Nanopositioning and Nanomeasuring Machine

User Manual

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BEFORE YOU BEGIN

Read this users' guide through carefully before commencing to use the instrument.

Failing to follow the instructions and observe the precautions appearing in this users' guide might cause safety hazards or conditions that could lead to personal injuries and/or damage the instrument.

Although this guide has been prepared with the utmost care, no liability is assumed for any errors or omissions. We retain the right to alter those products described herein and their specifications at any time without prior notice.

WARRANTY

Those items of equipment described herein are warranted for a period of one (1) year from date of shipment. All rights to claim warranty shall be voided in the event that said items of equipment have been opened, mishandled, or used for other than their intended purposes.

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Safety Information

- Do not expose the device to rain or other moisture.
- Take care that the air vents and other openings remain clear and free of other objects. The air vents should have at least 10 cm of space.
- Do not place the device in hot, sunny, moist or dusty locations.
- Do not expose the device to strong vibrations.
- The device must be placed on a stabile table which is designed for the correct weight and dimensions.
- Mind the correct activating sequence and always turn on the mains switch (labelled ‘Power’) first and always turn it off last.
- The device must be deactivated before switching off the mains. This means that DSP LED 2 and the ‘Enable’ LEDs of the motor units must be off. Only after that may the motor units are turned off with the switch labelled ‘Amplifier’ and the device itself be turned off with the ‘Power’ switch.
- Only change out the specimen while the device is deactivated.
- Do not allow objects to fall onto the corner mirror or the machine in general. Impacts can cause the wrung parts to separate and must be avoided.
- When installing and operating sensors, mind the corner mirror’s range of motion and its covering.
- When beginning a measurement, the specimen is placed directly onto the corner mirror stage and this should be done with extreme care. Use one of the protective glasses included in order to prevent damage to the stage. Removing the reflecting mirror cover is not allowed under any circumstances.
- Changes in the controller parameters could lead to destruction of the device. Therefore, changes to the controllers are not permitted.
- Always operate the device at 220 V to 240 V AC, 50 Hz.
- Only use the emergency switch in actual emergencies!

The power-supply/signal-analyzer unit incorporates a He-Ne-laser that uses high voltages for its operation and is capable of reaching output powers in excess of 2 mW. Its beam is transmitted from the power-supply/signal-analyzer unit to the sensor head by a fiberoptic cable. The interior of the power-supply/signal-analyzer unit thus harbours electrical hazards due to the presence of the line voltage and high voltages, as well as eye hazards due to laser emissions (the laser employed falls under Laser Safety Class 2M). The power-supply/signal-analyzer unit and sensor head should thus be opened only by persons who have been trained by SIOS Meßtechnik GmbH.

CAUTION!	Failure to observe these notices could lead to serious health hazards or eye injuries, including blinding.

The safety regulations to be observed by manufacturers and users of laser devices are those specified under DIN EN 60825-1 (VDE 0837 Part 1):2001-11. All provisions of this standard related to the design and construction of laser systems have been observed in engineering both instruments.

Note:	All safety regulations stipulated under DIN EN 60825-1 (VDE 0837 Part 1): 2001-11 should be observed at all times while the laser is operational.

Electronic modules, except for the power-supply modules, may be removed from the power-supply/signal-analyzer unit's rack by unscrewing their front-panel fastening screws and sliding them forward.

CAUTION!	Removing a power supply or the power-supply module may expose wiring terminals on their rear panels that carry line voltage while the power-supply/signal-analyzer unit is switched on.

To gain access to the laser and its fiberoptic coupler, remove the screws fastening the rear panel of the power-supply/signal-analyzer unit to the unit and remove the panel.

CAUTION!	The laser requires a high DC-voltage, which is provided by a power supply located immediately adjacent to the laser, for its operation. Always unplug the power-supply/signal-analyzer unit's line cord from the electrical outlet before removing its rear panel.

Preface

Nanopositioning and nanomeasuring technology is on the cutting edge of modern precision engineering and measurement technology. High-accuracy measurement on the nanometre level has wide-reaching applications in many fields of science and engineering. Many organisations on the international scale are involved in developing this relatively new technology.

This manual will attempt to give an overview of different aspects of one such device that brings nanomeasuring technology to reality. The device is known as the Nanopositioning and Nanomeasuring Machine (NMM-1).

The manual is divided into the following chapters:

Chapter 1 describes the background and metrological basis for the device. This includes such topics as the realisation of the Abbe comparator principle and a description of the basic functionality.

Chapter 2 describes the installation of the device as well as tips for the initial setup.

Chapter 3 offers a summary of the basic machine operation with some examples of actual measurement procedures.

Chapter 4 gives an overview of the software necessary to operate the NMM machine.

Chapter 5 gives some tips for caring and maintaining the machine in order to ensure reliable operation.

Chapter 6: describes some necessary steps in case of problem do occur.

The authors hope you find this manual helpful and informative. Comments, questions and suggestions are very welcome and should be directed to the manufacturer. Successful measuring!

1 Background and Functionality

The main goal of the nanomeasuring machine is to provide a three-dimensional positioning and measuring range of 25 mm x 25 mm x 5 mm with a resolution 0.1 nm. The machine must be traceable to the international standards and to the definition of the meter with the highest possible accuracy and an uncertainty of less than 10 nm. Finally, it must be possible to apply different task-appropriate surface-sensing probes and tools to the job at hand. All of these goals means that the NMM is capable of handling a wide spectrum of applications. It is even possible – through the use of AFM or STM probes – to use the machine for long-range scanning probe microscopy.

1.1 Mechanical Systems and Optics

1.1.1 Abbe Comparator Principle

The most important principle for the NMM was formulated in the 19th century by the German professor Ernst Abbe. This principle states that the specimen's line of measurement and the normal's line scale must be aligned in order to avoid first-order measurement deviations. The cause of these measurement deviations is the systematic and the random tilting of the measuring instrument's guide elements. The calculation of first-order deviations can be derived from figure 1.1 and it can be described with equation 1.1. The measuring object is positioned on a measuring mirror and is scanned from above with a contact system which is fixed to the frame. Object movements along the z-axis are measured from below using an interferometer. The measuring object and the measuring mirror are shown both in a straight and in a tipped position. Because the contact system is attached to the frame, the contact point becomes the pivot point about which the object and the mirror tilt.

$$\Delta l_1 = s \cdot \tan(\varphi) \qquad (1.1)$$

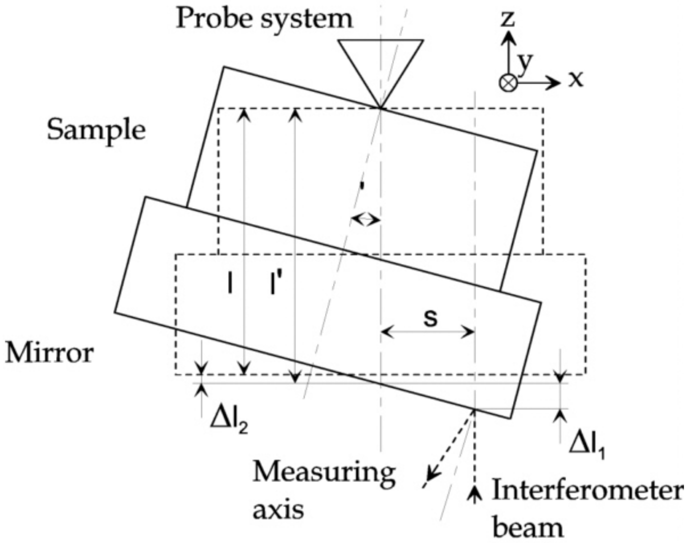


Figure 1.1: First- and second-order measurement deviations

Not only does the tilt φ influence the calculation but also the lateral offset s between the measurement axis of the length measuring system and the measuring section. In multi-coordinate measurement technology the measuring sections are made up of straight lines running through the contact point of the probing element with the measuring object and running parallel to the coordinate system axes. According to equation 1.1 there are two possibilities to reduce the deviations. One method is the Abbe comparator principle which reduces the lateral offset s. The other possible is the reduction of tilt in the guideways. Only first-order deviations can be avoided through the realisation of the Abbe comparator principle. Tilting also causes second-order deviations. If the interferometer measurement axis is flush with the working section, only the deviation Δl_2 can occur. Equation 1.2, which is derived from figure 1.1, can be used to calculate this deviation.

$$\cos(\varphi) = \frac{l}{l'}$$

$$\Delta l_2 = l' - l = \frac{l}{\cos(\varphi)} - l = l \cdot \left(\frac{l}{\cos(\varphi) - 1} \right) \qquad (1.2)$$

The deviation is dependent on the tilt φ and the distance *l* resulting from the thicknesses of the measuring object and the measuring mirror. The second-order deviations are always positive, whereas the sign first-order deviations is dependent on the angle value.

1.1.2 Design Variants

In accordance with the statements made in previous section, it was necessary to find a concept for implementing the Abbe comparator principle in the nanopositioning and nanomeasuring machine. In many length measuring devices this fundamental principle is realised through the correct arrangement of the specimen and the normal. However, in order to apply the principle in coordinate measuring equipment an appropriate concept for arranging the drive and measuring systems had to be developed in order to make sure the axiom is fulfilled for all three coordinates.

In coordinate measuring systems the measuring object is contacted by the probe at one specific point. At the same time the measured values of both the probe system and the length measuring system are recorded. In order to complete a measurement at different points on the object surface, the measuring object and the probe system must be positioned relative to each other in all three coordinates. The linear guideways and drive systems are used for this purpose. The guideways exhibit both translational and rotational guide errors. These rotational errors are the cause of the deviations illustrated in section 1.1.1.

Through the combination of more than one guideway, the errors of the individual guides add together to form a total error. This creates the requirement that the number of guideways be minimised. Only three linear guides should be used for the realisation the three translational degrees of freedom. Because either the measuring object or the probe system must be guided in each of the coordinate axes, the number of possible arrangements of the guide-drive system is reduced to four (see figure 1.2).

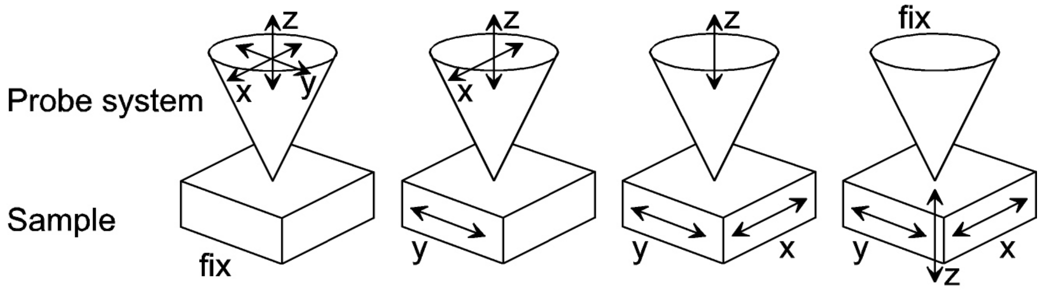


Figure 1.2: Possible arrangements of drive and probe systems

1.1.3 Basic Set-up

As previously stated the required measurement precision of an NMM machine can only be achieved through the implementation of the Abbe comparator principle in all three dimensions. By comparing the design variants given in section 1.1.2, it becomes obvious that only one set-up yields the necessary precision. In the chosen arrangement the probe system and the three length measuring systems are fixed together onto a stable frame. The measuring axes of the length measuring systems must intersect at the contact point of the probe system (see figure 1.3). The frame material should possess a very small thermal coefficient of expansion so that no significant length measurement uncertainty arises from changes in temperature.

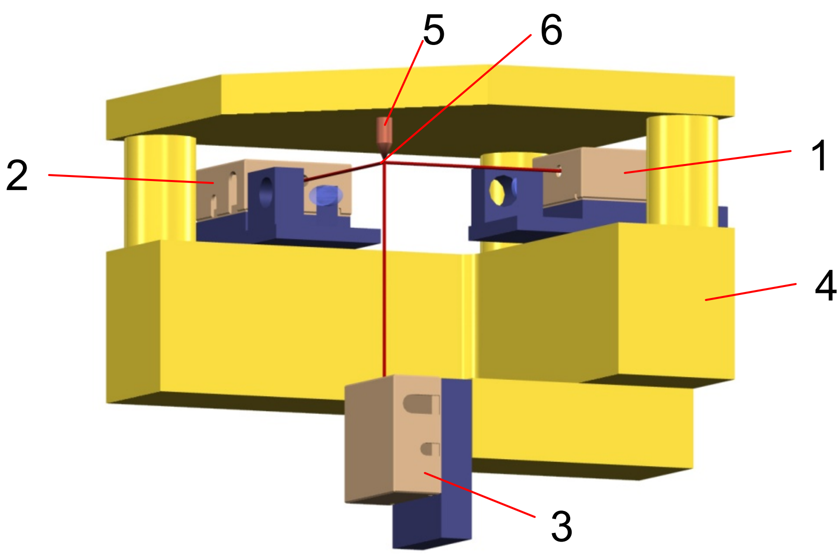


Figure 1.3: Arrangement of the probe and length measuring systems: 1 x-interferometer, 2 y-interferometer, 3 z-interferometer, 4 Zerodur® frame, 5 probe system, 6 Contact point of the probe system with the measuring object

During the measurement the measuring object and the frame and measuring system must be positioned with respect to each other in that way, that one of the two assemblies is moved. However, a movable set-up for the frame and measuring system should be avoided because the frame could deform itself during a movement, which could lead to measurement deviations. The deformations could either occur dynamically or be caused by constantly changing loads. The large mass of the frame and the measuring systems could severely limit the positioning and measurement dynamics. For these reasons a movable arrangement for the measuring object is preferable.

Interferometers are used in the NMM machine as length measuring systems. These are the only systems which possess the necessary high measurement resolution and accuracy and they allow the traceability of the length measurement. The interferometers require reflectors which must be fixed to the measuring object. The outer reflecting faces of the corner mirror serve as the measuring reflectors of the NMM machine. The measuring object lies on top of the corner mirror and is moved together with it.

The corner mirror is mounted onto a three-axis guide-drive system, a combination of a roller guideway and an electromagnetic drive for each of the x- and y-axes. The x-axis is mounted to the foundation and carries the y-axis and the z-axis is in turn carried by the y-axis. Three round, short roller guideways and four electromagnetic drives are used for the z-axis. Because of the small guide lengths, the possible tilt errors of this guide are significantly higher than the errors of the other axes. Additional optical angle measuring systems mounted on the frame measure the tilt of the corner mirror at both of the lateral mirror faces (see figure 1.4). Angular control of the tilt angle about the x- and y-axes is possible with the angle measurement data and the four individual drives. The entire guide-drive system must possess an opening for the z-axis measuring beam. The size of the opening must be adapted to the range of motion because the measuring beam must not be interrupted.

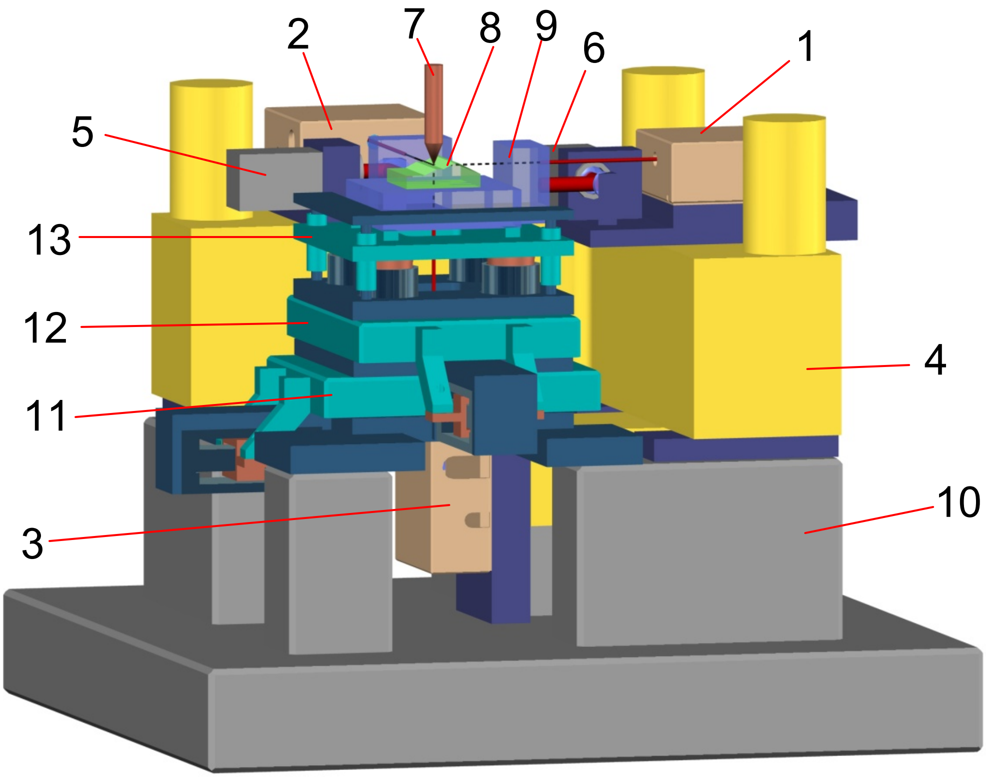


Figure 1.4: Basic set-up of the NMM machine: 1 x-interferometer, 2 y-interferometer, 3 z-interferometer, 4 Zerodur® frame, 5 Roll and yaw angle sensor, 6 Pitch and yaw sensor, 7 probe system, 8 Measuring object, 9 Corner mirror, 10 Foundation, guide-drive systems of the 11 x-axis, 12 y-axis 13 z-axis

The guide-drive system is rigidly fixed to the foundation. The Zerodur® frame with the measuring systems is mounted to the foundation at three points. The thermal coefficients of expansion of the Zerodur® frame and the granite foundation differ greatly. This would lead to mechanical stress and deformation in the case of a rigid connection between the two parts. In order to avoid the resulting length measurement deviations, both parts are only connected rigidly at on support point. Additionally, using this arrangement prevents mechanical feedback from the guide-drive system to the Zerodur® frame. Consequently, the metrology frame and the connecting elements of the guide-drive system are separately constructed and are thus mechanically decoupled from one another.

1.1.4 Mechanical and Optical Sub-assemblies

The goal of the design was a compact mechanical and optical design foundation. Accordingly, the sub-assemblies are arranged in such a way as to only require a square foundation of only 420 mm x 420 mm. Without the probe system the assembly has a total height of 340 mm (see figure 1.5). Defined mechanical and electrical interfaces are provided for the contact system that make simple installation and interchange possible for the user. Three threaded shafts project from the housing and a Zerodur® plate for a portal mount can be fixed to these shafts. The probe system is fixed to this set-up in such a way that the contact point coincides with the intersection point of projected measuring axes of the interferometers. This basic set-up can be classified into the following sub-assemblies according to their function:

- Foundation and Zerodur® frame
- Guide-drive system
- Measuring corner mirror and measuring object stage
- Length measuring systems
- Angle measuring systems
- Probe or contact system

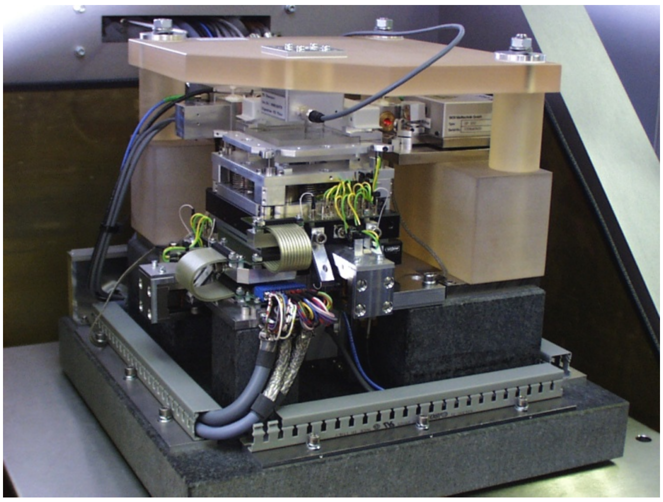


Figure 1.5: Mechanical and optical set-up

Foundation and Zerodur® frame

The main component of the foundation assembly is a massive granite body. This body is made up of a base slab with four columns installed. The columns support the Zerodur® frame as well as the guide-drive system.

Guide-drive system

Linear guideways are necessary for the realisation of the nanopositioning and nanomeasuring machine. These guides must demonstrate a large range of motion and simultaneously allow sensitive, high-precision movements on the nanometre level. The motion of the NMM machine is provided by linear electromagnetic drives. The functionality of these DC linear motors is based on force exerted on a charge-carrying conductor in a magnetic field. The resulting Lorentz force is described by equation 1.3.

$$\vec{F} = I \cdot (\vec{l} \times \vec{B}) \qquad (1.3)$$

The drive system generates a force which accelerates the mass of the movable parts of the guideway and the drive (see figure 1.6). The frictional forces created by the guide elements must also be overcome. The minimum positional resolution is dependent on the control loop and on the resolution of the measuring systems used. The stability of the speed of motion is also dependent on the control loop. Because this drive possesses neither form nor force closure, a constant position regulation is required in order to hold a constant position.

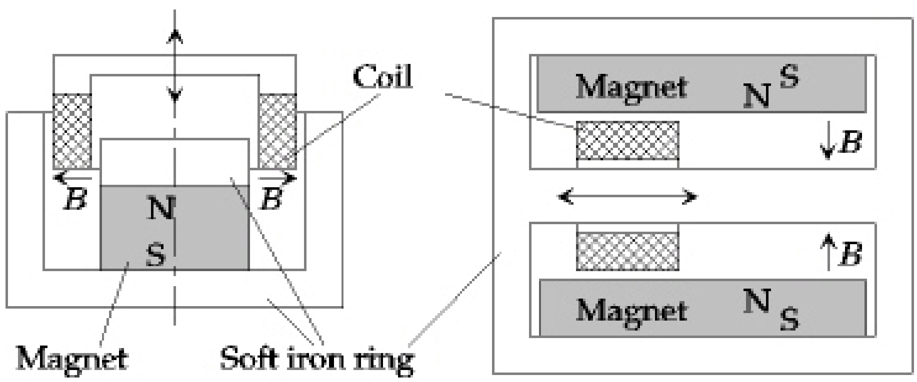


Figure 1.6: Functionality of the z-drive (left) and the x- and y-drives (right)

Measuring corner mirror

An important element of the NMM machine is the measuring corner mirror. This component serves as the reference coordinate system during the measurements. The corner mirror is made of Zerodur® plates with a reflective coating on one side. The two smaller plates are wrought sideways onto the largest plate (see figure 1.7). The accuracy of the outer reflective surfaces is λ/20. The orthogonality deviations arising during manufacturing are better than two arcsec (2”). However, these accuracies are insufficient for the demands of the NMM machine. For this reason the deviations were measured interferometrically before installation. The results are used for online measurement correction in the measuring machine.

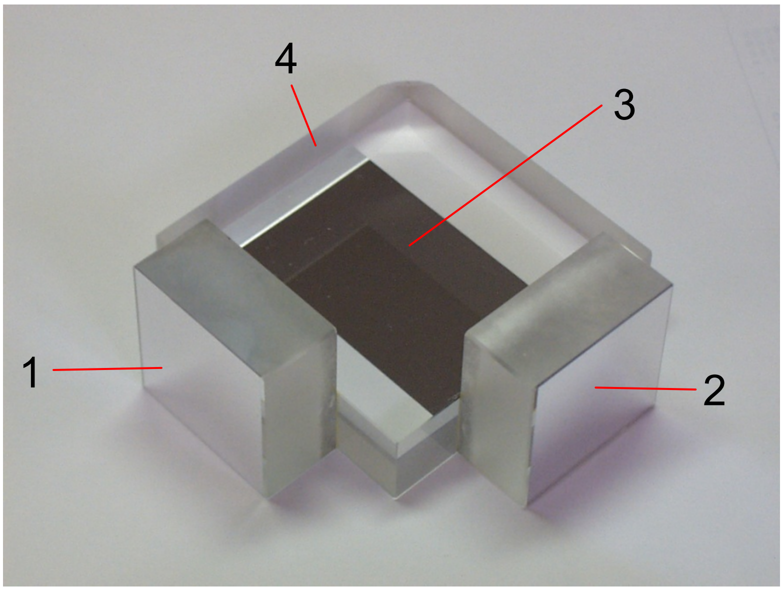


Figure 1.7: Measuring corner mirror: 1 x-Interferometer mirror surface, 2 y-Interferometer mirror surface, 3 z-Interferometer mirror surface, 4 Object stage

The corner mirror is installed into the mounting such that the interferometer measuring beams strike the mirror surfaces at right angles. Additionally, the angle sensors measure the tilt of the two sideways mirror surfaces. Finally, the specimen is placed of the corner mirror.

Length measuring systems

Interferometers of the type SP-500 (manufactured by SIOS) are the primary component used in the length measuring systems.

Angle measuring systems

The angle sensors in use are based on the principle of the autocollimation telescope. The measuring beams are directed to the corner mirror using an adjustable deflection mirror. The electric measuring signals of the autocollimator are sent to the supply and processing device for further processing.

Probe or contact system

The primary task type for the NMM machine is the precision analysis of specimens. For that, a system for probing and sensing the measuring object is necessary. Various tactile and optical techniques can be utilised in the sensor according to the measurement task and the choice of method is heavily dependent on that task. Therefore, the mechanical, electronic and software interfaces of the device were designed to be both simple and flexible to allow the widest possible range of applications.

An analogue, displacement-proportional output signal from the contact system is required for integration into the measuring value processing system. The resolution capacity of the probe should be equal to the interferometers in the NMM. The operating range can be small, however, since the signal is only used by the control system to probe the specimen surface. Changes in specimen height are tracked by the control system and the corner mirror and also the specimen is adjusted accordingly. Outside of the operating range the probe should output a defined signal to the control system, e.g. positive or negative saturation voltage (see figure 1.8).

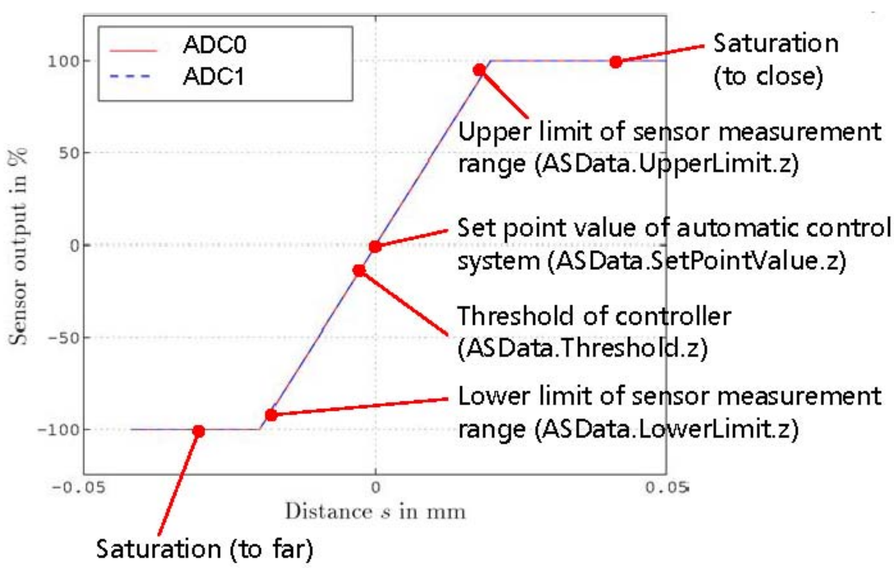


Figure 1.8: Typical probe characteristic curve

One example of a probe is a focus sensor (see figure 1.9). This sensor type has an atypical characteristic curve. The signal dependency on the distance to the focal point is shown in figure 1.10. The linear region which is useful for measurements lies between the minimum and the maximum of the difference signal. The linear region represents the physical range of 3 µm to 20 µm and is dependent on the laser output power, the signal gain and the reflectivity — the same as the slope of the characteristic curve. The recognition and retrieval of the measuring range is made difficult by the curve’s shape. Reliable probing is only possible with prior information about the position of the focal point. The required direction of motion to the specimen must be known externally while the probe is operating outside of the linear region.

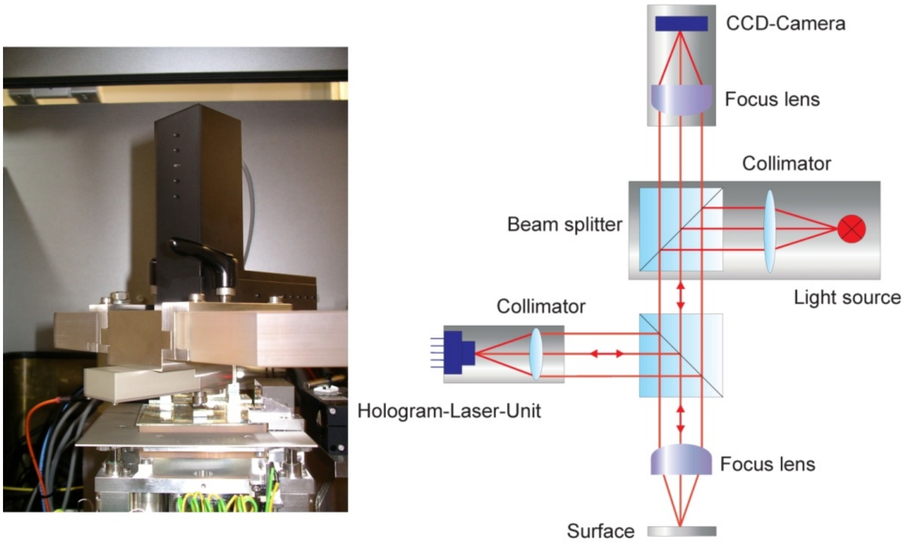


Figure 1.9: Focus sensor

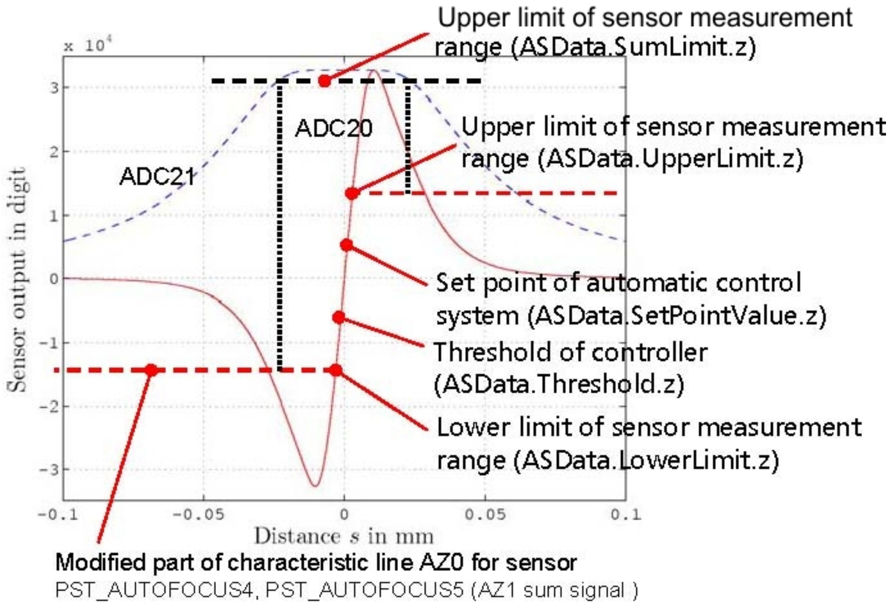


Figure 1.10: Typical characteristic curve for a focus sensor

A significant increase in horizontal and vertical resolution is only possible using the methods of scanning probe microscopy. One especially useful technique is atomic force microscopy (AFM).

The main component of an AFM sensor element is a very fine pyramid-shaped silicon tip fixed to the end of a small cantilever (see figure 1.11). The tip angle is approximately 50° to 60° in the direction of the cantilever and 40° to 50° in the transverse direction. A tip radius of < 10 nm can be achieved. The entire tip is has a height between 10 µm and 15 µm. The form and dimensions of the cantilever are dependent on the operating mode. For a contact-mode sensor typical dimensions are a length of 450 µm, a width of 50 µm and a thickness of 2 µm. Additionally, a reflective surface can be applied to the back side in order to facilitate optical displacement measurement.

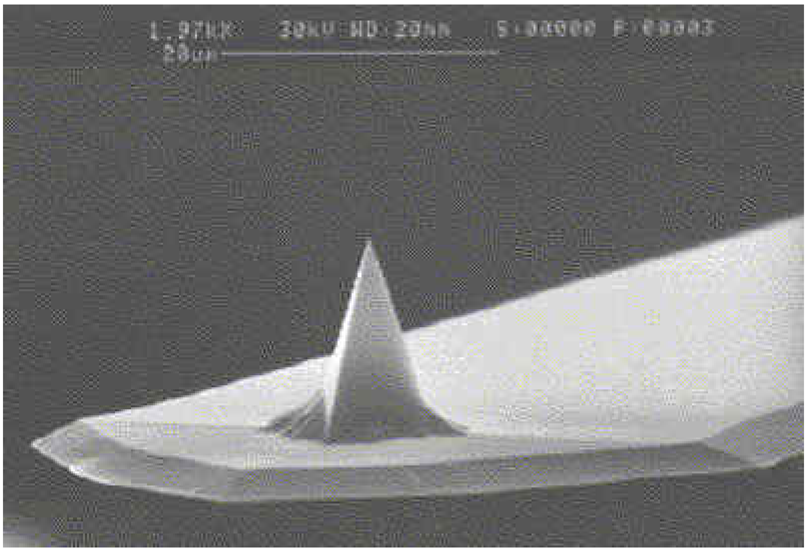


Figure 1.11: AFM cantilever with silicon tip
(source: NANOSENSORST is a trademark of NanoWorld AG - Copyright by NanoWorld AG)

Contact mode, non-contact mode and various dynamic modes have prevailed as standard operating modes for AFM probes. In contact mode the tip remains in constant physical contact with the specimen surface, using the arising repulsive force for cantilever displacement. Non-contact mode utilises attractive force between the tip and the specimen and the tip is located at a distance of several nanometres above the specimen surface. The dynamic modes utilise stimulated oscillations to measure the changes of those oscillations as a function of the repulsive or attractive forces between the tip and the specimen. Atomic force microscope systems allow the highest possible lateral resolution on the specimen surface because of the very small contact radii.

In most types of scanning probe microscopes the sensor element is moved over the measuring object surface with the help of a piezotube. In these systems the position of the contact tip is set using the control voltages of the piezoelements. The position value has relatively large deviations due to the thermal and piezoelectric properties of the adjustment mechanism. However, the probe system only serves as a zero-point sensor in the NMM machine and the contact point is stationary, which reduces the effects of those deviations considerably. The only set-up required is one with a sensor element and a system for measuring the displacement. Additionally, this assembly can be outfitted with an oscillator to allow dynamic-mode scanning. Please, refer to the corresponding manual of AFM used together with the NMM.

1.2 Electronics

Aside from the mechanical and optical set-up, there is an extensive electronics assembly for the NMM machine which provides the electric current supply and which gathers and processes the measuring data. Because the electronic components generate a significant amount of heat, a physical separation was provided between the mechanical-optical assembly and the electronic supply and processing device. Accordingly, only the mechanical-optical set-up is required to be under metrologically superior conditions, such as with climatisation and vibration and acoustic isolation. The two main device components are connected through optical and electric cables.

Three frequency stabilised He-Ne lasers serve as the light source for the interferometers. The laser light is fed into the laser unit (see subsection 1.2.4) using polarisation preserving optical waveguides (see figure 1.12). The electric interferometer measuring signals as well as the angle and temperature sensors are carried to the interferometer unit (see subsection 1.2.3). This unit is responsible for the electronic pre-processing of the measuring signals, which are then passed on to the DSP unit (see subsection 1.2.2). This component contains demodulation and analogue-digital converter assemblies for synchronous acquisition of the sensor measuring signals. After the primary measurement processing step in the DSP, the controller input signals are output through digital-analogue converters to the motor amplifiers in the motor unit (see subsection 1.2.1). The amplified control signals are fed directly into the six electromagnetic drives. The supply and processing electronics are integrated into a 19-inch housing and is connected to a computer. The interface for control commands and measuring data between the NMM machine and the computer is USB. The user specifies the measurement procedure by running scripting commands on the computer.

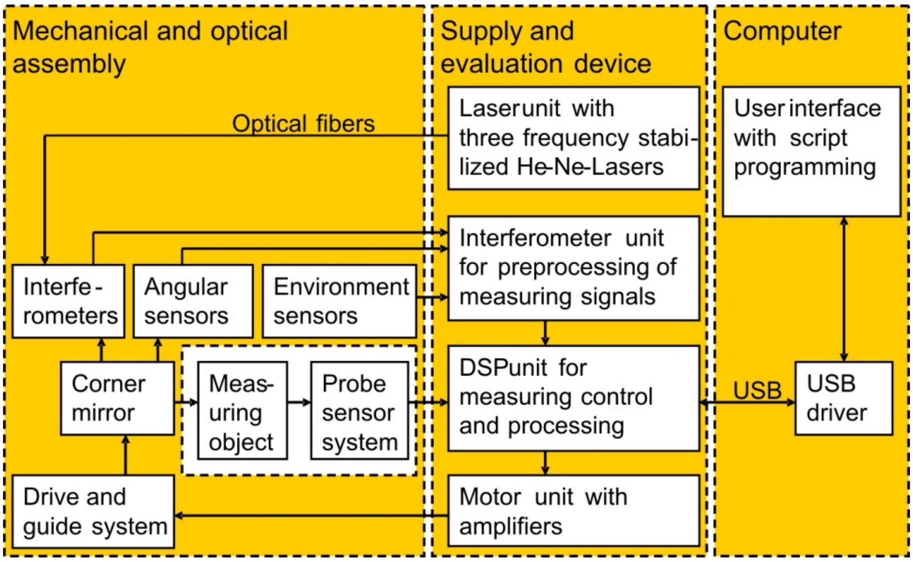


Figure 1.12: Electronics structure of the NMM machine

1.2.1 Motor Unit

The motor unit contains the motor drivers and their power supplies. The motors are directly connected to this unit. All control signals are carried through the two front-side connections with the DSP unit. The drivers can be activated with the DSP unit. The activation status is indicated by the green LEDs labelled ‘Enable’ on the amplifier modules; these LEDs light up after a successful activation. Thermal circuits have been integrated into the drivers in order to protect against heat damage. Overheating is indicated by the red LEDs labelled ‘Fault’. These signals are also processed by the DSP and lead to a deactivation of the motor drivers.

1.2.2 DSP Unit

The digital signal processor (DSP) unit is the heart of the electronics assembly. All measurement and control signals are processed by the DSP. Accordingly, all signals must be fed into and received from the unit. Both a mains switch and a reset button are located on the left side. The four LEDs indicate the operational state of the device.

Number	Colour	Function
1	red	Mains indicator
2	green	Device is active
3	green	Device is in motion or is measuring
4	yellow	USB is active (blinking indicates an active transfer)

Table 1.1: LED allocation in the DSP

The software for documenting and processing the measurement reading is executed on the DSP unit. The program is loaded from flash memory and the module hardware and periphery modules are initialised. After that, device-specific configuration data are loaded from flash memory. These data are adapted to each individual device. Then, the USB interface and the interrupt timer are initialised, after which the timer modules and interrupt processing are enabled. From this point forward the main program of the DSP runs in an infinite loop, where commands received by the USB interface control the measuring and programming procedure of the device.

1.2.3 Interferometer Unit

The components in this unit deal with measurement data pre-processing for the interferometers and the angle measuring systems. The breakdown of the assembly can be found in figure 2.1. For a more detailed description of the assembly and its operation, please confer the instruction manual for the miniature plane-mirror interferometer (SP 120/500/2000) and the position-sensitive quadrant-diode detector.

1.2.4 Laser Unit

Three stabilised lasers are contained within the laser unit. The stabilisation status of each laser is indicated by the corresponding LEDs. Correct measurements can only be performed when all three lasers are stabile. Please mind the information contained in the instruction manual for the miniature plane-mirror interferometer (SP 120/500/2000).

1.3 Data Acquisition and Processing

The measurement information attained through the mechanical and optical systems are gathered and analysed in the electronics unit. The flow of information within the electronics unit and the DSP in particular is shown in figure 1.13. The sensor signal inputs are prepared in the supply and processing device, specifically in the interferometer unit (see subsection 1.2.3). The values for the interferometer signals as well as for air temperature, air pressure and the angle sensors are transferred to the DSP unit. After the signals are correctly conditioned by the tacho-controller and the A/D-D/A converters, the signals are available for software processing in the DSP itself. The procedure shown in figure 1.15 is carried out at a frequency of 6.25 kHz.

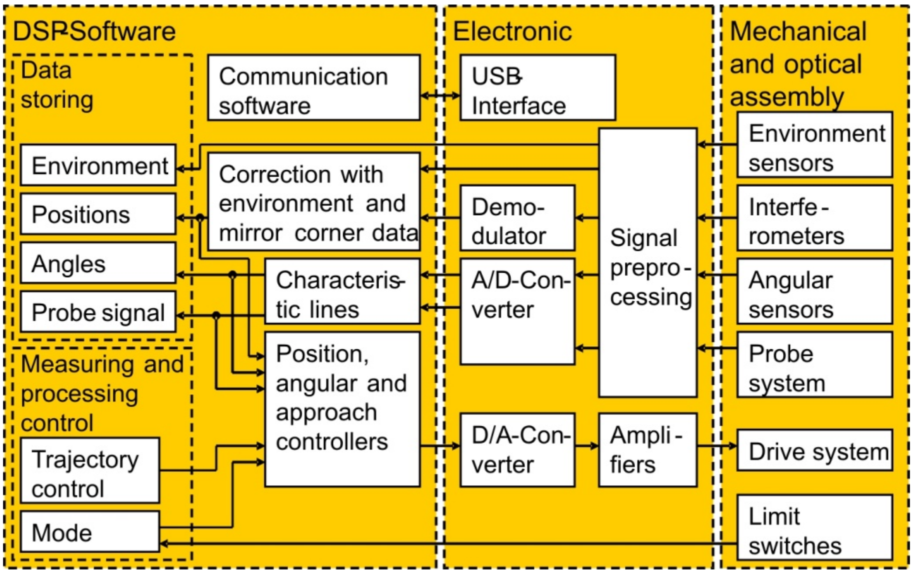


Figure 1.13: Basic principle for data acquisition and processing

In order to increase accuracy in the NMM machine, it is necessary to correct the interferometric length measurements using additional data. Two correction algorithms have been implemented in the measurement post-processing procedure. As can be seen in figure 1.15 the first correction uses environment information (air temperature, air pressure and humidity) to adjust the refractive index of air. If a direct humidity sensor is not installed, an assumed vapour pressure of 1150 Pa is used. All in all, the influencing factors taken into account by the DSP are dead-path (difference between the lengths of the reference and measuring paths after zeroing the counter), the refractive index after zeroing, the current refractive index, the wavelength of the laser in a vacuum, the interferometer factor and the division factor.

A further algorithm corrects the length measuring data using the corner mirror correction data. The contour of each individual corner mirror is measured after installation and a high-order function is used to represent that contour. Using this function, it is possible to significantly reduce measuring errors resulting in surface planar deviations. The determination of the function coefficients occurs directly through the use of the measured values of the corner mirror. Equations 1.4, 1.5 and 1.6 show the functions as they are implemented and the parameters are calculated with regression algorithms.

$$\begin{aligned} x_c = {} & x + k_{x0} + k_{x1} \cdot y + k_{x2} \cdot z + k_{x3} \cdot y \cdot z + k_{x4} \cdot y^2 + k_{x5} \cdot z^2 \\ & + k_{x6} \cdot y \cdot z^2 + k_{x7} \cdot y^2 \cdot z + k_{x8} \cdot y^3 + k_{x9} \cdot z^3 \end{aligned} \quad (1.4)$$

$$\begin{aligned} y_c = {} & y + k_{y0} + k_{y1} \cdot x + k_{y2} \cdot z + k_{y3} \cdot x \cdot z + k_{y4} \cdot x^2 + k_{y5} \cdot z^2 \\ & + k_{y6} \cdot x \cdot z^2 + k_{y7} \cdot x^2 \cdot z + k_{y8} \cdot x^3 + k_{y9} \cdot z^3 \end{aligned} \quad (1.5)$$

$$\begin{aligned} z_c = {} & x + k_{z0} + k_{z1} \cdot x + k_{z2} \cdot y + k_{z3} \cdot x \cdot y + k_{z4} \cdot x^2 + k_{z5} \cdot y^2 \\ & + k_{z6} \cdot x \cdot y^2 + k_{z7} \cdot x^2 \cdot y + k_{z8} \cdot x^3 + k_{z9} \cdot y^3 \end{aligned} \quad (1.6)$$

The uncorrected values *x, y* and *z* are the ones used at the beginning of each equation. After the correction is carried out, the measuring values can be saved and utilised within the control system.

With the additional use of the A/D-converter data as well as the angle and contact sensor data, the interferometer can be used for whatever further purposes the user deems necessary. The values from A/D-converters, the angle sensors and the probe are first linearised in order to provide a more useful data stream. Also, further processing of these data is dependent on the sequence control and the positioning or measuring commands that are currently executing. The most important of the positioning and measuring commands can be found in chapter 4.

Any fault – critical or otherwise – that may arise can cause the machine to stop its motion or to deactivate itself automatically. Additionally, dragging-error recognition has been implemented which indicate cases where large differences between the control quantities and the control variables has arisen. To prevent damage to the machine, the velocity of the corner mirror is monitored at all times. If the tolerances should be exceeded, the drives are automatically deactivated. The NMM machine will respond with specific error messages, should any of these conditions arise. More information can be found in chapter 5 regarding troubleshooting.

2 Installation and Initial Steps

2.1 Required Conditions

A vibration-dampening or -isolating assembly is required for the positioning and measuring table. It is important to keep in mind that the device weighs approximately 85 kg. The electronics unit should be placed well away from the measuring table such that heat emissions do not affect the measuring systems and that good usability is guaranteed. The estimated cable length between these main device components is about 2.5 m.

Climatisation around the NMM machine is highly recommended to keep measuring conditions stabile. Although care has been taken in the design of the device to compensate for environmental factors, it is still recommended to keep the temperature, air pressure and humidity as stable as possible. If the NMM machine is placed in a climate-controlled chamber, the users are advised to minimise the number of entrances and exits into and out of that chamber.

2.2 Physical Installation

While moving the machine, careful attention should be paid to the corner mirror-stage assembly since the component is not fixed on its own and could be damaged if allowed to impact the sides of the device. The manufacturer recommends fixing the component in one position during any transporting of the device. Also, any of the optical components could be damaged or knocked loose by significant impacts during installation.

Great care should be taken in the levelling of the device. Significant measurement deviations could arise as a result of any tilting of the entire mechanical optical assembly.

2.3 Control Elements and Connections

The primary control elements consist of:

1 Motor switch — Power switch for the motor units

2 Fan switch — Power switch for the fans located in the cover of the electronics case

3 Main switch — Main switch for the entire device

4 USB connection — Control and data interface with the PC

5 DSP unit switch — Power switch for the DSP unit

6 Interferometer switch — Power switch for the interferometer units

7 Laser switch — Power switch for the laser units

8 Motor supply — Voltage supply for the motor amplifiers

9 Motor amplifiers — Motor end-stage drivers

10 Probe system — Interface for probe signals

11 X-Laser status — Stabilisation display for the x-axis laser

12 Y-Laser status — Stabilisation display for the y-axis laser

13 Z-Laser status — Stabilisation display for the z-axis laser

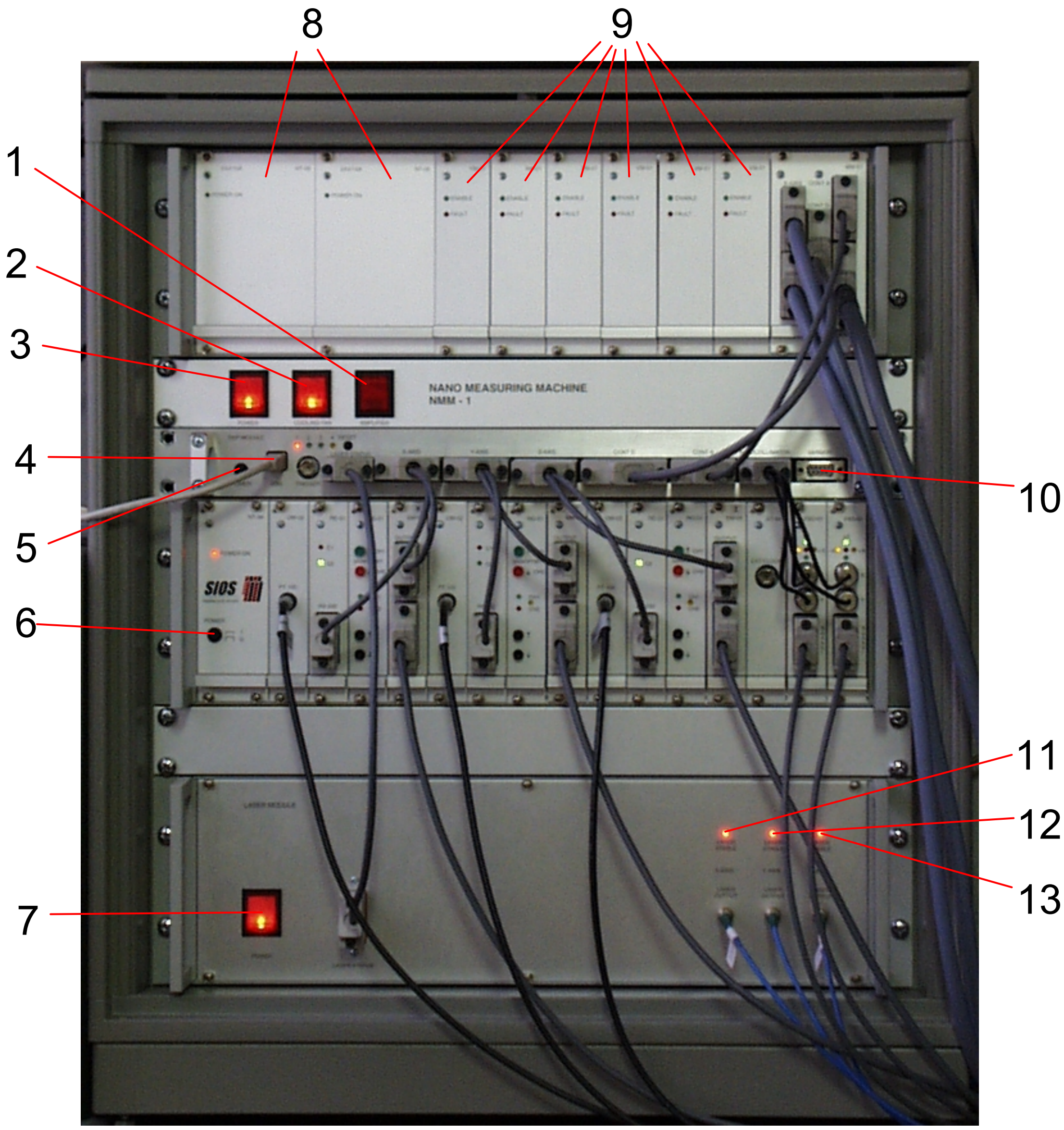


Figure 2.1: Front side of the entire electronics unit

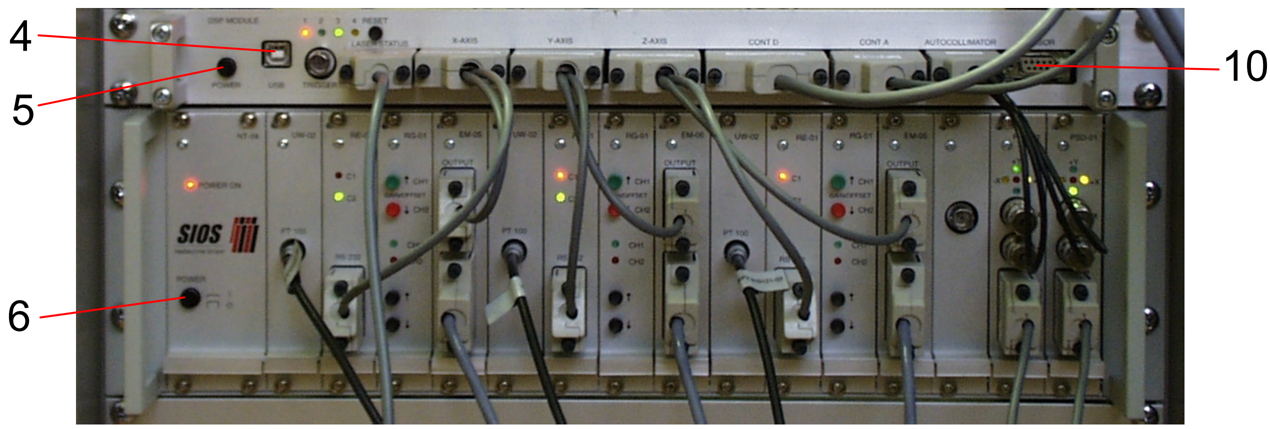


Figure 2.2: Close-up of a section of the electronics

2.4 Sensor Installation and Dimensions

During the installation of a probe system, it must be kept in mind that the nanomeasuring machine contains materials with a very small coefficient of expansion. It is therefore suggested to use mounting plates made of an FeNi36 alloy or Zerodur®. The appropriate dimensions can be seen in figure 2.3. The mass of the entire probe unit resting on the Zerodur columns may not exceed 5 kg.

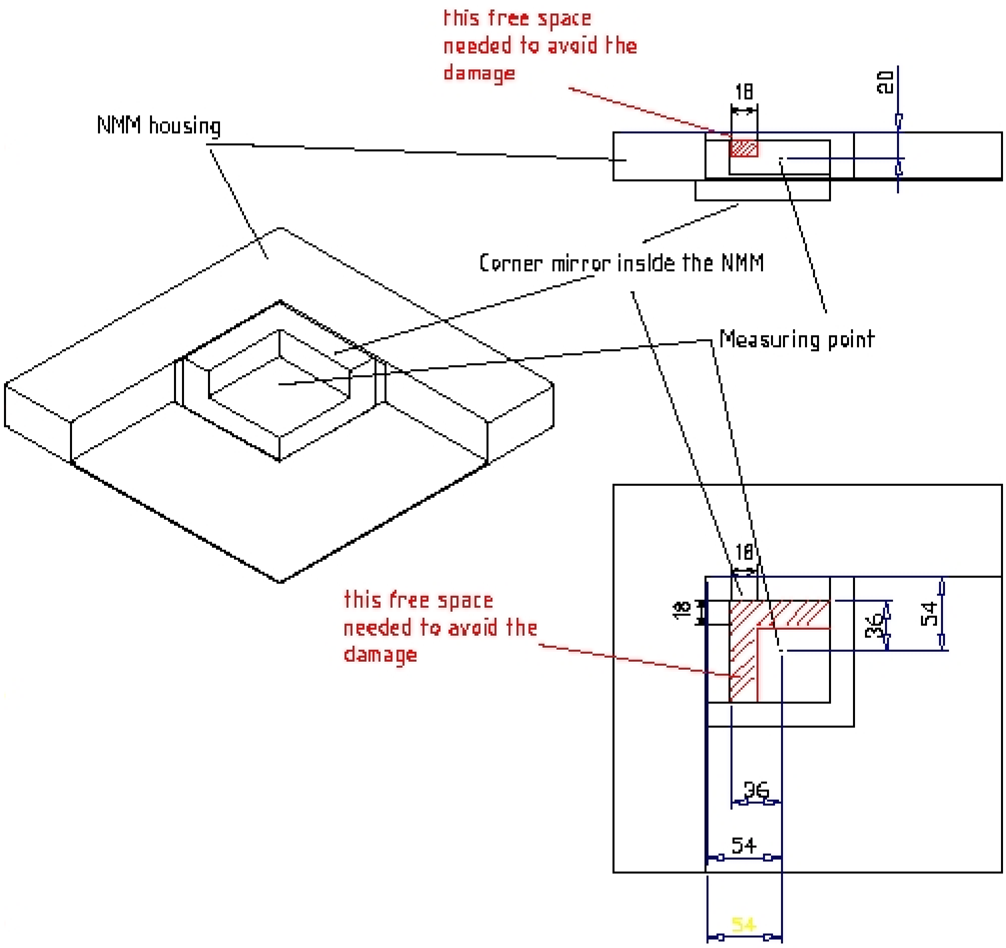


Figure 2.3: Middle position of the NMM corner mirror inside the NMM-1

Warning:	Control of the NMM and the probe system must be set up in a way that will prevent damage to both components.

The NMM machine requires an analogue voltage signal from the probe in order to function properly. This signal is fed into the DSP using the 15-pin high-density D-subminiature socket (the probe sensor must be outfitted with a 15-pin high-density D-subminiature connector). Table 2.1 shows the pin allocation of for the DSP socket labelled ‘Sensor’.

Pin	**Type**	**Description**
1	16-bit ADC (-10 V … + 10 V)	Analogue input adc20 or A_{z0}
2	AGND	Analogue ground
3	not connected	reserved
4	not connected	reserved
5	not connected	reserved
6	16-bit DAC (-10 V … + 10 V)	Analogue output 0
7	16-bit ADC (-10 V … + 10 V)	Analogue input adc21 or A_{z1}
8	DGND	Digital ground
9	DGND	Digital ground
10	TTL (low = OK, high = FAULT)	ProbeSystemStatus
11	16-bit DAC (-10 V … + 10 V)	Analogue output 1
12	AGND	Analogue ground
13	not connected	reserved
14	not connected	reserved
15	not connected	reserved

Table 2.1 Pin allocation of the ‘Sensor’ socket

3 Working with the Machine

The basic design of the NMM machine allows the device to be universally utilised and to be adapted to virtually any measurement task. The device can operate either as a nanopositioning or as a nanomeasuring machine.

3.1 Before Beginning a Series of Measurements

Whenever the NMM machine is in operation, it is important to keep the axis orientation in mind in order to avoid any damage to the machine. Figure 3.1 shows the direction of each of the three coordinate axes.

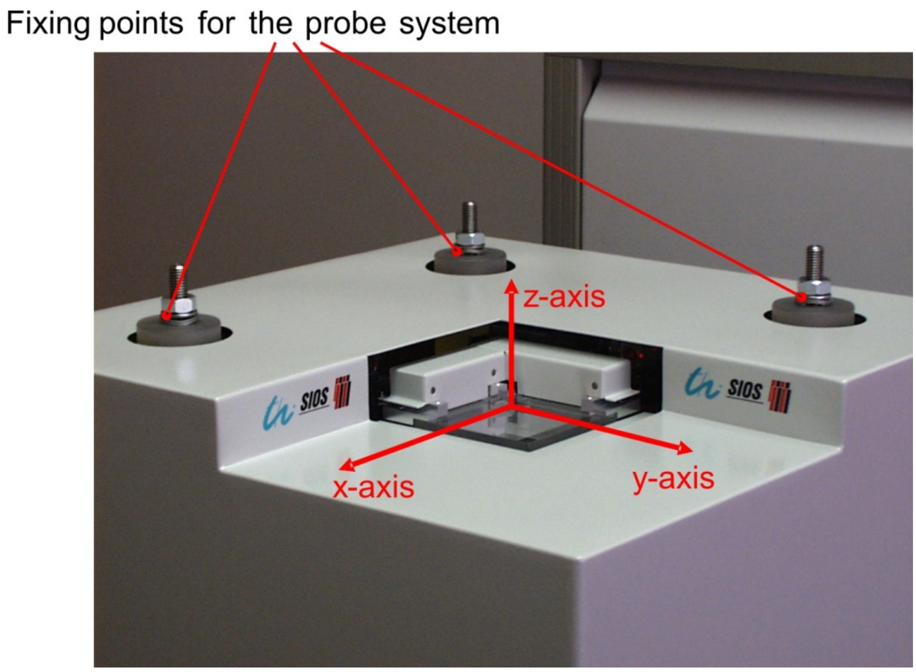


Figure 3.1: Measuring axes of the NMM

If the NMM machine is to be used as measuring system (see section 3.3), it is first necessary to calibrate the sensor for operation in the device. The measuring values recorded by the 15-bit A/D converters from the sensor are converted by the NMM software into displacement-dependent values calculated from the cubic functions labelled equations 3.1 and 3.2.

$$A_x = kaz0[0] + kaz0[1] \cdot adc20 + kaz0[2] \cdot adc20^2 + kaz0[3] \cdot adc20^3 \qquad (3.1)$$

$$A_y = kaz1[0] + kaz1[1]\cdot adc21 + kaz1[2]\cdot adc21^2 + kaz1[3]\cdot adc21^3 \qquad (3.2)$$

The function coefficients (kaz0[0…3] and kaz1[0…3]) can be set by the user using software configuration commands and are in the units of A/D-digits. These must first be determined by using the characteristic curves and running a simple set of calibration procedures. The standard contact sensor has a characteristic curve similar to the figure 1.8 (reproduced here as figure 3.2 for clarity).

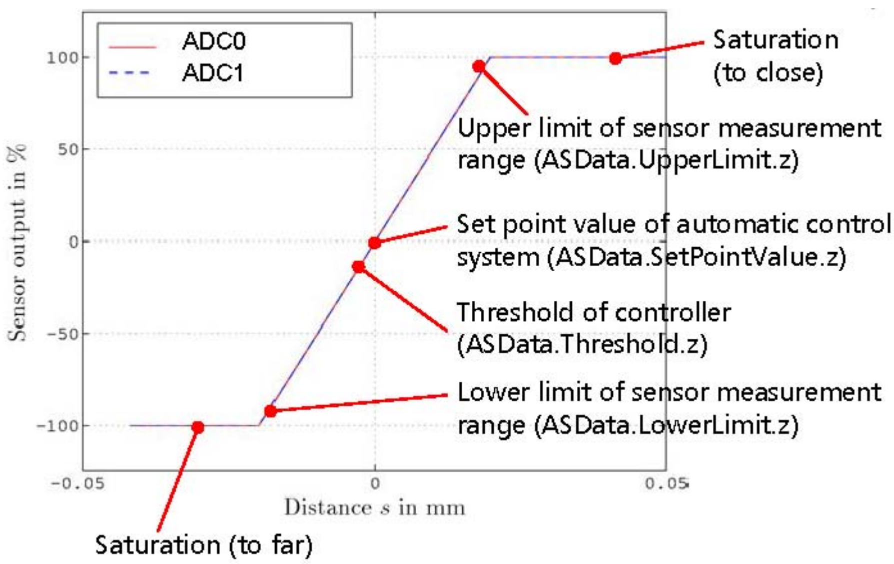


Figure 3.2: Typical probe characteristic curve

Warning:	The contact value must indicate the position of the specimen surface with the same orientation as that of the z-axis interferometer value. Failing to do so could cause measuring errors and even damage to the device during movement!

Outside of its measuring range the sensor must output its maximum or minimum analogue voltage according to its position. During an automatic contact procedure, the position control is automatically switch to the contact value after the lower threshold value is exceeded (‘asd.ALowerLimit.z’ in m). The threshold values provide the sequence controller with the capability to recognise dangerous and possible damaging situations and all losses of contact with the surface. These have the effect of immediately stopping any measuring commands.

Aside from the simple probe signals shown above, non-standard signals can also be handled by the NMM machine's sequence controller, such as those from a focus sensor. Figure 1.10 (reproduced here as figure 3.3 for clarity) shows the path of both the difference and summation signals for a standard focus sensor. No definitive detection of the position of the sensor relative to the specimen surface is possible outside of the measuring range (±0.01 mm). For this reason the user must take care that measurement operating range of the sensor is reached during the initial feed motion toward the surface. The NMM software is able to detect when the device reaches the difference signal minimum using the lower threshold value ('asd.ALowerLimit.z' in m) and switches the position control to the contact system at that time. The threshold values must be chosen in such a way that the quasi-linear region of the curve is contained within those values.

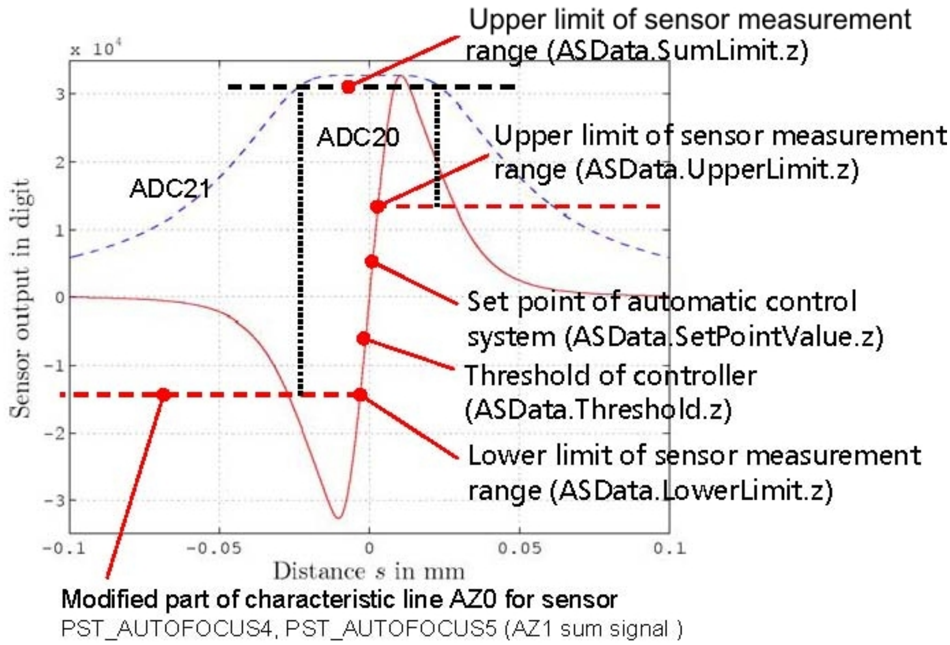


Figure 3.3: Typical characteristic curve for a focus sensor

Probe calibration can be carried out directly in the NMM machine. After the sensor has been installed, the operating range must be found using a gauge block or a similar object. Actual example scripts are included with the software package to assist in determining the correct values for these parameters, which can be found in the 'add' data structure (see chapter 4 and the software help package). Further processing to form a contact value is dependent on the sensor type set in 'asd.SensorType'.

3.2 Using the Machine as a Positioning System

Manipulation and machining of an object lying on the corner mirror is possible with a tool installed in place of the probe system. For precise positioning it is necessary to bring the contact point of the tool into the intersection of the interferometer measuring axes in order to avoid first-order measurement deviations. Furthermore, many types of sensors can be installed to measure aspects other than distance to the object, such as temperature, reflectivity or magnetic and electric fields. For the operating mode ‘nanopositioning machine’ the device control loop is closed without including the measuring object. Positioning is only accomplished using the length measurements from the interferometers.

Functioning as a nanopositioning machine is shown in figure 3.4. To simplify the graphic, the guide-drive system and the positioning control loop for the x-axis has not been shown. Also, both the angle regulator about the y-axis and the drives required for angle control of the z-axis have been removed. The interferometer and the angle measuring systems directly measure the position and the angle of the corner mirror. The measuring signals of these systems serve as the control variables. The command variables of the position control are calculated according to the positioning command given by the user through the scripting program. The regulating quantities of the x- and y-axis position controls are amplified and fed into the drives. For z-axis positioning the four drives are controlled with the same variable. The rotation controllers about the x- and y-axes serve to compensate for rotational guideway errors. Accordingly, the two controllers keep the horizontal position constant. This is done by individually controlling the four z-drives. The control signals of the z-drives are formed by the summation of quantities from the position controller and the two angle controllers. The signal of the optional contact system can be registered by the control system but the probe signal does not influence the actual positioning of the object.

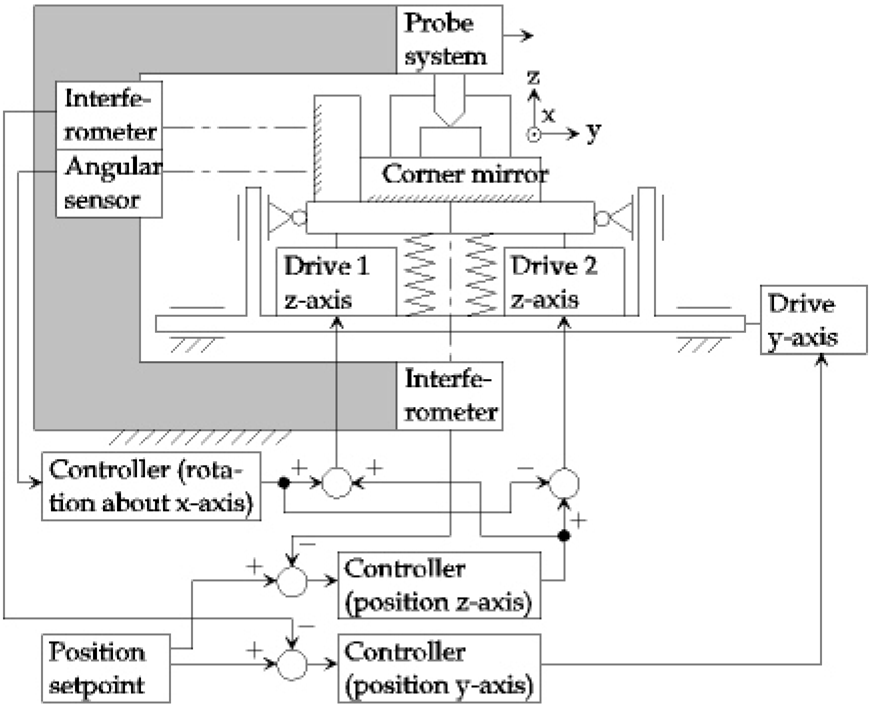


Figure 3.4: Functioning as a nanopositioning machine

The rotational and translational guideway errors cause displacement of the corner mirror. Because the position and angle are directly measured at the corner mirror, the control system is capable of correcting these deviations. This principle can be briefly demonstrated using the example of a movement in the y-direction. The y-axis control loop matches the position of the corner mirror according to the modified set point (see figure 3.4). During this process positional shifts in the z-direction can occur through the guideway errors and are registered by the interferometer. The control loop of the z-axis compensates this shift through a corresponding countermovement with the drives.

The NMM machine control system reduces the deviations arising from the guide system. The effects of the rotational guide errors on the measurement result are minimised by the control system. The translational guide deviations do not become a part of the general measurement error because the position of the measuring object is measured directly from the corner mirror.

3.3 Using the Machine as a Measuring System

The operating mode as a nanomeasuring machine requires a probe contact system which provides a displacement measuring signal. However, before beginning a measurement the probe system must be brought into contact with the measuring object. For this, the device first performs a movement as a positioning system of the corner mirror and the object in the z-direction (see section 3.2). As soon as the probe system comes into contact with the specimen, the control system switches into the nanomeasuring operating mode. The controlling variable of the z-axis position control is now the measured distance between the probe system and the specimen and the distance is kept at a constant value (see figure 3.5). All other control loops retain the same functionality. If an x- or y-repositioning should occur, the corner mirror is moved in accordance with the profile of the measuring object. Acquisition of the contour of the specimen is thus achieved using the interferometer signal. The guideway errors do not cause measurement deviations in this mode. After completing the measurement, contact with the specimen is released and the device resumes normal operation as a nanopositioning machine.

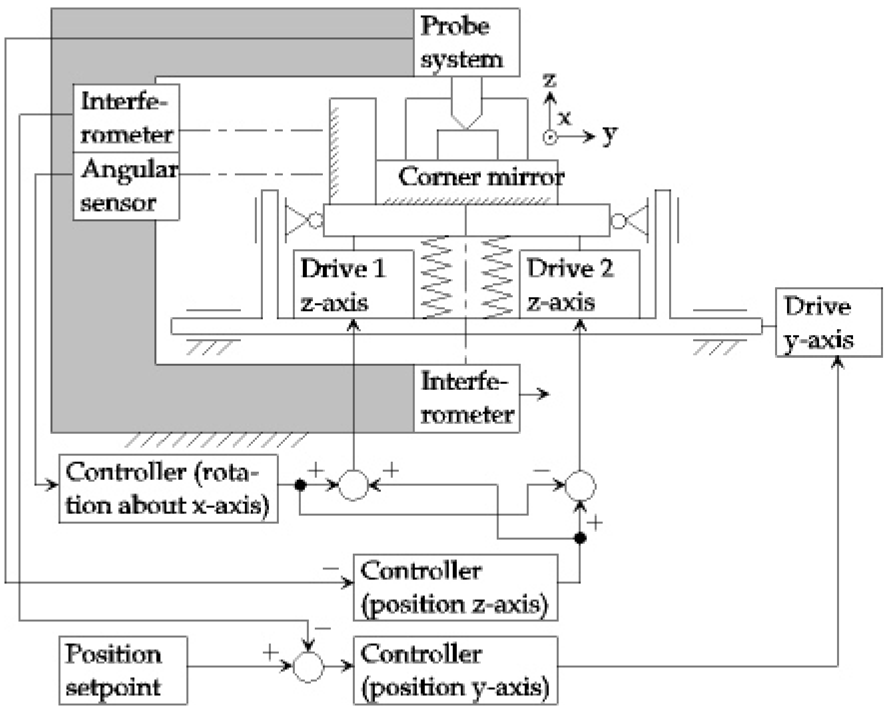


Figure 3.5: Functioning as a nanomeasuring machine

3.4 After all work is done

Tip: Because the lasers require between 5 and 30 minutes to warm up, it is advisable to leave the NMM machine in a deactivated but powered-on state until no more measurements are to be completed.

Warning:	Before turning off the mains switch, the device must be in a deactivated state. LED 2 on the DSP and the motor LEDs labelled ‘Enable’ must be off. After that, the motors may be turned off using the switch labelled ‘Amplifier’ or using the mains switch. Only use the emergency switch in an actual emergency!

4 Software

In order to use the device, a PC with two free USB ports is necessary. This computer must be running a Windows® version no earlier than Windows 98 and must have USB support.

Please mind the instructions on the included CD before installing the software. The first time the NMM is connected to the computer, he operating system will prompt the user to insert a disc with the appropriate driver, which is on the CD. After a successful installation a device labelled ‘NanoMeasuringMachine’ can be found as a ‘SIOS Device’ under the Device Manager. Now, the control software may be installed. In order to make use of the software help files, an internet browser is necessary and must be installed.

The following is a brief outline of the command groups available to the software user.

Basic commands are used for reading, deleting and writing data in the address area of the DSP and for resetting the DSP unit.

Configuration commands allow the easy configuration of the NMM machine. With these commands the parameters of the measuring systems, control system and motion control may be changed and adapted.

Measuring and positioning commands, together with the following group, are the most important and most often used. The commands control the initialisation and the actual measurement and motion.

Data exchange commands allow the actual control and collection of the measuring data gathered with the other command groups. The selection of data sources and the transfer of measuring data are executed with commands of this group.

The next few sections deal with specific information about some of the commands. Further information can be found using the software help function.

4.1 Commands Listed by Category

Positioning Commands:

- MoveToPoint
- MoveToPointMeasure
- MoveToPointDynamic

Measuring Commands:

- MeasurePoint
- MeasureCoarseLine
- MeasureFineLine
- MeasureDynamicLine

4.2 Command Descriptions

MoveToPoint

This command executes a simple positioning of the corner mirror. The target coordinates and the desired motion limits (v_{max}, a_{max}, r_{max}) are used to calculate the course of movement. The coordinates may be absolute or relative.

MoveToPointMeasure

This command executes a positioning of the corner mirror while simultaneously recording values. Individual movements are calculated from the target coordinates and the step size (see figure 4.1). The system pauses movement at each interim point (1), waits until the control deviation of the x-, y- and z-axes lies within the desired range and then records the measuring value. After that, the actual machine motion continues. An individual movement (2) occurs using the fine-speed limit values. Finally, the corner mirror is moved to the target coordinates (3).

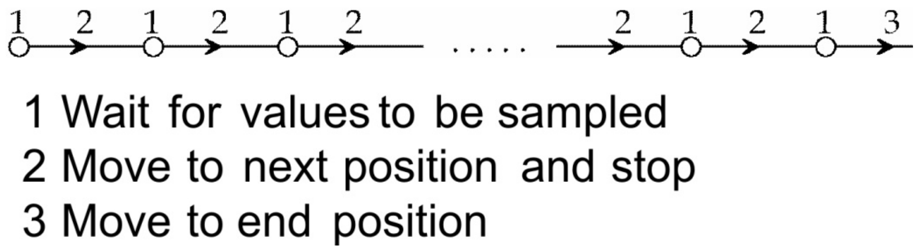


Figure 4.1: Measurement sequence of the functions ‘MoveToPointMeasure’ and ‘MoveToPoint-Dynamic’

MoveToPointDynamic

This command is similar to ‘MoveToPointMeasure’. The difference is that the stage motion is not paused during measurement recording; a continuous motion is used throughout (2 and 3). The measuring values are recorded as soon as the path generator reaches a whole-number multiple of the step size.

MeasurePoint

This command executes a scan of one point on the specimen surface. As seen in figure 4.2, the sequence begins with a movement in the z-direction (1). The speed used is, of course, the contact limit. As soon as the probe signal reaches its lower threshold value, the z-axis positioning control switches to the contact signal (2). After the system has stabilised and the control deviation of the x-, y- and z-axes lies within the desired range, the device actually takes the measurement. Finally, the z-axis position control is switched back to the interferometer signal and the stage is returned to its starting position (3) at coarse speed.

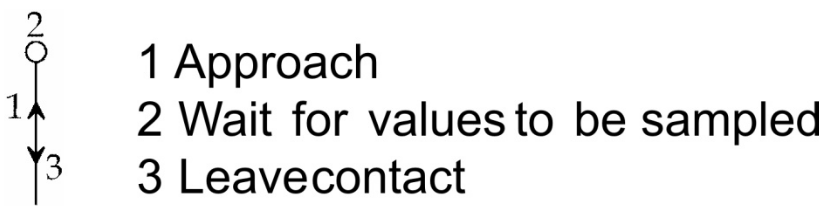


Figure 4.2: Measurement sequence of the function ‘MeasurePoint’

MeasureCoarseLine

This command expands the sequence of the command ‘MeasurePoint’ over several points along a line. The individual measurements are connected along a line as shown in figure 4.3. The inter-point movements (4) and the final movement (5) are executed with coarse speed. The distance between each measuring point is given by the step size. The final step is to move the stage to the target coordinates.

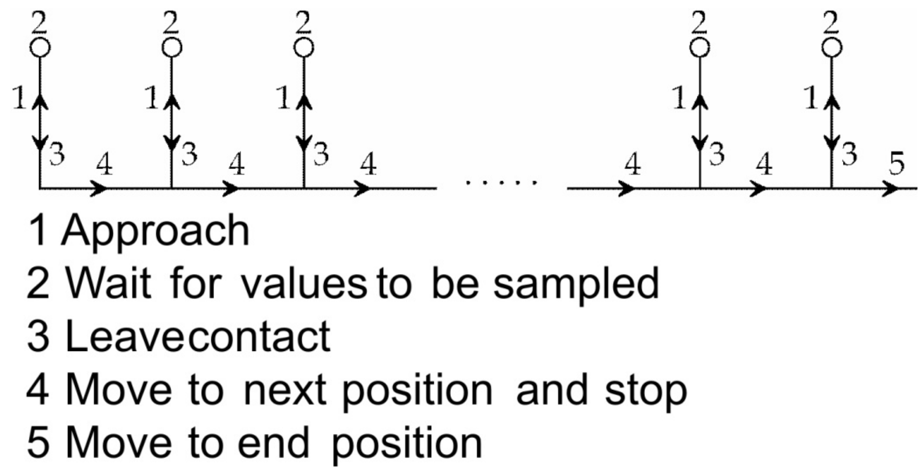


Figure 4.3: Measurement sequence of the function ‘MeasureCoarseLine’

MeasureFineLine

The command ‘MeasureFineLine’ is very similar to ‘MeasureCoarseLine’, with the primary difference being that the inter-point movements (4) are executed with the contact system instead of with the interferometer system (see figure 4.4). These movements are executed with fine speed. Only after the last measurement is taken is contact with the specimen released.

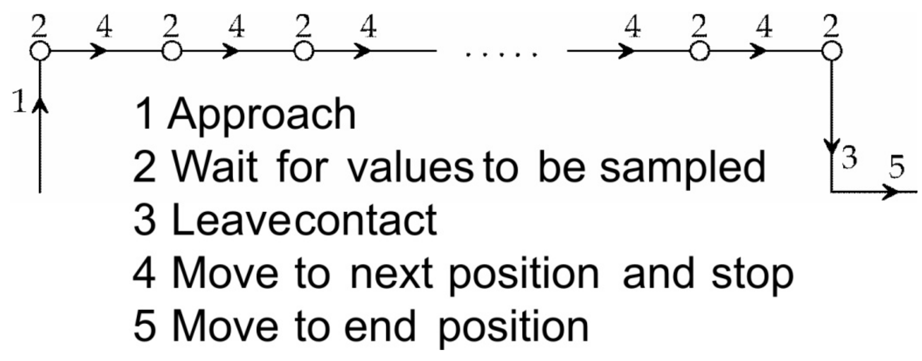


Figure 4.4: Measurement sequence of the function ‘MeasureFineLine’

MeasureDynamicLine

The command 'MeasureDynamicLine' is very similar to 'MeasureFineLine', only that the motion along the surface is continuous. Measurement recording is done as soon as a whole-number multiple of the step size is reached, as in the case of 'MoveToPointDynamic'. The probe system remains in contact with the surface until the (x,y) end position is reached (5) and is only detached at the very end (3).

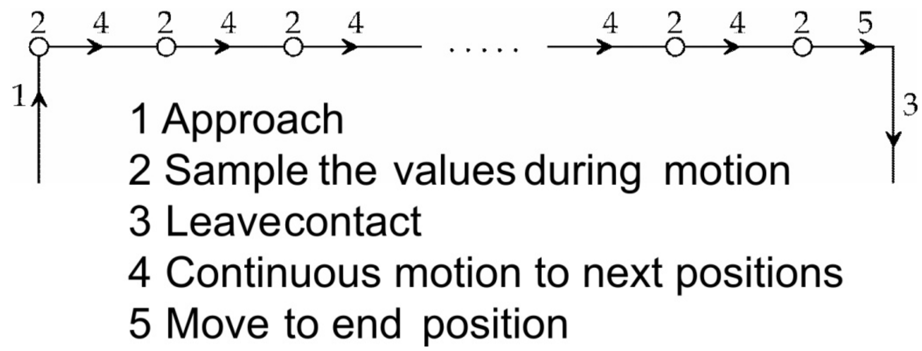


Figure 4.5: Measurement sequence of the function 'MeasureDynamicLine'

5 Troubleshooting

Normal return values during operation:

ANSW_OK

Command correct

ANSW_READY

System ready

Return values resulting from script programming errors:

ANSW_FORBIDDEN

Command not allowed for the normal users. There are several commands for setting up the machine. The access level is coded in the software dongle.

ANSW_NODATA

No data in memory

ANSW_UNKNOWN_FUNC

Command unknown

ANSW_UNKNOWN_PARA

Command parameter unknown or incorrect

ANSW_ERROR

General error

ANSW_SYSTEM_NOTACTIVE

System not active. The machine must first be activated in order to use this command (the command 'Activate' must be executed successfully). This error can also occur after an error event occurs within the control system, causing the machine to be deactivated automatically – the 2nd LED on the electronics unit will be off in this case. ('GetErrorDescription' can be used to determine the exact cause of the error in such a case.)

ANSW_SYSTEM_ACTIVE

System active. The machine must first be deactivated in order to use this command.

ANSW_NO_CONTACT

Discrete control not active. The z-axis control system is using the interferometer signal and must first be switched into contact mode using a measuring command or the command 'ApproachSurface'.

ANSW_CONTACT

Discrete control active. The z-axis control system is using the probe system and must first be switched back into interferometer operation using the command 'LeaveSurface'.

ANSW_NOT_STOPPED

System in motion.

ANSW_STOPPED

System not in motion

Return values resulting from errors during motion or measurements:

These errors cause the device to stop immediately.

ANSW_LIMIT

Limit switch was thrown. Also occurs when the probe system indicates a fault or the NMM machine reads the probe as out of range.

ANSW_PROBEFAULT

Sensor status signal missing.

ANSW_PROBEUPPERLIMIT

Sensor out of safety range – upper limit exceeded

ANSW_PROBELOWERLIMIT

Sensor out of safety range – lower limit exceeded

Critical errors:

These errors cause the device to deactivate itself automatically. They may also occur when no script is currently running as soon as the control system has been initialised.

ANSW_FAULT

Motor amplifier fault. One or more of the motors are in an end position; the motor amplifiers must be switched off and back on to clear this fault.

ANSW_TRACKING

Dragging error during motion. The controller deviation has exceeded tolerances during a motion. The system will automatically deactivate the controller system. Check the motion speed parameters. This error can also occur if the movement is stopped by physical contact between a fixed and a moving part.

ANSW_LASERNOTSTABLE

Laser not stabile. Each laser requires between 10 and 30 minutes to warm up. The stabilisation state is indicated by the three green LEDs on the laser unit. The machine can only be activated if all three lasers are stable. If a laser remains unstable after a reasonable warm-up time or one of lights is blinking, please contact the manufacturer. The control system is deactivated if this error arises.

ANSW_VELOCITY

Velocity monitoring error. The motion speed was too high and should be reduced.

ANSW_INTSIGLOW

Interferometer signal too low. If at any time the interferometer sine and cosine signals levels are too low, the control system is deactivated. The stage must be manually moved in all axes in order to bring the signal controllers into synchronisation. Also see the users’ guide for the interferometer SP-500.

ANSW_ENVIRONMENTFAULT

Invalid environment measurement.

6 Appendix

Technical Specifications

Mains Voltage	220 V – 240 V AC, 50 Hz
Sampling and Controller Frequency	6250 Hz
Interferometers	3 Miniature Plane-mirror Interferometers, Type SP 500
Measurement Resolution	0.1 nm
Measuring Volume	25 mm x 25 mm x 5 mm
Measuring Unit Dimensions	Confer Drawings
Measuring Unit Mass	ca. 85 kg
Electronics Unit Dimensions	553 mm x 600 mm x 700 mm
Electronics Unit Mass	ca. 95 kg

Dimensions

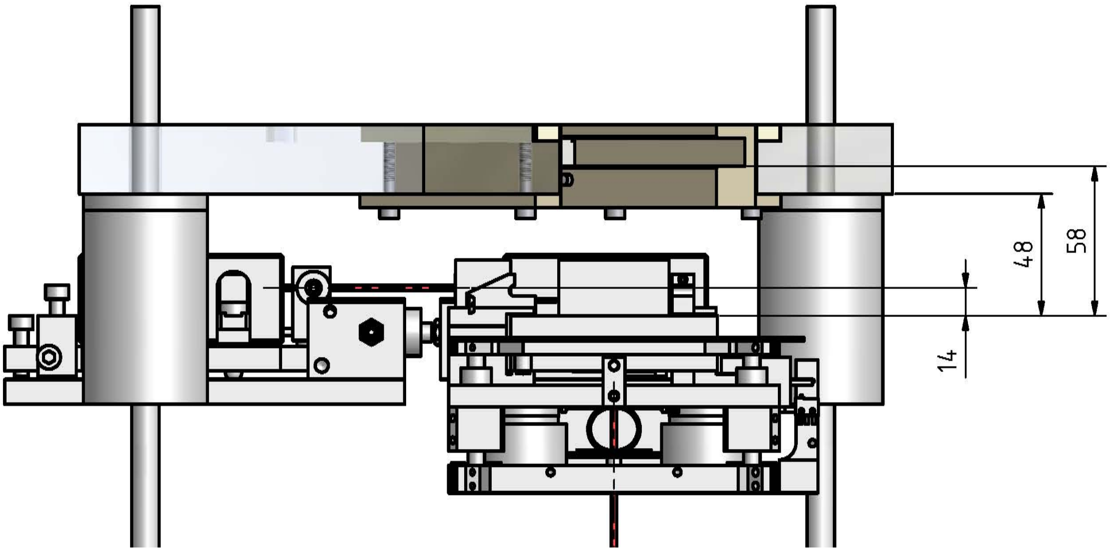


Figure 6.1: Free space within stage with fixed Zerodur plate and 6 mm Invar spacer

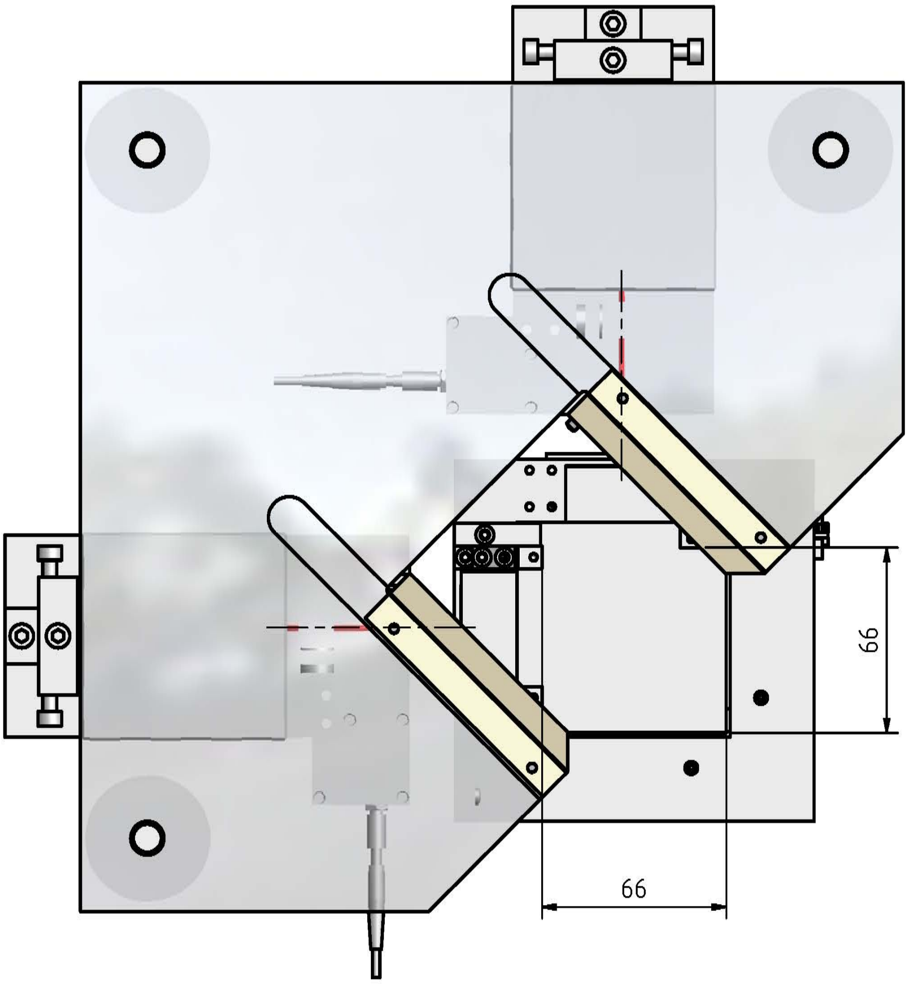


Figure 6.2: Top view of figure 6.1

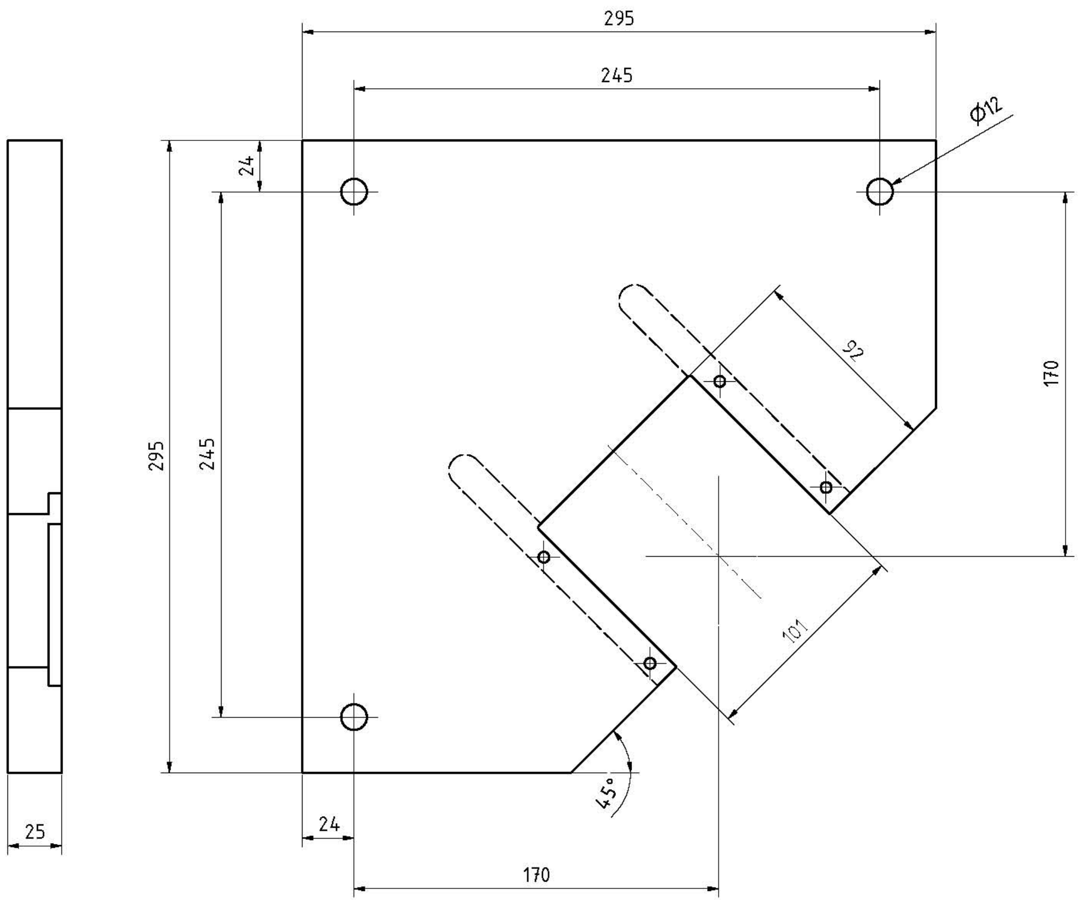


Figure 6.3: Zerodur plate

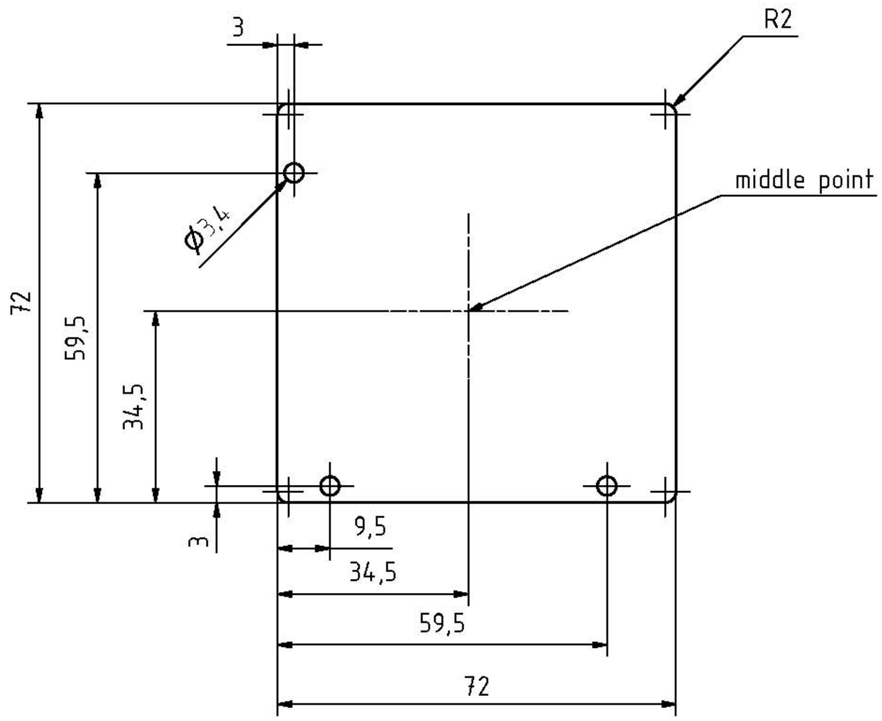


Figure 6.4: Fixing plate for samples

Controller

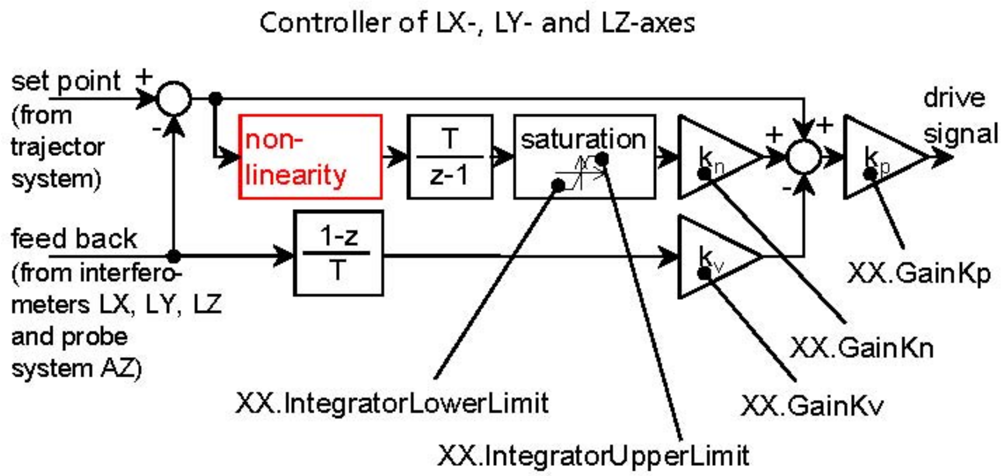
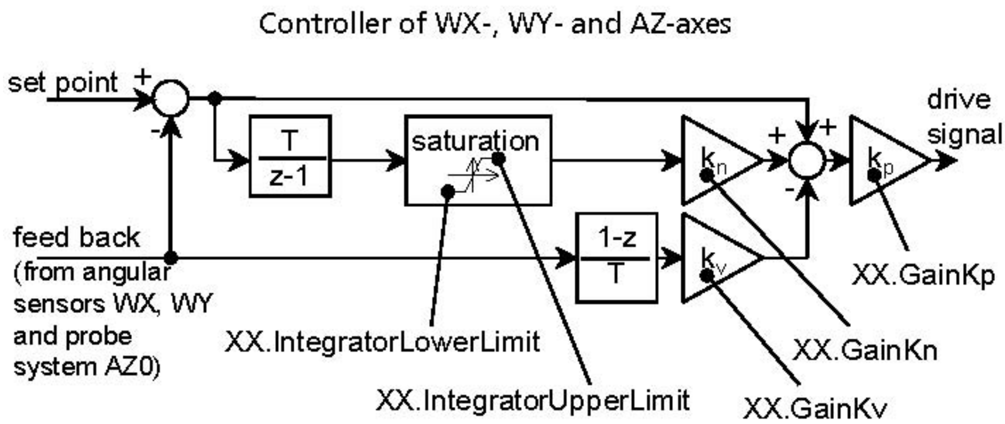


Figure 6.5: Controller of LX-, LY- and LZ-axes



Controller for WZ-, AX- and AY-axes not available!

Figure 6.6: Controller of WX-, WY- and AZ-axes

Examples of all system parameters

```
[SNData]
SN=NMM-1 0010

[IFDataX]
LamVak=6.32991234e-07
TotStrecke=-0.0125
Lte=20.0
Ldr=101300.0
Rlf=50.0
IntFak=2
UartBR=19200
UartDB=8
UartSB=1
UartPA=N
TCMODType=1
EA=0
EB=1
EC=0
ED=0
EE=500
DataProc=6

[IFDataY]
LamVak=6.32991234e-07
TotStrecke=-0.0125
Lte=20.0
Ldr=101300.0
Rlf=50.0
IntFak=2
UartBR=19200
UartDB=8
UartSB=1
UartPA=N
TCMODType=1
EA=0
EB=1
EC=0
ED=0
EE=500
DataProc=6

[IFDataZ]
LamVak=6.32991234e-07
TotStrecke=0.02
```

Lte=20.0
Ldr=101300.0
Rlf=50.0
IntFak=2
UartBR=19200
UartDB=8
UartSB=1
UartPA=N
TCMODType=1
EA=0
EB=1
EC=0
ED=0
EE=500
DataProc=6

[IFDataA]
LamVak=6.32991234e-07
TotStrecke=0.0
Lte=20.0
Ldr=101300.0
Rlf=50.0
IntFak=2
UartBR=19200
UartDB=8
UartSB=1
UartPA=N
TCMODType=1
EA=0
EB=1
EC=0
ED=0
EE=500
DataProc=6

[IFDataB]
LamVak=6.32991234e-07
TotStrecke=0.0
Lte=20.0
Ldr=101300.0
Rlf=50.0
IntFak=2
UartBR=19200
UartDB=8
UartSB=1
UartPA=N
TCMODType=1

EA=0
EB=1
EC=0
ED=0
EE=500
DataProc=6

[IFDataC]
LamVak=6.32991234e-07
TotStrecke=0.0
Lte=20.0
Ldr=101300.0
Rlf=50.0
IntFak=2
UartBR=19200
UartDB=8
UartSB=1
UartPA=N
TCMODType=1
EA=0
EB=1
EC=0
ED=0
EE=500
DataProc=6

[WSData]
kx[0]=0.0
kx[1]=2.060322e-006
kx[2]=3.908954e-006
kx[3]=6.550774e-005
kx[4]=-6.095367e-005
kx[5]=-9.978991e-005
kx[6]=2.911730e-004
kx[7]=-3.317254e-003
kx[8]=-8.056541e-004
kx[9]=1.647090e-003
ky[0]=0.0
ky[1]=2.101708e-006
ky[2]=7.780535e-006
ky[3]=-8.484773e-006
ky[4]=-5.574912e-005
ky[5]=-1.866146e-004
ky[6]=9.416749e-004
ky[7]=-6.267917e-004
ky[8]=-1.071663e-003
ky[9]=8.120312e-003

kz[0]=0.0
kz[1]=-2.349678e-007
kz[2]=2.283028e-007
kz[3]=-4.866172e-005
kz[4]=2.151834e-007
kz[5]=-1.501766e-005
kz[6]=6.472719e-004
kz[7]=1.575241e-003
kz[8]=3.153170e-004
kz[9]=2.892707e-004

[ADData]
kwx0[0]=0.0
kwx0[1]=0.0015
kwx0[2]=0.0
kwx0[3]=0.0
kwx1[0]=0.0
kwx1[1]=0.0015
kwx1[2]=0.0
kwx1[3]=0.0
kwy0[0]=0.0
kwy0[1]=0.0015
kwy0[2]=0.0
kwy0[3]=0.0
kwy1[0]=0.0
kwy1[1]=0.0015
kwy1[2]=0.0
kwy1[3]=0.0
kaz0[0]=0.0
kaz0[1]=1.0
kaz0[2]=0.0
kaz0[3]=0.0
kaz1[0]=0.0
kaz1[1]=1.0
kaz1[2]=0.0
kaz1[3]=0.0
kax[0]=0.0
kax[1]=1.0
kax[2]=0.0
kax[3]=0.0
kay[0]=0.0
kay[1]=1.0
kay[2]=0.0
kay[3]=0.0

[RGData]
LX.AdaptationGain=26

```
LX.AdaptationLowerLimit=6.00e-009
LX.AdaptationUpperLimit=3.0e-007
LX.IntegratorLowerLimit=-100
LX.IntegratorUpperLimit=100
LX.GainKn=26
LX.GainKv=0.01
LX.GainKp=1.3e+8
LY.AdaptationGain=31
LY.AdaptationLowerLimit=7.0e-009
LY.AdaptationUpperLimit=3.0e-007
LY.IntegratorLowerLimit=-100
LY.IntegratorUpperLimit=100
LY.GainKn=60
LY.GainKv=0.00999999977648258
LY.GainKp=1.3e+8
LZ.AdaptationGain=42
LZ.AdaptationLowerLimit=9.0e-009
LZ.AdaptationUpperLimit=5.0e-008
LZ.IntegratorLowerLimit=-100
LZ.IntegratorUpperLimit=100
LZ.GainKn=60
LZ.GainKv=0.01
LZ.GainKp=5.75e+7
AZ.AdaptationGain=25
AZ.AdaptationLowerLimit=6.0e-009
AZ.AdaptationUpperLimit=3.07e-007
AZ.IntegratorLowerLimit=-100
AZ.IntegratorUpperLimit=100
AZ.GainKn=100
AZ.GainKv=0.01
AZ.GainKp=10e+8
WX.AdaptationGain=1.0
WX.AdaptationLowerLimit=1.0e-9
WX.AdaptationUpperLimit=1.0e-9
WX.IntegratorLowerLimit=-1.0
WX.IntegratorUpperLimit=1.0
WX.GainKn=500.0
WX.GainKv=0.01
WX.GainKp=7.0
WY.AdaptationGain=1.0
WY.AdaptationLowerLimit=1.0e-9
WY.AdaptationUpperLimit=1.0e-9
WY.IntegratorLowerLimit=-1.0
WY.IntegratorUpperLimit=1.0
WY.GainKn=500.0
WY.GainKv=0.01
WY.GainKp=7.0
```

AX.AdaptationGain=25.0
AX.AdaptationLowerLimit=6.0e-9
AX.AdaptationUpperLimit=300.0e-9
AX.IntegratorLowerLimit=-100.0
AX.IntegratorUpperLimit=100.0
AX.GainKn=100.0
AX.GainKv=0.01
AX.GainKp=1.0e+8
AY.AdaptationGain=25.0
AY.AdaptationLowerLimit=6.0e-9
AY.AdaptationUpperLimit=300.0e-9
AY.IntegratorLowerLimit=-100.0
AY.IntegratorUpperLimit=100.0
AY.GainKn=100.0
AY.GainKv=0.01
AY.GainKp=1.0e+8

[BGData]
CoarseMotion_vm=0.001
CoarseMotion_am=0.01
CoarseMotion_jm=0.1
FineMotion_vm=0.00005
FineMotion_am=0.00001
FineMotion_jm=0.01
ApproachMotion_vm=0.000005
ApproachMotion_am=0.0001
ApproachMotion_jm=0.001
LInaccuracy_x=5e-9
LInaccuracy_y=5e-9
LInaccuracy_z=5e-9
WInaccuracy_x=1
WInaccuracy_y=1
WInaccuracy_z=1
AInaccuracy_x=5e-9
AInaccuracy_y=5e-9
AInaccuracy_z=5e-9
TrackingError_x=5e-5
TrackingError_y=5e-5
TrackingError_z=5e-5

[ASData]
ProbeSensorType=0
SetPointValue_x=0.0
SetPointValue_y=0.0
SetPointValue_z=0.0
UpperLimit_x=40000
UpperLimit_y=40000

UpperLimit_z=40000
LowerLimit_x=-40000
LowerLimit_y=-40000
LowerLimit_z=-40000
Threshold_x=-1e-6
Threshold_y=-1e-6
Threshold_z=-1e-6
ContSetPoint_x=1e-6
ContSetPoint_y=1e-6
ContSetPoint_z=1e-6
ActuatorScale_x=1
ActuatorScale_y=1
ActuatorScale_z=1
SumLimit_X=32000
SumLimit_y=32000
SumLimit_z=32000
OutputMask=0