SPP 1476
Small Machine Tools

Small Machine Tools for small Workpieces

DFG
Priority Program funded by the
German Research Foundation (DFG)

Publisher and content responsible:

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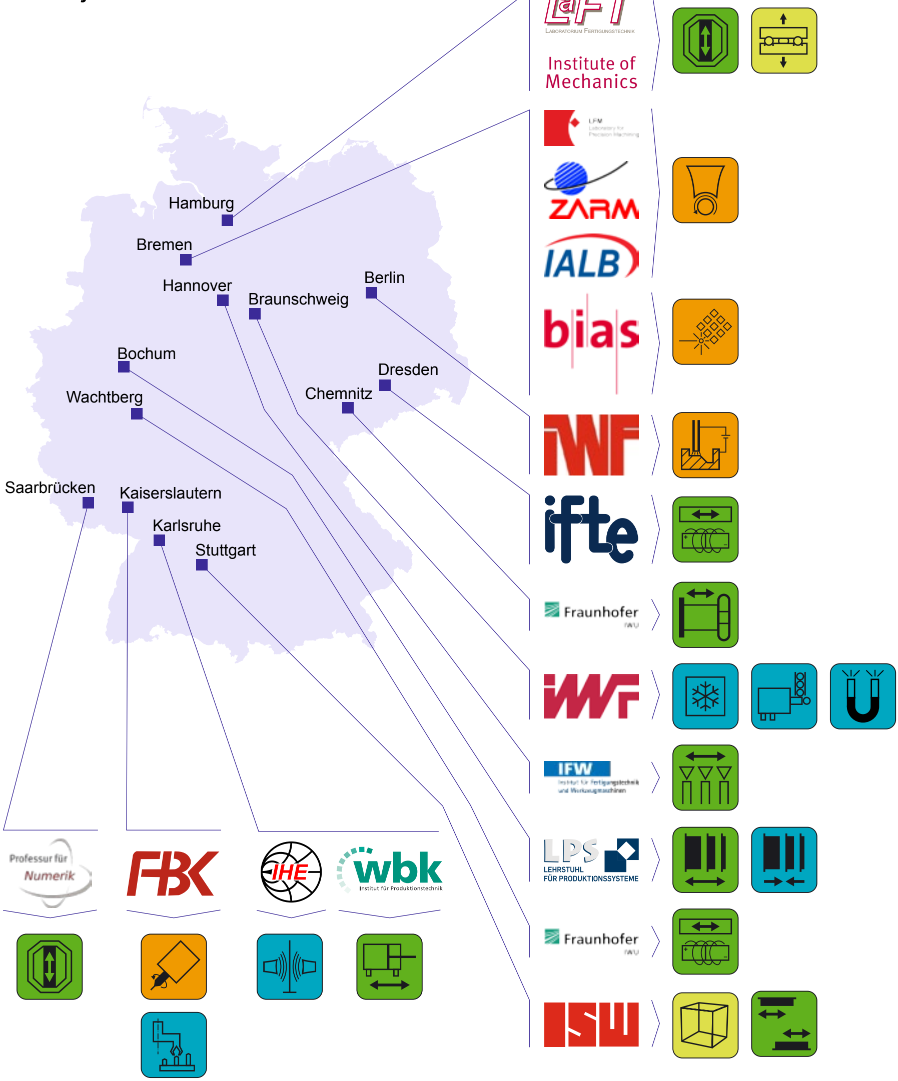
Project Information

Project Partners

13 Projects – 18 Research Institutes



Summary

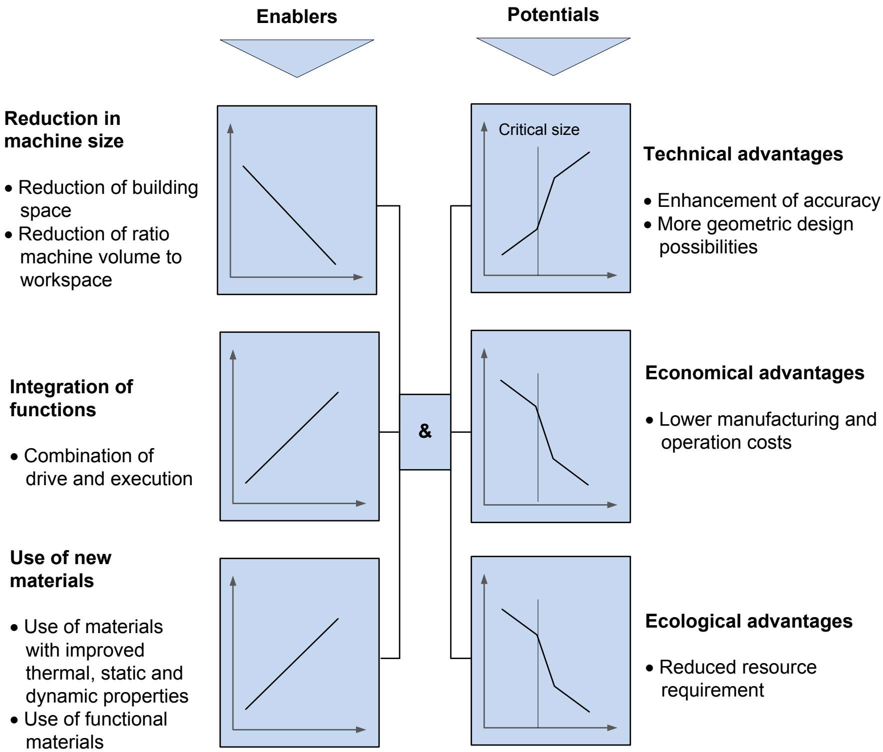
The Priority Program SPP 1476 of the German Research Foundation “small machine tools for small workpieces“ consists of projects of 18 leading institutes of the production technology allocated to 13 German universities. During the project period of 2010–2016 the goal of the Priority Program was to provide new, size-adjusted, modular machine tools for micro manufacturing. In close collaboration new modules have been developed at different institutes, so that desired machinery can be assembled and disassembled ad hoc and task-orientated from the different modules.

Participating Universities/ Research Institutes

Idea of DFG Priority Program SPP1476

For the workpieces in numerous fields such as medical, optics, biotechnology, mechatronics, fluidics, (micro) mould, tool manufacturing and micro reactor technology, enhanced miniaturisation, functional integration and complexity increase are essentially needed for the produced innovative products to be economically successful. Current research activities are primarily devoted to scaling of manufacturing processes and formation of complex process chains for the production of micro workpieces. However, an intensive research is needed to qualify necessary micro-manufacturing machine tools according to the new requirements. These needs can be derived from a consideration of simple parameters, such as the installation space, size of the working space, the need for operating power or the moving masses of machine tools. These parameters are in considerable disproportion to the volume or mass of small workpieces of only few millimetres with structures in micrometre range.

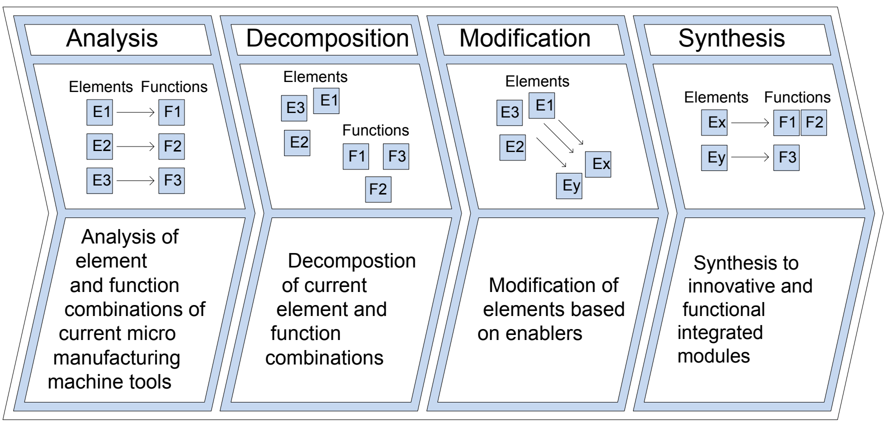
The aim of the Priority Program is the development and prototype testing of scientific methods for building new machine tools for micro production, which are adapted to characteristic technological and technical parameters of the corresponding micro workpieces. In the Priority Program the main focus is on machine tools for material removal process utilising mechanical (machining), thermal (laser), electro thermal (electrical discharge machining) and electrochemical energy. These new machines have technical, economic and ecological benefits. They enable production of complex parts with higher accuracy from a large range of materials and are also characterised by a higher inherent variability in structure and location of the installation site. Economic and ecological advantages are realised by low costs and lower consumption of resources for the development and operation of the machine. In particular, steep improvements of the mentioned properties are achieved by bringing down the critical size of the developed manufacturing equipment.



After falling below a certain size small machine tools enable the introduction of new or known but still not used machine tool technologies and elements. As opposed to today’s evolutionary development of the machines these technologies enable innovative leaps, i.e., revolutionary steps in the development and operation of the machines.

Approach

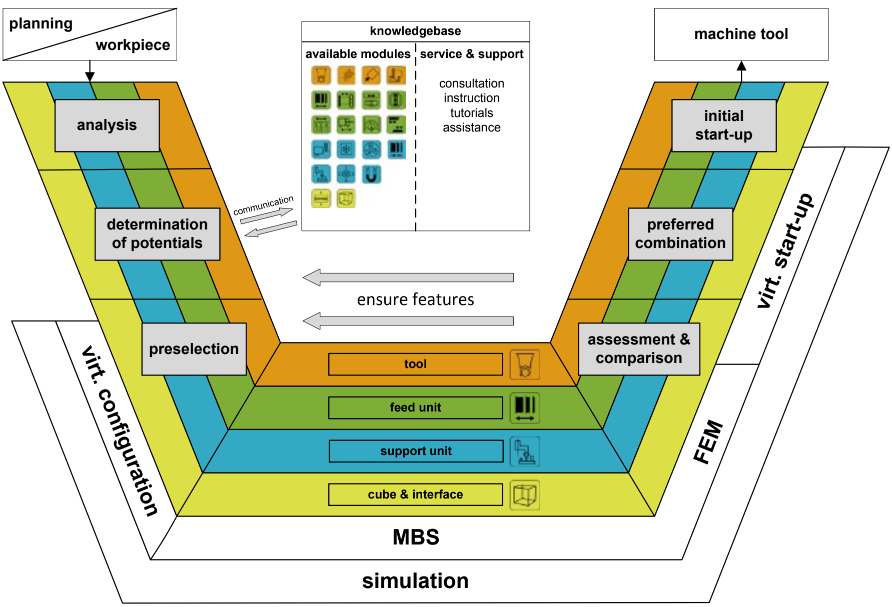
For the solution of the highly interdisciplinary problem, a systematic scientific approach was applied. In the beginning the analysis and decomposition of element-function assignments of today's micromachining equipment was carried out. Their modifications in combination with a variety of technology enablers and basic technologies allowed synthesis of new function integrated modules. In a final complexity stage machine tools have been created that can be integrated and disintegrated ad hoc and task oriented from the modules. A key technology enabler is falling below a critical sice of the modules from where the new base technologies such as new materials, functional materials, kinematics and topologies, control / regulation procedures, modularisation concepts, as well as usage of mechanical, energy and information interfaces can be used. Based on the high variability of the new machine tools, the applicability of the new machine concepts has been proven through development of functional models. This function models are exhibited at the Priority Program´s stand at the Hanover trade fair 2016. A detailed presentation of the exhibits and their specific configurations can be found in this booklet.



Configuration Process

How modules are combined to a small machine tool for micro manufacturing

To take advantage of the modularity generated within the SPP 1476, procedures are required to support the combination of the available modules provided by the project partners to a function adapted machine tool system. Exemplarily a procedure is explained that consists of a module database with additional service functions and a V-model as a planning tool for the different categories of modules (tools, feed units etc.). Unlike other reconfigurable modular machine kits, this system is rather user- than producer-related.



The combination of modules to a machine tool is determined by the production requirements of a certain workpiece. Not the module but the workpiece itself with its geometrical and technological properties is the starting point for a workpiece orientated reconfiguration.

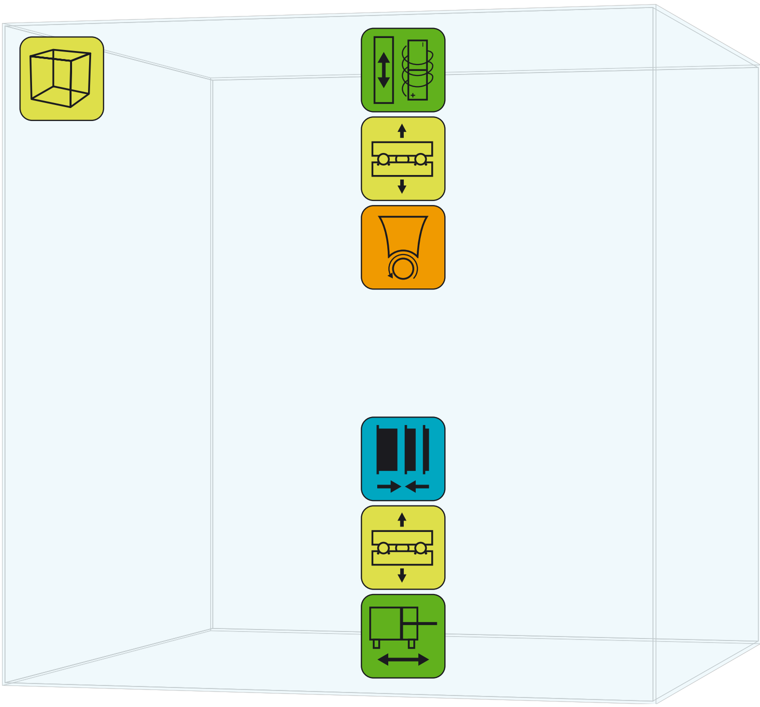
A knowledge base, especially the module database, is used to determine the potential of various theoretical combinations. The module database contains for example the geometry, machining methods, number of revolutions, minimal x-coordinate, accuracy in y-direction, interfaces and performance data of the modules.

During communication between the user and the knowledge base, process variables such as number of workpieces or the already owned modules are considered. The result of the potential determination is a range of possible combinations respectively modules that are graded by the estimated task fulfilment. The following simulations ensure the previously defined performances. Simultaneously the modules and possible combinations are assessed and compared. After choosing a preferred combination a virtual and then an initial start-up of the machine tool is realised.

Sample Machine Tool Configurations

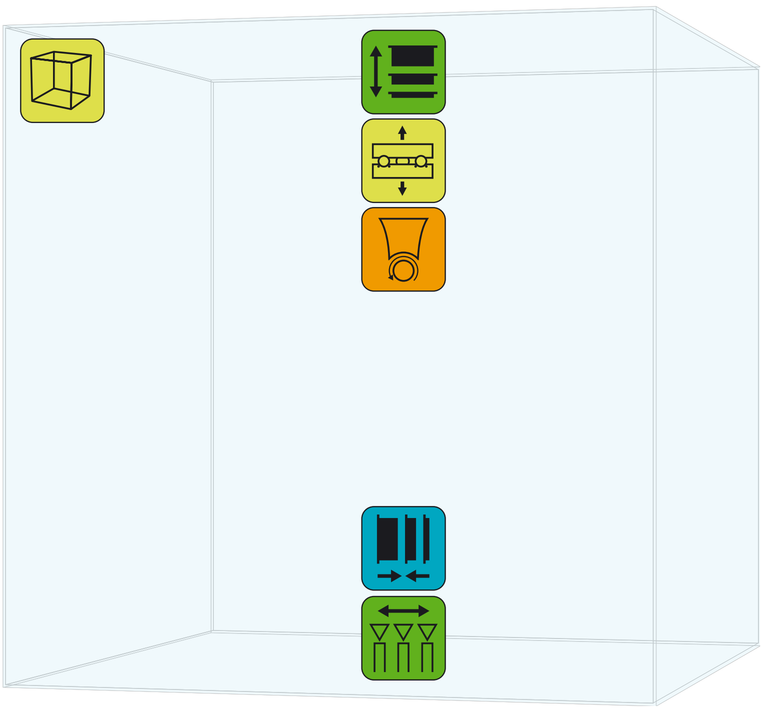
Configuration Ia

In this configuration, a GrindBall (→ p. 18) is moved by an Electrodynamic-Feed-Unit (→ p. 36). The workpiece is fixed with a SMA Chuck (→ p. 32) and moved by a Hydraulic Axis (→ p. 30). The connection of the modules is implemented by a Multifunctional Interface (→ p. 44).



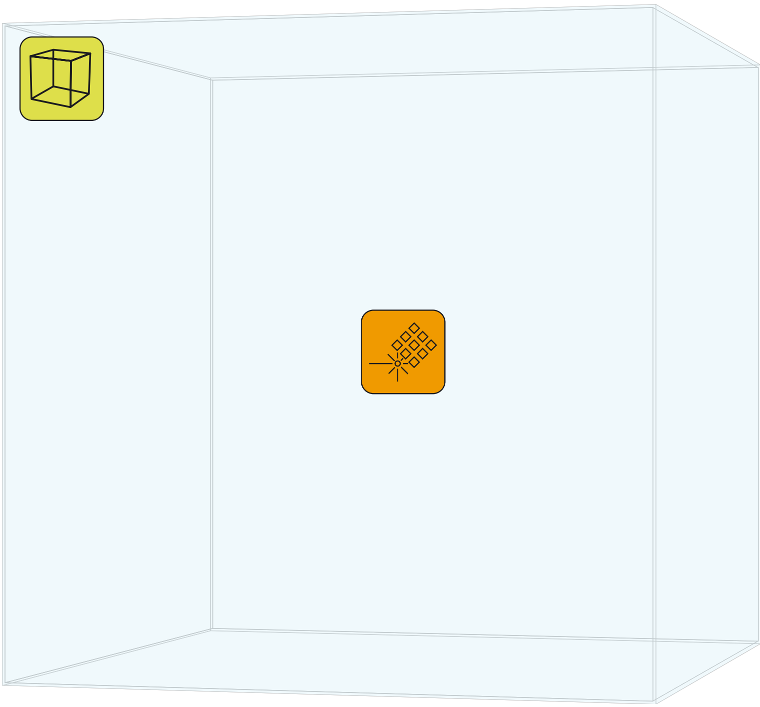
Configuration Ib

In this configuration, a GrindBall (→ p. 18) is moved by an Electrodynamic-Feed-Unit (→ p. 32). The workpiece is fixed with a SMA Chuck (→ p. 32) and moved by a Hydraulic Axis (→ S. 34). The connection of the modules is implemented by a Multifunctional Interface (→ p. 44).



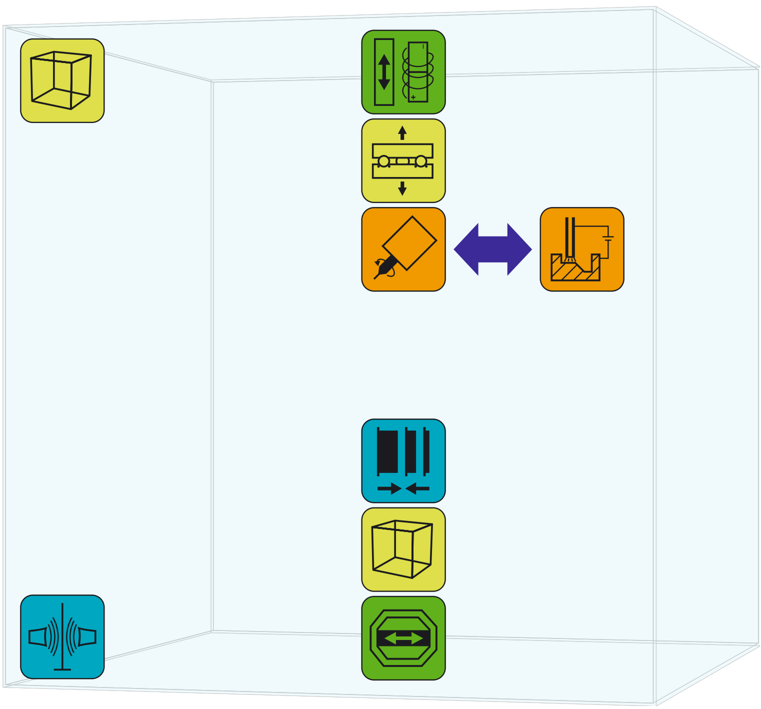
Configuration Ic

In this configuration, a DMD-Jet (→ p. 22), a compact processing module for the flat laser-induced electrochemical machining, was incorporated in the Cube (→ p. 46).



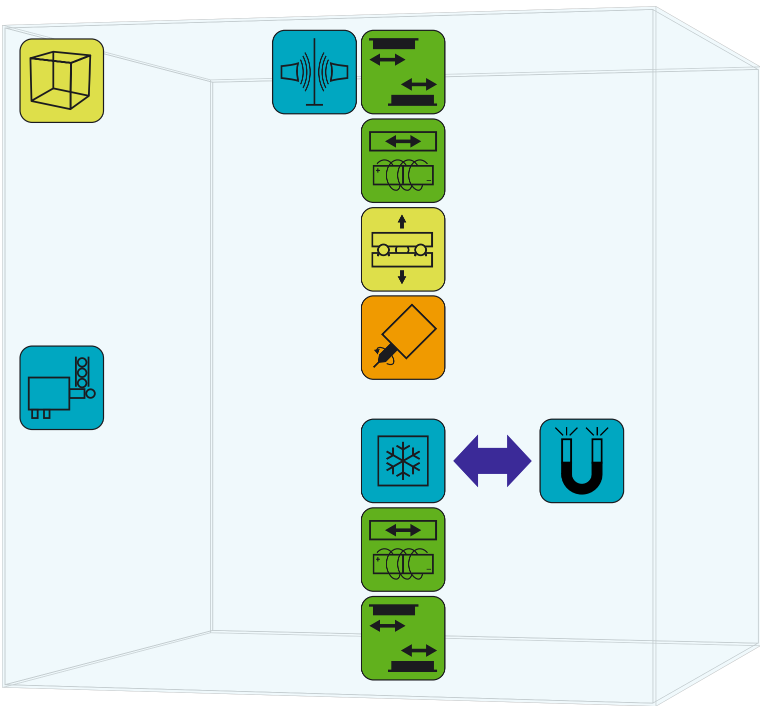
Configuration II

In this configuration, an air bearing and controlled Tool Spindle (→ p. 18) is moved by an Electrodynamic-Feed-Unit (→ p. 36). The work-piece is fixed with a SMA Chuck (→ p. 32) and moved by an X-Y Feed Unit based on Compliant Mechanisms (→ p. 38). The connection of the modules is implemented by a Multifunctional Interface (→ p. 44). A change of the spindle to a Micro-EDM (→ p. 20) can be carried out. The translational movements are measured by three Radar Sensor Systems (→ p. 42).

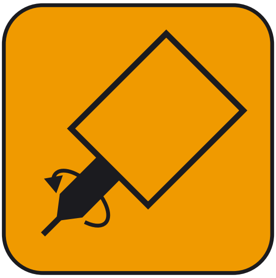
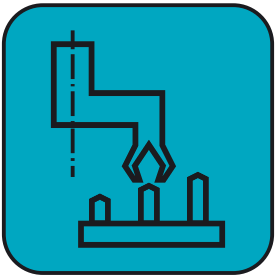
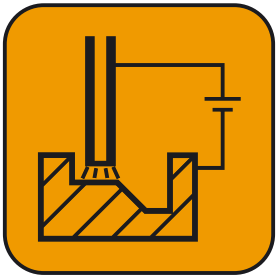
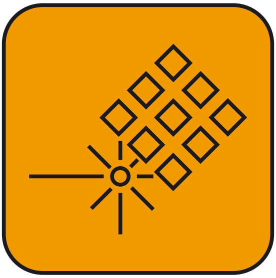


Configuration III

In this configuration, an air bearing and controlled Tool Spindle (→ p. 18) is moved by an Electrodynamic-Feed-Unit (→ p. 36). Furthermore, a co-operative movement of the tool and workpiece (→ p. 46) is implemented and measured by a Radar Sensor System (→ p. 42). The workpiece is optionally fixed with a Magnetic or a Adhesion Chuck (→ p. 46). The connection of the modules is implemented by a Multifunctional Interface (→ p. 44). Workpiece exchange is done with an automatic Workpiece Supplier (→ p. 46).

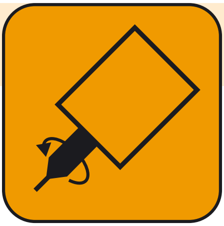


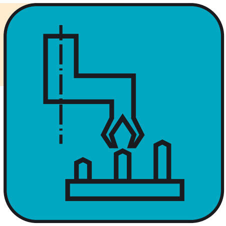
Tools


Tool Spindle

Tool Spindle with replaceable Rotor Modules.





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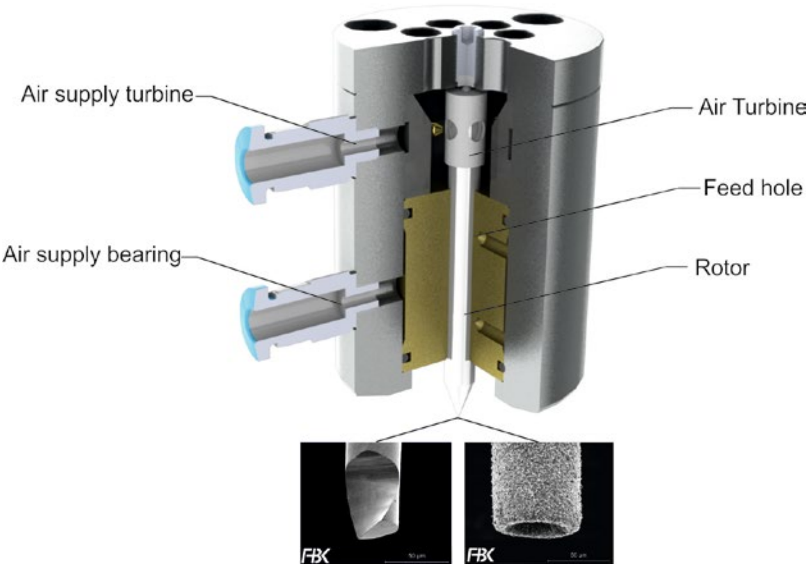
An important requirement, for the production of micro components and structures with micromachining is to provide fast and accurate tool-spindles. Thereby, two basic requirements are made to the tool spindle of the machine tool. First, a very high rotational speed of the spindle rotor is needed to provide an adequate cutting speed by using micro tools with diameters smaller than 100 µm. Second, a low run-out error is simultaneously needed to get good cutting conditions. Both requirements are seldom fulfilled together.

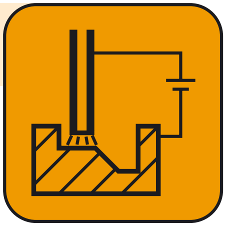


In most cases the conflict between low run-out error and high rotational speed results from the design and size of the spindle. To achieve a low run-out error with a simultaneously high rotational speed, air bearing spindles, propelled by an air turbine, were developed by the Institute for Manufacturing Technology and Production Systems (FBK). This spindles reaches rotational speeds up to 300,000 rpm and a run-out error under 1 µm.

Size	35 x 25 mm
Mass	125 g
Rotational speed	300,000 r/min
Run-out	< 1 µm

Dry-EDM Module

Module for micro-electrical discharge machining with gaseous dielectrics.



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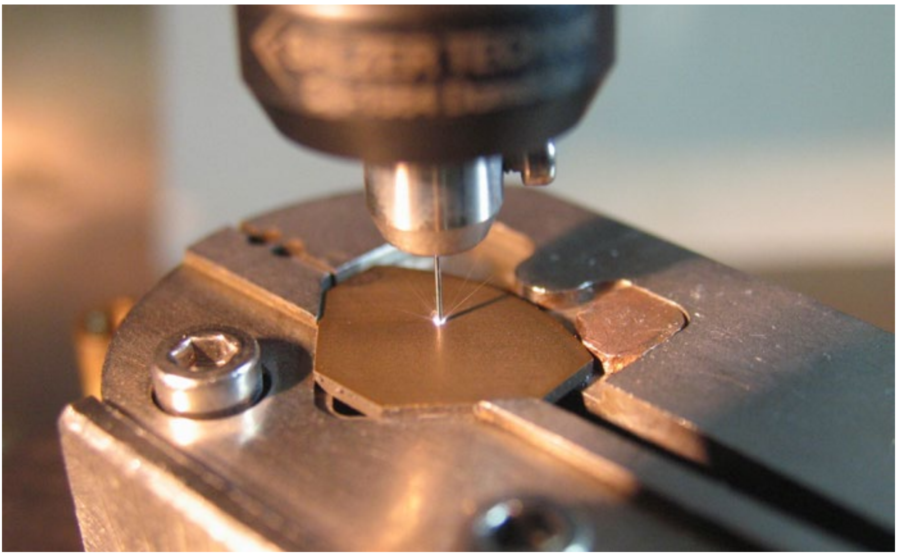
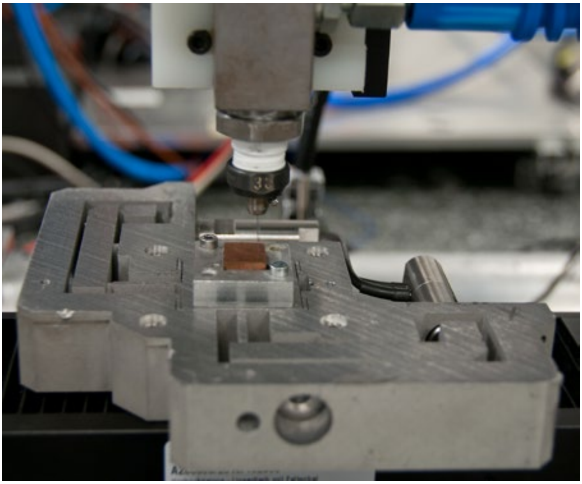


The importance of Electrical Discharge Machining (EDM) process is increasing, especially for the machining of electric conductive ceramic materials within the field of micro-production technology. Due to its thermal working principle, EDM is particularly suitable because it allows almost force free machining, independent of the material's mechanical properties. However, the use of liquid dielectrics, such as deionized water or oil, complicates the set-up of the EDM machine. Dry-Electrical Discharge Machining (dry-EDM) is an alternative EDM process, which uses gases such as air, oxygen, helium, nitrogen, and argon as a dielectric fluid. In this case the whole machine can be simplified.

As part of the research project SPP 1476 in the Institute for Machine Tools and Factory Management (IWF) of the Technical University Berlin the technology of dry-EDM milling of carbide has been developed. Besides the development of this technology, a new module and a control concept for dry-electrical discharge milling was designed and implemented. For this purpose the high-frequency movement, caused by the gap width control, and the feed were split into two different motion systems.

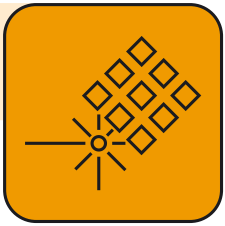


The manufacturing of three-dimensional micro-structures using dry-EDM milling is innovative and offers an economical and especially ecological alternative to established machining processes.

Dimensions	150 x 150 x 35 mm
Working Fluid	Gaseous dielectric
Drives	Piezo actuator
Control	Open source

DMD-Jet

Control of the laser induced temperature field for the realisation of a compact machining module for planar laser material processing.



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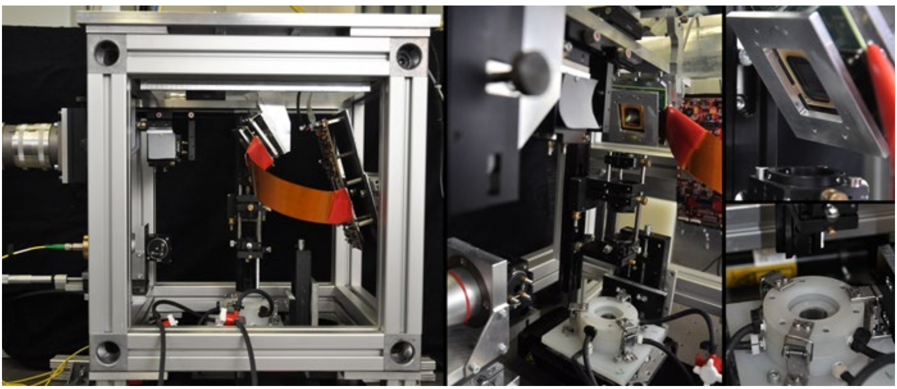
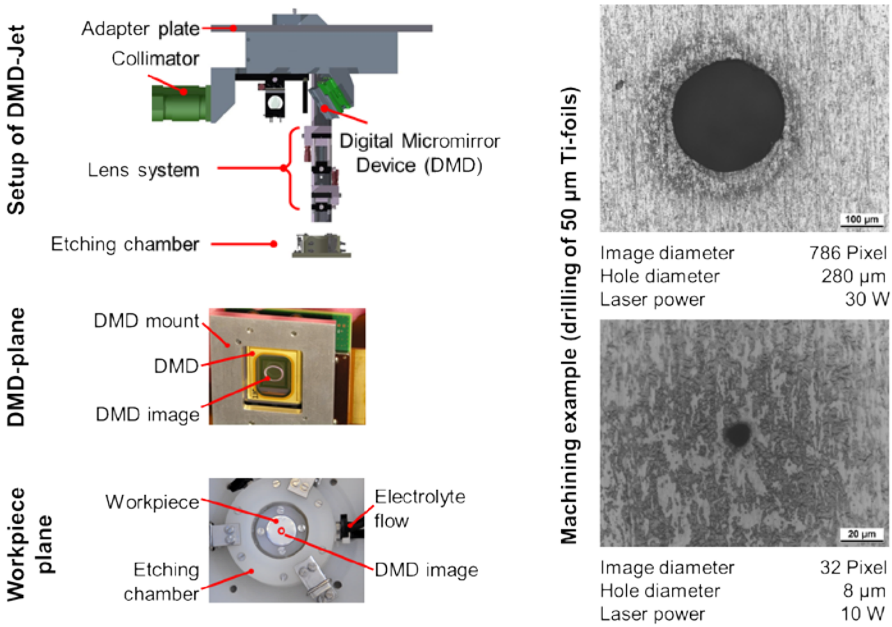


The ambition of miniaturised metallic micro-components in the industrial manufacturing is opposed by the disproportion between machine size and component size. Laser chemical removal offers a contactless and smooth micro machining of metals using comparatively low laser power densities, which make the use of diffractive optical elements such as digital micromirror device (DMD) possible. Thus, machining accuracy can be increased.
In this project, DMD-technology and laser-based micro processing are combined for the first time in a laser chemical machining procedure. The aim was to realise and characterise a compact module for simultaneous 2D machining, which can be combined with other modules for a qualified use in micro fabrication.



Cube dimension	450 x 450 x 450 mm
Laser	Fiber-laser; 1,080 nm; 300 W
DMD	1,024 x 768 Pixel
Materials	Titanium; stainless steel (50 µm foils)
Electrolytes	5 mol H_3PO_4, 1.9 mol H_2SO_4

GrindBall

Tool drive and bearing concepts for micro grinding tools (GrindBall).

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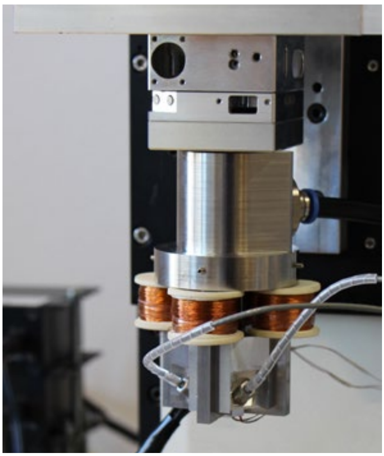
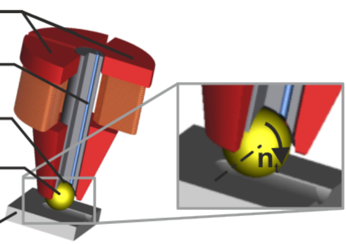


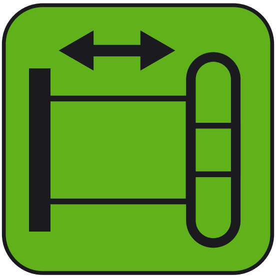
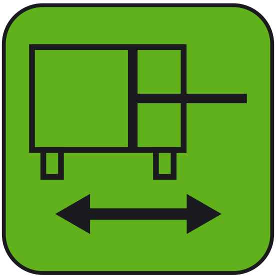
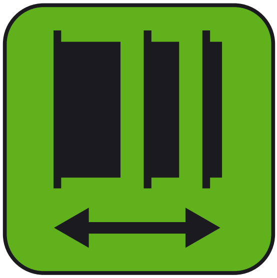
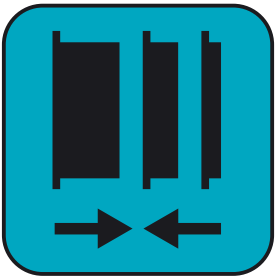
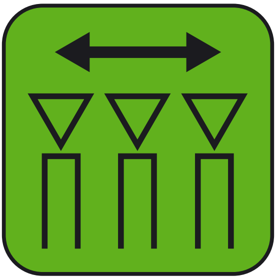
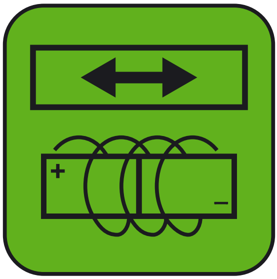
In several fields of application, such as medical technology, optics and electronics, the continuous miniaturisation of complex parts requires small machine tools that are adapted to the workpiece dimensions. These miniaturisation requirements are transferred to the machining components of small machine tools and the latter should have a minimal installation space and have to be able to machine workpieces with a high accuracy. One example of a miniaturised machining component is the GrindBall module for grinding of hard and brittle materials.
The GrindBall module comprises an electromagnetic tool bearing system, a fluid dynamic tool drive and a spherical grinding tool. The positioning and drive principles used in the module enable the spherical tool to perform a contact free grinding process, i.e. the tool has no mechanical connection to the module itself. The contact free bearing and the fluidic drive also provide a unique process kinematics that allows for a lower surface roughness at the bottom of machined grooves.



The fluid dynamic simulation and design of the fluidic channels state that the GrindBall module achieves the optimal operating point at tangential cutting forces F_t = 0.1 N, with a grinding power of Pc = 1,1 W. At the same time, the braking torque of approx. $M_B = 7 \cdot 10^{-6}$ Nm, induced by the electromagnetic bearing is negligible. By using a steel with lower remanence (max. 0.1 T), it is possible to increase the magnetic force to a maximum of approx. 1 N, so that the GrindBall module will be able to reach a maximum grinding power of 1.1 W by using hydraulic oil as tool drive fluid.

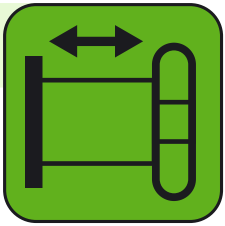
Dimensions	Ø60 x 150 mm
Mass	approx. 400 g
Max. rotational speed (theor.)	12,000 min^{-1}
Grinding power (theor.)	1.1 W

Actuators


Hybrid actuator

Development of a multifunctional feed axis for small machine tools.



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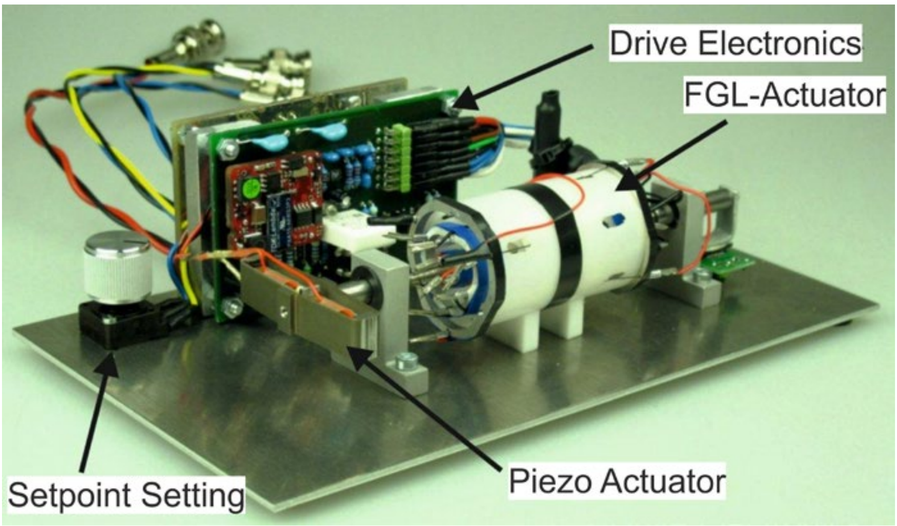

The objective of the project is to develop a multifunctional drive axis for small machine tools of microfabrication. Unlike conventional drive principles here the advantages of piezoceramics and shape memory alloys (SMAs) are combined in one hybrid actuator. The shape memory actuator is used to realise the stroke along the work space and the piezoelectric actuator ensures precision and dynamics. The properties of these smart materials further enable to combine functions. For example, drive- and guidance function can be combined in one element, since the unused degrees of freedom can be covered by the solid state properties of smart material actuators. The design of new control concepts is a further focus of the work. There are two concepts investigated; the independent control of the sub-actuators, as well as cascaded control concepts of the entire module. The ability of the hybrid actuator system is tested by experiments and show the proof of the concept. As a result, there are two functional prototypes of feed axis. One prototype shows a high transverse stiffness and the other one is optimised considering multifunctionality and reduced total mass. The figure shows the second prototype of the hybrid actuator including control electronics.

Technical Data

	SMA actuator	**Piezo actuator**	**Hybrid actuator**	**Requirement**
Stroke	6 mm	0.5 mm	6.5 mm	5–10 mm
Force	50 N	40 N	40 N	50 N
Dynamics	0.2 Hz	200 Hz	200 Hz	200 Hz
Mass	60 x 33 x 33 mm	12 x 50 x 10 mm	60 x 50 x 35 mm	Min.
Cross section	30 g	25 g	80 g	Min.
Stroke ratio			0.1	Max.
Force density			0.5 N/g	Max.

Highly accurate hydraulic feed unit

Highly integrated active feed unit for micro manufacturing with favorable ratio of build and work space.

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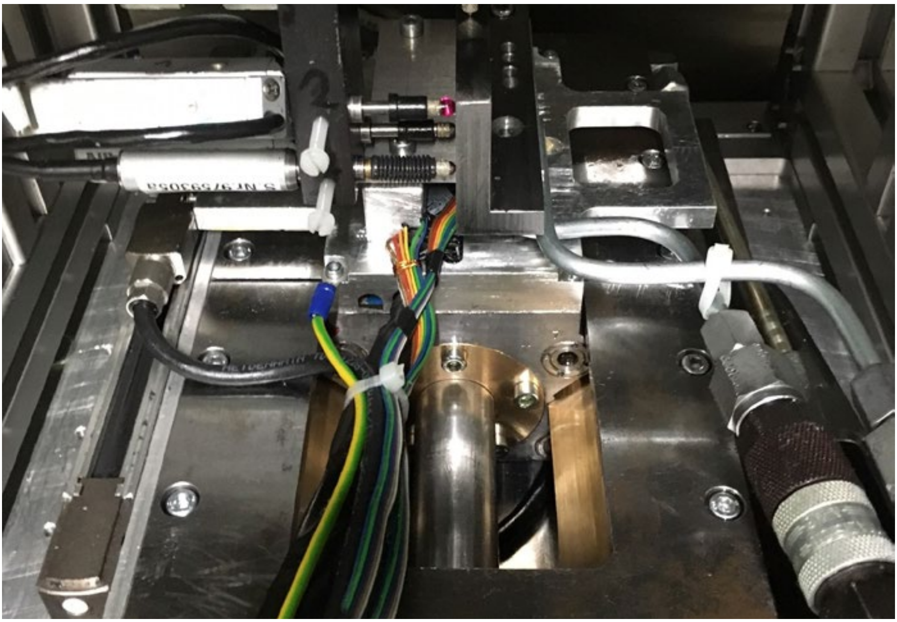
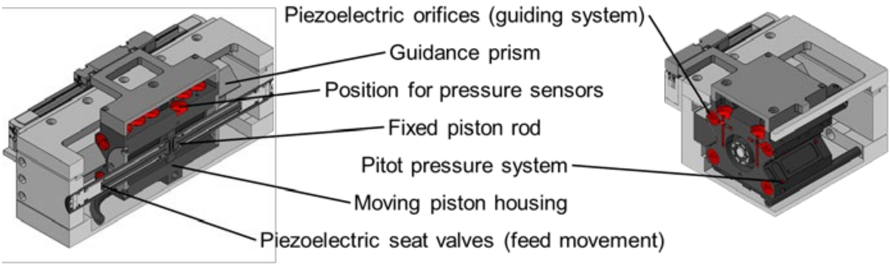


Feed axes in machine tools are used to position tool and workpiece relative to each other. Hence they are of great importance to achieve high machine accuracy. Highly accurate positioning also enables the machine to incorporate geometric errors of different machine components and therefore compensate errors. The concept of the highly integrated feed axis with favorable ratio of build and work space uses different approaches to achieve such compensation and accuracy. The feed movement of the axis is realised with a mobile piston housing that moves on an oil supplied fixed piston rod. In combination with a highly accurate glass scale, piezoelectric valves allow high accuracy and stiffness of the axis. In addition, a hydrostatic guiding system with a total of eight pressure pockets is integrated within the axis module. These are located right above two opposing guidance prisms and can be separately controlled with additional piezoelectric orifices. Controlling the oil flow through the pressure pockets enables the axis to adjust to external forces but also extends its abilities for error compensation. By controlling the

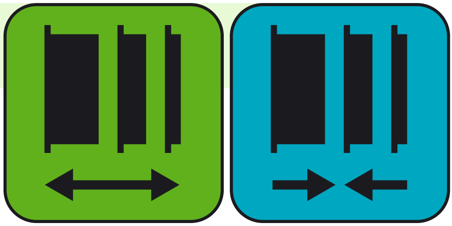


individual gap widths of the pressure pockets, small compensational movements can be made in three rotatory and two additional linear degrees of freedom. The resulting gap widths can be measured with a pitot pressure system. This concept enables the axis to compensate axis-internal errors just as geometric errors of other machine tool components. In addition, the use of oil as a multifunctional fluid medium allows a comparatively compact overall size of the axis.

Travel	100 mm
Two-sided positioning accuracy	3.8 µm
Max. velocity	4,000 mm/Min

SMA actuation and clamping units

Modular desktop machining center with SMA actuation.



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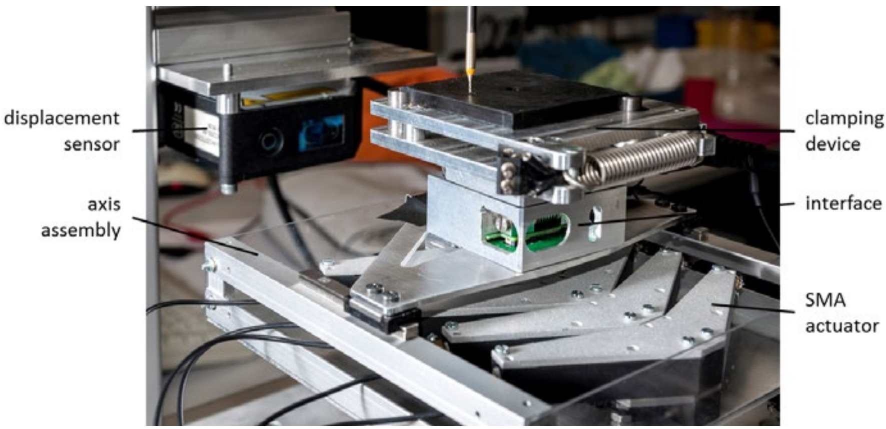
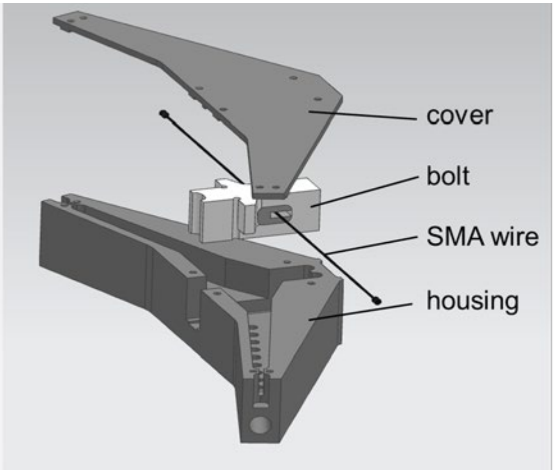


In the context of SPP 1476 „Small machine tools for small work pieces“, the chair of production systems is developing a modular axis for machine tools consisting of multiple actuators.



The individual actuators are powered by a shape memory alloy (SMA) wire which pushes a bolt out of the housing to create a displacement. For a greater overall displacement, the axis contains multiple actuators in a serial arrangement. Three axis assemblies can be combined to form a 3-axis-machine. Each axis can reach a positioning accuracy of around 1 µm. By standardising the actuators, these axes could be sold at a very competitive price.

Alongside the development of this innovative drive concept, a clamping device with SMA actuation was devised. This device will be used in different machine configurations within the SPP 1476. The clamping force is provided by a conventional spring, while the SMA wire is used for opening the device automatically.

Dimensions (x-axis)	150 x 150 x 40 mm
Mass	500 g
Accuracy	1 µm

Fluid dynamic drive

Compact machine modules for micro machining.

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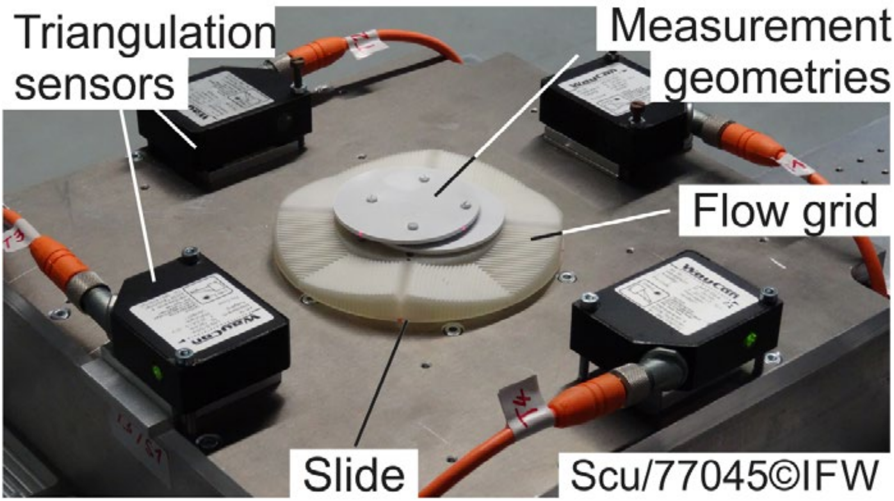
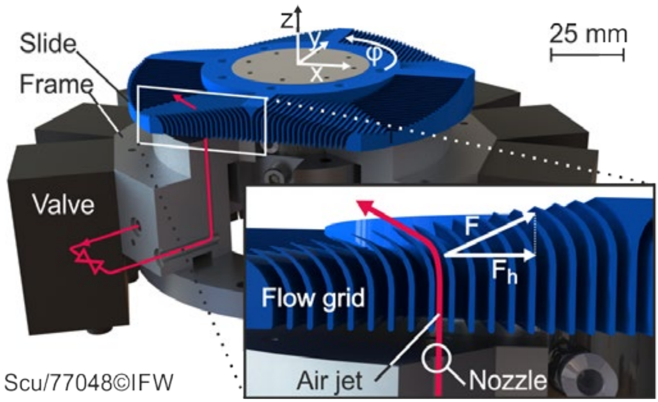


Efficient, flexible micro machining requires dynamic, multi-axis feed movements. Since the potential for significant size reduction of common serial kinematic chains is limited, a novel planar drive for the use in small machine tools has been developed. This drive is based on a fluid dynamic working principle and integrates the drive and guiding functionality of three conventional machine axes in a very compact design. It consists of two main components, namely the moving slide and the stationary frame. The slide has an outer diameter of only 120 mm and can be positioned in the x and y-direction within a workspace diameter of 22 mm. It can also perform unrestrained rotations around the z-axis regardless of its position.

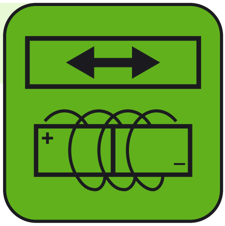


A magnetically pre-stressed aerostatic bearing guides the slide frictionless in the plane of motion. 8 areas of flow grids with alternating orientations are arranged on the outer part of the slide. Each of the twelve nozzles, incorporated into the frame, forms actuator with the opposing flow grid on the slide. The figure shows an air jet streaming out of a nozzle, and being deflected on the flow grid. The horizontal component F_h of the resulting reaction force F drives the slide. Each air jet is controlled individually by a proportional valve which is directly attached to the frame. Position and orientation of the slide is measured by four laser triangulation sensors. Two circular disks of defined diameter are attached eccentrically to the slide (see figure p. 34). The lateral surface of each disk is scanned by two sensors of perpendicular orientation.

Workspace (X,Y)	Ø 22 mm
Rotations (φ)	> 360°
Feed force	1.2 N
Mass slide	0.393 kg

Small compact linear and planar direct drives

Compact Uni- and Multiaxial Electrodynamic Feed Units for Small Machine Tools.



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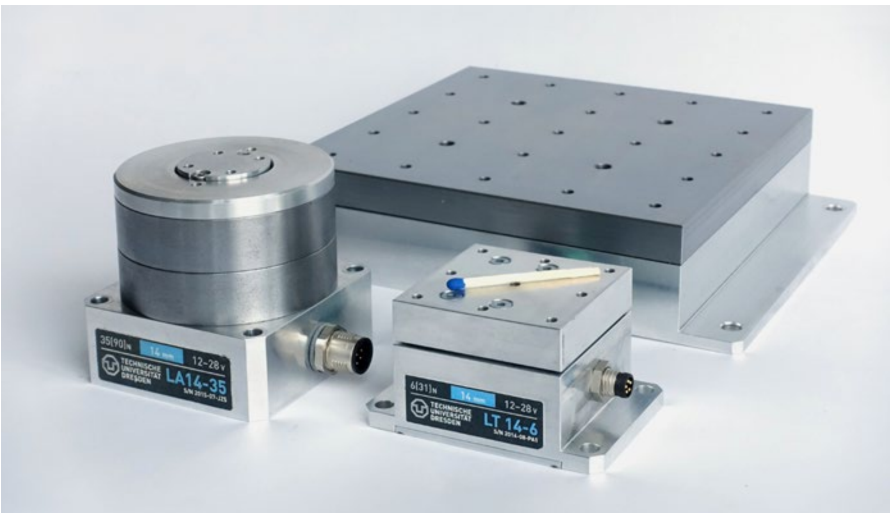
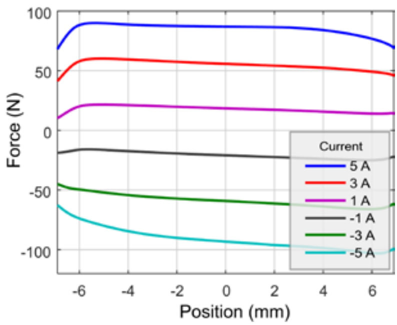
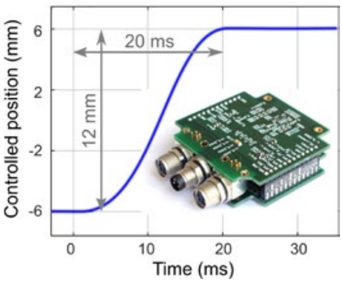


Short travel ranges up to approx. 25 mm enable linear direct drives with simple single-phase design, eg. for small machine tools or automation. Especially designs with moving magnet(s) and an iron core stator winding allow for large actuator constants, i. e. high forces at little losses and small volume. Different types of those compact, dynamic and cost-effective linear axes and tables as well as a novel planar direct drive have been developed, built and tested. They feature:

- integrated ball or flexure guides,
- integrated incremental or absolute position sensors with resolutions from 0.16 to 1.25 µm,
- embedded flatness-based position control,
- “sensorless” force control,
- control commands via EtherCAT, USB or RS 232.

A compact linear axis with integrated ball guide and embedded control is exemplarily shown below, together with its measured force-position-current characteristic and a measured controlled step response. A variant with flexure guide is available too, eg. for precision applications.





Linear Axis LA 14-35	
Travel range	14 mm
Nominal/peak force	±35 / ±90 N
Dimensions	65 x 65 x 63 mm
Sensor resolution	1.25 µm
Supply voltage	12…28 VDC
Interfaces	EtherCAT, RS232

Feed-units based on flexible mechanisms

Qualification of functional integrated feed-units based on flexible mechanisms in small machine tools for small workpieces.

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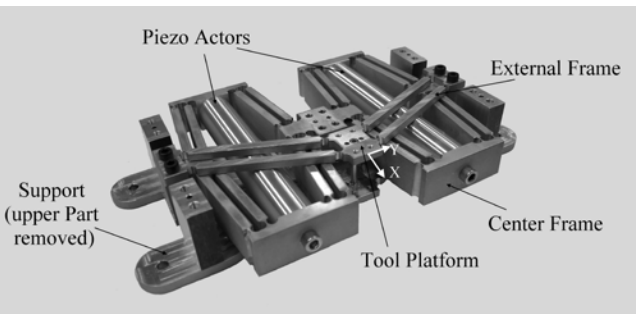
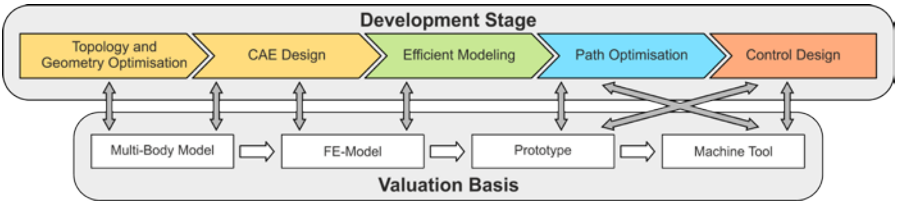


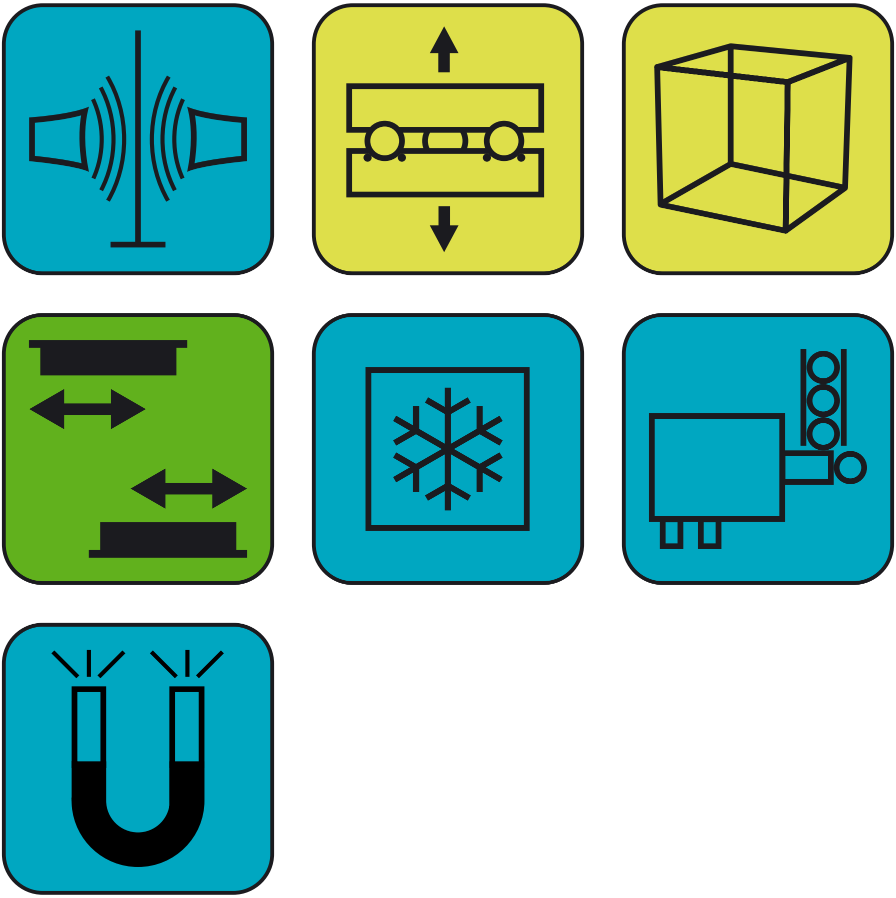
In the course of the joint project a holistic, non-intuitive development process of feeding units on basis of compliant mechanism has been derived. Design engineers and end users from small machine tools based on flexible mechanisms were provided with a scientifically secured and standardized approach to product development. This allows the design of optimal constructive solutions. The process includes the creation of topology and geometry of the elastic joints. Furthermore a corresponding modeling is provided which can be used in mathematical path optimization and design of the adjustment control. By direct integration of development tools into a holistic system the development processes can be designed efficiently.



Exemplary the derived development process was applied by means of a feed unit with two degrees of freedom. The module consists of two piezoelectric actuators whose travel ranges are amplified by a compliant mechanism. Thus, a working space in the X and Y direction was generated, in which a tool or workpiece can operate. To integrate the feed unit optimally into a modular machine tool an adaptive controller was developed that adapts the current configuration and load of the machine tool. The feed unit can be integrated into small machine tools by using interfaces.

Dimensions	210 x 175 x 57.5 mm
Mass	1,750 g
Travel	1.6 x 3.5 mm
Accuracy	1 µm

Additional Modules



High accuracy millimeter wave radar for micromachining

Millimeter wave radar sensors for high accuracy position measuring in small machine tools.

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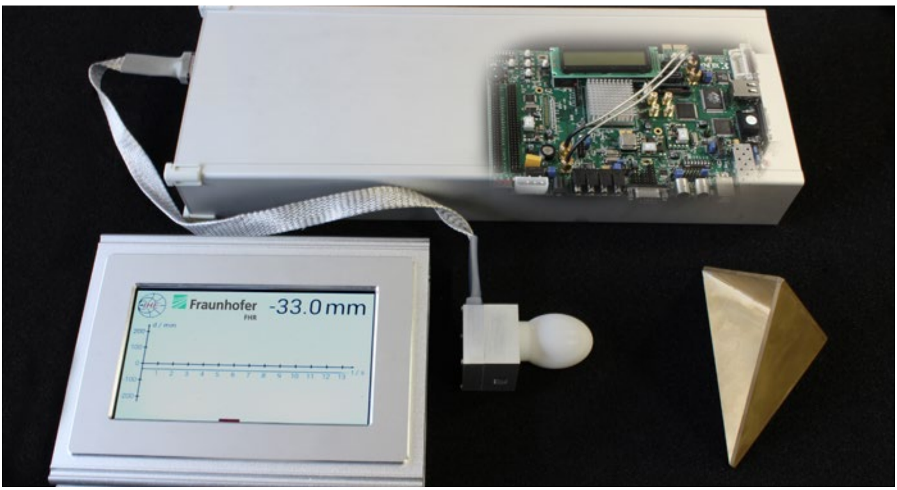
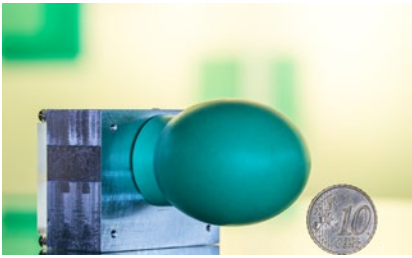
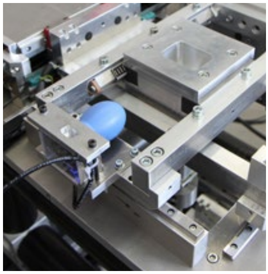




In cooperation of the two institutes FHR and IHE a high precision radar sensor was realized, which features a flexible integration in different micro machining modules. The feasibility of high precision and robust absolute measurements near the tool center point is one of the main advantages of the radar technology. The advancing miniaturisation of the micro machining modules developed in this program requires an adaptive measurement system, which cannot be satisfied by conventional state-of-the-art measurement systems, as there are multiple requirements for the sensor:



- Adaptive, miniaturised measurement solution for a flexible integration in micro machining modules
- High precision measurements near the tool center point for small and large distances with µm-accuracy
- Robust measurements even under harsh environmental conditions like flying swarf, coolant mist, etc.
- Low-cost integration.

The realised radar sensor uses an integrated SiGe transceiver MMIC which allows a cost-effective, mass-market-capable solution. The system is working in the frequency range from 68 GHz to 93 GHz providing a high modulation bandwidth of 25 GHz leading to a range resolution of a few mm and a single-digit µm-accuracy. In combination with the FPGA backend measurement rates up to 100 Hz can be achieved, thus a closed loop control of the micro machining tool can be realised.

Dimensions (radar)	40 x 50 x 77 mm
Mass (radar)	185 g
Accuracy	Standard deviation on fixed target < 1 µm
Absolute accuracy	< 5 µm
Measuring rate (FPGA)	100 Hz / 10 ms
Interface (FPGA)	Ethernet

Multifunctional mechanical interface for small modular machine tools

Multifunctional and intelligent mechanical interface for a quick and precise (re)configuration of small modular machine tools.

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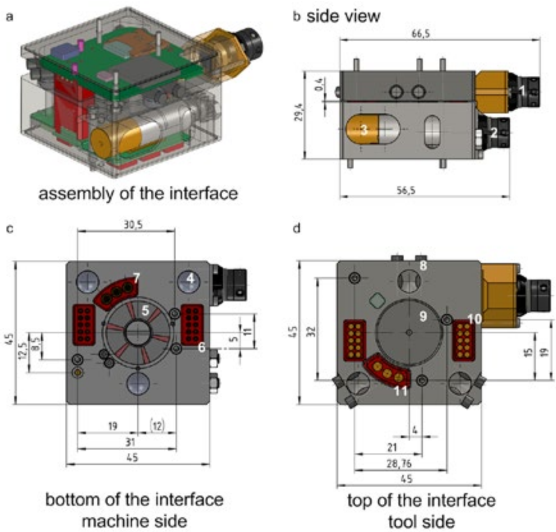
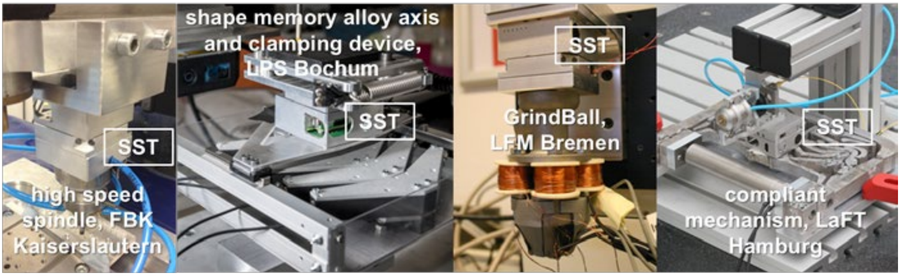


1	external Minimax connector, tool side
2	external Minimax connector, machine side
3	EC-motor
4	ceramic sphere
5	magnetic system
6	signal connector contact pins
7	power connector contact pins
8	carbide rod
9	magnetic flux plate
10	counterpiece signal contacts
11	counterpiece power contacts

Small machine tools for micro manufacturing offer various potentials for modularisation based on the miniaturisation itself. To (re)configure these modules quickly, precisely and with low expenditure to suitable machine tools, interfaces are essential which provide mechanical positioning and the possibility to transfer electrical energy and information.
Therefore, a multifunctional interface (SST) was developed to couple the modules introduced within the priority program. It is also applicable for versatile assembly systems or as a standardised tool connection for small industrial robots.



Successful verification of the SST in small machine tools by (from left to right): using it as a mechanical coupling within a milling/drilling process, using it to transmit signals and power, not influencing or being influenced by magnetic fields, withstanding high acceleration.

The table shows a summary of the interface characteristics.

High precision mechanical coupling through a six point contact and a switchable magnetic system; precision of approx. 0.5 µm (translation) and 0.3´´ (rotation); approx.70 N holding force when closed, approx. 1.5 N remaining force when opened, steplessly adjustable; max. load 170 N
intelligent, safe and automated coupling (identify modules, count number of configurations, deny incompatible configurations, file error budgets of specific configurations)
Harness and save production sequences/histories on workpiece carriers, module generation, tool wear profiles and sensor signals
Signal transmitting via 20 pins; energy transmitting via 3 power pins, 120 W each
Modular, scalable, replaceable, adaptable by the user

Small machine tool

Modular structured and (re)configurable machine tools for micro machining by means of cooperative axis motion.

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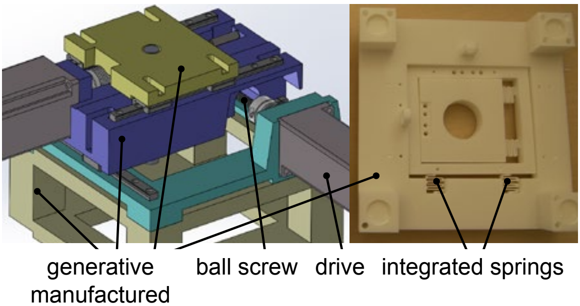
Up to now production of micro machined workpieces takes place on machine tools which are unreasonably large regarding their installation and working space compared to the micro structures that have to be machined. This leads to the approach to set up machine tools that are adjusted to the work pieces that are manufactured. Size-adjusted machines cannot only be set up by down scaling, a basic new construction of frames, drives, and kinematics is necessary.
With the new design approach of the modular Production Cube Module and cooperative axis drives an overall more compact construction can be achieved. Combinations of different production technologies can be achieved by exchanging adapter plates due the possibility of re-configuration.
Further down scaling to small machine tools allows the use of generative manufacturing methods. As a result, individual and flexible machine tools can be designed and novel micro structures can be integrated.



Workpiece clamping systems have big influences on workpiece quality during machining. Especially in micro machining high flexibility of workpiece clamping represent an important requirement. This allows fast and simple clamping and therefore processing of all kinds of components, geometries, and materials. The developed adhesion clamping device can be used with water and wax as a clamping medium. It is possible to clamp any kind of workpiece material. The developed magnetic clamping device is based on permanent magnets. It allows clamping of ferromagnetic materials that are often used in mould-making. Both of these workpiece clamping devices achieve clamping forces of up to 30 N in feed direction.

	Dimensions	Mass
Magnetic clamping	Ø40 x 30 mm	150 g
Adhesion clamping	Ø45 x 36 mm	65 g
Printed machine tool	150 mm³ (without motors)	approx. 5 kg
Small machine tool	450 x 450 x 700 mm	approx. 80 kg

Notes

The whole is more
than the sum of its parts.

— Aristotle