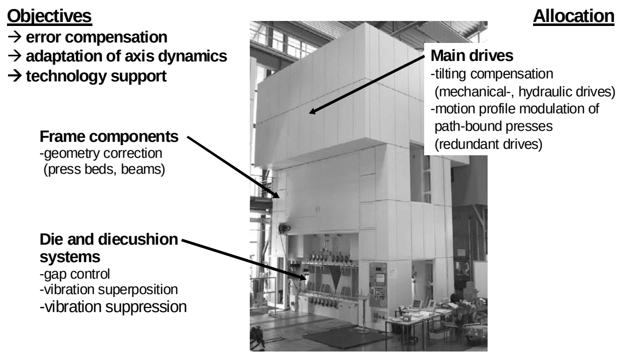

Fig. 10: Functionality allocation by mechatronic systems for forming machine tools.

4 CONCLUSIONS

Mechatronics enable a supreme development methodology for machine tools. The technological developments in the individual domains of the basic structure – mechanics/ materials, transformation systems – sensor/ actuator systems and data processing will characterize the future development of "intelligent" machine tools.

Over the next few years, the emerging trends will be the increasing use of self-optimizing, in part adaptronic components and the use of ever more efficient control systems for model-supported compensation of machine errors and process control. All functionality of machines will become electronically enhanced and thus mechatronic functions.

Optical waveguides permit interference-free communication between sensors, information processes and actuators with high bandwidths. Sensors based on optical principles, including industrial image processing, achieve the very highest information density. At the same time, the speed of data processing by optoelectronics will further increase in the future.

The following can therefore be identified as driving the further development of mechatronics technology and hence, as a consequence, the development of machine tools:

1. Information technology based on Moore's law [7].
2. Adaptronics (and the associated manufacturing processes of microsystem technology) for lightweight construction and for increasing the level of integration of the components.
3. Optics as the universal new basic system type.

Reconfigurability as a necessary pre-requisite for the flexibility of machine tools demands mechatronic machine tool components with Plug & Play functionality. This requires the creation and standardization of interfaces which are uniform in terms of their mechanical, energy and information technology aspects. These machine tool components must at the same time be strictly function-oriented in their design. They must be subjected to a comprehensive description of their functionality in terms of both hardware and software structures. Analogies with developments in computer technology or robotics will become more prominent.

In our vision of the future, the boundaries between robotics and machine tools will become diffuse in mechatronic manufacturing resources. This trend will go hand in hand with a fundamental transformation in terms of kinematic structures, but above all in the architecture of control systems. One of the major challenges will be to guarantee the reliability of these mechatronic systems in order to meet economic demands in terms of the availability of production systems.

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