3D-Probing System for Micro-Components

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presented by
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Zürich, March 2012
Thomas Liebrich
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<th>Description</th>
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<tbody>
<tr>
<td>1D</td>
<td>one dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>two dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>three dimensional</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>CMM</td>
<td>Coordinate Measuring Machine</td>
</tr>
<tr>
<td>CSY</td>
<td>Coordinate System</td>
</tr>
<tr>
<td>EDM</td>
<td>Electro-Discharge Machining</td>
</tr>
<tr>
<td>ETVE</td>
<td>Environmental Temperature Variation Error</td>
</tr>
<tr>
<td>EVE</td>
<td>Environmental Variation Error</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Variable Differential Transducer</td>
</tr>
<tr>
<td>METAS</td>
<td>Federal Office of Metrology METAS (Bern, Switzerland)</td>
</tr>
<tr>
<td>NPL</td>
<td>National Physical Laboratory (Teddington, United Kingdom)</td>
</tr>
<tr>
<td>PTB</td>
<td>Physikalisch-Technische Bundesanstalt (Braunschweig, Germany)</td>
</tr>
</tbody>
</table>
### Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>N</td>
<td>Force</td>
</tr>
<tr>
<td>$Hz$</td>
<td>$\frac{1}{s}$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$L_0$</td>
<td>m</td>
<td>Initial length</td>
</tr>
<tr>
<td>$\text{MPE}_E$</td>
<td>m</td>
<td>Maximum permissible error of indication of a CMM [1]</td>
</tr>
<tr>
<td>$\text{MPE}_P$</td>
<td>m</td>
<td>Maximum permissible probing error [1]</td>
</tr>
<tr>
<td>$T$</td>
<td>°C</td>
<td>Temperature</td>
</tr>
<tr>
<td>$U(k=2)$</td>
<td>$m / \frac{N}{m}$</td>
<td>Expanded uncertainty with coverage factor $k$, typically 2</td>
</tr>
<tr>
<td>X, Y, Z</td>
<td>-</td>
<td>Directions of a cartesian coordinate system</td>
</tr>
<tr>
<td>X(CMM), Y(CMM), Z(CMM)</td>
<td>-</td>
<td>Axes of a coordinate system, which is defined by the CMM</td>
</tr>
<tr>
<td>$c_X, c_Y, c_Z$</td>
<td>$\frac{N}{m}$</td>
<td>Stiffness in X-, Y- and Z-direction</td>
</tr>
<tr>
<td>$d, l$</td>
<td>m</td>
<td>Distance / length</td>
</tr>
<tr>
<td>$h$</td>
<td>s</td>
<td>Hour, equal to 3600 s</td>
</tr>
<tr>
<td>$nm$</td>
<td>m</td>
<td>Distance / length, equal to $10^{-9}$ m</td>
</tr>
<tr>
<td>$r$</td>
<td>m</td>
<td>Radius of a circle or a sphere</td>
</tr>
<tr>
<td>$t$</td>
<td>m</td>
<td>Thickness</td>
</tr>
<tr>
<td>$u_i$</td>
<td>$m / \frac{N}{m}$</td>
<td>Standard uncertainty of contributor $i$</td>
</tr>
<tr>
<td>$u_c$</td>
<td>$m / \frac{N}{m}$</td>
<td>Combined standard uncertainty</td>
</tr>
<tr>
<td>$w$</td>
<td>m</td>
<td>Width</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$\frac{1}{K}$</td>
<td>Thermal expansion coefficient</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>m</td>
<td>Wave length of light</td>
</tr>
<tr>
<td>$\mu m$</td>
<td>m</td>
<td>Distance / length, equal to $10^{-6}$ m</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>m</td>
<td>Change of a length</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>K</td>
<td>Change of a temperature</td>
</tr>
</tbody>
</table>
Metrological terms and their definitions used in this thesis are adopted from the "International Vocabulary of Basics and General Terms in Metrology" (VIM) [2]. The most used terms are following:

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>Process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity.</td>
</tr>
<tr>
<td>Metrology</td>
<td>Science of measurement and its application.</td>
</tr>
<tr>
<td>(Measurement) accuracy</td>
<td>Closeness of agreement between a measured quantity value and a true quantity value of a measurand.</td>
</tr>
<tr>
<td></td>
<td>NOTE: The concept &quot;measurement accuracy&quot; is not a quantity and is not given a numerical quantity value.</td>
</tr>
<tr>
<td>(Measurement) repeatability</td>
<td>Measurement precision under a set of repeatability conditions of measurement.</td>
</tr>
<tr>
<td>(Measurement) uncertainty</td>
<td>Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.</td>
</tr>
<tr>
<td></td>
<td>NOTE: The uncertainties are estimated as proposed in [3].</td>
</tr>
<tr>
<td>Calibration</td>
<td>Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties</td>
</tr>
<tr>
<td></td>
<td>provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.</td>
</tr>
<tr>
<td>Sensor</td>
<td>Element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured.</td>
</tr>
<tr>
<td>Resolution</td>
<td>Smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.</td>
</tr>
</tbody>
</table>
Abstract

Miniaturisation of components, e.g. fuel injection nozzles with diameters less than 100 \(\mu m\) or hearing devices, results in increasing demands in 3D-metrology to prove the geometric specifications of the manufactured components without damaging them. Additionally, manufacturing processes can only be further improved if the uncertainties of the metrology used are clearly smaller than the specifications to be checked. This applies to the manufactured components as well as the machine tools used for the fabrication.

In this work a new 3D-probing system is presented, which is based on capacitive sensors to measure the deflection of the probing element. Its design is not only optimised for isotropic stiffnesses at the probing element, but also for an economically priced manufacturing and assembly. For designing the geometry of the probing system, especially the one of the flexure hinges, a procedure based on the Finite Element Method (FEM) is presented and checked by force measurements. Therewith it is possible to determine the stiffnesses at the probing element by simulations and adapt those to given specifications before the probing system is realised. By means of this design tool and due to the measurement principle it is possible to adjust the probing system to different measuring tasks and applications, e.g. as probing system for micro-coordinate measuring machines (CMM’s), for conventional CMM’s or for machine tools.

A 3D-probing system with isotropic stiffnesses at the probing element of \(84 \frac{N}{m} \pm 25 \frac{N}{m}\) is presented, which is applicable on micro-CMM’s to measure small and sensitive components without damaging their surface. The experimental stiffness is checked by force measurements and is determined to be \(78 \frac{N}{m} \pm 26 \frac{N}{m}\). Requirements in design, manufacturing, assembly and simulation to achieve this conformance between measured and simulated stiffnesses are presented.

The geometric checking of the probing system is done on the high-precision CMM ISARA. The linearity error in probing direction is 0.12 \(\mu m\) for a deflection of the probing element up to 10 \(\mu m\). The maximum permissible probing error (MPEp) is measured to be 0.67 \(\mu m\). The repeatability is determined by repeated measurements of a reference sphere.
in 541 measuring points, which results in a mean repeatability over all measuring points of 0.01 \( \mu m \). Therewith it is possible to compensate the probing errors of the probing system. Even after an enforced collision of the probing element with the workpiece the mean repeatability over 541 measuring points before and after the collision is just 0.02 \( \mu m \). The environmental variation error (EVE) is determined to be less than 0.54 \( \mu m \) during a measurement time of 16 hours in an air-conditioned measuring room, which temperature is controlled to be within \( 20^\circ C \pm 0.25^\circ C \) and not to change more than \( 0.1^\circ C \) per hour.

Its differences to existing probing systems for miniaturised components are the large measurement range, the possibility to replace the probing stylus and the simple mechanical setup with components manufactured with standard metal cutting machine tools.
Zusammenfassung

Die stetige Miniaturisierung von Bauteilen, wie beispielsweise Einspritzdüsen mit Auslassdurchmessern kleiner als 100 $\mu$m oder Hörgeräte, führt zu steigenden Anforderungen an die 3D-Messtechnik, damit die geometrischen Merkmale der hergestellten Bauteile ohne deren Beschädigung überprüft werden können. Zudem können Fertigungsverfahren nur verbessert werden, wenn die Messunsicherheiten der verwendeten Messverfahren deutlich kleiner sind als die zu prüfenden Toleranzen der hergestellten Bauteile bzw. der verwendeten Werkzeugmaschinen.


Es wird ein Tastsystem für den Einsatz auf Mikro-Koordinatenmessgeräten mit isotropen Steifigkeiten am Tastelement von $84 \frac{N}{m} \pm 25 \frac{N}{m}$ präsentiert, welches sich dadurch für die Vermessung von kleinen und sehr empfindlichen Bauteilen eignet, ohne deren Oberfläche zu deformieren. Die mit Kraftmessungen experimentell überprüfte Steifigkeit beträgt $78 \frac{N}{m} \pm 26 \frac{N}{m}$. Die Voraussetzungen und Anforderungen an das Design des Tastsystems, dessen Simulation sowie die Herstellung und Montage der einzelnen Komponenten werden erläutert, damit Simulation und praktische Umsetzung übereinstimmen.
Zusammenfassung

Die geometrische Prüfung auf dem hochgenauen Koordinatenmessgerät ISARA ergibt einen Linearitätsfehler in Antastrichtung von 0.12 $\mu m$ über einen Verfahrweg von 10 $\mu m$. Die Antastabweichung (MPE$_P$) beträgt 0.67 $\mu m$. Die mittlere Wiederholgenauigkeit des Tastsystems wird durch wiederholte Messungen an einer Referenzkugel mit jeweils 541 Antastpunkten bestimmt und beträgt 0.01 $\mu m$. Damit besteht die Möglichkeit, die Antastabweichungen des Tastsystem zu kompensieren. Selbst nach einer kontrollierten Kollision des Tastelementes mit dem Werkstück beträgt die gemittelte Wiederholgenauigkeit bei 541 Antastpunkten vor und nach der Kollision lediglich 0.02 $\mu m$. Der Einfluss sich ändernder Umgebungsbedingungen (EVE) beträgt über eine Messdauer von 16 Stunden weniger als 0.54 $\mu m$ in einem klimatisierten Messraum, dessen Temperatur innerhalb von $20^\circ C \pm 0.25^\circ C$ liegt und während einer Stunde nicht mehr als $0.1^\circ C$ ändert.

Die Unterschiede zu bestehenden Tastsystemen für miniaturisierte Bauteile sind der grosse Messbereich, die Möglichkeit den Taststift zu wechseln sowie der einfache mechanische Aufbau mit Komponenten, welche auf konventionellen Werkzeugmaschinen für die Metallbearbeitung hergestellt werden.
Chapter 1

Introduction and State of the Art of Tactile Probing Systems

New manufacturing technologies enable the miniaturisation of components and its features, e.g. fuel injection nozzles with diameters less than 100 $\mu$m, components for cameras and computers or hearing devices. This results in increasing demands in 3D-metrology to prove the geometric specifications of the manufactured components without damaging them and, on the other hand, to improve the manufacturing technologies.

For measuring such miniaturised components, conventional CMM’s are not applicable because of

- their probing forces in the range of 0.05 $N$ up to 1 $N$. This probing forces are too high for small probe diameters and damage the workpiece to be checked;

- the limitations of the minimal probing sphere diameter of approximately 1 $mm$;

- their measurement uncertainty in the range of several $\mu m$, which is often higher than the specifications to be checked.

Therefore, some special CMM’s and probing systems for measuring small components have been realised. These systems are less limited in the above mentioned properties and are therefore the state of the art in measuring miniaturised components with low uncertainties in the sub-$\mu m$-range (see section 1.5).

In this thesis a new tactile 3D-probing system is presented to measure such miniaturised components. Due to the simple design, FEM can be used to obtain target stiffnesses of the probing system and thus target probing forces, which extend the applicability of this probing system. Furthermore, the applicability is increased by a replaceable probing stylus
in contrast to existing probing systems. The components of the probing system are manu-
factured with standard metal cutting machine tools. The advantages and disadvantages
of the new 3D-probing system are discussed.

An extensive discussion of the need of a new probing system and the research gap to be
filled is done in section 1.6.

1.1 Outline of this thesis

In this introductory chapter an overview of coordinate metrology is given. The continuing
trend of miniaturisation of components and their consequences concerning metrology are
also shown. The chapter concludes with the motivation for a new 3D-probing system,
which is derived from deficiencies of the state of the art.

In chapter 2 the design process of the new 3D-probing system is presented. To calculate
probing forces or permissible deflections of the probing element, the FEM software ANSYS
is used. Using the FEM tool, a probing system with isotropic stiffnesses at the probing
element of \( 84 \frac{N}{m} \pm 25 \frac{N}{m} \) is realised and experimentally checked. Furthermore, the man-
ufacturing as well as the assembly of the probing system are discussed. Another tool for
designing the probing system is an uncertainty estimation of the deflections of the probing
element. Therewith, the specifications of the sensors to be used and their alignment can
be predicted.

In chapter 3 the setup of the new 3D-probing system, based on capacitive sensors which
are best applicable, is described. Measurement results to determine the accuracy of the
probing system and an uncertainty estimation are discussed.

Finally, concluding remarks and recommendations for future improvements are presented
in chapter 4.

In appendix A the results of the probing system based on Fizeau Interferometry are pre-
sented, a system realised as first prototype of the presented probing system. It is based
on an idea of Mitutoyo for measuring the flatness and parallelism on wavers [4]. The ad-
vantages are its simple mechanical setup and that only one measurement device is needed
to measure the deflections of the probing element in X-, Y- and Z-direction.

In appendix B details of the designing with FEM, the manufacturing of the components
and the assembly of the probing system are discussed.

Considerations on force measurements executed in this work are summarised in appendix C.

In appendix D the detailed evaluation of different measurement principles for determining
the deflection of the probing element are presented.

1.2 Coordinate metrology

A CMM is a device to measure the spatial coordinates of a point on an object. A typical CMM is shown in figure 1.1. To determine the X-, Y- and Z-coordinates of a point on a surface, a non-contacting probing system or a contacting probing system (see chapter 1.2.1) is moved relatively to the workpiece to be checked. The probing system is moved by a drive unit (see chapter 1.2.2) till it contacts the surface of the workpiece to be checked. In contrast to a non-contacting probing system, a contacting probing system needs material contact with the surface being measured [1]. Typical workpieces to be checked by CMM’s are gear boxes, cylinder blocks, gear wheels, impellers or components of machine tools (so almost all cubical, axially symmetric and not axially symmetric components) [1], [5], [6], [7]. The individual measuring points on an object, determined in a common coordinate system, are combined by best-fit algorithms for the measured surfaces, e.g. planes, cylinders, spheres or cones [8], [9]. Afterwards, deviations in form, position, orientation and size from the nominal geometry are evaluated and compared with tolerances of the statements on the drawing [10].

![Figure 1.1: Typical coordinate measuring machine with three linear axes.](source: www.leitz.de)
The basic components of a CMM are

- a probing system (see chapter 1.2.1) which senses the workpiece to be checked by touching it or in a contactless way. One possibility to classify probing systems are the degrees of freedom they measure, e.g. 1D-, 2D- or 3D-probing systems;

- a drive unit (see chapter 1.2.2) to move the workpiece or the probing system to be checked into the measurement range of the probing system. Typically, each linear direction of motion is enabled by a component moving along a guideway. The moveable components are often guided by air bearings and their position is measured by linear scales. When measuring workpieces with complex geometries and limited accessibility for the probing stylus, an additional axis of rotation is used, e.g. for measuring the surface of an impeller;

- a machine base, typically of granite and isolated against vibrations of the environment;

- a control system and an operator panel;

- software with a model of the CMM to compensate geometric errors of the probing system and the drive unit. Typically, the drive unit has the major influence on the accuracy of a CMM. In [11] and [12] the geometric motion errors, which cause an imperfect motion between probing element and workpiece, are separated in component errors (e.g. positioning error of a linear axis) and in location errors (e.g. squareness error between two linear axes).

Because of widespread use of contacting probing systems and an increasing demand in checking mechanical properties, this thesis focuses on contacting sensors. A main advantage of contacting sensors is the mechanical contact with the surface of the component to be checked. The sensors are mostly independent of surface and material properties like the optical reflectivity, transparency or the surface roughness. Further advantages are low measurement uncertainties down in the nm-range as well as the possibility of different probing styli, probing extensions and probing elements. This enables the measurement of coordinates of points on surfaces which are difficult to access, exemplary an undercut. The huge field of application is limited by the speed of measurement or by probing forces, which may damage the surface of the component to be checked, even if they are in the mN-range.

The advantages of non-contacting sensors are their high flexibility and the possibility of extensive measurements of points on a surface. Additionally, they are applicable for measuring sensitive, soft or non-rigid components.
Often mechanical properties like roughness, deviations in form, diameters or fits have to be checked, and this is generally more accurate with mechanical probing compared to optical probing, which has its advantages for checking optical properties like the reflectivity or scattering.

### 1.2.1 Probing systems

The probing system of a CMM is a sensor which detects the contact or distance to the workpiece to be checked. This measurement can be tactile or contactless. Depending on the workpiece to be checked, a tactile or a contactless probing system has advantages. Contactless probing systems include triangulation sensors, focusing techniques, microscopy, interferometry, photogrammetry, fringe projection systems or multilateration [13], [14].

In the following, only tactile probing systems with mechanical interaction with the workpiece are of interest [1], [6], [15]. A tactile probing system uses a probing element, typically a sphere or a disk with diameter between 1 mm and 8 mm on a stylus. When measuring the spatial coordinates of single points on a surface, the probing element is in contact with the workpiece to be checked (see figure 1.2).

In manual guided CMM’s the probe is fixed or a touch-trigger probe is used, in contrast to numerically controlled CMM’s with touch-trigger or measuring probes [15]. A touch-trigger probe generates a signal if the deflection of the probing element exceeds a certain

![Figure 1.2: Typical probing head for conventional coordinate measuring machines (source: Leitz [16]).](image-url)
threshold. Touch-trigger probes are the most commonly used probing systems in CMM’s as well as in machine tools (e.g. machining centres, see section 1.3). Their main application is discrete-point probing: the probing element is moved between two measuring points without touching the workpiece. For scanning measurements with a permanent contact between probing element and workpiece, measuring probing systems are indispensable. These systems determine the deflection of the probing element by measurements and have therefore the smallest uncertainty and repeatability. Typically, such systems are used for scanning and in high-precision CMM’s which are placed in air-conditioned and vibration isolated measuring rooms.

To increase the applicability of probing systems, especially for measuring free-form surfaces like impellers, articulating probing systems are used. An additional positioning device with two axes of rotation, mounted between ram and probing system, enables any angular orientation of the probing stylus in space (see figure 1.3).

To specify the measurement uncertainty of a probing system, ISO proposes that the maximum permissible probing error (MPE) is used [1]. Manufacturers of probing heads instead often use for declaration of measurement uncertainties for touch-trigger probes the repeatability, which is in the range of 0.35 \( \mu m \) up to 0.7 \( \mu m \), and for measuring probing systems the resolution, which is specified to be less than 0.1 \( \mu m \).

Typical probing forces for conventional probing systems are in the range of 0.05 \( N \) up to 1 \( N \) [18], the stiffness, depending on the length of the probing stylus, is in the range of
1.2 Coordinate metrology

1000 $\frac{N}{m}$ up to 5000 $\frac{N}{m}$ [16].

The requirements on a probing system for CMM’s are [15]:

- preferably high repeatability of the probing procedure;
- preferably large measurement range to avoid damages at the probing system during probing (e.g. pretravel and overtravel [15]) or when changing the probing stylus;
- linearity over the complete measurement range (which might be compensated);
- probing forces which don’t damage the workpiece to be checked, e.g. by plastic deformations. Probing forces are related to the stiffnesses of the probing system and its moved mass, especially during the first contact of the probing element with the workpiece: the higher the moved mass, the higher is the impact of the probing element on the surface to be measured (see also chapter 1.4.2 and figure 1.9). The probing element and workpiece are moved relatively before they contact. This first contact is similar to a collision which generates a signal in the probing system and the drive unit is stopped by the control system. But not only the first collision damages the surface, also the bouncing of the probing element after the first contact [19];
- isotropic probing behaviour, which means that the probing system has the same stiffnesses at the probing element in each probing direction. This results in the same probing forces at constant deflections of the probing element during probing, independent from the probing direction. Otherwise, if the stiffnesses at the probing element are anisotropic, the maximum permissible deflection of the probing element during probing is limited by the probing direction with the highest stiffness in order to keep the probing forces constant. Consequently, the probing velocity is also limited by the probing direction with the highest stiffness and results in a lower permissible probing velocity;
- possibility to replace the probing element, e.g. various styli or stylus extensions;
- thermal stability;
- isolation against vibration.

1.2.2 Drive units

The drive unit with typically three linear axes generates the relative motion between the probing element and the workpiece to be checked. As mentioned before, an additional
axis of rotation is used for surfaces difficult to access, e.g. impellers. There are many alternatives to arrange the single axes, e.g. fixed table cantilever CMM’s, moving bridge CMM’s or Gantry CMM’s [1]. Depending on the accuracy of the CMM, expressed in the MPE value [1] which also includes partly the accuracy of the probing system, the drive unit has to fulfil following requirements:

- geometric accuracy of the axes, which is defined by component and location errors like positioning or squareness errors [11], [12];

- repeatability of the axes, which also limits the possibility to increase the accuracy by compensation [12] or reversal methods [20];

- vibration isolation to eliminate disturbances from the environment [21], [22];

- thermal stability to decrease thermal errors caused by CMM internal sources or external influences [23], [24];

- long-term stability to preserve the (calibrated) geometry of the CMM.

1.2.3 Calibration of CMM’s

In a first step, the geometric accuracy of the drive unit is checked by calibrating and compensating single component and location errors with adequate measurements [11]. Afterwards, the acceptance and reverification for the CMM is proven according to the ISO 10360 series "Acceptance and reverification tests for coordinate measuring machines (CMM)". The acceptance test as proposed in [25] or [26] consists of length measurements at gauge blocks or other reference objects like ball plates [27] in different positions and orientations. Therefore, the performance of a CMM - the combination of the drive unit with the probing system - in its whole working area is checked.

1.3 Coordinate metrology on machine tools

Another field of application of probing systems is the use in machine tools, especially in machining centres. There are three main operation purposes [28], [29]:

- workpiece presetting to find reference points on the workpiece which are used in the NC-program of the machine tool;

- workpiece measurement to check its geometry before the next machining operation
is started or to evaluate machining trends in mass production;
- tool measurement to determine its length and radius or the wear of the tool.

The probing systems used for workpiece presetting and workpiece measurement are typically touch-trigger probes (see figure 1.4) as discussed in section 1.2.1 with a probe repeatability in the range of $1 \, \mu m$. The systems used for tool measurements are touch-trigger probes as well as optical systems. The contactless optical systems have the advantage to determine tool length and radius at the same speed of rotation as during manufacturing, even for very small tools. Another advantage is to really get the effective material removal profile of the tools.

![Diagram of a touch-trigger probe](image)

Figure 1.4: Touch-trigger probe for use in machining centres (source: Heidenhain [29]).

In [28] test procedures are described to evaluate the performance of tactile probing systems as a component of a machine tool. So the results of these tests depend on the machine tool, the environment, the probing software and on the probing system itself. The suggested tests include ETVE tests as suggested in [30], repeatability tests as well as 1D-, 2D- and 3D-probing error tests, depending on the capability of the probing system.
1.4 Metrology for micro-components

Developments in precision engineering enable the miniaturisation of workpieces and components. The motivation behind this are "new applications, better performance, less expensive and higher quality" [31]. The increasing request for precision in machine tools is shown in figure 1.5.

This progress in manufacturing of miniaturised components can only be verified and further improved if metrology is even more accurate [10]. To sketch the dimensions of these micro-components, which are measured by tactile coordinate measuring machines, the following definition of micro-components related to coordinate metrology is suggested:

The outer dimensions of micro-components range from several millimetres up to the metre. Independent from this outer dimensions a micro-component has geometric features in the microscale with tolerances on micrometre level or even less. Micro-components cover small parts with intricate geometries (e.g. injection nozzles) as well as large parts with complex, tight tolerated and high quality features (e.g. mirrors for telescopes).

Some examples of advanced manufacturing processes as well as examples of micro-components are listed in section 1.4.1.

1.4.1 Fabrication of micro-components

As mentioned in section 1.4, there is an increasing demand for micro-components. In this chapter some examples for such components are summarised. The progress in production engineering is enabled by new and advanced manufacturing processes like micro-milling, micro-EDM, micro-ECM, micro-powder injection moulding, hybrid processes like laser assisted micro-milling [32] or laser assisted micro-grinding [31], [33], [34], [35].
Health applications like miniaturisation of medical-technical tools to enable endoscopic surgery without pain, e.g. micro-needles [36] as shown in figure 1.6 or miniaturised components for implants, e.g. an inducer for a micro-bloodpump [37] as shown in figure 1.7 A. Other examples are low-cost medical diagnostics by miniaturised lab-on-chip devices like micro-fluidics [38] or integrated multiple lab processes [39], [40] or hearing devices.

Environmental regulations to reduce emissions, e.g. fuel injection nozzles with diameters less than 100 $\mu m$ [41], [42] or micro-structured components in combustion engines [43].

Optics like large scale optics for telescopes with permissible deviations in the nanometre range, aspherical lenses or freeform optics as shown in figure 1.7 B.

Additional functionality by constant or even decreasing size of the components, e.g. micro-acceleration sensors in cars [46], devices for telecommunication, cameras (see figure 1.7 C), television, computer, the storage of data or fibre-optic light guides.
1. Introduction and State of the Art of Tactile Probing Systems

1.4.2 Consequences concerning metrology

To decide if a manufactured component fulfils its geometric specifications, the uncertainty of the used measuring equipment has to be considered [10]. If manufacturing enables the fabrication of smaller tolerances for deviations in size, form, position and orientation, the measurement equipment has to be improved as well. Otherwise, the conformance or non-conformance of workpieces with the specifications can’t be proven.

Design / specification phase

![Image of specification zones](image)

Verification phase

- To enable accessibility of the probing element to very small geometric features on the micro-component to be checked (e.g. holes with diameters less than 1 mm or cylinders with length in the range of several mm), smaller probing elements (diameter...
less than 500 $\mu m$) have to be used. Typically, conventional probing elements have diameters between 1 mm and 8 mm;

- The probing forces of conventional CMM’s are in the range of 0.05 N up to 1 N. This results in combination with small probing elements (e.g. probing spheres with diameter less than 500 $\mu m$) in plastic surface deformations on the workpiece to be checked because the Hertzian stress is too high [47]. Figure 1.9 shows lasting deformations on the surface of an aluminium workpiece at each measuring point [7], [19], [48];

![Probing force X and Y: ~0.020 N in Z: ~0.025 N Diameter of probing sphere: 3 mm](image)

Figure 1.9: Lasting deformations on an aluminium workpiece, caused by point-wise tactile probing with probing sphere of diameter 3 mm on a conventional CMM. The stiffness of the probing system is in the range of 2000 N/m.

- Highest requirements concerning metrology arise if macro- and micro-components should be measured with identical relative tolerances and uncertainties:
  If a diameter 200 mm $\pm$ 10 $\mu m$ is reduced with the same relative tolerances to a diameter 2 mm $\pm$ 0.1 $\mu m$, then the measurement uncertainty should also be reduced in the same relation. A suitable value for the measurement uncertainty for checking the big diameter is 2 $\mu m$, so the uncertainty for checking the small diameter should be only 0.02 $\mu m$;

- The limited accuracy of conventional CMM’s with MPE-values in the range of 1 $\mu m$ up to 5 $\mu m$ plus a length depending error contribution prevents a conformance checking for micro-components with their tight tolerated deviations in form, orientation, size and position. Especially the requirements on the accuracy of the drive unit increase extremely if measurement uncertainties less than 0.5 $\mu m$ in a
workspace of about 100 $mm \times 100 mm \times 100 mm$ have to be fulfilled. Examples are the metrology frame to decrease the influence of external forces on the measurement of the axes position, high-precision laser interferometers or the Abbe principle [49], [50], [51], [52], [53], [54], [55].

1.5 State of the art of tactile probing systems for micro-components

In this section an overview of existing probing systems is given. It’s a non-exhaustive enumeration without rating. The different systems are classified in three main groups (see chapter 1.5.1 up to 1.5.3), depending on the technique to determine the deflection of the probing element [48]. All presented probing systems have been developed to measure micro-components with low probing forces and small measurement uncertainties. Table 1.1 gives a short summary over the existing probing systems.

Table 1.1: Summary of existing probing systems for coordinate metrology of micro-components.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Metas</td>
<td>26 (isotropic)</td>
<td>0.5</td>
<td>$\pm 200$</td>
<td>5</td>
<td>50</td>
<td>inductive</td>
</tr>
<tr>
<td>IBS Triskelion</td>
<td>70 (isotropic)</td>
<td>0.5</td>
<td>$\pm 10$</td>
<td>-</td>
<td>15</td>
<td>capacitive</td>
</tr>
<tr>
<td>NPL</td>
<td>10 (isotropic)</td>
<td>0.1</td>
<td>$\pm 20$</td>
<td>-</td>
<td>-</td>
<td>capacitive</td>
</tr>
<tr>
<td>TU Eindhoven</td>
<td>17 (X, Y), 100 (Z)</td>
<td>0.1</td>
<td>$\pm 20$</td>
<td>4</td>
<td>-</td>
<td>piezo-resistive</td>
</tr>
<tr>
<td>XPress Gannen XP</td>
<td>400</td>
<td>0.4</td>
<td>$\pm 10$</td>
<td>2</td>
<td>45</td>
<td>piezo-resistive</td>
</tr>
<tr>
<td>PTB / Werth</td>
<td>-</td>
<td>$\ll 1$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>optical</td>
</tr>
<tr>
<td>Mitutoyo UMAP</td>
<td>-</td>
<td>0.001</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>piezo</td>
</tr>
</tbody>
</table>
1.5 State of the art of tactile probing systems for micro-components

So there are some similarities in the requirements of the already realised probing systems with the new probing system presented in this thesis from chapter 2 and following chapters. A main distinguishing feature is the handling of the probing systems and their sensitivity to large deflections of the probing element, which often result in a damage of the probing stylus or the hinges. To this effect the new probing system should be less sensitive and more user-friendly. Further objectives of the new 3D-probing system are summarised in chapter 1.6.

1.5.1 Analogue probing systems

Analogue probing systems use internal measurement systems like capacitive or piezo-resistive sensors or LVDT’s to determine the deflection of the probing element. Several systems exist with uncertainties in the range of only 10 \( \text{nm} \).

**Metas probing system:** This measuring probing system (see figure 1.10) is based on parallelograms with integrated flexure hinges to enable a motion of the probing stylus in three directions. All three axes are inclined at 45° by reason of symmetry in respect to gravity. The isotropic stiffness is 26 \( \frac{N}{m} \) which results in probing forces of about 0.5 \( mN \). The probing system has a repeatability in the range of 5 \( nm \) [56], [57], [58].

![Metas probing system](image)

**NPL probing system:** At NPL a probing system was developed which uses capacitive sensors to measure the deflection at three target discs, see figure 1.11 [53]. The

![NPL probing system](image)
weight of the moveable component is 350 \textit{mg} and is supported by three flexure hinges, made of beryllium-copper. The system has an isotropic stiffness of 10 \textit{N/m} and a measurement range of ±20 \textit{µm}.

**IBS Triskelion:** \textit{IBS Precision Engineering} developed and distributes the probing system \textit{Triskelion} (see figure 1.12). Monolithic flexure hinges connect the housing of the probing system with the moveable part where the probing stylus is mounted. The system has a resolution of 3 \textit{nm}, a 3D-measurement uncertainty less than 15 \textit{nm} and an isotropic stiffness at the probing tip of 70 \textit{N/m}, which results in probing forces of approximately 0.5 \textit{mN}. The measurement range is ±10 \textit{µm} [59].

**Xpress Gannen XP:** A very sensitive probing system is the \textit{Gannen XP}, see figure 1.13. Based on a silicon chip with integrated piezo elements, the colliding mass is only
34 mg. The 3D-uncertainty is approximately 10 nm. The repeatability is 2 nm, the stiffness at the probe tip about 400 N/m and the measurement range 30 µm. The probing force is specified to be less than 0.4 mN [60].

**Figure 1.13:** The *Gannen XP*, an high-precision tactile probing system. On the left: The chip of the probing system. In the middle and on the right: The realised probing system (source: *Xpress* [60]).

**TU Eindhoven:** Due to impact forces and bouncing of the probe tip during probing, a probing system based on an optical measurement system was developed [61]. Therewith, all six degrees of freedom can be measured, even at probing speeds up to 70 mm/s. The measurement uncertainty is approximately 1 µm.

Another probing system developed at *TU Eindhoven* is based on silicon hinges, see figure 1.14. During probing three elastic hinges are distorted. With integrated piezo-resistive strain gauges on the elastic hinges the 3D-deflection of the probing sphere is determined [62], [63].

**Figure 1.14:** 3D-probing system based on three slender rods (source: *TU Eindhoven* [63]).
1.5.2 **Opto-mechanical probing systems**

This category of probing systems uses optical metrology to determine the deflection of the probing element.

**PTB / Werth**: Different 2D- and 3D-probing systems have been developed, all based on a fibre probe. The probing systems use a microscope with CCD camera to detect the X- and Y-position of the probing sphere. With an additional optical system the Z-deflection of the probing sphere is determined, see figure 1.15. The probing sphere is melted on a glass fibre which is illuminated and thereby makes the sphere visible for the camera. The spheres have diameters down to 20 µm. By reason of the fibre, the stylus is less breakable. Due to the fibre the probing forces are, depending on the type of the probing system, in the range of some µN, which enables the measurement of even very sensitive components without damaging the surface. The MPE is about 0.3 µm [64], [65], [66].

![Figure 1.15: Probing system from PTB / Werth based on a glass fibre.](image)

On the left: Schematic setup of the 2D-probing system for detecting the horizontal deflection of the probing sphere.  
On the right: Realised 3D-probing system Werth Fiber Probe 3D-WFP (source: PTB / Werth [64], [66]).

1.5.3 **Vibrating probing systems**

The third category of probing systems uses a vibrating element to detect the contact between probing element and workpiece. Furthermore, a vibrating element reduces the probing forces.
1.5 State of the art of tactile probing systems for micro-components

**Mitutoyo UMAP (Ultrasonic Micro and Accurate Probe):** The **UMAP130** probing system (figure 1.16) uses the change in the amplitude of the vibrating probing element to detect contact with the workpiece. The repeatability is about 0.1 \( \mu m \), the contact force about 1 \( \mu N \) [67], [68], [69].

![Figure 1.16: Mitutoyo UMAP probing system with vibrating probing element (source: [69]).](image)

**1.5.4 Micro-coordinate measuring machines**

In this section an overview of some realised coordinate measuring machines for micro-components is given. They have in all three axes high resolution scales (smaller 10 \( nm \)) and low 3D-measurement uncertainty (smaller 500 \( nm \)) in a workspace of at least 25 \( mm \times 25 mm \times 5 mm \) in common.

**Zeiss F25:** The **F25** from Zeiss (see figure 1.17) has a workspace of 130 \( mm \times 130 mm \times 100 mm \) with a measurement uncertainty of 250 \( nm \) at a resolution of 7.5 \( nm \). As probing system a tactile as well as an optical system can be used. The tactile probing system is based on a silicon chip membrane with integrated piezo-resistive elements [70]. The diameter of the probing sphere is between 100 \( \mu m \) and 700 \( \mu m \), the stiffness at the probing sphere is less than 500 \( \frac{N}{m} \). The MPE depends on the measuring length \( L \) and is specified for temperatures between 19.5\(^\circ\) and 20.5\(^\circ\) to be less than \((0.25 + \frac{L}{600}) \mu m \) (for calculating the MPE).
the length unit \( mm \) has to be used for the measuring length \( L \), the MPE\(_p\) is less than 0.3 \( \mu m \).

![Figure 1.17: Coordinate measuring machine Zeiss F25 (source: Zeiss [70]).](image)

**SIOS Nano-positioning and nano-measuring machine NMM-1:** This 3D-CMM has a measuring range of 25 \( mm \times 25 mm \times 5 mm \) with a resolution of 0.1 \( nm \) [71], [72]. Tests with several probing systems, optical and tactile, have been carried out [73]. The drive unit is based on the Abbe Comparator principle. Figure 1.18 shows the setup of the drive unit.

![Figure 1.18: Nano-measuring machine NMM-1 from SIOS (source: SIOS [72]).](image)
**IBS ISARA 400**: This CMM (see figure 1.19) has a workspace of \(400 \text{ mm} \times 400 \text{ mm} \times 100 \text{ mm}\) with positioning accuracy less than \(\pm 0.5 \mu m\) during still-stand. The position of the three linear axes is measured by laser interferometers with a resolution of \(1.6 \text{ nm}\) fulfilling the Abbe principle. A special metrology frame, which is stress-free coupled to the base frame, eliminates the actuator forces from the position measurement of the mirror table. The 3D-measurement uncertainty (including probing system) is said to be \(109 \text{ nm}\) [74], [75], [76].

![Coordinate measuring machine ISARA 400 from IBS (source: IBS [76]).](image)

1.6 **Motivation**

The demand for miniaturised industrial products forces the manufacturing technology to improve their processes, machines and metrology to enable a fabrication of such components. The motivating forces of this trend are extremely manifold: the implementation of an increasing number of functions in a product, environmental regulations to reduce emissions, biotechnology, health applications or the consumer request of having portable products. A key technology to fulfil the above mentioned requirements of miniaturised products is **micromachining** [77], [78]. With reduced outer dimensions of a component, the tolerances for deviations in size, form, position and orientation also decrease. Section 1.4.1 gives some examples of miniaturised components and their applications.

As consequences of this development the measurement uncertainties have to be reduced. Only if manufacturing technology and **metrology** are improved in lockstep, a miniaturised component with appropriate reduced tolerances can be checked for conformance or
non-conformance with specifications. Thereby not only requirements for the sensor to determine the coordinates of measuring points on a surface arise, but also for the drive unit, which moves the sensor relative to the workpiece to be checked. These requirements are exemplary a high resolution in the $nm$-range or high repeatability on the sub-micrometre level. Additionally, the environment of such metrology equipment has to be thermal stable and isolated against vibrations. A functional failure of miniaturised components like acceleration sensors, hearing devices, control modules or implants like blood pumps can have extensive, undesirable effects.

As summarised in section “State of the Art” (see chapter 1.5), there are some probing systems for miniaturised components commercially available. The probing systems are based on different techniques to convert the deflection of the probing element into an electrical signal or to measure the coordinates of points on a surface by optical methods. Partially, these probing systems have uncertainties in the $nm$-range and an isotropic stiffness at the probing element less than 100 $\frac{N}{m}$. The deficiencies of existing probing systems are:

- their small measurement range of partial only $\pm 10 \, \mu m$, which makes the systems extremely susceptible to damages caused by inadvertent handling or deflections of the probing element, which exceed their measurement range. Additionally, the small measurement range results in a challenging stopping performance of the drive unit used;

- the missing possibility to replace the probing stylus, e.g. after a collision or to change the size of the probing element;

- a complex manufacturing of the components (e.g. etching) as well as a time-consuming and challenging assembly. For most probing systems, the moveable component is realised by fine flexure hinges. These flexure hinges are, apart from the probing stylus, the most critical component after a collision of the probing element with the workpiece.

Resulting from the above mentioned deficiencies, the motivation for presenting another 3D-probing system is detailed in following enumeration and summarised in table 1.2:

- Development and experimental verification of a FEM tool to design probing systems for micro-components. Therewith, the properties of the presented probing system, e.g. its stiffness at the probing element or its measurement range, are adjustable by simulations for specific measurement tasks before the probing system is manufactured. This enlarges the field of application of the presented probing system and makes it design applicable for conventional CMM’s or machine tools;
- Design of a 3D-probing system for micro-components with following properties:
  - Small probing forces to avoid lasting deformations on the workpiece to be checked. These probing forces should be in the range of several $mN$ and are therewith clearly smaller than those of conventional probing systems, which are up to 1 $N$;
  - Stiffness at the probing element smaller than $100 \frac{N}{m}$, which is at least smaller by factor 10 than the stiffness at the probing element of conventional probing systems with up to $5000 \frac{N}{m}$;
  - Possibility for skilled operator to replace the probing stylus without special tools, e.g. after a breakage of the probing stylus or to use a probing element with other dimensions;
  - Measurement range of at least $\pm 0.1 \ mm$, which is clearly larger than the over-travel distance of a CMM at a probing speed of 1 $\ mm/ s$. Additionally, this large measurement range makes the probing system unsusceptible to damages caused by its handling and installation on the CMM;
  - A simple mechanical setup whose components can be manufactured with metal cutting machine tools (like milling machines, grinding machines, electro-discharge machines or laser cutting machines);
  - Measurement uncertainty in the sub-$\mu m$-range;
  - Experimental validation of the 3D-probing system.

Table 1.2: Summary of the demands on the new 3D-probing system.

<table>
<thead>
<tr>
<th>Demand</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probing forces</td>
<td>$\leq 5 \ mN$</td>
</tr>
<tr>
<td>Stiffness at probing element in X-, Y- and Z-direction</td>
<td>$\leq 100 \frac{N}{m}$ (isotropic)</td>
</tr>
<tr>
<td>Measurement range</td>
<td>$\geq \pm 0.1 \ mm$</td>
</tr>
<tr>
<td>Measurement uncertainty</td>
<td>$\leq 1 \ \mu m$</td>
</tr>
</tbody>
</table>
Chapter 2

Design of the 3D-Probing System

In chapter 1.2.1 and 1.6 the demands on probing systems are summarised. The particular requirements on probing systems for micro-components are small probing forces in a preferably large measurement range, an isotropic probing behaviour [53] and, because of the threat of damaging the fragile probing system, a fabrication, assembly and replacement as simple as possible.

As presented in the state of the art in section 1.5, different design principles exist for supporting the moveable components of a probing system for micro-components:

- Vibrating probing systems, which measure the change of the amplitude or phase of the vibration of the probing stylus, have the advantage of reduced probing forces. Great efforts are necessary to focus the vibration only on the probing stylus and to isolate the drive unit of the CMM against the vibration;

- Fibre probing systems, based on an (optical) fibre with the probing element at one end, have the advantage of very small probing forces in the $\mu N$-range. Disadvantages are the anisotropic stiffnesses at the probing element as well as a measurement uncertainty in the range of $0.5 \mu m$;

- Silicon-based probing systems use membranes or flexure hinges of silicon to support the probing stylus. In addition with resistive sensors the deflection of the probing element is measured, but also other techniques are used. The probing speed of silicon-based probing systems is limited due to its inertia, which gives false readings [79];

- Flexure hinges based probing systems offer manifold possibilities in their design and metrology for measuring the deflection of the probing element. The flexure hinges may be arranged stacked or in one plane. The stacked design has the disadvantage of higher moved masses compared to a design in one plane. Additionally, the selection
of the material of the flexure hinges enlarges the field of application of this design principle.

Using a morphological analysis as shown in table 2.1, the diversity of solutions of probing systems used on CMM’s is systematically structured and the total set of relationships is investigated.

Table 2.1: Morphological analysis for probing systems used on CMM’s. Bold text: realised solution for the presented probing system.

<table>
<thead>
<tr>
<th>Functional properties</th>
<th>Partial solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kind of probing</strong></td>
<td>optical</td>
</tr>
<tr>
<td>Number of operated axes</td>
<td>one (1D)</td>
</tr>
<tr>
<td>Elasticity between probing element and workpiece</td>
<td>none</td>
</tr>
<tr>
<td>Measurement of deflection of probing element</td>
<td>none (fixed)</td>
</tr>
<tr>
<td>Operating point during measurement</td>
<td>kept constant (active probe)</td>
</tr>
<tr>
<td>Read-out of measurement signal</td>
<td>static</td>
</tr>
<tr>
<td>Replacement of probing stylus</td>
<td>none</td>
</tr>
</tbody>
</table>

Based on the morphological analysis, the functional properties as presented in table 2.1 of the realised 3D-probing system for micro-components are chosen to be:
- A tactile probing system with mechanical interaction between probing element and workpiece to be checked. As mentioned in section 1.2, contacting probing systems have the main advantage of being independent of optical surface and material properties of the workpiece to be checked, e.g. its reflectivity or roughness;

- A 3D-probing system shall be realised due to its possibility to probe a workpiece from five directions without re-clamping it, e.g. in ±X-direction, ±Y-direction and in Z-direction;

- The probing stylus shall be supported by joints, which reduces the probing forces compared to a fixed probing stylus. A parallel alignment of the joints reduces the probing forces due to lower moved masses compared to a serial alignment of the joints. The design of the joints mainly determines the stiffness at the probing element. Due to its advantages like small friction or high repeatability (see section 2.1), the new 3D-probing system is built-up on flexure hinges. As presented in section 2.2.2, FEM is used to evaluate different parallel alignments of the flexure hinges;

- To provide a probing system with highest accuracy, a measuring probing system is realised, see section 1.2.1;

- Realisation of a probing system with a switching operating point during measurement, which means that the suspension of the probing stylus is not moved actively by actuators to keep its position and orientation constant during measurement. Thereewith, the dynamics of the probing system are improved as well as the moved mass is reduced;

- Enabling a dynamic read-out of the measurement signal, which means that during the read-out at least one component is moving. The probing system can be used for discrete-point probing as well as for scanning;

- The possibility to replace the probing stylus enlarges the field of application of the probing system, because different probing elements can be used, adapted on the workpiece to be checked. In contrast to an automatic change of the probing stylus, a manual change of the probing stylus reduces the moved masses of the probing system, which reduces the stiffness at the probing element and therewith the probing forces.

In section 2.1 the setup of the probing head is presented, before the design process and its evaluation are discussed in chapter 2.2 and its subsections. The manufacturing and assembly is described in section 2.3. The verification of the FEM simulations is done by force measurements, see chapter 2.4. Due to conformance between simulated and measured
stiffnesses within their uncertainties, the developed design tool can be used as discussed in section 2.5 to improve the probing performance. Furthermore, the measurement principle to determine the deflection of the probing element is presented as well as an estimation of the theoretical uncertainty at the probing element. For the probing system with an isotropic stiffness, a weight compensation is realised as presented in section 2.5.4. Finally, the stiffnesses of the improved 3D-probing system are verified by force measurements and compared with the simulated stiffnesses.

2.1 Setup of the probing system

Conventional probing systems are typically based on three independent moving directions, e.g. a parallelogram with spring elements for the motion of the probing element in X-direction, a second parallelogram for the motion in Y-direction and a third parallelogram for the Z-motion of the probing element. A disadvantage are the orientation errors between the three serial arranged moving directions, which limit the accuracy of such systems.

In high-precision probing systems for use in checking micro-components the moving directions are arranged parallel to avoid orientation errors like a squareness error between the X- and Y-direction. These systems typically are based on flexure hinges (see figure 2.1) in order to fulfil also the requirement of low probing forces.

By reducing the dimensions of a rigid structure on a certain section, at least one relative rotation of the two adjacent and compared to the flexible part relatively rigid sections is enabled [80], [81]. Compared to classical hinges, flexure hinges have following main advantages [51]:

- no backlash and hence a high repeatability;
- no wear and therefore reduced maintenance;
- small friction (only internal friction) and hence less structural hysteresis;
- no lubrication needed.

For designing the flexure hinges the FEM is used. In chapter 2.2 the simulations are discussed. The basic concept of the 3D-probing system is a simple mechanical setup, whose components are easy to manufacture and easy to assemble. The probing head consists of four components and is shown in figure 2.2:

Figure 2.2: Design of the probing head based on flexure hinges with coordinate system.

A base plate which is the fixed structure of the probing head and which is clamped to the fixture with the sensor. The sensor detects the change in the position and orientation of the moveable plate of the probing system.

A moveable plate at which the probing stylus is mounted. The base plate and the moveable plate are connected by flexure hinges.

The flexure hinges enable a translation in Z-direction and two rotations around the A- and B-axis (see figure 2.2). The flexure hinges are manufactured of a monolithic thin foil with desired thickness (see chapter 2.2.3, 2.3 and 2.5).

A probing stylus which is screwed in the moveable plate and therefore replaceable, e.g. after a collision with the workpiece to be checked.

A deflection of the probing element results in a change of the A- and / or B-orientation of the moveable plate as well as in a change of its Z-position. This is detected by a sensor: in a first feasibility study, this sensor is a Fizeau interferometer (see appendix A). The advantage is that only one sensor is needed to detect the A-, B- and Z-deflection of the moveable plate [82], [83]. But the disadvantages of this measurement principle like a low
speed of the image processing or high costs of the interferometer caused a replacement of the Fizeau interferometer by three capacitive sensors as presented in chapter 2.5.1.

2.2 Simulation of probing behaviour

For simulating the probing behaviour, the FEM software ANSYS is used. In a first step, the probing behaviour of different geometries of the flexure hinges is evaluated (see subsection 2.2.2). The final design of a first prototype is presented in section 2.2.3. The stiffness of flexure hinges strongly depends on their geometry and material properties [84], so in subsection 2.2.4 an uncertainty estimation for the FEM simulation is presented. By choosing three different thicknesses of the flexure hinges (thickness of 60 $\mu m$, 80 $\mu m$ and 120 $\mu m$, respectively), the stiffness of the probing system can be varied by a factor 8.

2.2.1 Considerations on the FEM simulation

The critical components of the probing system are the flexure hinges, because they have the main influence on the probing behaviour. For meshing the flexure hinges, the sweep method with SOLID 186 elements is chosen (see figure 2.3 B). These elements are hexahedrons with 20 nodes. At each node, the element has three translational degrees of freedom. This element type supports amongst others large deflections, stress stiffening and plasticity. The other components are modeled with SOLID 187 elements, which are tetrahedrons with 10 nodes, having also three translational degrees of freedom at each node. This element is well suited for irregular meshes. It is able to model the same phenomena as the SOLID 186. The contacts between the single components are modeled by TARGE 170 and CONTA 174 elements, which have the same geometric properties as the solid element face, on which they are located. If the element surface pervades the target segment elements on a specified target surface, the elements are defined as being in contact [85].

By refining the mesh size, the convergence of the solution is checked. For the flexure hinges with size of 11 $mm \times 0.6 \ mm \times 0.08 \ mm$ (length \ width \ thickness), an element size of 0.2 $mm \times 0.1 \ mm \times 0.01 \ mm$ or rather 5 elements per $mm$ length, 10 elements per $mm$ width and 100 elements per $mm$ thickness is sufficient (see appendix B.1). With this element sizes, other geometries of flexure hinges are meshed. In figure 2.3 C and D the resulting deflection of the moveable components and the stress in the flexure hinges by an acting force are shown.

ANSYS offers a linear solver and a non-linear solver for "large deformations". The latter takes geometrical non-linearities into account. Using the linear solver, the bending of the
Design of the 3D-Probing System

![Diagram of the 3D-Probing System](image)

Figure 2.3: Modeling the probing system in FEM software ANSYS. A: Complete meshed probing system. B: Detail of meshed flexure hinge. C: Resulting deflection of the probing element under the influence of a probing force (blue = 0 µm, red = 41.6 µm). D: Resulting stress in the flexure hinges caused by an acting probing force (blue = 0.1 \( N/mm^2 \), red = 46.6 \( N/mm^2 \)).

Flexure hinges, caused by gravity, is not determined correctly, because this method does not include the strain in the flexure hinges. However, the different solver types have only diverging solutions if gravity causes a non-flatness of the flexure hinges. This non-flatness results in an increasing stiffness at the probing element in X-, Y- and Z-direction and is comparable to the properties of a disc spring (see appendix B.2 and B.5 for detailed results of simulations). The stiffness at the probing element is determined by applying a force at the probing element and calculating its deflection in direction of the force. Using the non-linear solver and varying the force, it can be checked if the stiffness is constant or a function of the deflection. In contrast to the linear solver, the non-linear solver as well as measurements result in a non-linear stiffness at the probing element.
2.2 Simulation of probing behaviour

Due to a non-linear deflection force curve, a linear solution is only valid, if the non-flatness of the flexure hinges, caused by gravity, is corrected by a weight compensation (see section 2.5.4) or if the non-flatness has insignificant influence on the stiffness. Using the non-linear solver, the non-flatness and its consequences on the stiffness can be estimated.

The first prototype of the probing system, presented in section 2.2.3, has a moving mass of only 0.0011 kg, which is supported by the flexure hinges. This is a small mass compared to the stiffness in Z-direction, therefore the influence of gravity and the non-flatness of the flexure hinges are negligible.

2.2.2 Influence of different geometries of the flexure hinges

As mentioned in section 1.4.2, probing forces have to be in the range of a few mN or even less to avoid lasting deformations on surfaces of micro-components. Additionally, an isotropic probing behaviour, which means same stiffness at the probing element in X-, Y- and Z-direction, is required. Another assessment criterion for evaluating different geometries is to avoid deflections of the moveable plate in the X- and Y-direction as well as a rotation C during deflecting the probing element (see figure 2.2 for definition of the coordinate system), because a basic principle of the 3D-probing system is a transformation of a motion of the probing element in X-, Y- and Z-direction in a motion of the moveable plate in Z-, A- and B-direction. To measure the position in Z and the orientation A and B of the moveable plate, a sensor is used with measuring direction Z, because all three permitted motions of the moveable plate result in a Z-translation. So the three degrees of freedom of the moveable plate in X-, Y- and C-direction have to be suppressed by the flexure hinges, in contrast to the Z-, A- and B-direction.

[86] investigates systematically the influence of different geometries of the flexure hinges on the stiffness at the probing element. Therefore, external forces or moments are applied on the moveable plate, at which the probing stylus is mounted. Figure 2.4 summarises evaluated geometries. Geometries of the flexure hinges with angular (figure 2.4 C and D) or bent hinges (figure 2.4 E) have lower stiffnesses in X- and Y-direction compared to straight hinges (figure 2.4 A and B).

For determining the stiffness at the moveable plate in X-, Y- and Z-direction, an external force is applied on the moveable plate and its deflection under this load is calculated, which results in the stiffness of the moveable plate in X-, Y- and Z-direction. A moment around the X-, Y- and Z-direction results in a stiffness in A-, B- and C-direction.
The radial alignment of the flexure hinges (figure 2.4 A) shows the best results in the simulation (see appendix B.3) and is therefore chosen by following reasons [86]:

- The stiffness of the moveable plate in X- and Y-direction is higher compared to the other geometries (see table B.3). The angular flexure hinges have the smallest stiffness in the three directions to be locked and are therefore rejected;

- The stiffness of the moveable plate in Z-direction and around the A- and B-direction is higher compared to other geometries, but it is in the same range for the radial and tangential alignment ($59 \frac{N}{m}$ compared to $42 \frac{N}{m}$ and $6 \cdot 10^{-5} \frac{Nm}{rad}$ compared to $4 \cdot 10^{-5} \frac{Nm}{rad}$);

- The probing behaviour can be estimated roughly by calculations of beam theory and is therefore intuitive understandable (see section 2.5.3);

- The probing behaviour can be designed to be isotropic by adapting the length, width and thickness of the cube-shaped flexure hinges (see section 2.5.3);

- The flexure hinges are easy and economically priced to manufacture.
2.2.3 Final design of first prototype of the probing system

This first design of the probing system has an anisotropic probing behaviour in X-, Y- and Z-direction, which is not important for checking its probing forces and therewith the FEM simulation, the manufacturing, the assembly and the measuring chain of the force measurements. The experimental determination of its stiffness and the comparison with the simulation is the prior task: if the simulated results can be proven by measurements, then the FEM simulation can be used as a tool to improve the probing system and to adapt its specifications like probing forces or measurement range. If the task is e.g. checking the roundness of a sphere in three planes perpendicular to each other, the anisotropy would have an influence because of different conditions of friction.

The first prototype of the probing system is shown in figure 2.2 and 2.5. Its properties are summarised in table 2.2. The probing head is manufactured with three different thicknesses of the flexure hinges, 60 $\mu$m, 80 $\mu$m and 120 $\mu$m.

The probing stylus is a commercial stylus from N"ussler with a length of 16 mm and a diameter of the probing sphere of 2 mm. This stylus is not used for checking micro-components, but for checking the stiffness of the probing head because of its stiffness and unsusceptible handling.

All other components of the probing head are made of stainless steel 1.4310. The flexure hinges are manufactured from a cold rolled steel strip, see section 2.3.

The complete geometry is modeled in FEM, see figure 2.3. To determine the stiffness at the probing element, a force $F$ is introduced at the probing element and its deflection $d$ in direction of the force is calculated. The stiffness in direction of the acting force is
computed as shown in (2.3) on page 41.

Table 2.2: Summary of the simulated properties of the first prototype of the probing system. Definition of coordinate system see figure 2.2.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $\times$ width $\times$ thickness of flexure hinges [mm]</td>
<td>$11 \times 0.6 \times 0.06$ $11 \times 0.6 \times 0.08$ $11 \times 0.6 \times 0.12$</td>
</tr>
<tr>
<td>Material of the flexure hinges</td>
<td>stainless steel 1.4310</td>
</tr>
<tr>
<td>Length of probing stylus [mm]</td>
<td>16.0</td>
</tr>
<tr>
<td>Diameter of probing sphere [mm]</td>
<td>2.0</td>
</tr>
<tr>
<td>Simulated stiffness in X-direction at probing element [N/m]</td>
<td>11    25   85</td>
</tr>
<tr>
<td>Simulated stiffness in Y-direction at probing element [N/m]</td>
<td>11    25   85</td>
</tr>
<tr>
<td>Simulated stiffness in Z-direction at probing element [N/m]</td>
<td>62    145  485</td>
</tr>
<tr>
<td>Simulated critical deflection in X- and Y-direction of the probing element (von Mises criteria, with safety factor 2) [mm]</td>
<td>0.57  0.44  0.30</td>
</tr>
<tr>
<td>Simulated moving mass [g]</td>
<td>1.3</td>
</tr>
</tbody>
</table>

As discussed in section 2.4, the simulated and measured stiffnesses agree within their uncertainties (uncertainty of simulation and uncertainty of measurement), so the probing behaviour can be improved by the developed procedure, see chapter 2.5.

2.2.4 Uncertainty estimation for simulated stiffness

With an uncertainty estimation of the simulated properties of the probing system, the influence of material properties like density or Young’s modulus and manufacturing imperfections on the probing behaviour can be investigated. Each property has to be regarded as “uncertain”, but only the main uncertainty contributors are taken into account.

The range of each parameter is estimated from machine tool specifications, manufacturer
information and from experience found in literature. By combining these parameters in a suitable way, a minimum and maximum stiffness is calculated, from which range the uncertainty is estimated by assuming an uniform distribution [3].

The uncertainty is estimated for the three different thicknesses of the flexure hinges. The taken assumptions to estimate the uncertainties of the simulated stiffnesses are summarised in table 2.3.

Table 2.3: Assumptions to estimate the uncertainty of simulated stiffnesses at the probing element.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of the flexure hinges (Manufacturer information)</td>
<td>60 µm ± 3 µm</td>
</tr>
<tr>
<td></td>
<td>80 µm ± 4 µm</td>
</tr>
<tr>
<td></td>
<td>120 µm ± 4 µm</td>
</tr>
<tr>
<td>Width of the flexure hinges</td>
<td>0.6 mm ± 0.03 mm</td>
</tr>
<tr>
<td>Bottom radius at intersection to flexure hinges</td>
<td>0.5 mm ± 0.05 mm</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>200000 MPa ± 10 %</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3 ± 10 %</td>
</tr>
<tr>
<td>Length of probing stylus</td>
<td>16 mm ± 0.25 mm</td>
</tr>
</tbody>
</table>

The uncertainties of the simulated stiffnesses are summarised in table 2.4 and are calculated according to

\[ U = \frac{c_{\text{stiff}} - c_{\text{soft}}}{\sqrt{3}} \]  

with:

- \( U \): Uncertainty of simulated stiffness with coverage factor of 2;
- \( c_{\text{stiff}} \): Stiffness of stiff geometry;
- \( c_{\text{soft}} \): Stiffness of soft geometry.

The expanded uncertainty according to (2.1) marks the interval between upper and lower limits, so that the probability of the stiffness lying inside is equal to one [3].
Table 2.4: Uncertainty estimation for simulated stiffnesses at the probing element. Definition of coordinate system see figure 2.2. The length of the probing stylus is 16 mm.

<table>
<thead>
<tr>
<th>Thickness of flexure hinges</th>
<th>60 µm</th>
<th>80 µm</th>
<th>120 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property of geometry</td>
<td>ideal</td>
<td>soft</td>
<td>stiff</td>
</tr>
<tr>
<td>Stiffness in X [N/m]</td>
<td>11</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Stiffness in Y [N/m]</td>
<td>11</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Stiffness in Z [N/m]</td>
<td>62</td>
<td>45</td>
<td>83</td>
</tr>
<tr>
<td>Uncertainty U(k=2) in X [N/m]</td>
<td>4</td>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td>Uncertainty U(k=2) in Y [N/m]</td>
<td>4</td>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td>Uncertainty U(k=2) in Z [N/m]</td>
<td>22</td>
<td>52</td>
<td>144</td>
</tr>
</tbody>
</table>

2.3 Manufacturing and assembly of the probing system

A task in the development of the probing system is to design all components in such a way, that they can be manufactured with standard metal cutting machine tools. Although the probing system has a large measurement range (see table 2.2), the probing stylus and flexure hinges are put at risk of damage. So these components should be easy to manufacture and simple to replace in case of a damage. In section 2.3.1 the manufacturing of the flexure hinges is described, because they are the most critical components to fabricate. The assembly of the probing head is shortly shown in section 2.3.2.

2.3.1 Manufacturing of the flexure hinges

The flexure hinges are fabricated from a cold rolled steel strip 1.4310 by EDM. The stiffness of the flexure hinges is among other parameters determined by their thickness. Steel strip is dedicated as original material for fabricating flexure hinges because of its tolerated thickness, which saves a metal finishing of the thickness of the flexure hinges. The used steel strip with thicknesses between 60 µm and 120 µm is tolerated to be within 3 µm and
4 μm, see table 2.3. For manufacturing, the steel strip is clamped between two base plates, which facilitates handling. After cutting the geometry of the flexure hinges by EDM, their flatness is improved by a heat-treatment, furthermore internal stress is decreased. Because of the fine structure of the flexure hinges, each deviation in form, position, orientation and size from the nominal geometry as well as varying material properties have great influence on their stiffnesses. The influence of such deviations is estimated by simulations in section 2.2.4. Additionally, burrs affect the properties of the flexure hinges. In appendix B.5 the consequences of an imperfect manufacturing of the flexure hinges are discussed, which result in deviations of the measured stiffnesses from the simulated stiffnesses.

The manufacturing of the flexure hinges is checked by determining experimentally the stiffness of probing systems with four different, but nominal identical flexure hinges. The range of the determined stiffness in X- and Y-direction is $14 \frac{N}{m}$ at a mean stiffness of $126 \frac{N}{m}$. In Z-direction, the stiffness varies by a range of $52 \frac{N}{m}$ at a mean stiffness of $120 \frac{N}{m}$ (see appendix B.5.3).

2.3.2 Assembly of the probing system

The flexure hinges are clamped between two face-ground base plates as shown in figure 2.6. This has the advantage that no heat is introduced during the assembly. Moreover, the contacting area between flexure hinges and base plates is very flat (flatness is smaller than 1 μm), so the flexure hinges are not bent or distorted by their clamping. The upper base plate contacts with its whole face on the fixture of the probing head.

A careful assembly of the different components of the probing head is precondition for a repeatable clamping of the probing head (see appendix B.5.4) and a conformance of measured and simulated stiffnesses at the probing element.

2.4 Verification of simulated final design of first prototype with force measurements

The simulated stiffnesses of the probing system are checked by force measurements to verify the simulation of the probing system. The measurement setup and an uncertainty estimation are discussed in section 2.4.1 and 2.4.2, respectively. The results of the determined stiffness are discussed with respect to the uncertainties of measurement and simulation in section 2.4.3.
2. Design of the 3D-Probing System

2.4.1 Setup for checking stiffness and isotropy of the probing system

The setup to determine the stiffness of the probing system is shown in figure 2.7 and 2.8. The probing system is mounted at the end of the Z-axis ram of the CMM (see figure 2.7 A) and the force sensor on a rotary table as shown in figure 2.7 B and C, which is placed on the table of the CMM.

As soon as the force sensor contacts the probing element, the relative distance between
2.4 Verification of simulated final design of first prototype with force measurements

force sensor and probing element is reduced by a motion of the linear axes of the CMM in the sensitive direction of the force sensor [87]. This results in a force distribution as shown exemplary in figure 2.9. Therewith, the stiffness is calculated as shown in (2.3) on page 41. By changing the orientation of the rotary table (see figure 2.7 B and 2.8), the stiffness of the probing system in the horizontal XY-plane is determined.

![Figure 2.8: Schematic diagram of the force measurements to determine the stiffnesses at the probing element in the XY-plane.](image)

A: The force sensor is arranged parallel to the X-axis of the CMM by the rotary table. This direction is set to an angle of 0°.

B: The rotary table is positioned at 45°, so the force sensor displaces the probing element under 45° to the X-axis of the CMM.

The high-sensitive force sensor is based on a preloaded piezo-electric crystal with an output signal linear to the force to be measured [88]. Due to this measurement principle, small output signals (< 20 mN) have to be corrected by the drift, which is caused by draining of electric charge in the whole measuring chain (see appendix C.1). The resulting drift for the measurement system, consisting of force sensor and charge amplifier, is in the range of 0.23 mN up to 0.9 mN.
2. Design of the 3D-Probing System

2.4.2 Uncertainty estimation for probing force measurements

The stiffness of the probing system is determined by force measurements, for which the force sensor is moved relatively to the probing element. This distance is adapted to the assumed stiffness of the probing system, so that the measured force remains smaller than 10 mN. The uncertainty of the experimental determination of the stiffness is affected by three main contributors:

Evaluation of measured force:

For determining the change of the probing force when the probing head is moved relatively to the force sensor, the force step (see figure 2.9) has to be identified. If the force signal is not constant when the probing element is deflected, the measured force depends on the evaluation: the stiffness evaluated with the range of the force step is different from the stiffness evaluated with the force step defined by the mean force of the initial state to the mean force of the deflected state. The standard uncertainty for evaluating the force measurement, based on mean values, is estimated to be $u_{Evaluation} = 0.2 \text{ mN}$.

Positioning accuracy of the CMM:

The CMM contributes to the uncertainty of the determined stiffness, because its axes are used for the deflection measurement. The standard uncertainty of this contribution is estimated to be $u_{CMM} = 1 \text{ µm}$, mainly caused by the resolution of the linear scales of the CMM of 0.6 µm.

Figure 2.9: Characteristic time chart of the force signal (drift is corrected, see appendix C.1) to determine the stiffness of the probing system.
Force measurement:

For the uncertainty of the force measurement in the range of up to 10 mN following contributors to the uncertainty are taken into account:

- Uncertainty of the digitising of the analogue voltage signal:
  \( u_{\text{Digitising}} = 2\% \)

- Uncertainty of the charge amplifier (Kistler, Type 5011 B):
  \( u_{\text{Amplifier}} = 5\% \)

- Uncertainty of the force sensor (Kistler, Type 9203):
  \( u_{\text{Sensor}} = 5\% \)

- Uncertainty of the numerical compensation of force sensor drift (see appendix C.1):
  \( u_{\text{Drift}} = 5\% \)

These contributors have a standard uncertainty, which depends on the magnitude of the measured force and is therefore given as a percentage value of the measured force. The above mentioned standard uncertainties are estimated for a measurement range of up to 10 mN. Because this contributors are not correlated [3], their combined standard uncertainty \( u_{\text{Measurement}} \) is calculated by

\[
 u_{\text{Measurement}} = \sqrt{(u_{\text{Digitising}})^2 + (u_{\text{Amplifier}})^2 + (u_{\text{Sensor}})^2 + (u_{\text{Drift}})^2} \quad (2.2)
\]

\[
 = 8.9\% .
\]

The stiffness \( c \) is determined by measuring the change of the force \( F \) and dividing it by the corresponding deflection \( d \) between force sensor and probing element according to

\[
c = \frac{F}{d} . \quad (2.3)
\]

Because the force \( F \) and the distance \( d \) are independent, the standard uncertainty of the stiffness, \( u_{\text{Stiffness}} \), is calculated by the positive square root of the partial derivatives of (2.3) according to [3]. This standard uncertainty \( u_{\text{Stiffness}} \) is given by
2. Design of the 3D-Probing System

\[
u_{\text{Stiffness}} = \sqrt{\left( \frac{\partial c}{\partial F} u_{\text{Force}} \right)^2 + \left( \frac{\partial c}{\partial d} u_{\text{CMM}} \right)^2} 
= \sqrt{\left( \frac{1}{d} u_{\text{Force}} \right)^2 + \left( \frac{F}{d^2} u_{\text{CMM}} \right)^2} 
\]

(2.4)

with:
- \(F\) Measured probing force;
- \(c\) Stiffness at probing element;
- \(d\) Deflection of the probing element relative to the force sensor;
- \(u_{\text{CMM}}\) Uncertainty contribution of the CMM by moving its axes to deflect the probing element;
- \(u_{\text{Force}}\) Uncertainty contribution of the force measurement and force evaluation.

The uncertainty of the magnitude of the measured force, \(u_{\text{Force}}\), depends both on the force measurement itself and on its evaluation. This contributors, \(u_{\text{Measurement}}\) and \(u_{\text{Evaluation}}\), are independent and thereby combined to the standard uncertainty \(u_{\text{Force}}\) according to

\[
u_{\text{Force}} = \sqrt{(u_{\text{Measurement}})^2 + (u_{\text{Evaluation}})^2}.
\]

(2.5)

Because of the percentage fraction in \(u_{\text{Force}}\), this combined standard uncertainty is calculated for some assumed probing forces according to (2.5) and is summarised in table 2.5. Due to the higher stiffness in Z-direction compared to the X- and Y-direction, the relative motion between force sensor and probing element is only 5 \(\mu m\) in Z-direction instead of 50 \(\mu m\) in X- and Y-direction, see table 2.5 and table 2.6. Therewith, the measured force is for all measurements in the same order of magnitude (0.3 \(mN\) up to 4.3 \(mN\)). As it can be seen from (2.4), this results in clearly higher measurement uncertainties for the stiffness in Z-direction.
Table 2.5: Combined standard uncertainty for determining the probing force.

<table>
<thead>
<tr>
<th>Assumed probing force [mN]</th>
<th>Contributor</th>
<th>Standard uncertainty [mN]</th>
<th>Combined standard uncertainty $u_{\text{Force}}$ [mN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.31$^a$</td>
<td>Evaluation of force</td>
<td>0.2</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Force measurement</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>0.55$^b$</td>
<td>Evaluation of force</td>
<td>0.2</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>Force measurement</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0.73$^c$</td>
<td>Evaluation of force</td>
<td>0.2</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>Force measurement</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>1.25$^d$</td>
<td>Evaluation of force</td>
<td>0.2</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Force measurement</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>2.43$^e$</td>
<td>Evaluation of force</td>
<td>0.2</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Force measurement</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>4.25$^f$</td>
<td>Evaluation of force</td>
<td>0.2</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Force measurement</td>
<td>0.38</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Assumed probing force for a deflection of 5 µm at a stiffness of 62 N/m, see table 2.2.
$^b$ Assumed probing force for a deflection of 50 µm at a stiffness of 11 N/m, see table 2.2.
$^c$ Assumed probing force for a deflection of 5 µm at a stiffness of 145 N/m, see table 2.2.
$^d$ Assumed probing force for a deflection of 50 µm at a stiffness of 25 N/m, see table 2.2.
$^e$ Assumed probing force for a deflection of 5 µm at a stiffness of 485 N/m, see table 2.2.
$^f$ Assumed probing force for a deflection of 50 µm at a stiffness of 85 N/m, see table 2.2.

The combined standard uncertainty of the experimental stiffness, $u_{\text{Stiffness}}$, is determined according to (2.4) for a travel distance $d$ of the CMM of 50 µm in X- and Y-direction and 5 µm in Z-direction. Table 2.6 summarises the combined and expanded standard uncertainties for the experimental determination of the stiffness for some assumed probing forces. The continuous course of the stiffness in dependence on the probing force and on the travel distance of the CMM is shown in figure 2.10.
Table 2.6: Combined standard uncertainties of experimentally determined stiffnesses.

<table>
<thead>
<tr>
<th>Assumed probing force [mN]</th>
<th>Contributor</th>
<th>Standard uncertainty</th>
<th>Combined standard uncertainty [N/m]</th>
<th>Expanded standard uncertainty U(k=2) [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.31</td>
<td>Motion of CMM ( (u_{CMM}) )</td>
<td>1 ( \mu m )</td>
<td>42</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Determination of force ( (u_{Force}) )</td>
<td>0.20 mN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.55</td>
<td>Motion of CMM ( (u_{CMM}) )</td>
<td>1 ( \mu m )</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Determination of force ( (u_{Force}) )</td>
<td>0.21 mN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.73</td>
<td>Motion of CMM ( (u_{CMM}) )</td>
<td>1 ( \mu m )</td>
<td>51</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>Determination of force ( (u_{Force}) )</td>
<td>0.21 mN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>Motion of CMM ( (u_{CMM}) )</td>
<td>1 ( \mu m )</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Determination of force ( (u_{Force}) )</td>
<td>0.23 mN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.43</td>
<td>Motion of CMM ( (u_{CMM}) )</td>
<td>1 ( \mu m )</td>
<td>113</td>
<td>226</td>
</tr>
<tr>
<td></td>
<td>Determination of force ( (u_{Force}) )</td>
<td>0.29 mN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.25</td>
<td>Motion of CMM ( (u_{CMM}) )</td>
<td>1 ( \mu m )</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Determination of force ( (u_{Force}) )</td>
<td>0.43 mN</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( ^a \) Travel distance \( d \) of CMM: \( d = 5 \, \mu m \).

\( ^b \) Travel distance \( d \) of CMM: \( d = 50 \, \mu m \).

The measurement uncertainties can be reduced by using a capacitive force sensor (Femto-tools, Type FT-S160, see appendix C.1) instead of a piezo-electric force sensor. A capacitive force sensor has a higher resolution (2 \( \mu N \)) and a higher sensitivity (5 \( \frac{mN}{V} \)). This results in lower measurement uncertainties of the determined stiffness in the observed force range of up to 10 \( mN \). Exemplary, the expanded measurement uncertainty of a capacitive force sensor is 1.3 \( \frac{N}{m} \) compared to 8 \( \frac{N}{m} \) of a piezo-electric force sensor for determining the stiffness in X- and Y-direction of a probing system with flexure hinges of 60 \( \mu m \) thickness.
2.4 Verification of simulated final design of first prototype with force measurements

推广应用的结构传感器的缺点是其非常敏感的探针尖端，其横截面仅为50 µm × 50 µm，并且其测量范围有限，为10 mN。由于测量的刚度与电容传感器和电致伸缩力传感器的校准值相符合（13.9 \( \frac{N}{m} \) ± 1.3 \( \frac{N}{m} \) 比较13 \( \frac{N}{m} \) ± 8 \( \frac{N}{m} \) 为60 µm厚度的悬臂铰链和20.6 \( \frac{N}{m} \) ± 1.4 \( \frac{N}{m} \) 比较27 \( \frac{N}{m} \) ± 9 \( \frac{N}{m} \) 为80 µm厚度的悬臂铰链），电致伸缩力传感器被用于实验确定刚度。此外，模拟的刚度与使用电致伸缩力传感器测量的刚度相符合。

2.4.3 Comparison between simulated and measured stiffness at the probing element

The stiffness is checked in the horizontal XY-plane as well as in Z-direction (parallel to probing stylus, see figure 2.2). The uncertainties are summarised in table 2.4 for the simulation and in table 2.6 for the experimental determination of the stiffness.

As shown in table 2.7 and figure 2.11, the stiffness in X- and Y-direction conforms to the simulated values within their uncertainties. The checking is done for three different
thicknesses of the flexure hinges: 60 µm, 80 µm and 120 µm, respectively. Table 2.7 and figure 2.11 contain the averaged stiffnesses in the horizontal XY-plane over a complete 360° rotation of the force sensor relative to the probing system to be checked. The isotropy of the probing head, measured in steps of 45°, is shown in figure 2.12. It can be observed, that the relative isotropy becomes better with increasing thickness of the flexure hinges.

The results for the stiffness in Z-direction also agree within the uncertainties. Exemplary for flexure hinges with thickness of 120 µm, the measured stiffness is 532 \( \frac{N}{m} \pm 246 \frac{N}{m} \) compared to 485 \( \frac{N}{m} \pm 144 \frac{N}{m} \) for the simulated stiffness (see table 2.7 and figure 2.11).

Table 2.7: Comparison between measured and simulated stiffness for different types of probing systems.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Thickness of flexure hinges [µm]</th>
<th>Measured stiffness [\frac{N}{m}]</th>
<th>Simulated stiffness [\frac{N}{m}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X, Y</td>
<td>60</td>
<td>13 ± 8</td>
<td>11 ± 4</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>27 ± 9</td>
<td>25 ± 10</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>88 ± 18</td>
<td>85 ± 28</td>
</tr>
<tr>
<td>Z</td>
<td>60</td>
<td>-a</td>
<td>62 ± 22</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>-a</td>
<td>145 ± 52</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>532 ± 246</td>
<td>485 ± 144</td>
</tr>
</tbody>
</table>

\(^a\) Not determined experimentally.
2.4 Verification of simulated final design of first prototype with force measurements

Thickness of flexure hinges: 60 µm
Direction of deflection of the probing sphere: X, Y

Thickmess of flexure hinges: 80 µm
Direction of deflection of the probing sphere: X, Y

Thickness of flexure hinges: 120 µm
Direction of deflection of the probing sphere: X, Y

Thickness of flexure hinges: 120 µm
Direction of deflection of the probing sphere: Z

Figure 2.11: Graphical comparison between measured and simulated stiffness including the uncertainties $U(k=2)$ for different types of probing systems.
2. Design of the 3D-Probing System

Figure 2.12: Results of checking the isotropy of the probing system in the XY-plane in steps of 45° (bold black lines: orientation of the flexure hinges).
A: Probing system with flexure hinges of 60 μm thickness.
B: Probing system with flexure hinges of 80 μm thickness.
C: Probing system with flexure hinges of 120 μm thickness.
2.5 Improved 3D-probing system with isotropic stiffness

The first design of the probing system, as discussed in sections 2.2, 2.3 and 2.4, has different stiffnesses at the probing element in X-, Y- and Z-direction (see table 2.4). Therefore, an improved probing system is presented in this chapter. First in section 2.5.1, different techniques to measure the change of the Z-position and the change of the A- and B-orientation of the moveable plate are compared and evaluated. In section 2.5.2, an estimation of the uncertainty at the probing element and its main contributors are presented. Therewith, the requirements on the design of the improved probing system are determined. The FEM tool is used to design a geometry of the flexure hinges with an isotropic stiffness at the probing element (see section 2.5.3) as well as to estimate the uncertainty for the simulated stiffness (see section 2.5.5). A weight compensation for the moveable components of the probing system is presented in section 2.5.4. Finally in section 2.5.6, the experimental results for determining the stiffnesses are compared with simulations.

2.5.1 Selection of sensors

A deflection of the probing element causes a change in the Z-position as well as a change of the A- and B-orientation of the moveable plate, which needs to be measured. Different technologies to convert this change of position and orientation into an electrical voltage exist and are used as state of the art in metrology.

The design of the presented probing head enables the implementation of different measurement methods to determine the position of the probing element. In a feasibility study a Fizeau interferometer is used, see appendix A and [83]. Additionally, a triple beam laser interferometer has been used. In the following enumeration, some techniques are summarised:

- Capacitive measurement method:
  Capacitive sensors are available in different sizes with resolutions down in the nm-range or even smaller and a measurement range up in the mm-range. Precondition is an electrically conducting target, so that a change of the distance between surface of the workpiece and sensor results in a change of the capacitance. The change of capacitance is inverse proportional to the distance between surface of the target and sensor. This measurement method is a non-contacting one.
- Inductive measurement method:
  If a coil (primary coil) is supplied with an alternating voltage, a signal is induced to a second coil. This voltage depends on the relative motion between primary and secondary coil. It is a contacting measurement principle, which is realised in LVDT’s. These sensors are state of the art in conventional probing systems. The resolution is in the \( \mu m \)-range and the measurement range is in the \( mm \)-range.

- Optical measurement methods:
  Different optical techniques to determine the displacement of an object exist. With a laser, the relative displacement of the workpiece to the sensor can be measured by determining the time of flight, the phase shift between measurement and reference beam or by triangulation. For the application in the 3D-probing system, the laser interferometry has the best properties with a resolution in the sub-\( nm \)-range and measurement ranges up in the \( m \)-range. Further optical techniques are confocal sensors, which are available in different sizes with resolutions in the 10 \( nm \)-range and a measurement range up in the \( mm \)-range.

- Eddy current measurement methods:
  Eddy current sensors have resolutions down in the \( nm \)-range over a measurement range in the \( mm \)-range. An eddy current is induced in a conductive workpiece by the electro-magnetic field of the coil of the sensor. This results in a change of the impedance, which causes an electrical signal which is proportional to the distance between target and coil of the sensor. This measurement method is a non-contacting one.

- Resistive measurement methods:
  A measurement principle of this technology is implemented in strain gauges. They are based on materials, which change their electric resistance if they are stretched or bulged. The change of the electric resistance is measured by a Wheatstone bridge. The strain gauge has to be mounted properly on the surface of the target, otherwise the strain of the workpiece is not completely transferred into an electrical resistance. Probing systems based on this technology achieve resolution at the probing element of several \( nm \).

In table 2.8, the properties of different technologies are summarised and evaluated. The assessment criteria concerning the improved 3D-probing system are:

- Measurement range, which has to enable a deflection of the probing element of at least \( \pm 0.1 \ mm \);
- Resolution, which has to be in the \textit{nm}-range;

- Measuring rate, which has to be in the \textit{kHz}-range to enable motions of the probing element with several \textit{mm} or even more;

- Measurement force, which is needed to generate a signal in the sensor. Because of the already defined stiffness of the probing system, a non-contacting measurement principle is preferred because it has no influence on the stiffnesses at the probing element. Otherwise, the design of the flexure hinges has to be re-engineered;

- Size, which has to be smaller than several \textit{mm} in the outer dimensions to enable a compact probing system;

- Dissipation of energy, which has to be minimised to avoid a heating and a run-in period (see appendix B.6);

- Market price of the complete system, which has to be smaller than 20'000 CHF;

- Availability and experience at IWF.

Each measurement principle is classified in one of three possible classes, based on specifications of the state of the art for each technology. Following symbols are used:

- a ”+” means that the technology fulfils the demand completely or even exceeds it;

- a ”0” means that the technology fulfils the demand;

- a ”−” means that the technology does not fulfil the demand.

Based on its applicable properties, the capacitive measurement principle is chosen. Three capacitive sensors are used for measuring the orientation and position of the moveable plate and therewith the deflection of the probing element. The sensors used have a specified resolution less than 120 \textit{nm}, a linearity error less than 0.05 \% and a measurement range of 250 \textit{µm}.
Table 2.8: Comparison of measurement principles for potential use in the 3D-probing system. In assessment, one "−" causes total a "−". Details are summarised in appendix D.

<table>
<thead>
<tr>
<th></th>
<th>capacitive</th>
<th>inductive (LVDT)</th>
<th>confocal</th>
<th>interferometric (triple beam)</th>
<th>interferometric (Fizeau)</th>
<th>eddy current</th>
<th>resistive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement range: ±0.1 mm</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Resolution: &lt; 100 nm</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Measuring rate: &gt; 5 kHz</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Measurement force: &lt; 5 mN</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td></td>
</tr>
<tr>
<td>Size of sensor: diameter &lt; 8 mm</td>
<td>+</td>
<td>o</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Dissipation of energy: &lt; 5 mW</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>o</td>
<td>o</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Market price: &lt; 20'000 CHF</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>o</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Intermediate assessment</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Availability / experience at IWF</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>o</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Final assessment</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

2.5.2 Estimated measurement uncertainty at probing element

With an estimation of the measurement uncertainty at the probing element, the influence of the capacitive sensors used and of the geometry of the probing system are evaluated. In figure 2.13 A, the schematic view of the probing system based on capacitive sensors is
2.5 Improved 3D-probing system with isotropic stiffness

shown.

Figure 2.13: Setup of the 3D-probing system based on capacitive sensors. 
A: Schematic view of the probing system, based on capacitive sensors. 
B: Alignment of the capacitive sensors on a bolt circle.

Following contributors to the measurement uncertainty at the probing element are taken into account:

- Capacitive sensors:
  - Resolution of the capacitive sensors:
    The resolution of the sensors limits the resolution at the probing element, which are linked by the geometry of the probing system. The resolution of the capacitive sensors is transferred by the ratio between bolt circle diameter of the capacitive sensors and the length of the probing stylus into the resolution at the probing element (see figure 2.13). The used capacitive sensors have a specified resolution of 120 nm. Using the schematic setup of the probing system as shown in figure 2.14, the resolution of the capacitive sensors results in worst case in a resolution at the probing element of 213 nm in X-direction and 246 nm in Y-direction and is calculated as
2. Design of the 3D-Probing System

\[ r_X = L \sin \left( \arctan \left( \frac{r_S}{dX} \right) \right) = 213 \text{ nm} \]  
\[ r_Y = L \sin \left( \arctan \left( \frac{r_S}{dY} \right) \right) = 246 \text{ nm} \]

with:

- \( L \): Distance between target surface of movable plate to probing element (20 mm);
- \( dX \): Distance between sensor 1 and sensor 2 in X-direction (11.258 mm);
- \( dY \): Distance between sensor 3 and intersection line of sensor 1 with sensor 2 in Y-direction (9.75 mm);
- \( r_S \): Resolution of the sensors used (120 nm);
- \( r_X \): Resolution at probing element in X-direction due to resolution of sensors used;
- \( r_Y \): Resolution at probing element in Y-direction due to resolution of sensors used.

![Figure 2.14: Estimation of the resolution at the probing element.](image)

The worst case estimation for the resolution in Z-direction caused by the resolution of the capacitive sensors is 120 nm. The calculations to estimate the
standard uncertainties of the resolution at the probing element are following (assumption: rectangular probability distribution):

\[ u_X = \frac{r_X}{2 \sqrt{3}} = 62 \text{ nm} \quad (2.7) \]
\[ u_Y = \frac{r_Y}{2 \sqrt{3}} = 71 \text{ nm} \]
\[ u_Z = \frac{r_S}{2 \sqrt{3}} = 35 \text{ nm} \]

with:
- \( r_X \): Resolution at probing element in X-direction due to resolution of sensors used (213 nm);
- \( r_Y \): Resolution at probing element in Y-direction due to resolution of sensors used (246 nm);
- \( r_S \): Resolution of the sensors used (120 nm);
- \( u_X \): Uncertainty of the resolution at the probing element in X-direction due to sensors used;
- \( u_Y \): Uncertainty of the resolution at the probing element in Y-direction due to sensors used;
- \( u_Z \): Uncertainty of the resolution at the probing element in Z-direction due to sensors used.

- Calibration uncertainty of the capacitive sensors:
  The calibration uncertainty of the sensors used is a manufacturer information and has the same effect on the uncertainty at the probing element as the resolution of the sensors used. This contribution to the uncertainty is calculated as (assumption: rectangular probability distribution)

\[ u_{X,Y} = L \sin \left( \arctan \left( \frac{c}{d} \right) \right) \frac{1}{2\sqrt{3}} \quad (2.8) \]
\[ u_Z = \frac{c}{2\sqrt{3}} \]
with:

- \( L \) Distance between target surface of moveable plate and probing element (\( L = 20 \text{ mm} \));
- \( c \) Calibration uncertainty of the capacitive sensors for measuring displacement of 25 \( \mu \text{m} \) (\( c = 13 \text{ nm} \));
- \( d \) X- or Y-distance between two sensors (\( d_X = 11.258 \text{ mm} \) and \( d_Y = 9.75 \text{ mm} \)).

- Geometry of the probing system:
  - Bolt circle diameter of the capacitive sensors:
    The bolt circle diameter or rather the distance of the sensors to each other in X- and Y-direction is used for calculating the deflection of the probing element (see figure 2.14). An uncertainty of the X- and Y-distance of the sensors to each other results in an uncertainty in the calculation of the position of the probing element. The contribution of the uncertainty of the distance between the capacitive sensors is calculated as (assumption: rectangular probability distribution)

\[
    u_{X,Y} = L \left( \sin \left( \arctan \left( \frac{m}{d - u_d} \right) \right) - \sin \left( \arctan \left( \frac{m}{d + u_d} \right) \right) \right) \frac{1}{2\sqrt{3}} \quad (2.9)
\]

with:

- \( L \) Distance between target surface of moveable plate and probing element (\( L = 20 \text{ mm} \));
- \( d \) X- or Y-distance between two sensors (\( d_X = 11.258 \text{ mm} \) and \( d_Y = 9.75 \text{ mm} \));
- \( m \) Measurement range of the capacitive sensors (\( m = 25 \text{ \( \mu \text{m} \)} \));
- \( u_d \) Uncertainty of the X- or Y-distance between two sensors (\( u_d = 5 \text{ \( \mu \text{m} \)} \)).

- Squareness error between the capacitive sensors and the target surface of the moveable plate:
  Another influence of the geometry on the uncertainty at the probing element is the squareness error between the sensor axis and the target surface of the moveable plate. On the one hand, the squareness between sensor and target
surface of the moveable plate depends on their alignment after the assembly, on the other hand this squareness changes by deflecting the probing element. According to [89], the capacitive sensors are calibrated with the sensors perpendicular to the target surface. If the capacitive sensors and the target surface of the moveable plate are not perpendicular to each other, the spot shapes of the sensors are changed. This results in a measurement error $e$ due to a misalignment between sensor axis and target surface because of the different properties of the electric field and is computed as

$$e = \left(1 - \frac{\sqrt{1 - \left(\frac{r \cdot \Theta}{g}\right)^2}}{2}\right) g k$$  \hspace{1cm} (2.10)

with:

- $e$ Measurement error [m];
- $g$ Gap between capacitive sensor and surface of moveable plate directly under the sensor center axis [m] ($g = 125 \mu m$);
- $k$ Factor for field fringing errors, experimentally determined and typically in the range of 5;
- $r$ Radius of capacitive sensor area [m] ($r = 0.85 \text{ mm}$);
- $\Theta$ Squareness error between capacitive sensor and target surface of the moveable plate [rad] ($\Theta = 0.5^\circ$).

This error depends on the gap between the capacitive sensor and the target surface of the moveable plate. The smaller the gap, the larger is the measurement error. The calculated error, according to (2.10), is applied only on the measuring distance of the sensors and not on the complete gap, because the sensors are used for relative measurements. The contribution of the squareness error between capacitive sensor and target surface of the moveable plate is calculated assuming a rectangular probability distribution as:

$$u_{X,Y} = L \sin \left(\arctan \left(\frac{e \cdot \frac{m}{g}}{d}\right)\right) \frac{1}{2\sqrt{3}}$$

$$u_Z = \frac{e \cdot m}{2\sqrt{3} \cdot g}$$  \hspace{1cm} (2.11)
with:

- \( L \) Distance between target surface of moveable plate and probing element \((L = 20 \text{ mm})\);
- \( d \) X- or Y-distance between two sensors \((d_X = 11.258 \text{ mm} \text{ and } d_Y = 9.75 \text{ mm})\);
- \( e \) Measurement error according to (2.10) on page 57 caused by an angle between capacitive sensors and target surface of moveable plate \((e = 0.551 \mu m)\);
- \( g \) Gap between capacitive sensor and target surface of the moveable plate \((g = 125 \mu m)\);
- \( m \) Measuring distance of the capacitive sensors \((m = 25 \mu m)\).

- The form deviation of the probing element:

  The contribution of the form deviation of the probing element is calculated as (assumption: rectangular probability distribution)

  \[
  u_{X,Y,Z} = \frac{f}{2\sqrt{3}}
  \]

  with:

  - \( f \) Form deviation of the probing element \((f = 0.2 \mu m)\).

At the final design of the improved probing system, the tilting of the moveable plate, caused by a deflection of the probing element in X- or Y-direction of 10 \( \mu m \), results in a Z-motion at the capacitive sensors in the range of 3 \( \mu m \). Because of the small measuring distance of the capacitive sensors for a deflection of the probing element in the range of 10 \( \mu m \), the linearity error of the capacitive sensors is neglected, which is smaller than 0.05 \% over the full measurement range of 250 \( \mu m \). Additionally, the flatness of the target surface of the moveable plate is neglected because of the large measuring spot of the capacitive sensors with a diameter of 1.7 \( mm \): a tilting of the moveable plate of 1° results in a deflection of the moveable plate in X- and Y-direction less than 1 \( \mu m \), so the measuring spot of the sensors measure nearly on the same area.

In table 2.9, the measurement uncertainties at the probing element are summarised for the final design of the improved probing system with a bolt circle diameter of 13 \( mm \), which corresponds to nominal distances of the sensors in X-direction of 11.258 \( mm \) and in Y-direction of 9.75 \( mm \), see figure 2.14. The nominal distance from the target surface at
the moveable plate to the probing stylus is 20 \text{ mm}.

Table 2.9: Estimation of measurement uncertainties at probing element for final design of the improved probing system. Calculation of the standard uncertainties of each contributor is given in (2.7) on page 55 up to (2.12) on page 58.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution of capacitive sensors of 120 \text{ nm}</td>
<td>62</td>
<td>71</td>
<td>35</td>
</tr>
<tr>
<td>Calibration uncertainty of capacitive sensors: 12.7 \text{ nm} + 12.9 \cdot 10^{-3} \text{ \frac{nm}{\mu m}} over 25 \text{ \mu m}</td>
<td>7</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Uncertainty of distance between capacitive sensors: 5 \text{ \mu m}</td>
<td>23</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Squareness error between capacitive sensors and surface of moveable plate: 0.5°</td>
<td>56</td>
<td>65</td>
<td>32</td>
</tr>
<tr>
<td>Uncertainty of the form deviation of the probing element: 0.2 \text{ \mu m}</td>
<td>58</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Combined standard uncertainty</td>
<td>104</td>
<td>117</td>
<td>75</td>
</tr>
</tbody>
</table>

By varying the main uncertainty contributors, their influence on the expanded uncertainty of the deflection at the probing element is determined and shown in figure 2.15. The uncertainty at the probing element in X- and Y-direction is mainly determined by the bolt circle diameter and by the squareness error between the capacitive sensors and the target surface of the moveable plate. To reduce the uncertainties, the bolt circle diameter has to be increased, which is in contrast to the goal of minimising the moved mass of the probing system and therefore to reduce the stiffness at the probing element. A compromise is a bolt circle diameter of 13 \text{ mm}, because a further enlargement results in a less impressive reduction of the uncertainty and because of the possibility to design a probing system with an isotropic stiffness at the probing element smaller than 100 \text{ \frac{N}{m}} at outer dimensions of the flexure hinges smaller than 100 \text{ mm}. The influence of the squareness error, especially in Z-direction, has to be reduced by accurate manufacturing and assembling of the components. With smaller measuring distances at the capacitive sensors, which means smaller deflections of the probing element during probing, the uncertainty is also decreased. Typically, the coordinates of a point on a surface of the workpiece to be checked are taken
with a minimal deflection of the probing element, e.g. 1 \( \mu m \) up to 10 \( \mu m \). Therefore, the measuring distance at the capacitive sensors is in the range of several \( \mu m \) or less if the probing system is completely integrated on a CMM.

The resolution of the capacitive sensors limits the resolution at the probing element. But the influence of the resolution is less impressive as the influence of the bolt circle diameter. By changing the design, the probing system may therefore have a lower uncertainty at the probing element with low-resolution sensors compared to high-resolution sensors in a not optimised design.

Figure 2.15: Estimated uncertainty of the deflection at probing element in dependence on main contributors.

The resolution of the capacitive sensors limits the resolution at the probing element. But the influence of the resolution is less impressive as the influence of the bolt circle diameter. By changing the design, the probing system may therefore have a lower uncertainty at the probing element with low-resolution sensors compared to high-resolution sensors in a not optimised design.
2.5 Improved 3D-probing system with isotropic stiffness

2.5.3 Design of an isotropic 3D-probing system

The parameters to be changed are the length, width and thickness of the flexure hinges. Their influence on the stiffnesses at the probing element is calculated by FEM simulations for different geometries of the flexure hinges or rather different configurations of the three parameters. Varying only one parameter and keeping the others constant, the influence of this parameter on the stiffness at the probing element is determined. In table 2.10 the derived results of this variations and therewith the influence of each parameter on the stiffness are summarised. The detailed results are given in appendix B.4. It can be seen, that the width and thickness of the flexure hinges have the same influence on the stiffnesses in X-, Y- and Z-direction, so the only parameter to balance the stiffnesses in X- and Y-direction with the stiffness in Z-direction is the length of the three beams. The other parameters are chosen to adjust the stiffnesses to a certain level.

Table 2.10: Influence of the geometry of the flexure hinges on the stiffness of the probing system.

<table>
<thead>
<tr>
<th></th>
<th>Length (l)</th>
<th>Width (w)</th>
<th>Thickness (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness in X- and Y-direction</td>
<td>(\propto \frac{1}{l^2})</td>
<td>(\propto w)</td>
<td>(\propto t^3)</td>
</tr>
<tr>
<td>Stiffness in Z-direction</td>
<td>(\propto \frac{1}{l^3})</td>
<td>(\propto w)</td>
<td>(\propto t^3)</td>
</tr>
</tbody>
</table>

Deflecting the probing element results in a combination of bending, tensile, compressive and torsional stresses in the single beams of the three flexure hinges. For determining the influence of the geometry of the flexure hinges on the stiffness at the probing element in Z-direction, the single beams of the flexure hinges are mainly under bending stress. Therefore, the influence can be estimated by the beam theory, which calculates the spring constant \(c\) for elastic deformations of a cube-shaped beam as shown in figure 2.16 as

\[
c = \frac{E \, w \, t^3}{4 \, l^3}
\]

(2.13)

with:

- \(E\) Elasticity modulus;
- \(c\) Spring constant of bending beam;
- \(l\) Length of bending beam;
- \(t\) Thickness of bending beam;
- \(w\) Width of bending beam.
Figure 2.16: Schematic view of a bending beam, which serves for simplification of a flexure hinge to estimate the influence of its length, width and thickness on the stiffness at the probing element.

For the stiffnesses at the probing element in X-, Y- and Z-direction, the influence of the width and thickness of the flexure hinges can be reasoned by beam theory as shown in (2.13). However, the influence of the length of the flexure hinges on the stiffnesses at the probing element in X- and Y-direction is a superposition of the different stresses and therefore not only described in beam theory.

An isotropic 3D-probing system with a stiffness of $84 \frac{N}{m}$ at the probing element is designed with the FEM tool presented in chapter 2.2. The stiffness is chosen to be $84 \frac{N}{m}$ by following reasons:

- Small probing forces in the $mN$-range:
  For a deflection of the probing element of 10 $\mu$m (this is typically the overtravel distance of a CMM), the probing force is only 0.8 $mN$ to avoid plastic deformations of the components to be checked. Exemplary, the Hertzian stress on a planar surface of an aluminium component to be checked is less than $11 \frac{N}{mm^2}$ at a diameter of the probing element of 0.2 $mm$. Therewith, the Hertzian stress is clearly smaller than the yield stress (e.g. $55 \frac{N}{mm^2}$ for aluminium alloy 6061-O), so no lasting deformations on the surface of the workpiece to be checked are generated;

- The resulting probing forces are measurable with conventional force sensors (see chapter 2.4.2 and appendix C.1).

The steps for designing an isotropic probing system with FEM are shown in figure 2.17.
2.5 Improved 3D-probing system with isotropic stiffness

The resulting geometry of the flexure hinges has a length of 28.25 mm, a width of 1.2 mm and a thickness of 135 µm. The stiffnesses at the probing element is in X- and Y-direction 84 \( \frac{N}{m} \), in Z-direction 81 \( \frac{N}{m} \). The critical deflection of the probing element is 0.79 mm, the moving mass is 0.0104 kg. The probing forces for this geometry (0.84 mN for 10 µm deflection of the probing element) are comparable to other probing systems (see table 1.1) and are clearly reduced compared to conventional probing systems with approximately 0.05 N up to 1 N. The stiffness of the presented isotropic 3D-probing system can be further reduced or increased by changing the design of the flexure hinges.

A schematic view of the probing system with its main components is shown in figure 2.18.

### 2.5.4 Weight compensation for isotropic probing system

The improved probing system has a stiffness in Z-direction of 81 \( \frac{N}{m} \) (see table 2.11). The first prototype of the probing system, however, has a stiffness in Z-direction of up to 485 \( \frac{N}{m} \)
Design of the 3D-Probing System

Figure 2.18: Design of an isotropic probing system based on flexure hinges with thickness of 135 µm and an isotropic stiffness of 84 Nm in X-, Y- and Z-direction. (see table 2.2). The change of the stiffness is realised according to the procedure described in figure 2.17, whereby mainly the length of the flexure hinges is increased from 11 mm up to 28.25 mm. Therefore, the moveable components of the probing system, which are supported by the flexure hinges, are, due to gravity, deflected significantly more for the improved probing system. This results in a non-flatness of the flexure hinges, which is not caused by the manufacturing or the clamping and results in an increased stiffness (see appendix B.5.2).

As mentioned in section 2.2.1, there are two possibilities for handling this non-flatness:

- The flexure hinges are flat in the operating point of the probing system. Therefore, the non-flatness caused by gravity has to be compensated;

- The operating point for using the probing system is chosen for non-flat flexure hinges, whereby this non-flatness is caused by gravity and not by imperfect manufacturing. With non-linear FEM simulations, the stiffness at the probing element can be adjusted to be equal in X-, Y- and Z-direction. However, this approach results in very large probing systems, which is illustrated with following example based on FEM calculations: given is a probing system based on flexure hinges with fixed thickness (135 µm) and width (1.2 mm), but variable length. Thereby, the width and the
2.5 Improved 3D-probing system with isotropic stiffness

thickness are chosen to be in a conventional range for the material used of the flexure hinges. Starting at a length of the flexure hinges of 28.25 mm, at which the probing system has an isotropic stiffness at the probing element if the non-flatness due to gravity is compensated. For this configuration and without compensation of the non-flatness due to gravity, the ratio between stiffness in X-/Y-direction (211 \( \frac{N}{m} \)) and Z-direction (980 \( \frac{N}{m} \)) is 4.6. This ratio has to be equal one for an isotropic probing system, so the length of the flexure hinges is increased according to table 2.10. Increasing the length of the flexure hinges up to 145 mm results in stiffnesses in X-/Y-direction of 156 \( \frac{N}{m} \) and in Z-direction of 175 \( \frac{N}{m} \). This corresponds to a ratio of the stiffnesses of 1.1, which is an almost isotropic stiffness at the probing element. So without compensating the influence of gravity, the length of the flexure hinges has to be increased significantly to reach isotropic stiffnesses at the probing element. The outer dimension of the flexure hinges has to be increased in this example from 75 mm (using a weight compensation) up to approximately 310 mm (without weight compensation). To adjust the isotropic stiffnesses of the probing system without weight compensation (between 156 \( \frac{N}{m} \) and 175 \( \frac{N}{m} \)) to the level of the probing system with weight compensation (84 \( \frac{N}{m} \)), further changes of the geometry have to be done, which could result in a further increase of the length of the flexure hinges. Due to the influence of gravity on the stiffness, mainly in Z-direction, this approach does not result in usable outer dimensions of the probing system.

In this thesis, a weight compensation is realised as shown in figure 2.19. This enables smaller dimensions of the flexure hinges compared to the second above mentioned solution.

![Figure 2.19: Realisation of a weight compensation with damping system.](image)

The weight compensation is realised by the principle of a balance, so the optimal operating point of the probing system with flat flexure hinges is adjustable. The flexure hinges are
pulled in opposite direction of gravity by a thread, which is fixed with one end at the balance and with the other end at the moveable plate with the probing stylus. The stiffness of the flexure hinges, calculated by FEM without the weight compensation, is not influenced by the presented weight compensation.

Additionally, a damping system is implemented to reduce vibrations by letting the counter weight move in oil. The moveable plate with the probing stylus are supported by the flexure hinges and are therewith prone to vibrations. This vibrations are introduced by the CMM, the probing or the environment. Using the force sensor, the vibrations at the probing element are measured. Its amplitude is reduced by the damping system by a factor of approximately 30, see figure 2.20.

![Figure 2.20: Influence of the damping system on the vibrations at the probing element.](image)

2.5.5 Uncertainty estimation for simulated stiffness of an isotropic probing system

As mentioned in section 2.2.4, uncertainties in manufacturing of the components as well as uncertainties of the properties of the used material result in uncertainties of the simulated stiffnesses. The ranges of the single contributors are summarised in table 2.11 and are taken as input for worst-case calculations based on FEM: to estimate the uncertainty of the simulated stiffness, the listed parameters are changed within their uncertainties. With this configurations, the stiffness is recalculated and the standard uncertainty as well as the expanded uncertainty are determined. For determining the standard uncertainty of the
stiffness at the probing element, it is supposed as in section 2.2.4, that the uncertainty of the stiffness is described by a rectangular probability distribution with the lower boundary equal to the calculated minimal stiffness and with the upper boundary equal to the calculated maximum stiffness [3].

Table 2.11: Expanded uncertainties for the simulated stiffnesses of an isotropic probing system and underlying assumptions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of the flexure hinges (manufacturer information)</td>
<td>135 ( \mu m \pm 4 \mu m )</td>
</tr>
<tr>
<td>Width of the flexure hinges</td>
<td>1.2 ( mm \pm 0.03 mm )</td>
</tr>
<tr>
<td>Bottom radius at intersection to flexure hinges</td>
<td>0.5 ( mm \pm 0.05 mm )</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>200000( MPa \pm 10 % )</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3 ( \pm 10 % )</td>
</tr>
<tr>
<td>Length of probing stylus</td>
<td>16 ( mm \pm 0.25 mm )</td>
</tr>
<tr>
<td>Simulated stiffness at probing element in X-direction ( \pm U(k=2) )</td>
<td>84 ( N/m \pm 25 \frac{N}{m} )</td>
</tr>
<tr>
<td>Simulated stiffness at probing element in Y-direction ( \pm U(k=2) )</td>
<td>84 ( N/m \pm 25 \frac{N}{m} )</td>
</tr>
<tr>
<td>Simulated stiffness at probing element in Z-direction ( \pm U(k=2) )</td>
<td>81 ( N/m \pm 20 \frac{N}{m} )</td>
</tr>
</tbody>
</table>

2.5.6 Experimental verification of the improved 3D-probing system

The simulated stiffnesses are experimentally checked by force measurements: a piezoelectric force sensor is moved relatively to the probing element. Thereby, the force as well as the relative motion are measured. The setup is presented in section 2.4.1 on page 38. The relative motion between force sensor and probing element is for all measurements, independent of the direction of deflecting the probing element, 20 \( \mu m \). The assumed probing forces are therewith in the range of 1.7 \( mN \).

The estimation of the measurement uncertainty for the experimental determination of the stiffnesses is discussed in section 2.4.2. With the presented assumptions and equations, the resulting measurement uncertainty is shown in figure 2.21. For the assumed probing force, the expanded measurement uncertainty is 25 \( \frac{N}{m} \). The experimentally determined stiffnesses are summarised in table 2.12 and compared with the simulated values. Furthermore as
shown in figure 2.22, simulation and measurement agree within their uncertainties.

![Graph showing expanded uncertainty for determining the stiffness by force measurements with deflections of the probing element of 20 µm.](image)

Figure 2.21: Expanded uncertainty for determining the stiffness by force measurements with deflections of the probing element of 20 µm.

Table 2.12: Comparison between measured and simulated stiffness for isotropic probing system.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Measured stiffness $[\text{N/m}]$</th>
<th>Simulated stiffness $[\text{N/m}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X, Y</td>
<td>$78^a \pm 26$</td>
<td>$84 \pm 25$</td>
</tr>
<tr>
<td>Z</td>
<td>$96^b \pm 28$</td>
<td>$81 \pm 20$</td>
</tr>
</tbody>
</table>

$^a$ Mean value from measurements in XY-plane, each 45°, each measurement repeated once.

$^b$ Mean value from three measurements in Z-direction.

The isotropy of the probing system in the XY-plane is checked by force measurements each 45° (setup see figure 2.8 on page 39). The results are shown in figure 2.23. The range of the determined stiffnesses each 45° is $10 \text{ N/m}$ at a mean stiffness of $78 \text{ N/m}$. As already presented in section 2.3.1 and appendix B.5.3, the manufacturing of the flexure hinges, the critical component of the probing system, is repeatable.

The influence of the clamping and assembly of the probing system is investigated by
Direction of deflection of the probing sphere: X, Y

Direction of deflection of the probing sphere: Z

Figure 2.22: Graphical comparison between measured and simulated stiffness including the uncertainties U(k=2) for isotropic probing system.

As shown in figure 2.23, the measured stiffnesses in the XY-plane have the shape of
Design of the 3D-Probing System

an ellipse, which could be caused by the rolling direction during manufacturing the raw material, the cold rolled steel strip. This can be checked by manufacturing flexure hinges rotated 90° to each other from raw material with the same rolling direction. Afterwards, the stiffnesses in the XY-plane of the different flexure hinges can be checked with the same orientation of the flexure hinges during assembling the probing system as shown in figure 2.24. If the measured ellipse depends on the orientation of the flexure hinges relative to the rolling direction, then the ellipse is caused by the rolling direction.

![Diagram of flexure hinges with different orientations](image)

Figure 2.24: Proposal for checking the influence of the rolling direction of the raw material of the flexure hinges on their stiffness.

A: Manufacturing flexure hinges rotated 90° to each other in the same raw material, so that the hinges have different orientation relative to the (unknown) rolling direction of the raw material.

B: Checking the stiffnesses of the manufactured flexure hinges by assembling probing system with the same orientation of the different flexure hinges.

2.6 Summary

In this chapter different aspects of designing a 3D-probing system are discussed. In the first section 2.1, the setup of the probing system and its components are presented.

In the following section 2.2 the design tool, implemented in the FEM software ANSYS, is discussed. Different geometries of the flexure hinges are methodically evaluated with respect to their stiffness. The stiffness of the flexure hinges determines directly the stiffness at the probing element, which has to fulfil specifications smaller than 100 $\text{N/m}$ or even less. Thus, the optimal geometry under practical aspects like manufacturing, assembly and costs is chosen for the probing system: a radial alignment of three cube-shaped bodies results in probing forces in the specified $\text{mN}$-range and is, furthermore, scalable to other
probing forces. A first prototype of the probing system is designed, which has no isotropic stiffness at the probing element, but which is used for checking the simulations and their experimental verification.

In section 2.3 the manufacturing of the flexure hinges and the assembly of the probing system are presented. Cold rolled steel strip 1.4310 is used for fabricating the flexure hinges by electro-discharge machining. A great influence on the stiffness has the flatness of the flexure hinges, therefore the flexure hinges are heat-treated after the cutting process. The main aspect in assembling the probing system is to conserve the flatness of the flexure hinges. Therefore, they are clamped between two face-ground base plates.

Section 2.4 presents the experimental verification of the simulation by force measurements. The stiffness is determined experimentally and is compared with the simulated values. Simulation and measurement conform within their uncertainties, so the simulation as well as the manufacturing and assembling are controlled. This is the background for improving the 3D-probing system.

In section 2.5 the FEM tool is used for designing an improved probing system with an isotropic stiffness at the probing element. Because of the widespread field of application of the steel strip used, it is available with thicknesses from 0.01 mm up to more than 1 mm, which enables the design and fabrication of probing systems with almost any stiffness. By estimating the measurement uncertainties at the probing element, the influences of the resolution of the sensors used and their alignment are quantified to fulfil the requirements for the probing system concerning its resolution and uncertainty at the probing element. Comparing different geometries of the flexure hinges in respect to their stiffnesses, a radial alignment of the flexure hinges is chosen. In X- and Y-direction, the simulated stiffness is \( 84 \frac{N}{m} \pm 25 \frac{N}{m} \), the measured stiffness is \( 78 \frac{N}{m} \pm 26 \frac{N}{m} \). In Z-direction, simulation and measurement also conform within their uncertainties: \( 81 \frac{N}{m} \pm 20 \frac{N}{m} \) is the simulated and \( 96 \frac{N}{m} \pm 28 \frac{N}{m} \) is the measured stiffness. The manufacturing and assembling of the probing system is also checked: the stiffness in X-direction of different flexure hinges repeats within \( 14 \frac{N}{m} \) at a mean stiffness of \( 126 \frac{N}{m} \), which is higher compared to the simulated stiffness in X-direction due to a measurement setup without weight compensation. The stiffnesses in Z-direction of the four different flexure hinges repeat within \( 52 \frac{N}{m} \) at a mean stiffness of \( 120 \frac{N}{m} \), whereby the difference between measured and simulated stiffness is caused by a measurement setup without weight compensation. Reassembling the components of the probing system repeats within \( 9 \frac{N}{m} \) at a mean stiffness of \( 67 \frac{N}{m} \) in X-direction for five repeated measurements. To eliminate the influence of gravity, which causes a non-flatness of the flexure hinges and therewith a magnification of the stiffness, a weight compensation with a damping system is realised.
Chapter 3

3D-Probing System based on Capacitive Sensors

In this chapter the setup of the probing system on a CMM including its calibration are discussed and measurement results for checking the probing system are presented. The probing head with an isotropic stiffness at the probing element as presented in section 2.5 is therefor used. The setup of the probing system and its calibration are presented in section 3.1 and 3.2, respectively. The results of geometric 1D-checking of the probing system is discussed in section 3.3. The geometric 3D-checking is presented in section 3.4. The robustness of the probing system is checked by an enforced collision as presented in section 3.5. In section 3.6, the results of an EVE test are presented. This chapter ends with a summary in section 3.7.

3.1 Setup of test rig

This section is grouped in two subsections: the mechanical setup on the high-precision CMM ISARA (see section 3.1.1) and in a section which describes the calculation of the position of the probing element (see section 3.1.2).

3.1.1 Mechanical setup on CMM ISARA

The probing head as presented in chapter 2 is clamped by brackets in a fixture, which is connected to the Z-axis ram of the CMM, see figure 3.1. Therewith, the original probing system of the CMM is replaced by the new one presented in this thesis and it is also integrated into the numerical control of the CMM used, the ISARA from IBS Precision.
Engineering (see section 1.5.4). For calibrating and checking the probing system, a relative motion between workpiece and probing system is enabled by the drive unit of the CMM in X-, Y- and Z-direction.

In the following subsection, the procedure to determine the deflection of the probing element based on the three signals of the capacitive sensors used is presented.

### 3.1.2 Calculation of the position of the probing element

The measurement signals are the voltages at each capacitive sensor. With the calibrated sensitivity of each sensor, this voltages are transferred into a distance between sensor and moveable plate of the probing head (see figure 2.2). The relative deflection of the probing element from an initial point is determined by the three sensors as shown in figure 3.2: by measuring the change in Z-, A- and B-direction of the moveable plate and using the calibrated parameters like the length of the probing stylus, the position of the probing element is calculated. The calibration procedure is discussed in section 3.2.
3. 3D-Probing System based on Capacitive Sensors

3.2 Calibration of the probing system

In this section, the calibration procedure is described. The probing head is mounted at the Z-axis ram of the CMM and the probing element is deflected at a cuboid, see chapter 3.2.1. With an estimation of the calibration uncertainty as presented in section 3.2.2 the main uncertainty contributors are identified. This enables to define requirements on the measurement equipment used to meet specifications.
3.2 Calibration of the probing system

3.2.1 Procedure for calibrating the probing system

First of all, two different coordinate systems are introduced (see figure 3.3): one is the coordinate system of the CMM, which is defined by the CMM axes and which directions are labelled as X(CMM), Y(CMM) and Z(CMM). The other is the coordinate system of the probe head, which is defined by the three capacitive sensors and which directions are labelled as X(probe), Y(probe) and Z(probe). The direction of X(probe) is defined by the probe tips of sensor 1 and sensor 2, the direction of Y(probe) is perpendicular to X(probe) and crosses sensor 3. Therewith, Z(probe) as well as the origin are defined.

![Diagram of coordinate systems](image)

Figure 3.3: The six unknown parameters (red) have to be calibrated to identify the position of the probing element and the orientation of the probing head in the coordinate system of the CMM.

In following enumeration the steps of the calibration procedure are summarised:

**Unknown parameters** are the position of the probing element relative to the coordinate system of the probing head in an initial state

- \( X_0(\text{probe}) \);
- \( Y_0(\text{probe}) \);
- \( Z_0(\text{probe}) \);

as well as the orientation of the probing head (coordinate system of the probing head) relative to the coordinate system of the CMM:

- \( A_0(\text{probing head}) \);
- \( B_0(\text{probing head}) \);
- \( C_0(\text{probing head}) \).

So six unknown parameters have to be calibrated, see figure 3.3.
Deflecting the probing element at a cuboid in three perpendicular directions (see figure 3.4) gives nine equations for the six unknown parameters:

\[
\begin{align*}
\begin{pmatrix}
\delta X \\
0 \\
0
\end{pmatrix} &= T_{\text{probe}\rightarrow\text{CMM}} \begin{pmatrix}
0 \\
0 \\
Sensor 1
\end{pmatrix} + Q_1^{-1} \begin{pmatrix}
X_0(\text{probe}) \\
Y_0(\text{probe}) \\
Z_0(\text{probe})
\end{pmatrix} \\
\begin{pmatrix}
0 \\
\delta Y \\
0
\end{pmatrix} &= T_{\text{probe}\rightarrow\text{CMM}} \begin{pmatrix}
0 \\
0 \\
Sensor 1
\end{pmatrix} + Q_2^{-1} \begin{pmatrix}
X_0(\text{probe}) \\
Y_0(\text{probe}) \\
Z_0(\text{probe})
\end{pmatrix} \\
\begin{pmatrix}
0 \\
0 \\
\delta Z
\end{pmatrix} &= T_{\text{probe}\rightarrow\text{CMM}} \begin{pmatrix}
0 \\
0 \\
Sensor 1
\end{pmatrix} + Q_3^{-1} \begin{pmatrix}
X_0(\text{probe}) \\
Y_0(\text{probe}) \\
Z_0(\text{probe})
\end{pmatrix}
\end{align*}
\]

with:

- \(\delta X\) Deflection of the probing element by the drive unit in X-direction;
- \(\delta Y\) Deflection of the probing element by the drive unit in Y-direction;
- \(\delta Z\) Deflection of the probing element by the drive unit in Z-direction;
- \(T_{\text{probe}\rightarrow\text{CMM}}\) Transformation matrix from the coordinate system of the probing system into the coordinate system of the CMM;
- \(Q_i\) Describes the orientation of the moveable plate in the coordinate system of the probing system for each measuring point \(i\). \(Q\) is the transformation matrix from an orthonormal basis on the moveable plate, which is defined by three vectors: the normal vector of the moveable plate, the direction of the intersection of the moveable plate with the \(XZ\)-plane of the probe coordinate system and a vector which is perpendicular to the others;
- \(\begin{pmatrix}
X_0(\text{probe}) \\
Y_0(\text{probe}) \\
Z_0(\text{probe})
\end{pmatrix}\) Coordinates from intersection point of sensor 1 with moveable plate to center of the probing element, expressed in coordinates of a system which moves with the moveable components of the probing system.
The probing element is deflected in X-, Y- and Z-direction 10 µm.

**Solving this nine equations** for the six unknown parameters is done with a Nelder-Mead-method [90]. This is a non-linear optimisation technique for solving unconstrained non-linear problems without derivatives. The condition number for inversion of the transformation matrix $T_{probe\rightarrow CMM}$ is near 1, which indicates a well-conditioned matrix.

![Direction of probing](image)

(1) Probing stylus not deflected at cuboid
(2) Probing stylus deflected at cuboid

Figure 3.4: Calibration of the probing head by deflecting the probing element at a fixed cuboid.

### 3.2.2 Estimation of the calibration uncertainty for 3D-probing system

The calibration uncertainty, describing the quality of the calibration, is estimated for implementing the probing system on a high-precision CMM like *ISARA* (see table 3.1) and on a conventional CMM (see table 3.2) to identify the influence of the different contributors on the calibration uncertainty. Typically, conventional CMM’s have an accuracy of the drive unit in the range of several µm. High-precision CMM’s, however, have a positioning accuracy clearly smaller than 1 µm. Following enumeration contains the main contributors to the calibration uncertainty:

- **Accuracy of the CMM:**
  The CMM used has laser interferometers for each axis with a resolution of 1.6 nm. The positioning error $A$ [91] of its linear axes is estimated to be 0.1 µm. The effect of
the deviations of the drive unit from its nominal motions is estimated with a Monte-Carlo-simulation: the positioning errors of the linear axes are used as range, whose influence on the calibrated parameters and therewith on the calculated deflections of the probing element are estimated. The contribution of this change of the input parameters, the position of the linear axes of the CMM, is determined to be less than 0.04 \( \mu m \) for a deflection of the probing element in X- and Y-direction and insignificant (0.004 \( \mu m \)) for deflecting the probing element in Z-direction.

- Form deviation of the probing element:
  A deviation of the probing element from its nominal shape has the same influence as a positioning error of the drive unit. Manufacturer information is used to estimate this contributor: the form deviation of the sphere is specified to be less than 0.25 \( \mu m \), which results in an uncertainty contributor less than 0.1 \( \mu m \). This contributor can be reduced by determining the shape of the probing element, e.g. by error mapping [58].

- Accuracy of the capacitive sensors:
  The resolution and calibration uncertainty of the capacitive sensors are estimated to be less than \( \pm 0.06 \mu m \) (manufacturer information) and the repeatability of the detection of the change of the measurement signal is less than 0.2 nm. For constant unknown parameters \( X_0(\text{probe}), Y_0(\text{probe}), Z_0(\text{probe}), A_0(\text{probing head}), B_0(\text{probing head}) \) and \( C_0(\text{probing head}) \) the influence of changes in the measured signals on the position of the probing element is estimated with a Monte-Carlo-simulation to be less than 0.08 \( \mu m \) for deflecting the probing element in X- and Y-direction and less than 0.03 \( \mu m \) for a deflection of the probing element in Z-direction.

- Determination of the six unknown parameters:
  The used numerical solver needs initial values before starting the optimisation. The solution depends on these initial values and from the used algorithm. Varying the initial guess and comparing different solvers results in a constant solution, which is independed on the type of algorithm and its initialisation (at least for reasonable initial values).

- Sensitivity of the position of the probing element in dependence of the six calibrated parameters:
  The range of the six calibrated parameters is estimated by repeating the calibration procedure. In a next step, the measurement signals are calculated for a certain calibration of the probing head. Finally, the deflections of the probing element are calculated with the determined measurement signals and with the six parameters, which are varied in a range as mentioned above. The results of this Monte-Carlo-
3.2 Calibration of the probing system

simulation on the position of the probing element are less than 0.07 \( \mu m \).

Combining the mentioned uncertainty contributors accordingly to [3] results in an expanded calibration uncertainty of \( U_{\text{Calibration}}(k=2) = 0.29 \ \mu m \) and is summarised in table 3.1.

Table 3.1: Summary of the estimated calibration uncertainty on a high-precision CMM.

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Range</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy of drive unit</td>
<td>0.1 ( \mu m )</td>
<td>0.04 ( \mu m )</td>
<td>0.04 ( \mu m )</td>
<td>0 ( \mu m )</td>
</tr>
<tr>
<td>Form deviation of probing element</td>
<td>&lt; 0.25 ( \mu m )</td>
<td>0.10 ( \mu m )</td>
<td>0.10 ( \mu m )</td>
<td>0.01 ( \mu m )</td>
</tr>
<tr>
<td>Accuracy of capacitive sensors</td>
<td>±0.06 ( \mu m )</td>
<td>0.08 ( \mu m )</td>
<td>0.08 ( \mu m )</td>
<td>0.03 ( \mu m )</td>
</tr>
<tr>
<td>Determination of unknown parameters</td>
<td>-</td>
<td>insignificant</td>
<td>insignificant</td>
<td>insignificant</td>
</tr>
<tr>
<td>Sensitivity of position of probing element, depended on calibrated parameters</td>
<td>0.5( ^\circ ), 150 ( \mu m )</td>
<td>0.05 ( \mu m )</td>
<td>0.05 ( \mu m )</td>
<td>0.07 ( \mu m )</td>
</tr>
<tr>
<td>Expanded calibration uncertainty ( U_{\text{Calibration}}(k = 2) )</td>
<td>0.29 ( \mu m )</td>
<td>0.29 ( \mu m )</td>
<td>0.15 ( \mu m )</td>
<td></td>
</tr>
</tbody>
</table>

The form deviation of the probing element used and the accuracy of the capacitive sensors used are the main contributors to the calibration uncertainty. The influence of the capacitive sensors can easily be reduced using sensors with higher accuracy. The influence of the probing element can be reduced using a better probing element, exemplary calibrated using a error separation technique as presented in [58].

Estimating the calibration uncertainty for implementing the probing system on a conventional CMM with a positioning accuracy of the 3-axes drive unit of 1.2 \( \mu m \) results in an expanded calibration uncertainty of 1.04 \( \mu m \), see table 3.2. This comparison reasons the tough requirements on the accuracy of the drive unit used, enabled by high-resolution measurement systems for the linear axes, an alignment of the linear scales fulfilling the Abbe principle [49] and big efforts in improving the geometric accuracy.
Table 3.2: Summary of the estimated calibration uncertainty on a conventional CMM.

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Range</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy of drive unit</td>
<td>1.2 µm</td>
<td>0.50 µm</td>
<td>0.48 µm</td>
<td>0.05 µm</td>
</tr>
<tr>
<td>Form deviation of probing element</td>
<td>&lt; 0.25 µm</td>
<td>0.10 µm</td>
<td>0.10 µm</td>
<td>0.01 µm</td>
</tr>
<tr>
<td>Accuracy of capacitive sensors</td>
<td>±0.06 µm</td>
<td>0.08 µm</td>
<td>0.08 µm</td>
<td>0.03 µm</td>
</tr>
<tr>
<td>Determination of unknown parameters</td>
<td></td>
<td>insignificant</td>
<td>insignificant</td>
<td>insignificant</td>
</tr>
<tr>
<td>Sensitivity of position of probing element, depended on calibrated parameters</td>
<td>0.5°, 150 µm</td>
<td>0.05 µm</td>
<td>0.05 µm</td>
<td>0.07 µm</td>
</tr>
<tr>
<td>Expanded calibration uncertainty $U_{\text{Calibration}}(k = 2)$</td>
<td></td>
<td>1.04 µm</td>
<td>1.00 µm</td>
<td>0.18 µm</td>
</tr>
</tbody>
</table>

### 3.3 1D-checking of the probing system

The 1D-checking of the probing system is realised by deflecting the probing element in only one direction at a cuboid as shown in figure 3.5. After detecting contact between probing element and cuboid, the probing element is deflected by 10 µm.

Due to their high resolution and their alignment according to the Abbe principle, the laser interferometers of the CMM used are taken as reference scales for determining the linearity of the probing system in direction of the deflection as well as for determining the cross-motions of the probing element. The checking is done for deflections of the probing element up to 10 µm, which is the typical range for the application of a probing system on a CMM. The upper limit is defined by the pretravel and overtravel of the CMM [15], which are in the range of 10 µm [19]. The lower limit of typical deflections of the probing element is given by the deflection of the probing element when the coordinates of a point on the surface of the workpiece to be checked are measured. After detection of contact
of the probing element with the workpiece to be checked (upper limit), the deflection of the probing element can be controlled by the numerical control of the CMM to be clearly smaller than the above mentioned deflection (this depends on the measurement strategy of the manufacturer of the CMM). This strategy reduces the probing forces as well as the bending of the probing stylus, which enables an almost "force free contact" for measuring the coordinates of probing points [58].

Figure 3.6 A shows exemplary the results of the 1D-checking in X-direction.

Figure 3.6: 1D-checking of the probing system by deflecting the probing element 10 µm in X-direction.
A: Measured deflection of the probing element by the probing system (green) and by the laser interferometers of ISARA (red).
B: Difference of the measured deflections of the probing element between the probing system and the laser interferometers of ISARA.
In Y- and Z-direction the influence of the numerical control of the CMM can be seen, which is in the range of 50 nm. Due to a roll effect of the probing element for a deflection in X- and Y-direction, the Z-deflection measured by the probing system differs from the Z-deflection measured by the laser interferometer. In figure 3.6 B the differences between the measured deflections by the probing system and by the laser interferometers are shown.

In table 3.3 the results for 1D-checking the probing system in ±X-, ±Y and −Z-direction are summarised. The linearity error in X-, Y- and Z-direction is less than 0.12 μm at a deflection of the probing element of 10 μm (< 1.2 %) and may be caused by the capacitive sensors or error motions of the moveable plate of the probing system. As discussed in chapter 4, the influence of the linearity error during probing can be reduced by minimising the deflection of the probing element when the coordinates of the probing point are read-out by the numerical control of the CMM. The cross-motion, which is up to 0.65 μm, has no influence on the accuracy of the probing system because it is perpendicular to the direction of the deflection during probing.

Table 3.3: 1D-checking of the probing system for deflecting the probing element 10 μm in X-, Y- and Z-direction.

<table>
<thead>
<tr>
<th>Direction of probing</th>
<th>Linearity error in X</th>
<th>Cross-motion in Y</th>
<th>Cross-motion in Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>+X [μm]</td>
<td>0.11</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td>-X [μm]</td>
<td>0.11</td>
<td>0.14</td>
<td>0.49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direction of probing</th>
<th>Cross-motion in X</th>
<th>Linearity error in Y</th>
<th>Cross-motion in Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>+Y [μm]</td>
<td>0.14</td>
<td>0.12</td>
<td>0.65</td>
</tr>
<tr>
<td>-Y [μm]</td>
<td>0.11</td>
<td>0.11</td>
<td>0.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direction of probing</th>
<th>Cross-motion in X</th>
<th>Cross-motion in Y</th>
<th>Linearity error in Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>-Z [μm]</td>
<td>0.12</td>
<td>0.11</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### 3.4 3D-checking of the 3D-probing system

In section 3.4.1 the procedure for the 3D-checking of the probing system is presented and discussed. The experimental results are summarised in section 3.4.2.
3.4 3D-checking of the 3D-probing system

3.4.1 Procedure for 3D-checking of the probing system

To check the probing performance of a 3D-probing system, ISO proposes the measurement of a hemisphere of a calibrated reference sphere with 25 points, which are approximately evenly distributed on the surface of the hemisphere [92]. The result of this check is expressed as $MPE_P$ and describes the “error of indication within which the range of radii of a spherical material standard of size can be determined by a CMM”. Due to the widespread application of probing systems on CMM’s, their probing direction is not constant, e.g. for measuring the diameter of a borehole. Therefore, probing systems have to be checked by deflecting the probing element in different directions, which is realised by measuring a reference sphere. Because the CMM has to be moved for determining the $MPE_P$, the $MPE_P$ is influenced by the geometric accuracy of the CMM used, even for using small reference spheres. So determining the $MPE_P$ is an integral check, which is not only influenced by the probing system to be checked.

Probing on a hemisphere for checking a 3D-probing system has following advantages:

- The probing system to be checked deflects in different directions, at least in three perpendicular planes as shown in figure 3.7. As proposed by ISO, additional points between the three perpendicular planes can be probed. Therewith, an anisotropic stiffness at the probing element is detectable;

- The centre of the reference sphere is a mechanical reference point and valid for all measured points on the surface of the reference sphere. Therewith, a change of the zero position of the probing system to be checked between different probing directions is detectable;

- Reference spheres in different diameters are available with form deviations smaller
than 100 nm. In dependence on the intended uncertainty of checking the 3D-probing system, a reversal method to identify the form deviations of the reference sphere and the probing element is applicable [58];

- The geometric accuracy of the drive unit, which is defined by its component and location errors [11], [12], has reduced influence for small reference spheres because of its reduced travel range. Drive units fulfilling the Abbe principle are predestinated, because component errors like pitch, roll and yaw errors have only second order influence on the positioning accuracy.

The checking of the 3D-probing system on the high-precision CMM ISARA, which has reduced influence on the accuracy of checking the probing system, is presented in section 3.4.2.

3.4.2 3D-checking on a high-precision CMM

A reference sphere with form deviation of less than 20 nm and a diameter of 8 mm is probed in totally 541 measuring points. In figure 3.8 A the measured form deviations are shown for all measuring points.

![Figure 3.8: Influence of dirt and dust on measurements at a reference sphere. A: Measured form deviation at all 541 measuring points. The single outliers are caused by dirt and dust on the probing element and on the reference sphere. B: Measured form deviations at filtered measuring points. Elimination of the single outliers reduces the number of measuring points from 541 to 506.](image)

It can be seen that single outliers with an amplitude of up to 5 μm exist. Due to the
large number of measuring points it is possible to detect single outliers, which are most likely correlated to dust and dirt on the probing element and / or on the reference sphere. By repeating the measurement at the reference sphere with the same nominal probing points it can be checked if the outliers exist for each measurement and are therefore most likely caused by dirt on the probing element or on the reference sphere. As it can be seen in figure 3.8, measured form deviations larger than 0.3 µm are caused by dirt and are therewith eliminated. This reduces the number of measuring points from 541 to 506, which results in a MPEₚ of 0.67 µm.

The measured form deviations for the 3D-checking of the probing system are shown in figure 3.9 and have the shape of an ellipsoid. To identify the source of this characteristic shape, the probing system is rotated by 90°, which results in a rotation of the measured ellipsoid of 90°, too. Measuring another reference sphere with the same calibrated magnitude of the form deviation at another position of the reference sphere in the workspace of the CMM results also in a form deviation of 0.60 µm with identical shape of the ellipsoid. Therefore, the MPEₚ in the range of 0.6 µm and the measured form deviations with a shape of an ellipsoid are very probably caused by the probing system and not by the reference sphere, the 3-axes-drive unit of the CMM or the probing element.

![Figure 3.9: Checking the 3D-probing system on a high-precision CMM by measuring a hemisphere of a reference sphere in 506 measuring points.](image)

A: Spatial view (red: deviations showing outside of the surface of the reference sphere; green: deviations showing inside of the surface of the reference sphere).
B: View in XY-plane (red: deviations showing outside of the surface of the reference sphere; green: deviations showing inside of the surface of the reference sphere).

The measurements at the reference sphere are repeated three times to check the repeatability of the probing system. Measured form deviations larger than 0.3 µm are eliminated for all three measurements and the corresponding measuring points are excluded for de-
terminating the MPE_p because they are most likely caused by dirt. In figure 3.10 A the measured form deviations of the three measurements are shown. Apart from individual outliers repeatability of the measurements is very good, which can be seen in figure 3.10 B. This figure shows the maximum range of the measured form deviations for the three measurements. The mean range of the measured form deviations over 506 measuring points is 0.01 µm. The outliers may be caused by dust because of the total measurement time of approximately three hours. Due to the very good repeatability of the probing system the MPE_p can be reduced by a compensation or error mapping as presented in [58]. For compensating the probing errors a reference sphere with known or negligible form deviation is measured. Due to the known probing direction in each measuring point at the reference sphere, the measured deviations can be identified in their magnitude as well as in their three-dimensional direction. A compensation of probing errors by the numerical control is possible because the probing directions during measuring any workpiece are also known by the generated measuring programme or by the CAD data of the workpiece to be checked.

In contrast to the 3D-checking of the probing system on a high-precision CMM, the results of the checking on a conventional CMM can’t be used for determining the MPE_p: due to positioning errors in the µm-range, the probing system can’t be checked with smaller uncertainties compared to the geometric accuracy of the CMM used. Only if a CMM with accuracies clearly better than the expected accuracy of the probing system to be checked is used, a meaningful MPE_p can be determined. The 3D-checking of the probing system is also done on a conventional CMM with positioning accuracy of 1.2 µm and results in
3.5 Checking robustness of the probing system against collision

The robustness of the probing system is checked by a controlled deflection of the probing element clearly larger than the specified measurement range of $\pm 100 \mu m$. This is an important aspect of a probing system, especially of probing systems for micro-components with specified measurement ranges in the $\mu m$-range, because the limit of the measurement range is reached very quickly and could therefore damage the probing system or its components.

For simulating a collision of the probing element with the component to be checked, following procedure as shown in figure 3.11 is executed: first, the measured voltages of the capacitive sensors are reset when the probing element is not in contact with a workpiece. Then, the contact between probing element and workpiece is determined by a motion of the CMM. This position serves as reference point for deflecting the probing element. Next step is a motion of the CMM to deflect the probing element in Y-direction. Afterwards, the CMM is moved back so that the probing element is no longer in contact with the workpiece.

![Figure 3.11: Schematic setup for checking the robustness of the probing system by an enforced collision.](image)

If the measured voltages of the capacitive sensors are the same as before, the deflection was not critical. At a deflection of the probing element of 250 $\mu m$ one of the three capacitive sensors reaches the end of its measurement range, which means that the moveable plate (see figure 2.13 on page 53) is in contact with the tip of the capacitive sensor. The
moveable plate is in contact with all three capacitive sensors at a deflection of the probing element of 350 \( \mu m \). So a deflection of 400 \( \mu m \) is regarded as a critical collision of the probing element with the workpiece. For this deflection the measured voltages don’t come back to their initially reseted values. A further measurement at the reference sphere with 541 measuring points after the enforced collision results in a MPE\(_P\) of 0.55 \( \mu m \). Before the enforced collision the MPE\(_P\) is 0.60 \( \mu m \). So the MPE\(_P\) is not clearly influenced by deflecting the probing element up to 400 \( \mu m \).

Another interesting aspect is the repeatability of the probing system after the enforced collision. Therefore, the measured form deviations at the reference sphere in 498 measuring points of the sphere measurement before the enforced collision are compared with the measured form deviations at the reference sphere after the enforced collision. Comparing the form deviations of the measured reference sphere before and after the critical deflection of 400 \( \mu m \) results in a mean difference of 0.02 \( \mu m \) over 498 evaluated measuring points, see figure 3.12. Even after such a large deflection of the probing element, the probing system has still a very good repeatability.

![Figure 3.12: Checking the robustness of the probing system by comparing the measured form deviation of a reference sphere before and after an enforced collision.](image)

A: Measured form deviations at a reference sphere in 498 measuring points of two measurements. The second measurement is done after deflecting the probing element 400 \( \mu m \).
B: Maximum range of the measured form deviations between two measurements at single measuring points. The second measurement is done after deflecting the probing element 400 \( \mu m \) to simulate a collision.
3.6 Environmental variation error

The EVE [30] is checked in an air conditioned measuring room, which is also a clean room of class "ISO 7" [93]. The temperature is controlled to be within $20^\circ C \pm 0.25^\circ C$ and not to change more than $0.1^\circ C$ per hour. This are very good environmental conditions for the CMM, which are absolutely necessary for measuring components with measurement uncertainties in the sub-micrometre range.

During the measurement, the probing element is in Z-direction in contact with a workpiece made of Zerodur®, which has a thermal expansion coefficient less than $0.1 \cdot 10^{-6} \frac{1}{K}$. Therewith, the workpiece has negligible influence on the measurement. In figure 3.13, the measured deflections of the probing element in X-, Y- and Z-direction as well as the temperatures near the three laser interferometers of the CMM are shown.

The measured deflections of the probing element over the complete measurement time of 16 h are less than 0.54 µm. The EVE is determined for such a long measurement time.
because measurements at micro-components may last several hours. The temperatures are measured close to the laser interferometers and vary less than 0.31°C. It can be seen that the deflections are correlated to the temperatures, e.g. after a measurement time of 1 h and 13.5 h. The temperature in the workspace is best approximated by the temperature sensor at the laser interferometer of the Y-axis because it is the closest one to the workspace. The thermal expansion $\Delta L$ of the probing system in Z-direction is calculated as

\[
\Delta L = (\alpha_{\text{Probe}} - \alpha_{\text{CMM}}) \ L \ \Delta T \\
= (22 \cdot 10^{-6} - 2.6 \cdot 10^{-6}) \frac{1}{K} \ 0.1 \ m \ 0.31 \ K \\
= 0.6 \ \mu m
\]

with:

- $L$ Length from support of probing system to probing element ($L = 0.1 \ m$);
- $\Delta L$ Expansion of probing system due to thermal effects;
- $\Delta T$ Change of temperature ($\Delta T = 0.31 \ K$);
- $\alpha_{\text{CMM}}$ Thermal expansion coefficient of the metrology frame of the CMM (made of silicon carbide, $\alpha_{\text{CMM}} = 2.6 \cdot 10^{-6} \ \frac{1}{K}$);
- $\alpha_{\text{Probe}}$ Thermal expansion coefficient of the fixture of the probing system (made of aluminium, $\alpha_{\text{Probe}} = 22 \cdot 10^{-6} \ \frac{1}{K}$);

Due to the approximation of the thermal expansion of the probing system in Z-direction by (3.1) it is possible to reduce the EVE of the probing system by changing the material of its fixture: using a material with a smaller thermal expansion coefficient compared to aluminium, e.g. Invar® or Zerodur®, reduces the EVE according to (3.1). At least, the material of the fixture of the probing system should have the same thermal expansion coefficient as the material of the CMM.

### 3.7 Summary

In this chapter, the setup of the 3D-probing system and results of checking it are presented. In section 3.1, the mechanical integration of the probing system on the high-precision CMM ISARA is presented, which is used for the geometric 1D- and 3D-checking of the
probing system and for determining the EVE. Afterwards, the procedure to calculate the position of the probing system is discussed as well as the calibration of the probing system in section 3.2. Six unknown parameters have to be calibrated, which is done by deflecting the probing element at a cuboid in X-, Y- and Z-direction by a well-known distance. The expanded calibration uncertainty (k=2) is estimated using Monte-Carlo-simulations and is determined to be $0.29 \, \mu m$. The calibration uncertainty strongly depends on the geometric accuracy of the 3-axes drive unit. This can be seen by estimating the calibration uncertainty for implementing the probing system on a conventional CMM with an even less accurate positioning, which results in $1.04 \, \mu m$ (k=2). The Monte-Carlo-simulation can be used to study the influences of different contributors on the uncertainty of the calibration.

The linearity error of the probing system is checked for deflecting the probing element up to $10 \, \mu m$ and is determined to be less than $0.12 \, \mu m$ or $1.2 \%$, see section 3.3. In section 3.4 the MPE$_P$ of the probing system is determined to be $0.67 \, \mu m$. Due to the good repeatability of the probing system, which is $0.01 \, \mu m$ (mean value over 506 measuring points and three measurements), the MPE$_P$ of the probing system can be reduced by a compensation or error mapping. An enforced collision of the probing element with a workpiece is used to estimate the robustness of the probing system, see section 3.5. After the enforced collision, the repeatability of the probing system is $0.02 \, \mu m$ (mean value over 498 measuring points and two measurements). The EVE, caused by vibrations, thermal influences and further environmental disturbances, is determined to be less than $0.54 \, \mu m$ over a measurement time of 16 hours.
Chapter 4

Conclusion and Outlook

The probing system as presented in this thesis fulfils the requirements concerning its geometric accuracy for an application on a CMM to measure micro-components. The procedure for designing the probing system is based on FEM. Therewith, the stiffnesses at the probing element can be predicted by simulations before the first probing system is manufactured, which is an advantage compared to the current state of the art.

With an estimation of the uncertainty at the probing element as presented in this work, the requirements on the sensors used to measure the change of the position and orientation of the moveable plate or on the alignment of the sensors can be determined. In table 4.1 the uncertainties at the probing element as presented in section 2.5.2 are compared with the uncertainties of a probing system with following improvements:

- Sensors used with better resolution, e.g. 20 nm instead of 120 nm. Commercially available are sensors with resolution of 1 nm and a measuring range of 50 µm;
- Reduced squareness error between the sensors and the moveable plate, e.g. 0.25° instead of 0.5°. If the components of the probing system are manufactured with numerically controlled machine tools representing the state of the art in manufacturing, this reduction of the squareness error is reasonable and achievable.

This results in a reduction of the estimated measurement uncertainties at the probing element of up to 77%.

The weight balance of the probing system as presented in section 2.5.4 is another component of the probing system which can be improved. In this case, the size of the component and its design could be changed to increase the practicability of the probing system in industry.

From the design point of view the use of aluminium for the fixture of the probing system shows disadvantages because of its thermal expansion in dependence on the temperature
in the workspace. Using Invar® or Zerodur® instead of aluminium with a low thermal expansion coefficient of $\alpha_{\text{Probe}} = 0.2 \cdot 10^{-7} \frac{1}{K}$ reduces the magnitude of the thermal expansion from 0.6 $\mu m$ (for a fixture of the probing system made of aluminium) to 0.08 $\mu m$. Due to the main influence of the temperature on the EVE, the use of materials with low thermal expansion coefficients for the fixture of the probing system will result in an EVE in the range of 0.1 $\mu m$ or even less. Another possibility to reduce the influence of thermal effects is to use a material for the fixture of the probing system with the same thermal expansion coefficient as the CMM. By an additional housing of the probing system the EVE could also be reduced because the sensors would be in a more stable environment.

Table 4.1: Possibilities of improving the measurement uncertainties at the probing element. Calculation of the standard uncertainties of each contributor is given in (2.7) on page 55 up to (2.11) on page 57.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration of probing system as presented</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution of sensors: 120 $nm$</td>
<td>62</td>
<td>71</td>
<td>35</td>
</tr>
<tr>
<td>Calibration uncertainty of sensors: 13 $nm$</td>
<td>7</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Uncertainty of distance between sensors: 5 $\mu m$</td>
<td>23</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Squareness error between sensors and surface of moveable plate: 0.5$^\circ$</td>
<td>56</td>
<td>65</td>
<td>32</td>
</tr>
<tr>
<td>Combined standard uncertainty</td>
<td>87</td>
<td>101</td>
<td>48</td>
</tr>
<tr>
<td>Configuration of improved probing system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution of sensors: 20 $nm$</td>
<td>10</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Calibration uncertainty of sensors: 13 $nm$</td>
<td>7</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Uncertainty of distance between sensors: 5 $\mu m$</td>
<td>23</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Squareness error between sensors and surface of moveable plate: 0.25$^\circ$</td>
<td>14</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Combined standard uncertainty</td>
<td>30</td>
<td>37</td>
<td>11</td>
</tr>
</tbody>
</table>
For an application of the probing system on a CMM further probing strategies may be implemented: actually, the motion of the CMM during probing is stopped as soon as one of the three sensors reaches a specified trigger level. Afterwards, the position of the linear axes of the CMM as well as the voltages of the three capacitive sensors are read-out to calculate the deflection of the probing element. Thereby, the deflection of the probing element is approximately $10 \, \mu m$. Reducing the deflection of the probing element for determining the coordinates of the contact between probing element and workpiece to be checked reduces the probing forces and may result in a better repeatability of the probing system. With a reduced deflection of the probing element during probing, the influence of the linearity error of 1 % can be reduced: is the deflection during the read-out of the measurement signals only $1 \, \mu m$ instead of actually $10 \, \mu m$, the contribution of the linearity error is reduced from 0.1 $\mu m$ to 0.01 $\mu m$.

The MPE$_P$ of the presented probing system, 0.67 $\mu m$, is clearly better than the MPE$_P$ of conventional probing systems, which is typically in the range of several $\mu m$. Using a compensation or error mapping for improving the MPE$_P$ of the probing system could also be implemented if the probing system is component of a high-precision CMM comparable with the ISARA used for testing the probing system. The improvement of a numerical compensation can be estimated based on the mean repeatability of the probing system and for the same nominal deflections of the probing element during probing before and after the numerical compensation is realised: the mean repeatability is 0.01 $\mu m$, so the MPE$_P$ after compensation is estimated to be in the range of 0.02 $\mu m$.

Another aspect to be discussed is the applicability of the probing system. Due to its scalability regarding the stiffness at the probing element, the design principle of the probing system can be adapted to specific measurement tasks. As shown in figure 4.1 A, the geometry of the flexure hinges is adjusted using FEM to a configuration with isotropic stiffnesses at the probing element of $1140 \, \frac{N}{m}$. With this design the probing system can be used on conventional CMM’s, on CMM’s used in shop-floor conditions or machine tools. On the other hand as shown in figure 4.1 B, the design of the flexure hinges is changed to achieve isotropic stiffnesses at the probing element of only $18 \, \frac{N}{m}$, which makes the probing system applicable of checking even very sensitive components like optical ones without irreversible deformations caused by the probing element. Due to the actual technology of manufacturing the raw material of the flexure hinges, the stiffnesses at the probing element may be influenced by the rolling direction during manufacturing the cold rolled steel strip. This can be checked as presented in figure 2.24 on page 70.

Independent of the realised stiffnesses at the probing element, there is especially in contrast to conventional probing systems no need of adjusting its different directions of motions to
each other, which is one of the main advantages of the presented probing system.

**A**

Stiffness at probing element: 1140 N/m

**B**

Stiffness at probing element: 18 N/m

Figure 4.1: Modification of the geometry of the flexure hinges to specific requirements. For FEM simulations, a probing stylus with length of 16 mm and probing sphere with diameter of 2 mm is used.

A: Flexure hinges of a probing system with increased stiffnesses at the probing element of 1140 N/m (isotropic) for use on conventional CMM's or machine tools.

B: Flexure hinges of a probing system with reduced stiffnesses at the probing element of only 18 N/m (isotropic) for measuring very sensitive surfaces.
Appendix A

3D-Probing System based on Fizeau Interferometry

In a first feasibility study a Fizeau interferometer is used to determine the change of position of the probing element. The measurement principle is discussed in section A.1, the application for the 3D-probing system in section A.2. The checking of the probing system is presented in section A.3. Finally, in section A.4, the uncertainty of the probing system based on a Fizeau interferometer is estimated. This chapter closes with a summary in section A.5.

A.1 Fizeau Interferometry

A Fizeau interferometer is used to determine the shape of a surface. A fabricated workpiece, e.g. a mirror or a lens, is measured relative to the reference surface. Its setup is shown in figure A.1. The laser beam is divided in a reference beam and a measurement beam, which are superposed and generate an interference pattern [94], [95], [96], [97]. The interference pattern depends on the shape of the reference surface, on the shape of the surface under test as well as on their orientation to each other.

If the reference surface and the surface under test a perfectly flat, the interference fringes are straight lines. Thereby, the angular orientation of these fringes describe the rotational axis of the surface under test relative to the reference surface, and the distance between the fringes identify the angle of the tilting.

In surface testing, the information about the orientation of the reference surface relative to the surface under test is not used.
A.2 Setup of test rig

In this application, the relative orientation between reference element and surface to be checked is used to determine the position of the probing element, see figure A.2. Using a flat reference surface as well as a flat surface under test (with flatness $< \frac{\lambda}{10}$), the X-, Y- and Z-position of the probing element is determined with only one sensor instead of three as is the rule in conventional probing systems. Evaluating moreover the form deviation of the surface under test during measurements with the 3D-probing system, an information about damages or too high probing forces is given. A Z-translation of the probing element changes the interference pattern over the whole diameter of the laser beam only in its intensity, but not in its shape [83].

The setup is shown in figure A.3. The main components are the laser interferometer, the adjustment unit and the probing head [83]. The probing head has the same dimensions as presented in chapter 2. The laser beam is in an enclosed environment, so its less sensitive to
environmental disturbances. Also it is very compact, so it is less sensitive to vibrations. The image processing to determine the change of position of the probing element is described in section A.2.1.

### A.2.1 Image processing for determining the position of the probing element

The software for evaluating the position of the probing element is described in [83]. The relevant information about the position of the probing element is enclosed in the interference images. A deflection of the probing element causes a change in the phase of the light wave between reference beam and measurement beam. Thus an intensity modification of the superposed beam is generated, which results in a changing interference pattern [94], [95], [96]. Consequently, the maximum speed of deflecting the probing element is limited by the speed of the image processing. The direction of deflecting the probing element is given by the orientation of the interference fringes; the magnitude of the deflection is inversely proportional to the distance between the interference fringes. In a first step, an algorithm for determining the relative shift between two images is realised. The intention is to prove that the deflection of the probing element can be determined using a Fizeau interferometer. Actually, the image processing speed is very low, because the resolution of the interferometer is very high (480 \times 640 pixels). For detecting the
Z-motion of the probing element in real-time, another optical system would be needed, which enables image processing with at least 25 kHz for opportunity of scanning [15]. The main modules of the current algorithm are the following:

- Filtering the image in order to reduce noise;

- Edge detection in the intensity image;

- Detection of lines of the interference fringes by using Hough transform [98]. Their orientation is compared with an optimisation, which minimises the distance of intensity peaks on a section through the interferogram;

- The result is used for calculating the out-of-plane tilting of the surface under test referred to the reference surface;

- The distance between fringes in the interferogram is determined;

- Calculating the position of the probing element.

The output for detecting the axis of rotation by minimising the distance of the intensity peaks is shown in figure A.4. The developed algorithm is checked with simulated interference images between a perfect flat reference surface and a perfect flat surface under test: the sinus profile of the intensity is preset, so the orientation of the interference fringes
and the distance between themselves are known. The interference images are simulated directly, without any connection to the evaluation algorithm to be checked.

Figure A.4: Algorithm to evaluate the horizontal deflection of the probing element.
A.3 Checking of probing system

For calibrating the stylus length, the relative horizontal deflection of the probing element between two images is determined with the algorithm as described above and compared with the deflection measured by an additional 1D-length measuring device.

The repeatability of the probing system is determined to be 0.19 µm. This standard deviation is almost as large as the estimated uncertainty of the 1D-length measuring device, which is used to deflect repetitively the probing element. Consequently, the checking of the 3D-probing system is currently limited by the used 1D-length measuring device and the manual positioning device.

The drift has also been measured. For a measurement time of 4 hours the thermal drift is determined to be 0.16 µm (see figure A.5). The peak in figure A.5 (red curve) is caused by disturbances, e.g. persons walking through the laboratory, and is eliminated for the drift evaluation (blue curve in figure A.5). If the probing system is calibrated each 30 min, the drift can be reduced to 0.1 µm. During drift measurements, the probing element is not in contact with a workpiece. The test conditions are typical laboratory conditions with air conditioning to 20°C ± 0.5°C.

![Drift vs Measurement Time](image)

Figure A.5: EVE of 3D-probing system if probing element is freestanding (measurement uncertainty U(k=2) = 0.24 µm, see dashed lines).
A.4 Uncertainty estimation

The principal contributors to the measurement uncertainty of the 1D-length measuring device are the measuring uncertainty of the incremental probe ($\pm 0.2 \, \mu m$ over $12 \, mm$ measuring range) and the angular error of the probing direction from the deflecting direction (assumption: range $\pm 1.5^\circ$). The thermal drift is neglected, because the measurement time is smaller than 1 minute and the whole setup is temperature conditioned for at least 4 hours. The measurement uncertainty is $U(k=2) = 0.24 \, \mu m$ for measuring length smaller than $0.24 \, \mu m$.

The principal contributors to the measurement uncertainty of the 3D-probing system are the uncertainty of the interferometer and the performance of computing the orientation of the surface under test. For the fitting of the line with maximal gradient used in step 2 in figure A.4, a 95 % confidence interval is calculated. The uncertainty of the interferometer with the used reference surface is according to the manufacturer instruction $\lambda_{10}$, which results in a standard uncertainty at the probing element in horizontal direction of $0.11 \, \mu m$. The total measurement uncertainty is $U(k=2) = 0.24 \, \mu m$ for measuring length smaller than $0.24 \, \mu m$. The thermal drift is neglected for the same reason as described above. The results are summarised in table A.1. The direction of deflecting the probing element has no influence on the detected deflection.

A.5 Summary

The advantage of using a Fizeau interferometer to measure the change in the Z-position and A- and B-orientation of the moveable plate is that only one sensor is needed. In contrast to other measurement principles with multiple sensors, the alignment of the sensor is insignificant. Additionally, the information about the flatness of the surface under test can be used to detect damages caused by too high probing forces. For typical probing forces in the $mN$-range, this form deviation of the surface under test is in the $nm$-range or even smaller.

A main disadvantage is the low speed of the image processing of typical Fizeau interferometers. To measure the deflection of the probing element in real time, a high-speed camera as well as a high-speed image processing with at least $25 \, kHz$ are necessary. This requires a powerful light source, which is contrary to the intention of minimal application of energy into the probing system. For the image processing in real time, high-performance computing is required.

Because of these disadvantages, the Fizeau interferometer is replaced by three capacitive
Table A.1: Results of displacements measurements (measurement uncertainty $U(k=2)$).

<table>
<thead>
<tr>
<th>Detected deflection of probing element [$\mu m$] by</th>
<th>Relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D-length measuring device</td>
<td>3D-probing system</td>
</tr>
<tr>
<td>2.6 ± 0.23</td>
<td>2.42 ± 0.24</td>
</tr>
<tr>
<td>5.7 ± 0.23</td>
<td>5.60 ± 0.24</td>
</tr>
<tr>
<td>9.0 ± 0.23</td>
<td>8.87 ± 0.24</td>
</tr>
<tr>
<td>13.5 ± 0.23</td>
<td>13.48 ± 0.24</td>
</tr>
<tr>
<td>19.9 ± 0.24</td>
<td>19.94 ± 0.24</td>
</tr>
<tr>
<td>25.7 ± 0.24</td>
<td>25.78 ± 0.24</td>
</tr>
<tr>
<td>Measurement 2 with separate calibration</td>
<td></td>
</tr>
<tr>
<td>3.4 ± 0.23</td>
<td>3.44 ± 0.24</td>
</tr>
<tr>
<td>10.3 ± 0.23</td>
<td>10.47 ± 0.24</td>
</tr>
<tr>
<td>19.1 ± 0.24</td>
<td>19.12 ± 0.24</td>
</tr>
<tr>
<td>22.3 ± 0.24</td>
<td>22.19 ± 0.24</td>
</tr>
</tbody>
</table>
Appendix B

Designing and Manufacturing the Probing System

B.1 Influence of mesh size in FEM simulation

In table B.1 the influence of different mesh sizes is shown. The number of element per \( \text{mm} \) for meshing the flexure hinges is changed and the stiffness at the probing element is determined. If the stiffness changes less than 1 \%, the mesh size is not further refined.

Table B.1: Influence of element size on simulated stiffness.

<table>
<thead>
<tr>
<th>Number of elements per ( \text{mm} ) (length ( \times ) width ( \times ) thickness)</th>
<th>Simulated stiffness in X-direction ( \frac{N}{m} ) / Maximal von Mises stress in flexure hinges [MPa]</th>
<th>Simulated stiffness in Z-direction ( \frac{N}{m} ) / Maximal von Mises stress in flexure hinges [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 ( \times ) 2 ( \times ) 12</td>
<td>26.22 / 7.3</td>
<td>148.28 / 2.6</td>
</tr>
<tr>
<td>1 ( \times ) 3 ( \times ) 25</td>
<td>25.68 / 8.3</td>
<td>145.92 / 2.8</td>
</tr>
<tr>
<td>5 ( \times ) 10 ( \times ) 100( ^a )</td>
<td>25.46 / 8.9</td>
<td>145.22 / 2.9</td>
</tr>
<tr>
<td>10 ( \times ) 10 ( \times ) 200</td>
<td>25.39 / 9.5</td>
<td>144.74 / 3.0</td>
</tr>
</tbody>
</table>

\( ^a \) Used mesh size for FEM calculations.

In addition to the stiffness, the stress in the flexure hinges is regarded to define a sufficient mesh size. The stress is not smooth if the meshing of the flexure hinges is too rough (see figure B.1). Because of the not critical stress in the flexure hinges of 10 MPa, the
evaluation criterion are the stiffnesses at the probing element and not the stresses in the flexure hinges. The material used for the flexure hinges, stainless steel 1.4310, has a critical stress of approximately 200 MPa.

Figure B.1: Determining the von Mises stress in the flexure hinges for different mesh size. 
A: Non-smooth course of the stress in the flexure hinges. 
B: Smooth course of the stress in the flexure hinges.

B.2 Influence of linear and non-linear solver in FEM

Table B.2 shows the differences of the simulated stiffness at the probing element for a linear solver and a non-linear solver.

<table>
<thead>
<tr>
<th></th>
<th>Without gravity</th>
<th>With gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$c_X^a$</td>
<td>$c_Y^a$</td>
</tr>
<tr>
<td>First prototype of probing system$^c$</td>
<td>linear</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>non-linear</td>
<td>26</td>
</tr>
<tr>
<td>Isotropic probing system$^d$</td>
<td>linear</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>non-linear</td>
<td>84</td>
</tr>
</tbody>
</table>

$a$ $c_X$, $c_Y$, $c_Z$: simulated stiffness in X, Y, and Z-direction $[\text{N/m}]$.

$b$ $d$: deflection in Z-direction $[\mu m]$.

$c$ Thickness of flexure hinges: 80 $\mu m$.

d Thickness of flexure hinges: 135 $\mu m$.

For the first prototype of the probing system the differences between the two solvers...
are negligible because the moveable plate has less weight (0.00086 kg) compared to the moveable plate of the isotropic probing system (0.01 kg). Therefore, the non-flatness of the flexure hinges, which increases the stiffness at the probing element (see figure B.8), has a lower impact.

To determine the stiffness at the probing element, an external force is applied at the probing element and its deflection in direction of the force is calculated. The external force represents the probing force and acts on the system in addition to gravity. The linear solver gives equal results for the stiffness independent from the magnitude of the external force. The non-linear solver, however, determines a non-linear stiffness, see figure B.2. The simulated deflection of the probing element in Z-direction is measured from its initial deflection, which is defined as the deflection of the probing element under the influence of gravity, but without additional external forces.

![Figure B.2: Results of simulating the stiffness in Z-direction with the non-linear solver.](image)

For the experimental determination of the stiffness in Z-direction, the probing element is deflected in steps of 20 µm and the force at the probing element is measured. For the presented measurement results, the absolute deflection of the probing element from its initial deflection is unknown. Therefore, only the relative change of the deflection of the probing element is known and the corresponding change of the probing force is measured, see figure B.3. The measured stiffness in Z-direction seems to be linear, which is indeed not the case. The less the non-flatness of the flexure hinges is, the more the measured stiffness conforms with the simulated stiffness. As it can be seen in figure B.2, the non-linearity of the stiffness in Z-direction decreases with higher external forces in Z-direction.
B.3 Comparison of different geometries of the flexure hinges with respect to stiffness

and approximates to a linear course. For the presented measurements, the flexure hinges are already flat, so the measured stiffness is in the almost linear range and reaches for the last measurement position the simulated stiffness of $81 \, \text{N/m}$.

![Graph](image)

Figure B.3: Results of measured stiffness in Z-direction.

**B.3 Comparison of different geometries of the flexure hinges with respect to stiffness**

The influence of different geometries of the flexure hinges, e.g. a radial or tangential alignment or a straight or bended shape, on the stiffness at the moveable plate is investigated in [86]. In table B.3 the results for a radial, tangential and $50^\circ$ angular alignment (see figure 2.4) are summarised. The radial alignment of the flexure hinges has the highest stiffness in X- and Y-direction.

The basic principle of the probing system is to measure the motions of the moveable plate in Z-, A- or B-direction, because this three degrees of freedom result in a deflection of the upper surface of the moveable plate in Z-direction. Therefore, a sensor is used, which measurement direction is in Z-direction of the probing system.

The stiffness around the C-direction has to be carefully regarded if a probing stylus with an horizontal extension in X- or Y-direction is used, but this is not discussed in this thesis. The stiffness in the permitted directions Z, A and B are comparable between the radial
and the tangential alignment, so due to the higher stiffness in the X- and Y-direction, the radial alignment is chosen.

Table B.3: Evaluation of different shapes of the flexure hinges.

<table>
<thead>
<tr>
<th></th>
<th>Radial alignment of flexure hinges</th>
<th>Tangential alignment of flexure hinges</th>
<th>Angular alignment (50°) of flexure hinges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness in X-direction ( \text{[N·m]} )</td>
<td>44308</td>
<td>30876</td>
<td>1719</td>
</tr>
<tr>
<td>Stiffness in Y-direction ( \text{[N·m]} )</td>
<td>44521</td>
<td>30965</td>
<td>1721</td>
</tr>
<tr>
<td>Stiffness in Z-direction ( \text{[N]} )</td>
<td>59</td>
<td>42</td>
<td>4</td>
</tr>
<tr>
<td>Stiffness around A-direction ( \text{[Nm]} )</td>
<td>(6 \cdot 10^{-5})</td>
<td>(4 \cdot 10^{-5})</td>
<td>(1 \cdot 10^{-5})</td>
</tr>
<tr>
<td>Stiffness around B-direction ( \text{[Nm]} )</td>
<td>(6 \cdot 10^{-5})</td>
<td>(4 \cdot 10^{-5})</td>
<td>(1 \cdot 10^{-5})</td>
</tr>
<tr>
<td>Stiffness around C-direction ( \text{[Nm]} )</td>
<td>0.01</td>
<td>0.4</td>
<td>0.003</td>
</tr>
</tbody>
</table>

**B.4 Correlation between geometry and stiffness of the flexure hinges**

Given the radial alignment of the flexure hinges (see section 2.2.2), the influence of the dimensions of the flexure hinges on the stiffness at the probing element are estimated by FEM simulations. The parameters of the flexure hinges to be changed are the length, the width and the thickness. To determine the influence of a single parameter on the stiffness, only this parameter is varied, which results in a corresponding stiffness. In table B.4 the
simulated stiffnesses for different configurations of the flexure hinges are summarised.

Table B.4: Derivation of the influence of the geometry of the flexure hinges on the stiffness at the probing element by FEM simulations.

<table>
<thead>
<tr>
<th>Length [mm]</th>
<th>Width [mm]</th>
<th>Thickness [µm]</th>
<th>Stiffness in X- and Y-direction [N/m]</th>
<th>Stiffness in Z-direction [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.6</td>
<td>80</td>
<td>57</td>
<td>576</td>
</tr>
<tr>
<td>11</td>
<td>0.6</td>
<td>80</td>
<td>25</td>
<td>145</td>
</tr>
<tr>
<td>18.5</td>
<td>0.6</td>
<td>80</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>Proportionality to length $l$</td>
<td>$\propto \frac{1}{l^2}$</td>
<td>$\propto \frac{1}{l^3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.3</td>
<td>80</td>
<td>13</td>
<td>75</td>
</tr>
<tr>
<td>11</td>
<td>0.6</td>
<td>80</td>
<td>25</td>
<td>145</td>
</tr>
<tr>
<td>11</td>
<td>1.2</td>
<td>80</td>
<td>49</td>
<td>284</td>
</tr>
<tr>
<td>Proportionality to width $w$</td>
<td>$\propto w$</td>
<td>$\propto w$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.6</td>
<td>60</td>
<td>11</td>
<td>61</td>
</tr>
<tr>
<td>11</td>
<td>0.6</td>
<td>80</td>
<td>25</td>
<td>145</td>
</tr>
<tr>
<td>11</td>
<td>0.6</td>
<td>120</td>
<td>82</td>
<td>485</td>
</tr>
<tr>
<td>Proportionality to thickness $t$</td>
<td>$\propto t^3$</td>
<td>$\propto t^3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B.5 Imperfect manufacturing of the flexure hinges and its consequences

The flexure hinges are the most critical component for the stiffness at the probing element. Therefore, deviations in form, position, orientation and size from the nominal geometry should be avoided during manufacturing.

Generally, the flexure hinges can be manufactured by different technologies like laser cutting, waterjet cutting or electro-discharge machining. As mentioned in section 2.3.1, the
electro-discharge machining is chosen to manufacture the flexure hinges, because therewith the best results concerning form, position, orientation and size have been realised.

B.5.1 Influence of burrs on the flexure hinges

Exemplary for laser cutting, the influence of process parameters on the cutting area is shown [83]: imperfect manufacturing, caused by not optimised process parameters such as cutting speed, focal position, pressure of process gas or laser power, have great influence on the quality of the cut and on the cutting area, see figure B.4.

![Figure B.4: Influence of manufacturing parameters for laser cutting on cutting edge of flexure hinges. A and B: Burrs and burn marks at flexure hinges. C: No burrs and burn marks at flexure hinges with optimised cutting parameters. D: Cross-section through flexure hinge with burrs at cutting area.](image)

Burrs on the flexure hinges increase the stiffness because of the raised moment of inertia. Exemplary for the stiffness in X- and Y-direction, this raising is up to a factor of 3.3 for measured burrs (see figure B.4 D) on manufactured flexure hinges as shown in figure B.5.

The influence of burrs, burn marks and non-flat flexure hinges is shown exemplary in figure B.6: depending on the deviations of the flexure hinges from the nominal geometry, the simulated and measured stiffness differ by a factor up to 100.
B.5 Imperfect manufacturing of the flexure hinges and its consequences

Figure B.5: Influence of burrs at the flexure hinges on the stiffness at the probing element in X- and Y-direction.

Figure B.6: Result of checking the stiffness in X- and Y-direction of a probing system based on flexure hinges, manufactured with not optimised process parameters (bold black lines: orientation of the flexure hinges).

B.5.2 Influence of a non-flatness of the flexure hinges under no load

The stiffness of the flexure hinges strongly depends on their flatness under no load. If the foil is not flat the stiffness in Z-direction increases rapidly, because it performs like a disc
spring. To estimate this influence, the non-flatness of the flexure hinges is modeled by a double curvature as shown in figure B.7. Depending on this non-flatness, the stiffness in Z-direction raises by a factor of 10 up to 25 for measured effective geometries compared to ideal flat hinges. For six different components of flexure hinges, the non-flatness is determined to be between 100 $\mu$m and more than 250 $\mu$m, which exceeds the measuring range of the used sensor.

![Figure B.7: Non-flatness of the flexure hinges, which results in higher stiffness compared to flat hinges.](image)

The stiffness in X- and Y-direction is not as much affected by the non-flatness of the flexure hinges, see figure B.8. A deviation from the ideal shape of the flexure hinges has an higher impact for thin foils, which can also be seen in figure B.8. The stiffness of flexure hinges with a thickness of 60 $\mu$m rises considerably more than the stiffness of flexure hinges with a thickness of 120 $\mu$m. It is mentioned that this calculations only consider a double curvature of the flexure hinges, but not other effects like inhomogeneity of the material, burrs or deviations in position or size from the nominal geometry.

### B.5.3 Repeatability of the manufacturing of the flexure hinges

Four different flexure hinges with the nominal same geometry are fabricated to evaluate the repeatability of the manufacturing. Determining the stiffness at the probing element for each probing system, the repeatability of the manufacturing is checked. In table B.5 the experimental results are summarised.
B.5 Imperfect manufacturing of the flexure hinges and its consequences

Figure B.8: Simulated influence of non-flat flexure hinges on the stiffness at the probing element (thickness of flexure hinges: 60 µm and 120 µm).
A: Change of stiffness in Z-direction compared to flat flexure hinges.
B: Change of stiffness in X- and Y-direction compared to flat flexure hinges.

Table B.5: Repeatability of the manufacturing of flexure hinges.

<table>
<thead>
<tr>
<th>Flexure hinges</th>
<th>Stiffness in X- and Y-direction [$\frac{N}{m}$]</th>
<th>Stiffness in Z-direction [$\frac{N}{m}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>117</td>
<td>157</td>
</tr>
<tr>
<td>3</td>
<td>126</td>
<td>107</td>
</tr>
<tr>
<td>4</td>
<td>131</td>
<td>111</td>
</tr>
</tbody>
</table>

*a* Higher values compared to simulated stiffness in X- and Y-direction due to setup without weight compensation.

*b* Higher values compared to simulated stiffness in Z-direction due to setup without weight compensation.
B.5.4 Influence of the clamping of the probing head

A clamping of the probing head in its fixture (see figure 2.6) has great influence on the stiffness at the probing element. As mentioned in section 2.2.1, 2.3 and appendix B.5.2, the flexure hinges have to be clamped without distorting their flatness. Therefore, they are clamped between two face-ground base plates, which are again clamped against a flat surface. The repeatability of the determined stiffness in X-direction at the probing element after reassembling the probing head lies within $9 \frac{N}{m}$ (between $62 \frac{N}{m}$ and $71 \frac{N}{m}$) at a mean stiffness of $67 \frac{N}{m}$. For a not optimised clamping, the repeatability is much larger and varies by up to 50% of the nominal stiffness at the probing element.

B.6 Estimation of the heating of the moveable plate

Measuring the deflections of the moveable plate by non-contacting sensors, energy is introduced in the moveable plate. Exemplary for a Fizeau interferometer (see appendix A), an estimation of the heating of the moveable plate is presented.

Due to the reflectivity of the target surface (here the upper surface of the moveable plate), which is typically 99% or even higher, only 1% of the laser energy is absorbed by the moveable plate. The output power of Fizeau interferometers is typically smaller than 5 mW, which results in 0.05 mW absorbed by the moveable plate. The convective heat transfer coefficient is estimated to be $3 \frac{W}{m^2\cdot K}$ [99]. A schematic diagram of the constraints for the thermal FEM simulation is shown in figure B.9.

Using FEM simulations, the heating of the moveable plate, the probing stylus and the flexure hinges is determined. Therefore, the upper and lower base plate are set to a constant temperature of 20°C, which is also the environmental temperature. The thermal steady-
B.6 Estimation of the heating of the moveable plate

state simulation of the heating of the components, caused by the laser interferometer, results in a maximum heating of $0.014^\circ C$. This heating results in an expansion $\Delta L$ in Z-direction of the moveable plate and is estimated according to

$$\Delta L = \alpha \, L_0 \, \Delta T \quad \text{(B.1)}$$

$$= 12 \cdot 10^{-6} \cdot \frac{1}{K} \cdot 3.75 \, mm \cdot 0.014 \, K = 0.6 \, nm$$

with:

- $L_0$: Nominal thickness of the moveable plate ($L_0 = 3.75 \, mm$);
- $\Delta L$: Change of the thickness of the moveable plate;
- $\Delta T$: Change of the temperature ($\Delta T = 0.014 \, K$);
- $\alpha$: Coefficient of thermal expansion ($\alpha = 12 \cdot 10^{-6} \cdot \frac{1}{K}$).

Therefore, the expansion in Z-direction of the moveable plate due to thermal influences of the optical sensors is negligible.

The radial expansion of the moveable plate results, due to the assumption that the base plates which fix the flexure hinges have a constant temperature, in non-flat flexure hinges. Using FEM calculations, this non-flatness is determined to be $2 \, nm$ at an output power of the optical sensors of $5 \, mW$, which has negligible influence on the stiffness at the probing element.
Appendix C

Aspects on Measurements

C.1 Aspects on force measurements

The force measurements carried out in this thesis are done by using a piezo-electric force sensor (Kistler, Type 9203) and a charge amplifier (Kistler, Type 5011 B) from Kistler Instruments. The measured signals are affected by two main effects: The drain of electric charge in sensor, cable and charge amplifier (totaly 0.01 $\text{pC s}^{-1}$ up to 0.04 $\text{pC s}^{-1}$) and the reset / operate step ($\pm 0.01 \text{ pC s}^{-1}$). By using piezo-electric measuring equipment in small signal ranges, mainly the drift and in second order the reset / operate step have to be taken into account for determining the measurement uncertainty. This drift can be numerically compensated, if the force sensor is applied to the same force at the beginning of the measurement and at the end of the measurement. In figure C.1 the original force signal as well as the drift compensated signal are shown.

The drift compensation is done by fitting a straight line through the well-known period of load at the beginning and at the end of the measurement. The other measuring points are corrected by the values of the fitted straight line.

A capacitive force sensor (see figure C.2) used in this thesis is from Femtotoools, Type FT-S160. Its advantages compared to piezo-electric force sensors are the high resolution of 2 $\mu\text{N}$ and the high sensitivity of $5 \frac{m\text{N}}{V}$ [100]. Therewith, the probing force is measured with less uncertainties. But to use this capability, the positioning accuracy of the CMM has to be improved, because otherwise the uncertainty of the determined stiffness is dominated by the uncertainty contribution of the CMM according to (2.4) on page 42. Disadvantages of the capacitive force sensor are its very sensitive probe tip (cross-section of 50 $\mu\text{m} \times 50 \mu\text{m}$) as well as its small measurement range of 10 $m\text{N}$: because of the capacitive measurement principle, an internal structure is moved relatively to each other as soon as an external
force is applied at the probe tip. This motion is limited to 10 \( \mu m \), which handicaps finding the contact between probe tip of the force sensor and probing element of the 3D-probing system.

Figure C.2: A high-sensitive capacitive force sensor with measurement range of up to 10 mN.
Appendix D

Evaluation of Measurement Principles

Different measurement principles to determine the position and orientation of the moveable plate are evaluated based on the state of the art of commercially available systems. The detailed results of this evaluation are summarised in table D.1. Due to their measurement principle, resistive strain gauges have to be placed on the flexure hinges. Thereby, the simulated stiffnesses of the flexure hinges are clearly influenced, in contrast to the other measurement principles. Additionally, the assembly of the strain gauges may damage the flexure hinges and makes a replacement of the flexure hinges, e.g. after a collision of the probing element with the workpiece to be checked, difficult. Therefore, strain gauges are not used for the presented 3D-probing system.

If a measurement principle fulfils the demands as listed in table D.1, the technology may be used for the 3D-probing system, which is shown by a ”+” in table 2.8 on page 52. If the measurement principle is at the border line of fulfilling the demand, the symbol ”o” is used in table 2.8. Otherwise, by non-fulfilling the demand, a ”−” is used.
Table D.1: Evaluation of measurement principles for potential use in the 3D-probing system based on the state of the art of commercially available measurement equipment.

<table>
<thead>
<tr>
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<th>Measurement principle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>capacitive</td>
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<tr>
<td>Measurement range [mm]:</td>
<td>±0.1</td>
</tr>
<tr>
<td>Resolution [nm]:</td>
<td>10&gt;</td>
</tr>
<tr>
<td>Measuring rate [kHz]:</td>
<td>&lt;15</td>
</tr>
<tr>
<td>Measurement force [mN]:</td>
<td>n.a.(^b)</td>
</tr>
<tr>
<td>Size of sensor [mm]:</td>
<td>&gt;2(^c)</td>
</tr>
<tr>
<td>Dissipation of energy [mW]:</td>
<td>≈0(^e)</td>
</tr>
<tr>
<td>Market price [CHF]:</td>
<td>15'000</td>
</tr>
</tbody>
</table>

\(^a\) For standard optics and standard evaluation.
\(^b\) Not applicable.
\(^c\) Diameter of one sensor for clamping it in fixture, see figure 2.13 on page 53.
\(^d\) Size of sensor housing: 140 mm × 180 mm.
\(^e\) Negligible.
List of Publications


Bibliography


