D4.2 Robot positional accuracy and improvement strategy

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Samenvatting

Dit rapport markeert de voltooiing van Deliverable 4.2 ‘Positioneer systeem, nauwkeurigheid en verbeter strategieën’ dat deel uitmaakt van het project ‘NXT-GEN High Tech Composiet 03: Efficient & Proven Zero Defect Robotic Manufacturing "ZERO-D"’, werkpakket 4 ‘Inspectierobots’. TNO ontwikkelt een nieuwe niet-destructieve inspectietechniek gebaseerd op het detecteren van afstralend ultrageluid dat over het oppervlak van het te inspecteren object gaat met behulp van een Micro-Electrical Mechanical System (MEMS) array. Het specifieke type ultrageluid wordt Lamb-golven genoemd en wordt met behulp van een actuator in het plaatmateriaal gebracht. Deze techniek wordt Direct Velocity Mapping (DVM) genoemd en heeft specifieke voordelen ten opzichte van bestaande technieken, met name:

- relatief snel en schaalbaar;
- contactloos en schoon;
- benodigd slechts enkelzijdige toegang;
- schadedetectie kwaliteit vergelijkbaar met benchmarktechnieken;
- geschikt voor automatisering, waardoor de druk op schaars personeel afneemt;
- Een reductie in de directe kosten, wat concurrerende inspectie en productie mogelijk maakt.

DVM kan de dikte van relatief dunne structuren meten en de aanwezigheid van defecten snel en vroegtijdig detecteren. Wanneer er ondersteuningsstructuren achter de plaat aanwezig zijn, kan met DVM de mechanische verbinding tussen de componenten worden vastgesteld. Ondersteuningsstructuren hebben verder geen wezenlijke invloed op de kwaliteit van een DVM-meting.

Deze applicaties en voordelen maken de DVM technologie potentieel aantrekkelijk voor de volgende project use-cases, ontwikkeld in werkpakket 6 ‘Integrale inspectie systemen’:

- KLM: In-service inspecties van composiet vliegtuigen;
- Suzlon: In-line inspecties van windturbine liggers;
- GTM: In-line inspecties van composiet zonnepanelen voor ruimtevaarttoepassingen.

Een succesvolle introductie van een geautomatiseerd inspectiesysteem stelt deze industriële partners in staat om automatisch complexe structuren te inspecteren en de inspectietijd te verkorten, wat resulteert in een lagere belasting op het schaarse personeel en lagere kosten voor de kwaliteitsborging van hun producten.

Onderdeel van de DVM-setup is een positioneer systeem dat de sensorkop over het te inspecteren object verplaatst tijdens het scannen. Dit document beschrijft de gewenste nauwkeurigheid en oplossingsrichtingen om deze strenge positioneer eisen te verlichten dan wel te halen in de industriële omgeving van de 3 use-cases waarbinnen het DVM systeem moet opereren.

Summary

This report marks the completion of Deliverable 4.2 'Robot positional accuracy and improvement strategy' which is part of the project 'NXT-GEN High Tech Composiet 03: Efficient & Proven Zero Defect Robotic Manufacturing "ZERO-D"', work package 4 'Inspection robots'. TNO is developing a novel non-destructive inspection technique based on detecting dissipating ultrasound traveling over the surface of a structure under inspection using a Micro-Electrical Mechanical System (MEMS) array. The specific ultrasound type is called Lamb waves, which are introduced to the plate material using an actuator. This technique is called Direct Velocity Mapping (DVM) and has specific advantages over existing techniques in that it offers to be:

- a relatively fast and scalable inspection technique compared to existing techniques;
- a non-contact and clean inspection technique;
- a single sided access technique;
- a technique with comparable damage detection quality as benchmark techniques;
- a technique suitable for automation and thereby reducing the load on scarce personnel;
- a reduction in direct cost, resulting in a competitive inspection and production.

DVM can measure the thickness of plates and detect defects in plates. In the presence of support structures behind the plate, DVM can inspect the mechanical connection between the two components. The DVM measurement is not significantly hindered by support structures.

These characteristics make the DVM technology potentially attractive for the following project use cases developed in work package 6 'Integral inspection systems':

- KLM: In-service inspections of composite aircraft;
- Suzlon: In-line inspections of wind turbine girders;
- GTM: In-line inspections of composite solar panels for space applications.

A successful introduction of an automated inspection system will allow these industry partners to reduce the takt time of the inspection of complex structures with a lower load on scarse personnel, resulting in reduced cost for quality assurance of their products.

This report focusses on the concepts for these automated inspection systems.

Part of the DVM setup is a positioning system that moves the DVM sensorhead over the object under inspection during scanning. This document describes the desired accuracy and solution directions to reach these strict positioning requirements or alternative solutions with less tight requirements in the industrial environment of the 3 use cases within which the DVM system must operate.

Contents

Abbreviations

Abbreviation	Meaning
DVM	Direct Velocity Mapping
MEMS	Micro-Electrical Mechanical System
NDI	Non-Destructive Inspection
NDT	Non-Destructive Testing
TTL	Transistor-Transistor-Logic, well-defined voltage levels for representing binary values (0-5V)
ADC	Analogue to Digital Converter
US	Ultra Sound
MRO	Maintenance, Repair and Overhaul
ROI	Region of Interest

1 Introduction

1.1 NDT using MEMS array introduction

There are several different Non-Destructive Inspection (NDI) techniques available to determine if there are any defects in a structural element with each having its advantages and disadvantages. Some of the disadvantages are that some systems require contact with water (C-Scan) or the operating speed may be relatively low. Non-Destructive Technology (NDT) using a Micro-Electrical Mechanical System (MEMS) array to detect Lamb waves aims to overcome these disadvantages by offering a relatively fast and dry inspection method [1].

Lamb waves in plates were first described by Horace Lamb [4] and are elastic waves that are guided by the boundaries of the solid material in which they propagate. The specific velocity of a wave is dependent on the plate thickness, local density, and directional stiffness [2]-[5]. The latter is typical for anisotropic composite plates. Detecting irregularities in Lamb wave velocity and/or amplitude as a result of damage is the principle mechanism to detect damage. One characteristic of Lamb waves is a strong normal displacement of the antimetrical mode resulting in dissipating acoustic energy outside of the solid plate.

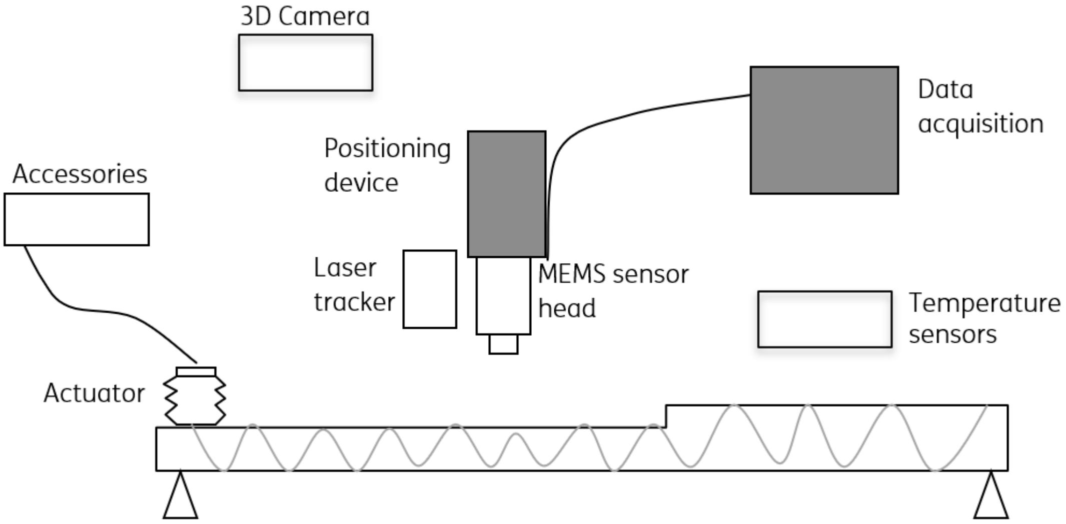


Figure 1.1: Schematic overview of the Direct Velocity Mapping NDT system.

Figure 1.1 depicts a schematic overview of the DVM system. An actuator with a piezo-electric element, introduces the Lamb waves into the plate and it is attached to the plate using a vacuum suction cup adaptor. The dissipating acoustic energy can be detected by the TNO developed MEMS sensor array system which is located at a distance of about 10cm above the plate. The MEMS sensor array can be positioned on an end-effector of a robot or it can be attached to a dedicated support frame. The position of the sensor is measured using a laser tracking system.

The DVM NDI technology offers the following advantages over existing technologies:

- A relatively fast inspection technique compared to existing techniques;
- A non-contact and clean inspection technique;
- A single sided access technique;
- Similar damage detection quality as benchmark techniques;
- Suitable for automation and thereby reducing direct cost and reduced the need for highly qualified personnel;
- Scalable solution as the sensor array can be extended.

1.2 Scan strategies

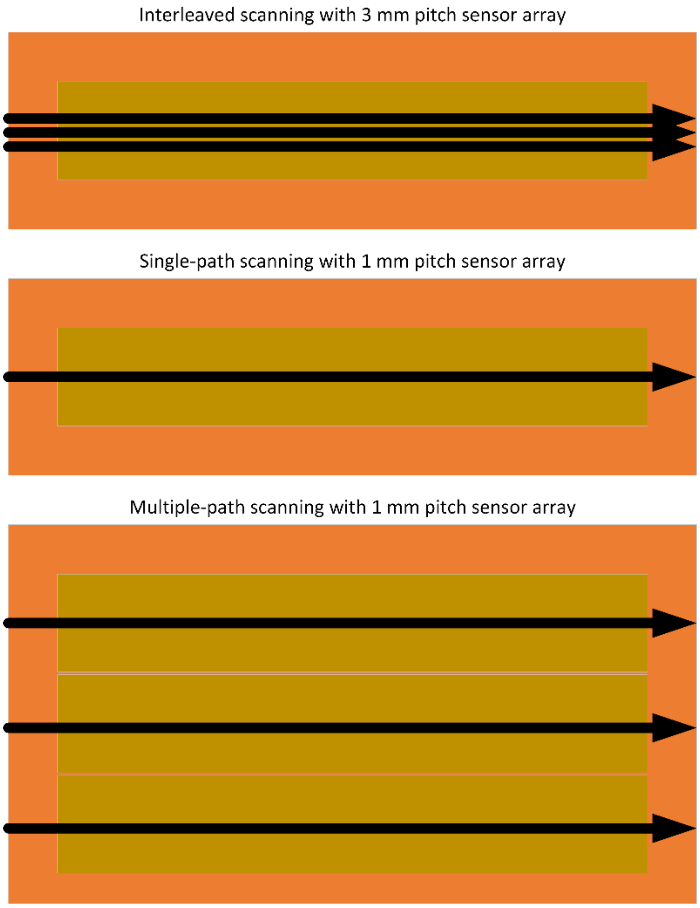
The latest sensor head developed by TNO, contains an array of 128 MEMS with a pitch of 3 mm due to the size of the microphones. As per D4.1 requirement S.07 [6] the required acoustical sampling pitch is 1 mm, the same area needs to be scanned three times where the array is shifted by 1 mm in the array direction for each scan. This scanning strategy is called interleaved scanning. The stringent positional requirements put restrictions on the operational design domain of this sensor head configuration. For the use cases in the NXT GEN High Tech Zero Defects project, a redesign of the sensor head is initiated.

To avoid interleaved scanning, a new sensor head with a MEMS pitch of 1 mm is developed. This sensor can be used in two ways. Either, the data from each scan lane is processed individually, or the acoustical data on a larger area consisting of multiple lanes is first collected and then processed in its entirety. The latter (called ‘multi-lane scanning’) has the advantage of an increased scan speed, whereas the former (called ‘consecutive single-lane scanning’) has reduced requirements on the positional accuracy of the positioning system. These stringent positioning accuracies are especially tight in industrial environments, as envisioned in the three uses-cases in the NXT GEN High Tech Zero Defects project.
When the lanes are processed individually, the samples across the lane-boundaries do not need to fulfil the acoustical sampling requirements derived in Section 2.2.

This leads to the three different scanning paths depicted in Figure 1.2:

- interleaved scanning (with a 3mm pitch sensor array);
- (consecutive) single lane scanning with a 1 mm pitch array;
- Multi-lane scanning with a 1 mm pitch array.

Interleaved scanning allows the use of a 3mm pitch sensor array, but has high positional requirements and the slowest acquisition rate. This is an interesting solution at low TRL levels to demonstrate the DVM concept. The main advantage of single lane scanning are its less stringent positional requirements. Multi-lane scanning with a 1 mm pitch array allows for the fastest acquisition rate and has intermediate positional requirements. These positional requirements will be discussed in detail in Section 2.4.


Interleaved scanning with 3 mm pitch sensor array

Single-path scanning with 1 mm pitch sensor array

Multiple-path scanning with 1 mm pitch sensor array

Figure 1.2: Three scanning strategies. The path of the sensor head is indicated by the arrows. Acoustical data is collected in the orange plane (span by the sensor head). The are of the sample where the thickness can be retrieved is indicated in brown.

1.3 Positioning system as a sub-system of the DVM system

The positioning system is one of the sub-systems of the DVM system (see Figure 1.3). Its purpose is to move the sensor head through a planar surface to enable scanning. During such a scan, at the passing of every sample point (roughly 1 mm apart), the acoustical source emits a signal, the sensor head picks up an acoustical signal using its many microphones, and the data acquisition system records this signal obtained at the planar scanning surface (Figure 1.1). A comprehensive description of the DVM technology is given in [1]. Since the acoustical signal is very short, this can happen at a relatively high speed of 20-100 mm/s, allowing scanning of 1-2 m^2 per minute. A flow chart of a measurement, Figure 1.4, shows the tasks of the positioning system, the user, the orchestrator and user interface software, and the data acquisition system and acoustical source. The high level architecture and the corresponding interfaces between these systems are defined in Chapter 4.

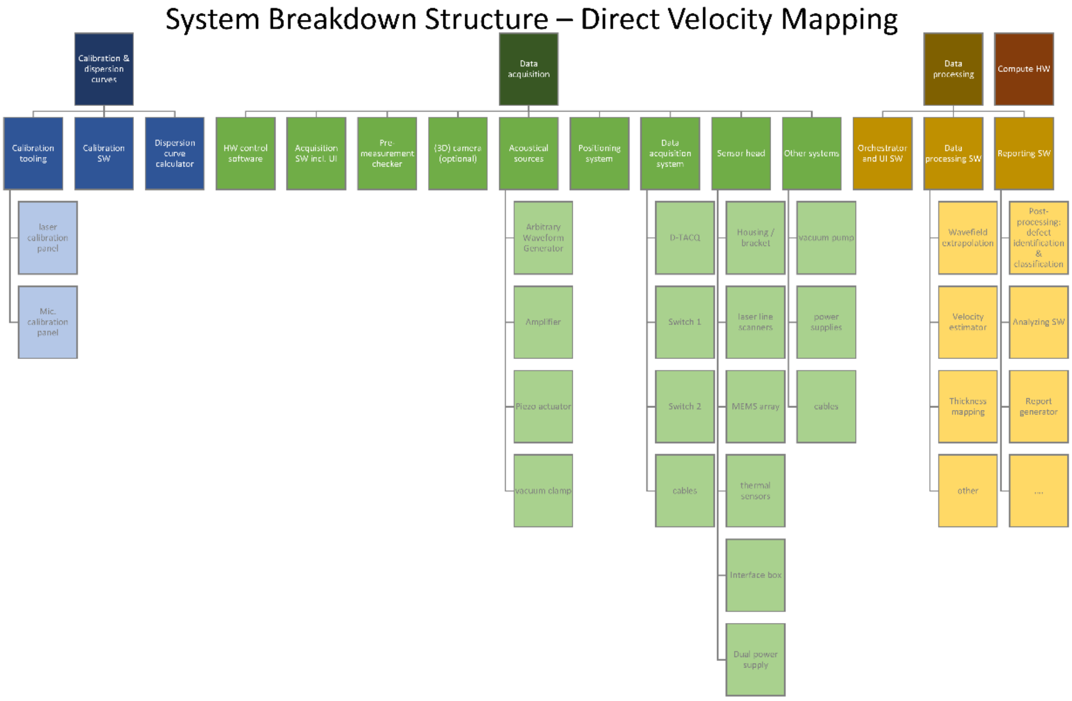


Figure 1.3: System breakdown structure of a direct velocity mapping system.

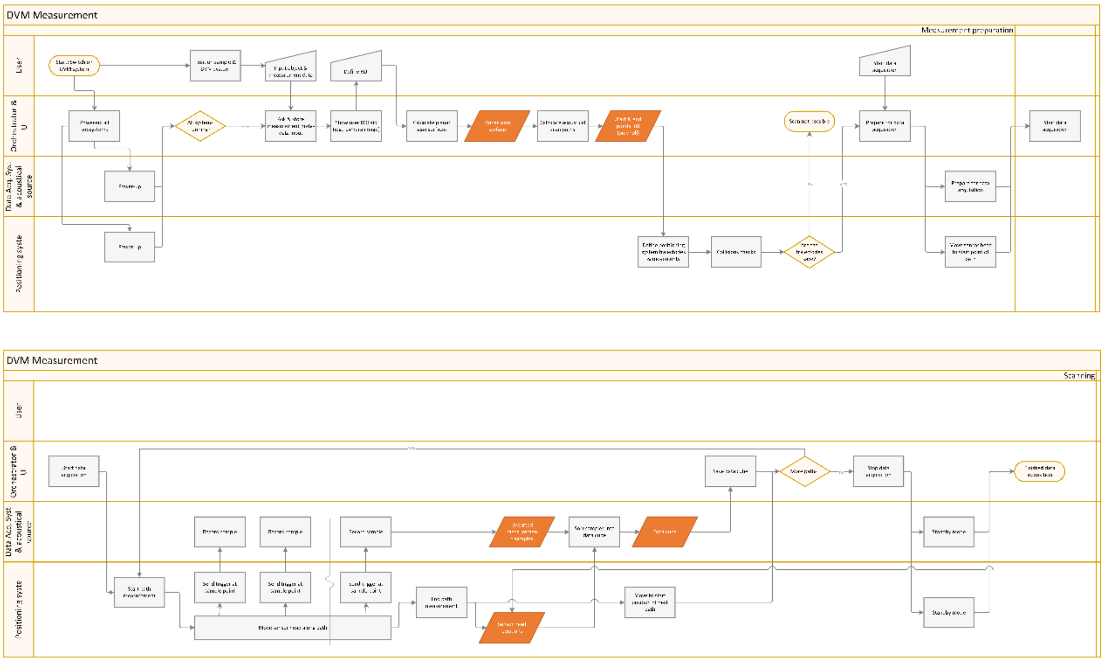


Figure 1.4: Flow chart of a DVM measurement, showing the roles of the user, the orchestrator & user interface software, the data acquisition system and acoustical source, and the positioning system.

2 Requirements on the positioning system

In this chapter the requirements on the positioning system are presented. Some of the most important requirements, are on the positional accuracy of the positioning system. These will be derived in Section 2.2.

2.1 Purpose of the positioning system

The purpose of the positioning system is to scan a surface above the sample with the sensor head in order to get a dense grid of measurement samples.
The positioning system interacts with the DVM system and will scan specific lanes (straight paths). The positioning system will initially perform a path planning and check if the movements are possible and safe to perform. If so, the positioning system will move the sensor head through this scan lane whilst it sends triggers to the acquisition system at the specified sampling positions (roughly every millimeter).
The positioning system is responsible for all steps in between the request and the actual movement. This explicitly includes the path planning and collision avoidance with the sample, other objects, or persons. The positioning system must plan and perform a safe and accurate scan.

2.2 Positional accuracy between samples

The requirements on the positional accuracy of the positioning system, are derived from the sampling requirements of the acoustical field.
DVM relies on measuring the acoustic waves radiated from a sample in a planar surface above the sample. The radiated sound originates from a propagating Lamb wave, the radiated wave propagates under an angle. Since the direction of this propagating Lamb wave is arbitrary, the measurement surface area has to be larger than the surface under inspection. The size of the measurement surface is chosen, such that the all the acoustic waves emitted in ±45° degrees from the area of interest will be measured properly (see Figure 2.1).

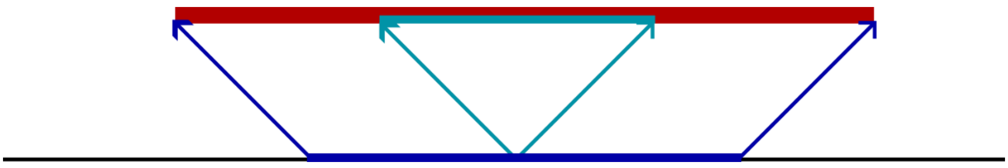


Figure 2.1: Sound waves emitted by a point (turquoise). The red sampling area captures all waves emited in +- 45 degrees from the blue area on the sample.

The spatial sampling rate in the measurement surface determines the smallest wavelength in air one can measure, which is related to the minimum defect size in the object under inspection. The minimal wavelength in air that can be sampled, is given by:

Eq. 2.2.1 $\lambda_{min} = 2\,p\sin(\theta),$

Where p is the pitch between samples and θ the angle between the propagation direction of the wave and the surface normal of the sampling surface (see Figure 2.2).

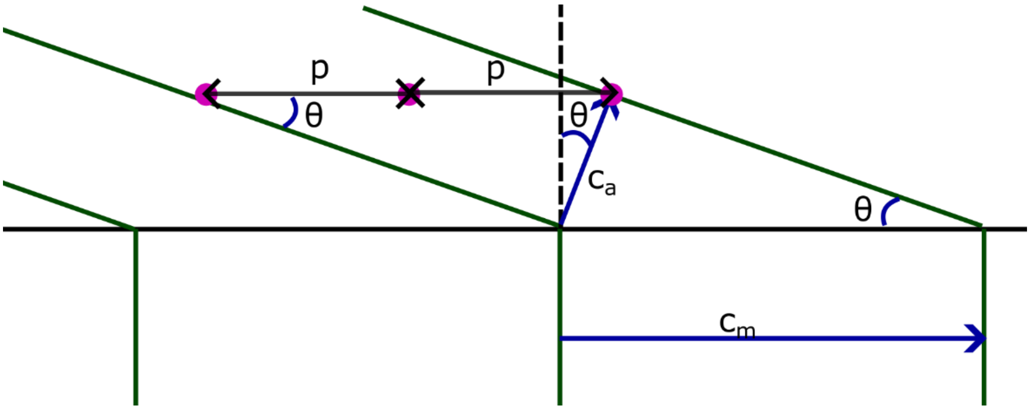


Figure 2.2: Acoustical wavefronts (green) are sampled by sample points (pink).

The current setup has a pitch of 1mm and an intended maximum angle of 45 degrees. As a result, the minimal wavelength that can be sampled is 1.4 mm, which corresponds to a frequency of about 240 kHz.

Due to positioning errors, the true positions of the sample points will deviate from the desired equally spaced grid in a flat surface. These positional errors, will cause phase errors in the measurement. Experience shows, that random phase errors smaller than $0.1\,\pi$ do not lead to significant issues. The in-plane positional error will be referred to as e_x and the out-of-plane positional error as e_z (see Figure 2.3).

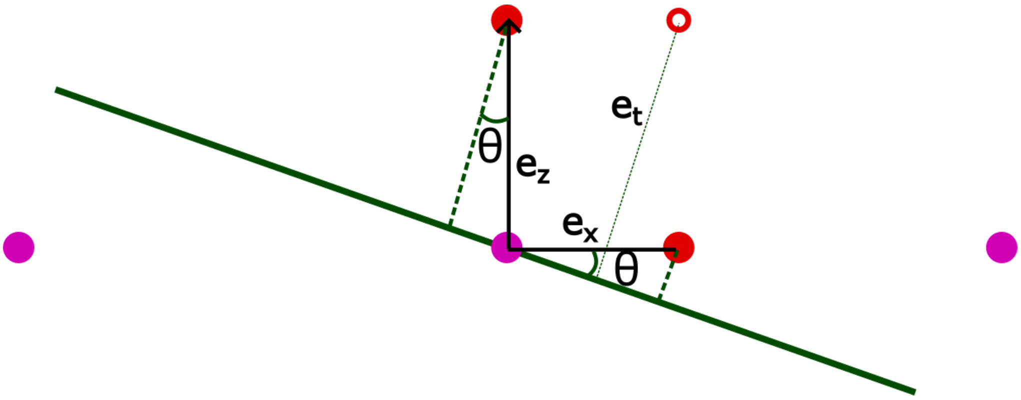


Figure 2.3: Phase errors due to positional errors in x and z.

These positional errors will cause a phase error of

Eq. 2.2.2 $\phi_e = \frac{2\pi}{\lambda}(e_x \cdot \sin(\theta) + e_z \cdot \cos(\theta))$

This function has extrema for the angles θ=0°, θ=45°, θ=90° or the maximum angle. Distributing the error equally over x and z, gives the following error budget:

Eq. 2.2.3 $\phi_e = \frac{2\pi}{\lambda}(e_x \cdot \sin(45) + e_z \cdot \cos(45)) \leq 0.05 \cdot 2\,\pi$

Eq. 2.2.4 $\frac{1}{\lambda\sqrt{2}}(e_x + e_z) \leq 0.05$

Eq. 2.2.5 $e_x \leq \frac{0.05\lambda}{\sqrt{2}}$ and $e_x \leq \frac{0.05\lambda}{\sqrt{2}}s$

Using the minimal wavelength derived above, the positional errors in x and z should both be smaller than 0.05 mm:

Eq. 2.2.6 $e_x \leq 0.05\,mm$ and $e_z \leq 0.05\,mm$

This requirement of 50 µm positional accuracy is derived for the most challenging combination of frequencies and wave directions. Fortunately, in practice ihe sensitivity to positional inaccuracies is lower, because most waves travel almost parallel to the z-axis, most waves have significantly lower frequencies than assumed above, and most positional errors occur randomly and not systematic.

Simulations were performed to further investigate the sensitivity of DVM on positional sampling errors. An ideal data set was created and then disturbed by adding a random Gaussian distributed time-delay to each sample point. This time-delay approximates a positional error of the sampling point. Several simulations and reconstructions where run with different noise levels. From the resulting DVM maps, it was visually determined that random noise with standard deviations beyond 0.25 µs resulted in significant artefacts in the DVM maps. For systematic noise (i.e. each row of samples has the same time-delay) this level was 0.125 µs. This corresponds to propagation distances of about 90 µm and 40 µm respectively.

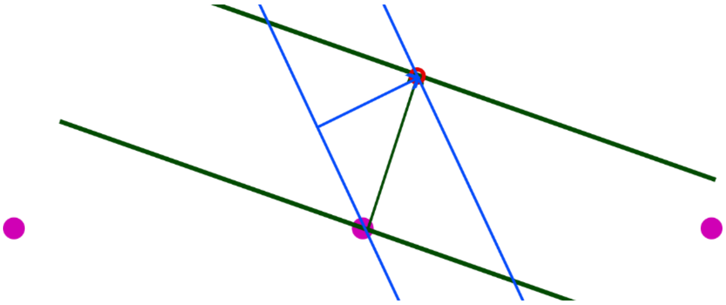


Figure 2.4: The phase delay depends on the positional error of the sample point and the frequency and direction of the sampled wave.

For the theoretical derivation of the sampling tolerances, an allowable phase error of $0.05 \cdot 2\,\pi$ was assumed. This is very close to the phase error due to a time-delay of 0.125 µs at the maximum frequency of 240 kHz. The two methods thus both provide an allowable tolerance on the positional accuracy of about 50 µm (1 sigma level) in-plane and out-off plane for systematic errors. For random errors, the budget is about double this error.

The above described requirements are on the positional accuracies of sample points. The manufacturing tolerances of the sensor head, the connection between the sensor head and the positioning system, and the positioning errors of the positioning system contribute to this positional in-accuracy (see Figure 2.5). A calibration procedure (see Section 2.3) compensates for these manufacturing errors.

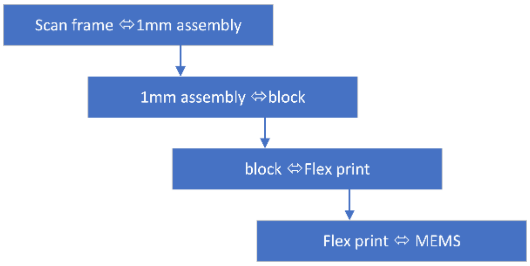


Figure 2.5: Error tree for positional errors.

2.3 Compensation by jitter correction

Jitter refers to the error due to different time delays between samples. The positional errors described in Section 2.2 cause time delays. Jitter correction is the method of adding additional time delays that (partially) compensate for the jitter.
In order to do this, the sampling error must be known. Jitter correction is for instance used to partially compensate for manufacturing tolerances of the MEMS array, which are determined using a calibration measurement.

The true sampling positions are usually unknown and can therefore not be corrected using jitter correction. In some cases, the positional errors can be approximated from the measurement data, e.g. when sampling the same position twice, and jitter correction can be applied.

It is important to note that jitter correction can only partially reduce the effect of positional errors because the amount of jitter (time-delay) due to a positional error depends on the propagation direction of the acoustic wave, which is unknown.

2.4 Positional requirements for different scan strategies

The positional error of a MEMS sensor can be caused by either a translation error or a rotation of the sensor head. The translation errors relate directly to the in-plane and out-off plane positional errors. They are discussed in Section 2.4.1. The effects of rotations around the x-, y- and z-axis are derived in Section 2.4.2, 2.4.3, and 2.4.4. respectively.
A 3D schematic depiction of the sensor head that defines the local coordinate system is shown in Figure 2.6. x- and y-axis are parallel to the planar surface with the MEMS sensors (in-plane), where the MEMS The sensors are distributed along the y-axis and the x-axis should align with the scanning direction.

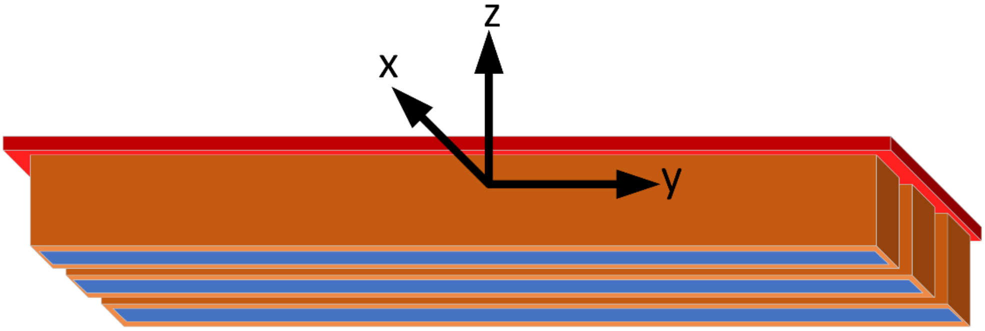


Figure 2.6: Schematic depiction of the sensor head and the local coordinate system. The strips of MEMS sensors are depicted in blue.

2.4.1 Positional requirements in x,y and z

The scanning strategies discussed in Section 1.2 each have different positional requirements. For the discussion below, the positional errors will be assumed to be normally distributed. For interleaved scanning, the samples between two neighboring lanes, need to be positioned with the tolerances described in Section 2.2. The positioning system will first scan one full path (of multiple decimeters), then return to its starting position and shift one millimeter laterally. As such, this requirement amounts to a repositioning error of less than 100 µm (1σ) in-plane and out-off-plane.
When performing a single-lane scan with the 1 mm pitch array, only neighboring scan positions need to fulfill the strictest tolerances described in Section 2.2. Scan positions that are a few millimeters apart, have much more relaxed tolerances. This implies that high frequency positioning errors are dominant compared to low frequency positioning errors. Crucially, this means that there are no significant requirements on the repositioning error of the positioning system.
This advantage disappears when performing multi-lane scanning with the 1mm pitch array. The samples in neighboring lanes will again have to meet the positional tolerances described in Section 2.2. This requirement can be relaxed by having neighboring lanes overlap by a few samples, estimate the relative positioning error, and using a jitter correction. Compared to interleaved scanning, the lateral shift is much larger (the width of a sensor head instead of 1 mm). From this perspective, single lane scanning is preferable.

The allowable tolerances on positional accuracy are summarized in Table 2.1.

Table 2.1: The required 1-sigma positional accuracy (in-plane | out-off plane).

Scan strategy	High-frequency (f> $\frac{1}{5\mathrm{mm}}$)	Low-frequency (f < $\frac{1}{5\mathrm{mm}}$	Repositioning tolerance
interleaved	100 µm | 100 µm	100 µm | 100 µm	100 µm | 100 µm
(consecutive) single-lane	100 µm | 100 µm	200 µm | 200 µm	1 mm | 1 mm
Multi-lane	100 µm | 100 µm	100* µm | 100* µm	100* µm | 100* µm

*) Jitter correction can significantly reduce the requirements.

2.4.2 Rotation around the x-axis

A rotation around the x-axis causes a tilt of the MEMS array. Single lane scanning is not sensitive to this rotation as long as it stays within a few degrees. Contrarily, multi-lane scanning is very sensitive to this rotational error (Figure 2.7).

Figure 2.7: Effect of misalignment due to a rotation in Rx.

For a sensor head of width w, a rotation in Rx of α degrees will lead to a shift of

$$dz = \mathrm{w} \cdot \sin(\alpha)$$

For a sensor head with a width of 400 mm, the requirement of a maximum z-shift of 100 µm, results in a maximum allowable tilt change of 0.014 degrees between neighboring lanes for multi-lane scanning.
At interleaved scanning, the sensor head only shifts by 1 mm instead of 400 mm between scans. Even at an angle of $\alpha = 5\,°$, two neighboring samples will be less than 100 µm apart in the z-direction.
Single-lane scanning has even more relaxed requirements on the angle α. In principle very large angles are possible, but it does reduce the size of the area that is scanned. Since the sound wave up to an angle of 45 degrees (with respect to the sample surface normal) need to be captured, an array at an 45 degree angle would have an acoustical scan width of zero. At 10 degrees, the scan width is reduced by about 12%, at 20 degrees by 25%. Based on this, a maximum angle of 10 degrees is required.
For all scanning strategies, the rotation around the x-axis must vary by less than 0.03 degrees over a scanning distance between 1 and 5 mm. Higher variations will lead to a variation in z-position of nearby samples by more than 100 µm.

2.4.3 Rotation around y-axis

Rotating the sensor head around the y-axis (angle β) is only an issue if there is an offset between the MEMS sensors and the y-axis. This is the case for the 1mm sensor array, which consists of three arrays of MEMS sensors (see Figure 2.8).

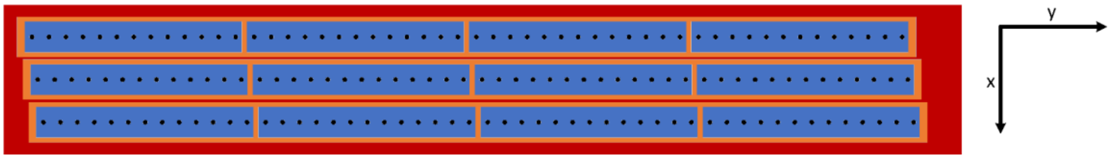


Figure 2.8: The 1mm sensor array depicted from below. The black dots indicate MEMS sensors. The 1mm sensor head consists of three MEMS arrays.

The distance between these arrays will be around 1 cm. Requiring the maximum z-shift to be below 100 µm results in a maximum angle of $\beta \leq 0.57\,°$.
The 3mm pitch sensor array, is insensitive to rotations around the y-axis.

2.4.4 Rotation around z-axis

Rotating the sensor head along the z-axis will cause a misalignment between the scanning axis and the x-axis of the sensor head. This has several effects.
Primarily, for both the 1mm and the 3mm pitch array, the sampling grid will be warped. Since the 1 mm pitch array is currently under development, it is unclear what the effect of this is on the quality of the DVM result. It is expected that rotations up to a few degrees are acceptable.

Secondary, for the 1 mm array, neighboring sampling points along the y-direction will have positional deviations in x and y. This is apparent from the concept behind the 1 mm sampling array, depicted in Figure 2.9. A 1 mm array, consists of three MEMS arrays which are shifted by 1 mm in the y-direction. Since the MEMS in each array are 3 mm apart, a scan in x will lead to sample points that are 1 mm apart.

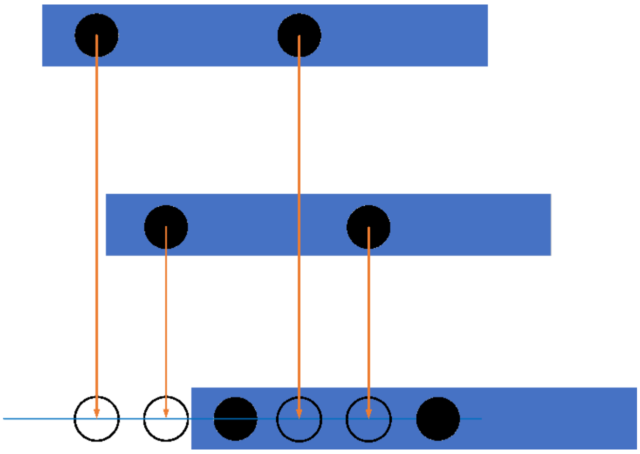


Figure 2.9: A small section of the 1mm sensor array seen from below. The three MEMS arrays are depicted in blue, with the individual MEMS shown as black dots. The orange arrows show the scan direction.

The effect of a rotation around the z-axis is shown in the figure below. The actual sampling positions (red) are shifted with respect to the desired sampling points.

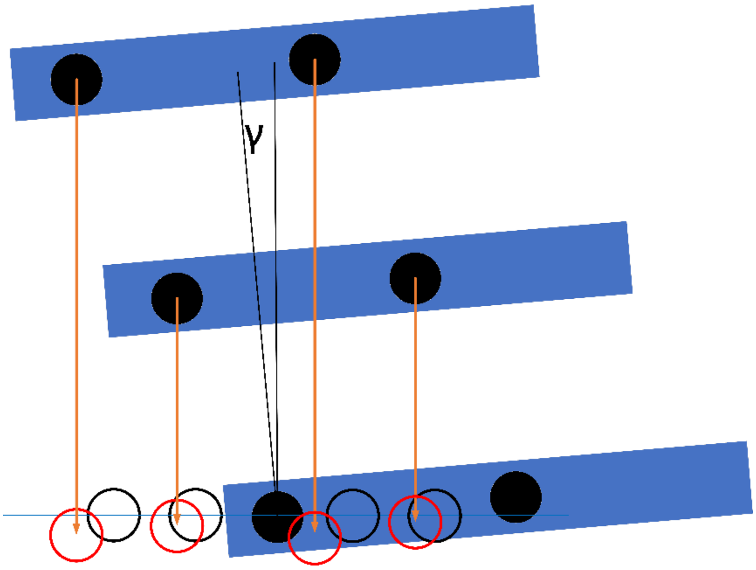


Figure 2.10: A rotation around the z-axis causes a misalignment of samples in a 1mm array.

To reduce this sampling error to less than 100 µm in array where the MEMS strips are 1 cm apart, the rotation around the z-axis should be less than 0.29 degrees.
For all scanning strategies and sensor heads, the rotation around the z-axis must vary by less than 0.03 degrees over a scanning distance between 1 and 5 mm. Higher variations will lead to a variation in x-position of nearby samples by more than 100 µm.

2.4.5 Summary of positional requirements

The accuracy of a sample position depends on the manufacturing tolerances of the sensor head, the accuracy with which the sensor head can be mounted on the positioning system, the positional accuracy of the sensor system, and the rotational accuracy of the positioning system.
It is assumed, that manufacturing tolerances of the sensor head can be fully compensated by a calibration procedure (using jitter correction). Inaccuracies in the mounting of the sensor head on the positioning system in the order of several millimeters are irrelevant since they only cause an overall shift of all samples. The positional accuracy of the positioning system does directly impact the sampling accuracy. The allowable tolerances are summarized in Table 2.1. They lead to the requirements listed in Table 2.2. This table also lists the requirements on the rotational accuracy of the positioning system. It is important to note, that this rotational requirement can be caused both by the rotational errors of the positioning system and the mounting of the sensor head on the positioning system.
Strictly speaking, multiple positional and rotational errors accumulate to the total positional error of a sample. It was decided to neglect this for now and base the requirement on each positional and rotational error on the maximum allowable sampling error.

Table 2.2: Positional requirements on the positioning system.

ID	Name/Summary	Requirement
	Interleaved – high-frequency positioning	For interleaved scanning, the 1σ positional errors of the positioning system must be below 100 μm in the scanning surface and below 100 μm in the direction perpendicular to the scan, at frequencies between 1/1mm and 1/L (where L is the length of a scan path).
	Interleaved – repositioning	For interleaved scanning, the repositioning error of the positioning system must be below 100 μm in the scanning surface and below 100 μm in the direction perpendicular to the scan.
	Single lane – high-frequency positioning	For single-lane scanning, the 1σ positional errors of the positioning system must be below 100 μm in the scanning surface and below 100 μm in the direction perpendicular to the scan, at frequencies between 1/1mm and 1/5mm.
	Single lane – low-frequency positioning	For single-lane scanning, the 1σ positional errors of the positioning system must be below 200 μm in the scanning surface and below 200 μm in the direction perpendicular to the scan, at frequencies between 1/5mm and 1/L (where L is the length of a scan path).
	Single lane – repositioning	For single-lane scanning, the repositioning error of the positioning system must be below 1mm in the scanning surface and below 1mm in the direction perpendicular to the scan.
	Multi-lane – positioning	For multi-lane scanning, the 1σ positional errors of the positioning system must be below 100 μm in the scanning surface and below 100 μm in the direction perpendicular to the scan, at frequencies between 1/1mm and 1/L (where L is the length of a scan path).
	Multi-lane repositioning	For multi-lane scanning, the repositioning error of the positioning system must be below 100 μm in the scanning surface and below 100 μm in the direction perpendicular to the scan.
	Interleaved – alpha	For interleaved scanning, the rotation around the x-axis must be below 5 degrees.
	Multi-lane – alpha	For multi-lane scanning, the rotation around the x-axis must be below 0.014 degrees.

ID	Name/Summary	Requirement
	Alpha variation	The rotation around the x-axis must vary by less than 0.03 degrees over a scanning distance between 1 and 5 mm.
	1 mm pitch – beta	For scans with the 1mm pitch sensor array, rotations around the y-axis must be below 0.57 degrees.
	1 mm pitch – gamma	For scans with the 1mm pitch sensor array, rotations around the z-axis must be below 0.29 degrees.
	Gamma variation	The rotation around the z-axis must vary by less than 0.03 degrees over a scanning distance between 1 and 5 mm.

2.5 Other requirements

This section lists the main requirements on the positioning system, apart from the requirements on positional accuracy listed in Section 2.4.

2.5.1 Scanning

In order to perform a save and usable scan, the positioning system must meet the following requirements.

Table 2.3: Scan related requirements for the positioning system.

ID	Name/Summary	Requirement
F1	Perform scan	The positioning system must perform a scan with a DVM MEMS sensor array, incl. the laser scanners.
F2	Scanning surface	The positioning system must scan a flat surface located in the air at a specified orientation with respect to the sample.
F3	Sample distance	The offset distance between the measurement area and the sensor head must be between 8 cm and 12 cm. This distance does not need to be adjustable.
F4	Path planning	The positioning system must plan and execute a trajectory based on a required scan area provided by the user (in the DVM system).
F5	No damage	The positioning system (and attached components) must never hit or damage the sample, other objects, or people.
P1	Scan speed	The positioning system must be able to perform measurement scans at a typical speed of 20 to 100 mm/s.
O1	Safety	The positioning system must guarantee that it will not pose a danger to people or objects when moving or stationary.

One of the main performance indicators of a positioning system is the size of the area that can be scanned. These requirements are use-case specific, whereas this document is written use-case agnostic. Therefore, no requirements are listed on the size of the scan area.

2.5.2 Load

The purpose of the scan is to take sensor measurements in a planar surface near the sample. Therefore, it is essential that the positioning system carries a sensor head and possibly auxiliary systems. Some positioning systems will have a small stroke and can therefore easily be connected to the fixed world with interface cables (e.g. power supply, data cables, vacuum cables, etc.). As a result, many auxiliary systems can be placed on the fixed world and the load of the positioning system is smaller. For positioning systems with a large stroke, the connection to the fixed world is more problematic. These systems will have more auxiliary systems on the positioning system and therefore carry a heavier load than the short-stroke systems.

Table 2.4: Weight and volume related requirements for the positioning system.

ID	Name/Summary	Requirement	Positioning system type
F5	Attach sensor head	It must be possible to attach a sensor head to the scanning part of the positioning system.	all
F6	Attach data acquisition system	It must be possible to attach the data acquisition system, consisting of up to two DTAQs and several switches, to the scanning part of the positioning system.	all
F7a	Low load	The short-stroke positioning system must be able to carry a load of 5 kg	short-stroke
F7b	High load	The long-stroke positioning system must be able to carry a load of 25 kg	long-stroke
F8	Attach camera	It must be possible to attach a (3D) camera to the positioning system that can fully image the scanned area.	All
F9	Attach sensors	It must be possible to attach temperature and air humidity sensors to the (scanning or stationary part of the) positioning system.	all
F10	Attach compute hardware	It must be possible to attach the compute hardware to the scanning part of the long-stroke positioning system.	long-stroke
F11	Parallel to sample	The positioning system must be able to angle the sensor head such that the lower surface of the sensor head (which contains the MEMS sensors) is parallel to the sample surface.	All
O2	Exchange sensor head	It should be possible to exchange the sensor head within one hour.	All

2.5.3 Other requirements

The table below lists all other requirements except for the requirements on the interfaces, which are the topic of Chapter 4.

Table 2.5: Other requirements.

ID	Name/Summary	Requirement
O3	Up-time	The positioning system should have an up-time of at least 80%.
O4	Continuous operation	It must be possible to operate the positioning system continuously for 10 hours.
F12	Trigger	The positional system must send a trigger system to the acquisition systems at each measurement position.
F13	Step size	It must be possible to set the step size, the distance between measurement positions where a trigger is generated, to 1 mm.
F14	Variable step size	It could be possible to set the step size to values between 1 and 5 mm.
F15	Relative position	During a measurement, the positioning system must register it's position with respect to the starting point of a measurement. At regular intervals during the measurement, this positional information must be transferred to the acquisition system.

2.6 Performance indicators

There are several factors that determine the performance of the positioning system, of which some important ones are:

- The positional accuracy;
- The scan speed;
- The size of the scan area;
- The range of object types that can be scanned;
- The environment in which the positioning system can operate;
- Ease of use.

The requirements on the positional accuracy of the DVM sensor head are discussed in Section 2.2. A more accurate positioning system, would allow for a larger error budget in other parts of the system (e.g. the tolerances in the sensor head construction).
The second performance indicator is the speed at which a scan can be performed. The higher the scan speed, the higher the throughput of the system. At some point, the scanning speed will be limited by the speed at which the acquisition system records data. Therefore scanning speeds beyond 20 cm/s are currently beyond reach.
The third performance indicator is the size range of the scan area. A large scan area allows for the scanning of a large area in one go. This enables the efficient measurement of large objects. The efficient measurement of a small object of course requires a small scan area. Therefore, the efficient measurement of a large range of objects requires flexibly setting the scan area from small to large.
The range of object types that can be scanned is not solely determined by the scan area. It also depends on the scan volume (the region in which scans can be performed), the size and weight of the objects that can be placed in this scan volume and the angle under which scans can be performed. Many other factors might influence the range of object types that can be measured by the positioning system. It is beneficial to have a single measurement system that can measure a very wide range of object types.

The fifth performance indicator relates to the range of the environments in which the positioning system can operate. This consists of a wide range of factors, like:

- The mobility of the positioning system.
- The temperature window in which it can operate.
- Are people allowed in the proximity of the positioning system during operation?
- Sensitivity of the positioning system to environmental factors (e.g. temperature, humidity, air flow, etc.).

A final performance indicator is the ease of use with which the positioning system can be operated. How much training does an operator require and how easy is it for the operator to program a scan area and start a measurement?

Each use-case will have its own set of requirements on these performance indicators, whereas this document is written without focussing on a specific use-case. Therefore, this document does not list requirements on these performance indicators.

3 Example positioning systems

The positioning system moves the sensor head over the sample to collect the DVM measurement data. The system must scan a planar surface by moving the sensor head across one or multiple lanes, sending triggers to the acquisition system at 1 mm intervals to record a DVM sample.

There are currently five positioning systems in use or under investigation: two dedicated xy-scan frames, for measuring about 2m^2 and an A4-size area respectively, one gantry robot for very large objects, an industrial robot and a cobot. The following sections briefly describe each system.

3.1 Scan frame

The original DVM positioning system consists of frame of metal beams of roughly 2x1.5x1 m^3 (length (x) x width (y) x height (z)) with two scanning axis (Figure 3.1). The system is optimized for high-positional accuracy and has an acoustical scan area (i.e. the size of the planar surface in which acoustical information can be recorded) of approximately 1.8 x 1.2 m^2. The position of the x- and y-stage are monitored using an encoder with a resolution of 1/800 mm. This is far below the required positional accuracy and therefore not a factor of influence. Due to the weight of the sensor head (4-10 kg), the frame will deform, causing an error in z-position and sensor head rotation. For interleaved scanning, the relative positional errors between neighboring samples will be far below the spec. For multi-lane scanning, the sensor head is shifted further, causing a z-shift of about 0.03 mm and a tilt of about 0.04°. Combined, this results in a z-position error of two neighboring samples of about 0.11 mm for multi-lane scanning. Although this does not meet the requirements on positional accuracy, the resulting DVM measurements provide good results. The system is therefore compatible with both the 1mm and 3mm MEMS array and all three scanning modes (interleaved, multi-lane, and single lane).

The scan frame has a high positional accuracy and can measure panels of about 1.6 m^2. The sensor head is mounted on the scanning system and the data acquisition system is located outside the positioning system. The drawbacks of this system are that it is very large, it cannot measure on objects that do not fit within the frame, and it is a dedicated system.

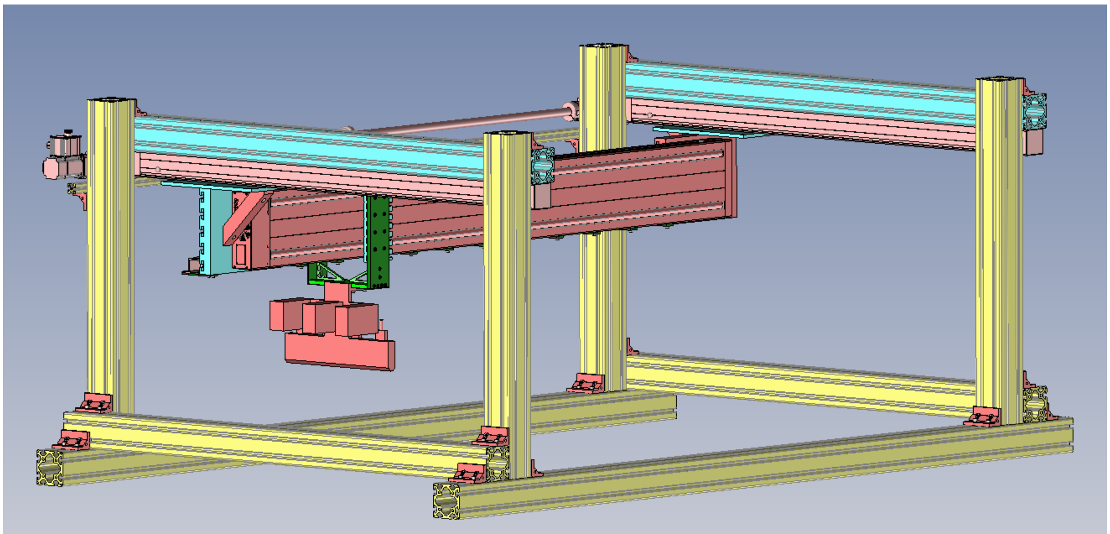


Figure 3.1: The XY-Scan frame located at TNO, using wo parallel short y-axes sporting one long x-axis. The DVM sensor head is shown mounted under the green parts.

3.2 Mobile scan frame

The mobile scan frame is a metal frame of about 0.7 x 0.7 m^2 on three feet that is designed to scan a single path (consisting of 3 interleaved scans) with the 3 mm sensor head (Figure 3.2). It has an x-stroke of about 0.6 m that allows for an acoustical scan area of about 0.4 x 0.6 m^2. The frame is currently under construction, so the positional accuracy is still to be determined but expected to easily conform to the requirements. The system weight is between 20 and 30 kg, which means it can easily be transported and used on site at partners. The frame can be placed on larger (horizontal) structures to measure A4-size segments of small or large objects. Both the sensor head and data acquisition system are mounted on the scanning system. The expected high positional accuracy allows for the most demanding scan mode: interleaved scanning with a 3 mm pitch sensor array, multi-lane scanning is not possible. With these scan strategies, the positioning errors as discussed in Chapter 2 can easily be realized. It is unclear if the additional acquisition hardware of the 1mm pitch sensor array would fit on the mobile scan frame. This will be explored in the next phase.

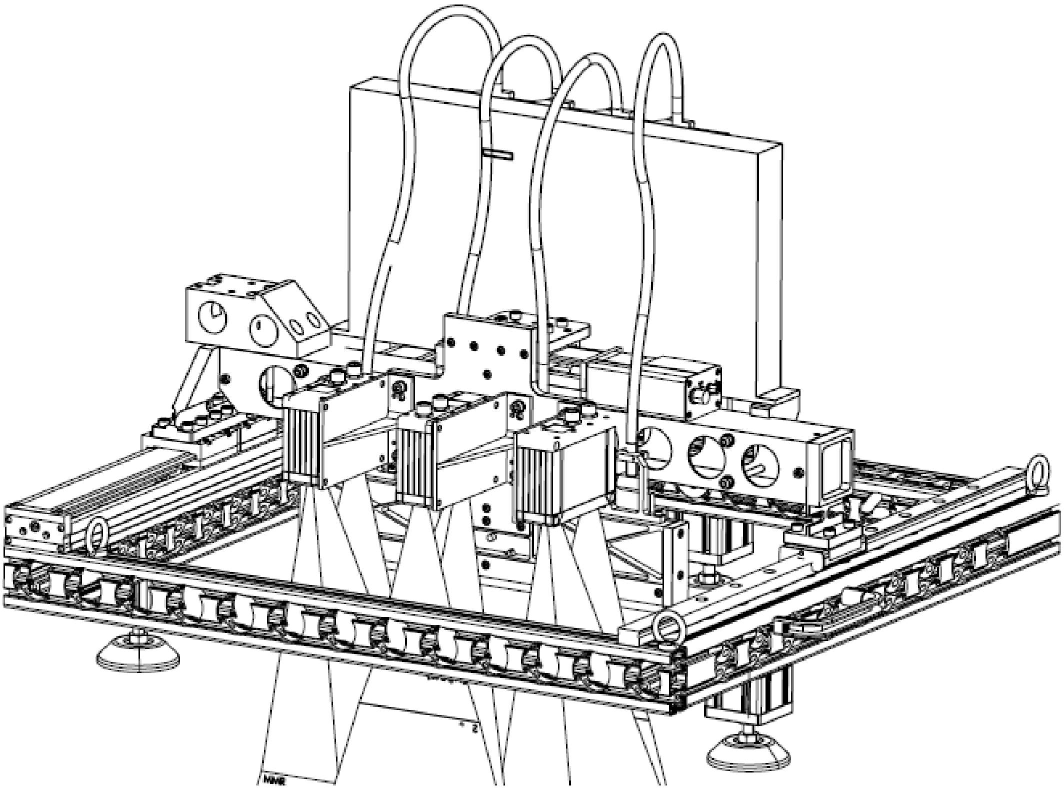


Figure 3.2: A technical drawing of a design for the mobile scan frame. The three laser line scanners and the scan ranges of their lasers are clearly visible. The MEMS array is mounted below and in front of the laser scanners. The cables connect the MEMS array with the vertically placed DTAQ.

3.3 Gantry robot

The gantry robot at SAM|XL is approximately 12 m x 10 m x 4 m in size and therefore enables the scanning of very large objects (Figure 3.3). It can perform linear movements along three axis and can rotate the scan head to scan objects that do not lie in the xy-plane. Due to the high load capacity of the gantry robot, almost the entire DVM system (including the computers) can be placed on the scanning system. This reduces the need for long cabling.

The positional accuracy of the gantry robot is in the order of 0.3 - 0.4 mm (3σ). This accuracy is reached by calibration and can be further reduced by active control. The current performance is reaching the positional requirements for the DVM system as discussed in Chapter 2. As a result, interleaved or multi-lane scanning will likely result in measurement artefacts and a reduced system resolution. Although this limits the domain of application, use-cases for such a system likely exist. Due to the mass of the gantry system, it is expected that most positional accuracy errors are in the larger spatial frequencies. The positional error between neighboring sample points within a single scan lane are probably much smaller. It is therefore expected that system will meet the requirements for single lane scanning with 1mm pitch sensor array. First results show good performance of the DVM integrated on the gantry. The gantry robot enables the measurement of very large objects at full resolution with a 1mm pitch sensor array, and at a reduced resolution with the 3mm array. A downside of a gantry robot is that it can only be operated in a closed or fenced area outside the vicinity of humans and require situation awareness to avoid collisions.

Figure 3.3: DVM sensor head mounted on a gantry robot on the weld jig of the Multi-Functional Fuselage Demonstrator, Airbus Clean Sky 2 project.

3.4 Industrial robot

Industrial robots are widely used for manufacturing and inspection purposes and have the load capacity to carry a DVM sensor head and acquisition system. This would allow for a very flexible measurement system with scanning volumes of up to 2m x 2m x 2m, using an existing positioning system.

Analysis of Ferranini et al. [5] showed that the positioning errors of a typical industrial robot are above 1 mm at linear scan speeds of 50 mm/s. Ferranini used a position feedback control (which directly used the absolute position of the robot) to reduce these (3σ) errors to below 0.1 mm (see Figure 3.4), which could be sufficient for interleaved and multi-lane scanning. These scan strategies are however also sensitive to the angular accuracy of the sensor head, which was not analyzed by the authors and would likely be beyond the spec of 0.014 degrees.

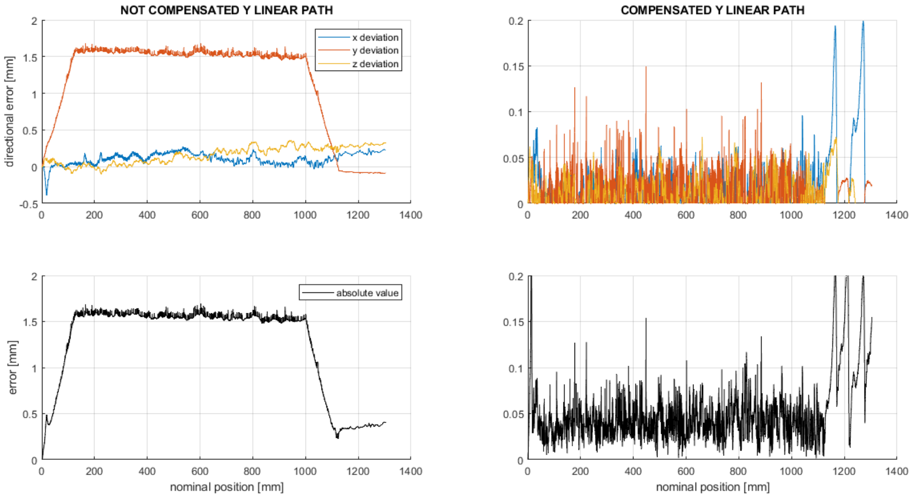


Figure 3.4: Positional accuracy of an industrial robot moved at 50 mm/s, with and without position feedback control (compensation). The low-frequency errors are significantly reduced by compensation. Data taken from (Sergio Ferrarini, 2024).

Single lane scanning with a 1mm sensor array is mainly sensitive to positional errors of neighboring points. As shown in Figure 3.5, the relative positional error of neighboring points is usually below 0.05 mm. The rotational error between neighboring sample locations is also likely to be small.

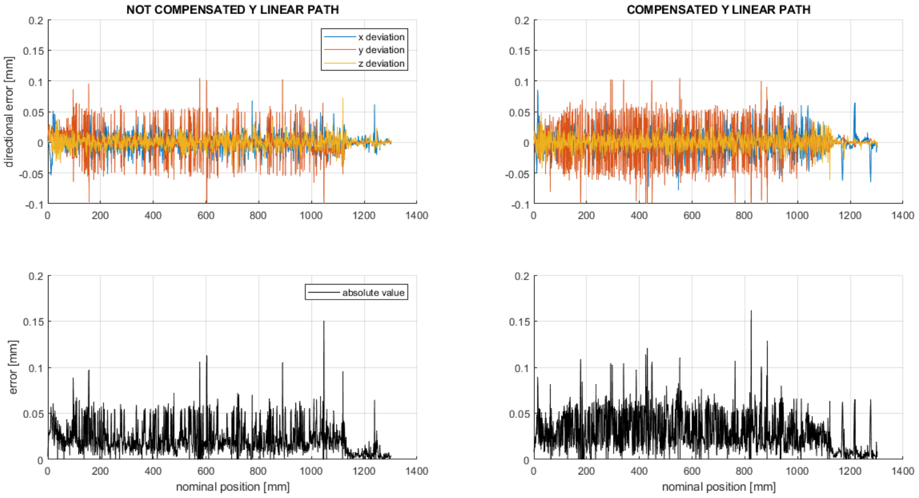


Figure 3.5: Positional error w.r.t. the previous sample point for an industrial robot moving at 50 mm/s. The position feedback control does not reduce the positional error. Data taken from [5], and adapted by TNO.

The maximum payload of industrial robots are typically much higher than the weight of the sensor head and the acquisition system. Considering the limited range and the decrease in positional accuracy with increasing load, it is beneficial to only put the sensor head and acquisition system on the robot, similar to the mobile scan frame in Section 3.2.

Figure 3.6: MEMS array mounted on an ABB industrial robot at SAM|XL. Part of the CADC project.

Industrial robots probably offer the positional accuracy needed for single lane scanning with the 1 mm sensor array. They could be a non-dedicated positioning system with a flexible scanning range. A downside of industrial robots is that they are only allowed to be used in a closed off area outside the vicinity of humans and require situation awareness to avoid collisions.

3.5 Cobot

Cobots are similar to industrial robots but can be operated while people are in close proximity. In general, they have a lower pay load, smaller working range, and worse positional accuracy.
Although many cobots do not meet the requirements of a DVM positioning system, several cobot manufacturers claim a positional repeatability around 0.1 mm, payloads sufficient for a sensor head and acquisition system, and a range of around a meter.

Figure 3.7: A DVM sensor head mounted on a cobot.

This suggests that cobots might be an adequate positioning system for single lane scanning with the 1 mm sensor array. Within the NXTGEN consortium, SAM|XL will test the positional accuracy of a cobot.

3.6 Summary

Table 3.1 summarizes the main characteristics of the different positioning systems.

Table 3.1: Main specs and evaluation of positioning systems.

System	Acoustical scan area	Positional accuracy	Compatible scan strategies	Domain of application	Status
Scan frame	1.8 m x 1.2 m	High (max. errors: xy: <0.01 mm, z: <0.11 mm)	Single lane, multi-lane, interleaved	Medium to large panels	Operational
Mobile scan frame	0.5 m x 0.6 m	High	Single lane, interleaved	A4-size regions of small or large horizontal surfaces	In development
Gantry robot	12 m x 6 m	Medium (rms error 10^{-1} mm)	Single lane	Very large objects	In development
Industrial robot	~ 2 m x 2 m x 2 m	Medium (rms error 10^{-1} mm)	Single lane	Non-dedicated, flexible system in industrial setting	Concept
Cobot	~ 2 m x 2 m x 2 m	Low	Single lane	Non-dedicated, flexible system. Low collision risks.	Concept

4 Interfaces

As mentioned in the previous chapters, the DVM sensor head is moved over the panel under inspection by a positioning system. For NXTGEN-ZERO-D, the panel can be a part of an airplane, a wind turbine blade or a composite panel with solar cells, as described in D4.1-NDT Requirements [6]. Two main configurations of the DVM sensor head are possible (Table 4.1). For small scan systems, the DVM sensor head only comprises the MEMS array, optical profilometers and temperature sensors. For larger scan systems, it is advantageous that the DVM sensor head holds all sensors, including the data acquisition system. The data acquisition system converts the analogue signals of the sensors to a digital format. From that perspective, the volume of the DVM sensor head is larger, has more weight, but the rugged cables are replaced by a single optical ethernet cable, a trigger cable and a power cable. A picture of the two configurations is given in Figure 4.1.

Table 4.1: DVM head for different positioning systems.

Interface	Small DVM sensor head	Large DVM sensor head
Application	Inspection of small (test) panels (max 0.5 m^2)	Inspection of large panels (up to many m^2)
applicable positioning systems	scan table cobot small / short range robot	scan table robot robot on linear rail gantry
Components on the DVM head	US sensor array with 128 MEMs profilometers temperature sensors	US sensor array with 128 -384 MEMs profilometers temperature sensors breakout board managed ethernet switch with POE and 10 GigE/SFP+ 1 or 2 multichannel ADCs power supply
Mechanical interface	small mounting plate	quick release interface
Electrical interfaces	4 rugged VHDCI cables (10m long) 1 Ethernet cable (cat5) BNC (TTL trigger*)	1 glass fiber (SFP+) 220V 2 BNC (TTL trigger* and emitted signal)
SW interfaces	control of profilometers read-out of profilometers	control of profilometers read-out of profilometers control of ADCs read-out of ADCs
Typical dimensions	30 cm x 45 cm x 20 cm (length, width, height)	40 cm x 50 cm x 60 cm (length, width, height)
Typical mass	5 kg	15-25 kg

* The trigger signal is preferable TTL, however 24V triggers can be converted using an opto-coupler.

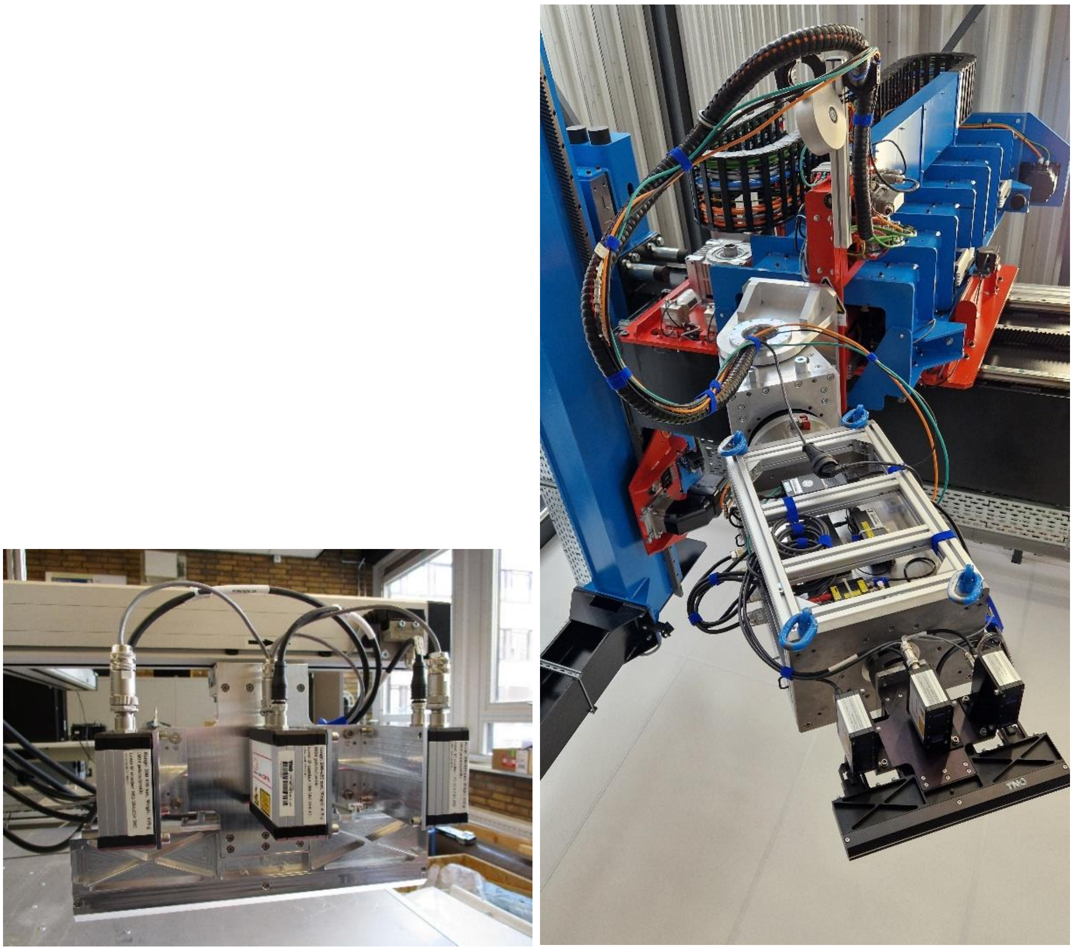


Figure 4.1: Two DVM head configurations (Left – small sensor head for inspection of small (test) panels, right – large sensor head for inspection of larger panels).

Different types of electrical interfaces are detailed; a trigger signal, the analogue signals, power and an ethernet connection. The interfaces are defined in more detail in the sections below.

4.1 Electrical interface

4.1.1 Small DVM sensor head

The small DVM sensor head comprises three electrical interfaces with the positioning system. The details of the 3 electrical interfaces are present in the sections below.

4.1.1.1 Trigger

The positioning system will provide triggers when the positioning is moving at a preset position. In general, the positioning system will move from A to B and will provide a trigger every 1 mm.
The trigger signal triggers the source, the acquisition system, the profilometers and thermometers. In practice, the trigger signal is routed from the DVM controller to the DVM sensor head.

The trigger signal is preferable TTL (0-5V), over a 50 Ohm coaxial cable with a SMA connector.
24V triggers can be converted using an opto-coupler.
For TTL, the cable length is limited to approximately 50m.

4.1.1.2 Analogue

The analogue signals from the MEMS array are connected to the ADC via a VHDCI cable. Each cable contains 32 coaxial cables from 32 MEMS microphones, resulting in a rugged VHDCI cable. This 68 Pin VHDCI cable has 32 coaxial cables each with a diameter of 0.8mm. The cable has a diameter of 8 mm and are 10m long. The cable has an outer diameter of 9.7 mm and a bending radius of typically 7 cm. For the current 1 mm pitch sensor head, 4 VHDCI cables are required and 12 cables for the 3mm pitch sensor head.

4.1.1.3 Ethernet

The profilometers are connected to POE ethernet. The ethernet cables provide power to the profilometers and allow communication to the DVM controller. A standard cat-5 ethernet cable is used for communication.

4.1.2 Large DVM sensor head

The details of the 3 electrical interfaces are present in the sections below.

4.1.2.1 Trigger

The positioning system will provide triggers when the positioning is moving at a preset position. In general, the positioning system will move from A to B and will provide a trigger every 1 mm.
The trigger signal triggers the source, the acquisition system, the profilometers and thermometers. In practice, the trigger signal is routed from the DVM controller to the DVM sensor head.

The trigger signal is preferable TTL (0-5V), over a 50 Ohm coaxial cable with a SMA connector.
24V triggers can be converted using an opto-coupler.
For TTL, the cable length is limited to approximately 50m.

4.1.2.2 Analogue

The ADC system will acquire the analogue signals from the MEMS array and the emitted signal from AWG that excite the ultrasonic source.
This analogue signal from the AWG is connected to the last channel of the ADC via a 50 ohm coaxial cable with a SMA connector. For proper SNR, the cable length is limited to approximately 50 m.

4.1.2.3 Ethernet

In the large sensor head, all acquired signals are digitized, aggregated and transferred to the DVM controller over ethernet. Due to the large data rate of the ADCs, 10 GigE is used. Aggregation of the ADCs, profilometers and thermometers is done via an power over ethernet (POE) switch. The communication between the ADCs and the switch and from the switch to the DVM controller is done via a 10 Gig SFP+ optical cable.

4.1.2.4 Power supply

A standard 220 V 50-60 Hz cable is used to provide 220V power at the DVM sensor head. The power consumption is 200 W max.

4.2 Software interface

To serve the functionality of the positioning system that can interface with the DVM system as described in section 1.3, a software interface between the positioning system and the DVM system is needed.
Currently, the communication to the positioning system is done at a low-level. In the near future, TNO wants to mature this by a high level API interface (Figure 4.2).
To enable this high level communication and to allow efficient DVM measurements, the interface between the acquisition system and the positioning system will be defined via an API library. The advantage of this high level interface is that the DVM controller and the positioning controller do not have to be aware about situation awareness issues (such as safety, collisions and maximum reach). This intelligence is controlled by the positioning system. In a production setting, the positioning system can extract standard configurations from a database, selected by the operator.

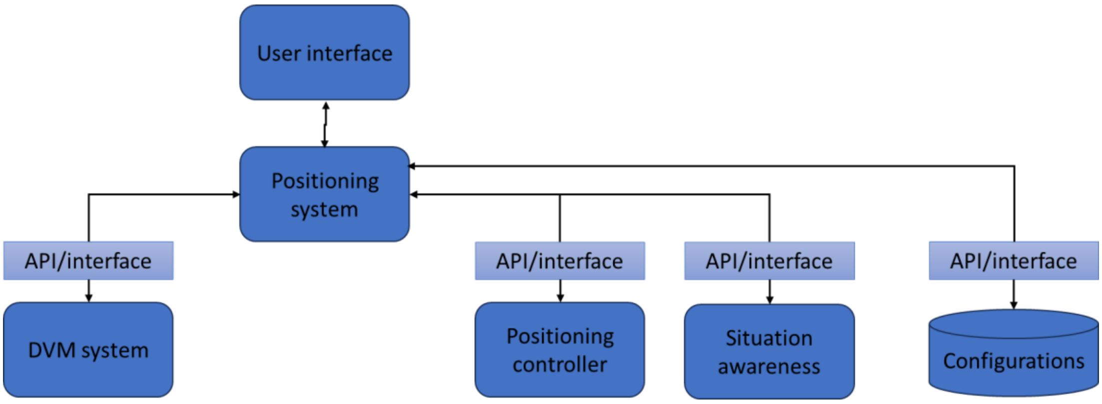


Figure 4.2: Required architecture to perform a DVM scan.

4.2.1 From DVM to positioning controller

A first draft of the required communication protocol in outlined. The following functions are defined that can be communicated from the DVM controller to the positioning controller:

4.2.1.1 DVM measurement preparation

- Start-up positioning system
- stop positioning system
- status request of the positioning system (idle / moving / off-line / ready to move / error)
- request error information
- reset positioning system
- request for version of positioning system (HW / SW)
- request for allowable ranges (range per DOF)
- request for allowable parameter ranges (speed, acceleration, mass, triggering interval, triggering method)
- Plan scan trajectories
- Move to start position of path X

- Start path measurement
- Shut-down positioning system.

4.2.1.2 Panel specific information

- request if the positioning system is able to scan surface ABCD (yes / no (due to limits / safety / collisions / mass / not idle / ...))
- request for location of the panel (lower left corner and size / coordinate system)
- request for home coordinate system (positioning system / world / other).

4.2.1.3 During measurements

- request current location
- check if positioning system is able to move from A to B (yes / no (due to limits / safety / collisions / mass / not idle / ...))
- move from A to B (A-6DOF, B-6DOF, trigger on/off, acceleration settings, max speed, trigger interval)
- request for trigger location of last move
- request last move parameters (move completed successfully, trigger on/off, acceleration settings, max speed, trigger interval, accuracy).

4.2.2 From positioning to DVM controller

The following functions are defined that can be communicated from the positioning controller to the DVM controller:

4.2.2.1 DVM measurement preparation

- status of the positioning system (idle / moving / off-line / ready to move / error)
- error information
- version (HW / SW)
- allowable ranges (parameters)
- allowable parameters ranges (speed, acceleration, mass, triggering interval, triggering method).

4.2.2.2 Panel specific information

- confirm positioning system is able to scan area ABCD (yes / no (due to limits / safety / collisions / mass / not idle / ...))
- location of the panel (lower left corner and size / coordinate system)
- home coordinate system (positioning system / world / other).

4.2.2.3 During measurements

- current location
- positioning system is able to move from A to B (yes / no (due to limits / safety / collisions / mass / not idle / ...))
- trigger location of last move
- last move parameters (move completed successfully, trigger on/off, acceleration settings, max speed, trigger interval, accuracy).

4.3 Mechanical interface

For the two types of DVM sensor heads, different mechanical interfaces are defined. The interfaces are primarily used as change systems to easily mount and dismount the sensor head on various positioning systems. In some situations, it is desirable to have an interface that allows effective tool exchange of the DVM sensor head on the positioning system, while remaining the mechanical alignment within spec. For the DVM sensor head, it is important that the sensor head can easily be mounted on standard positioning system.

For the small DVM sensor head, a light-weight interface is defined, which will be obsolete in the future. The mechanical realignment is limited, meaning that a recalibration of the sensor head is required after installation.

For the large DVM sensor head a quick release interface is used, enabling accurate repositioning and efficient tool exchange. Currently different robot/cobot systems use a variety of quick release systems.

At this moment DVM will be able to use three mechanical interfaces:

Figure 4.3: Example of a mechanical change system of SCHUNK for UR robots (UR+ | Changing by SCHUNK for Universal Robots (universal-robots.com))

4.3.1 Small interface plate

For the small DVM sensor head, a simple interface plate is used. The plate consists of a pattern of alignment holes for accurate positioning and will be mounted with several screws. Calibration of the DVM sensor head is mandatory after re-positioning of the head.

For mechanical interfacing with a robot or cobot, this interface plate is not suitable.

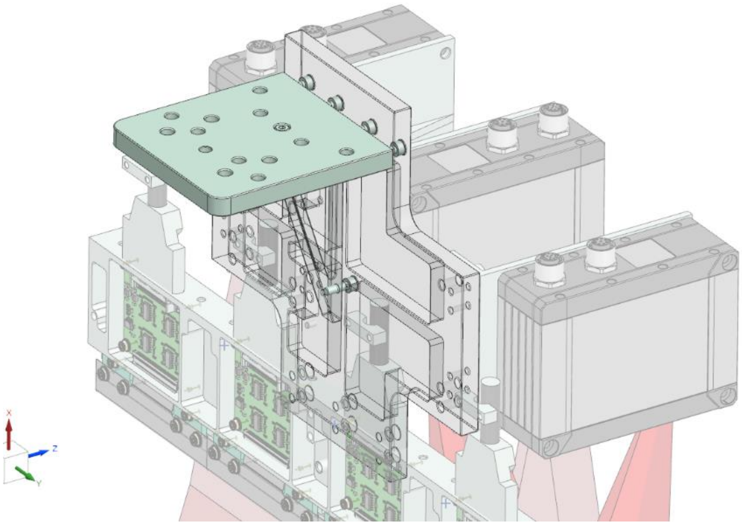


Figure 4.4: Location of the interface plate of the small DVM sensor head w.r.t. MEMS array and profilometers.

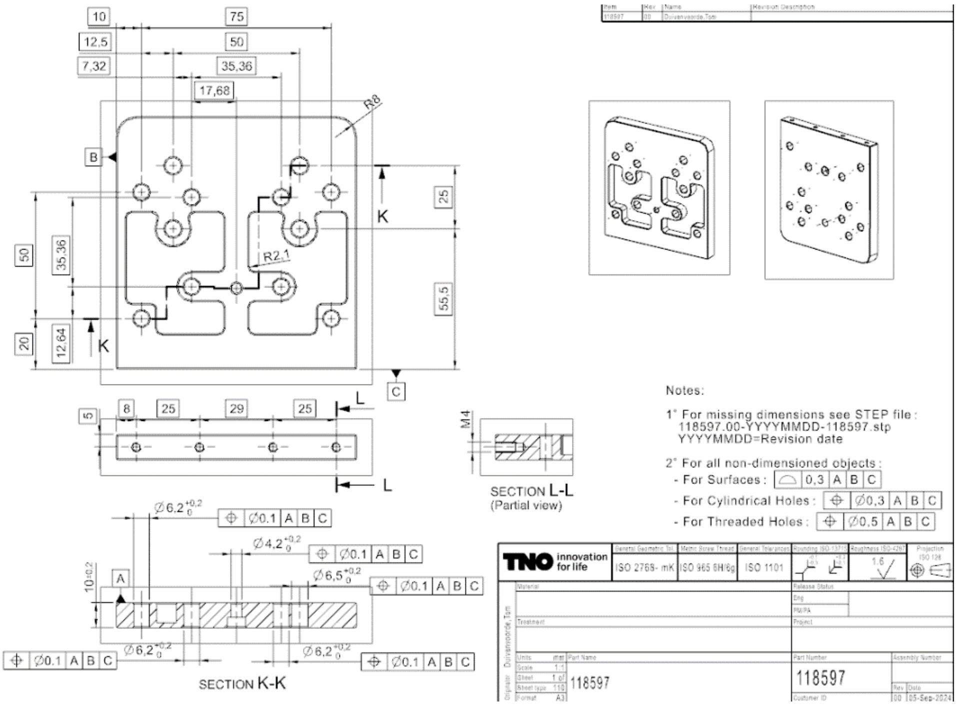


Figure 4.5: Drawing of the small interface plate used in the small DVM sensor head.

4.3.2 SCHUNK interface

The Schunk interface plate is dedicated for manual exchange of end-effectors on robots and cobots. Currently, the Universal Robots (UR) uses this mechanical interface, which will be supported by the large and small DVM sensor head (SHS Manual change system (schunk.com)).
Many variants of this kind of interface plate are available.

Figure 4.6: Example of a Schunk - SMS interface used on UR cobots.

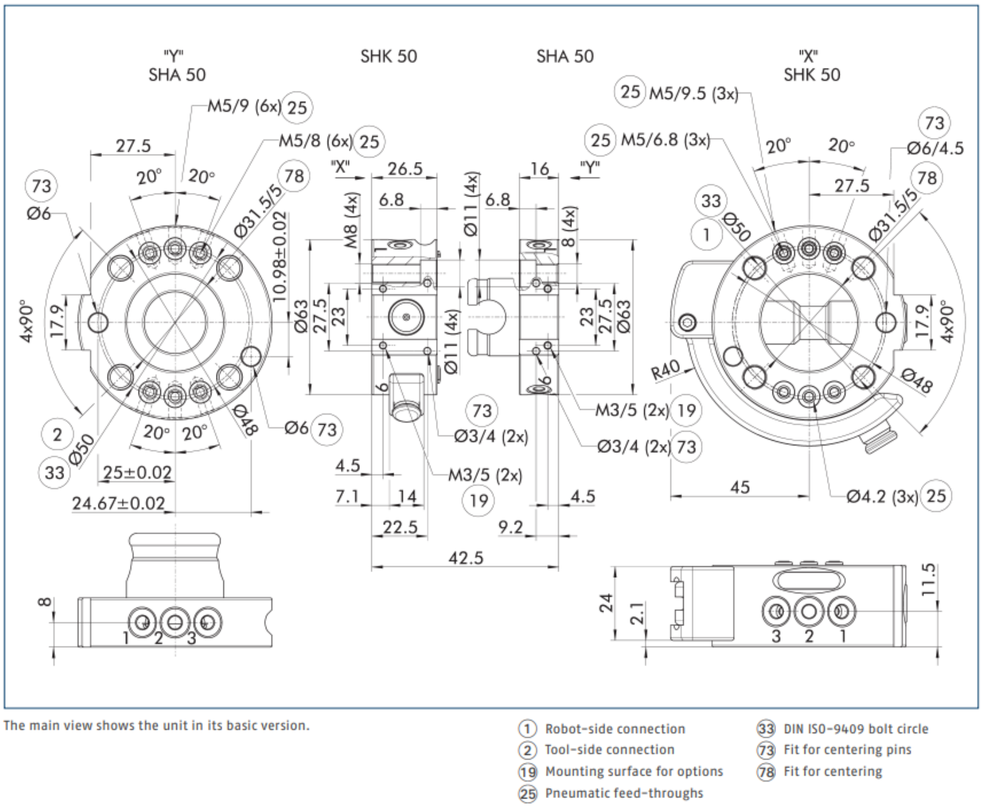


Figure 4.7: Mechanical drawing of the schunk SMS interface.

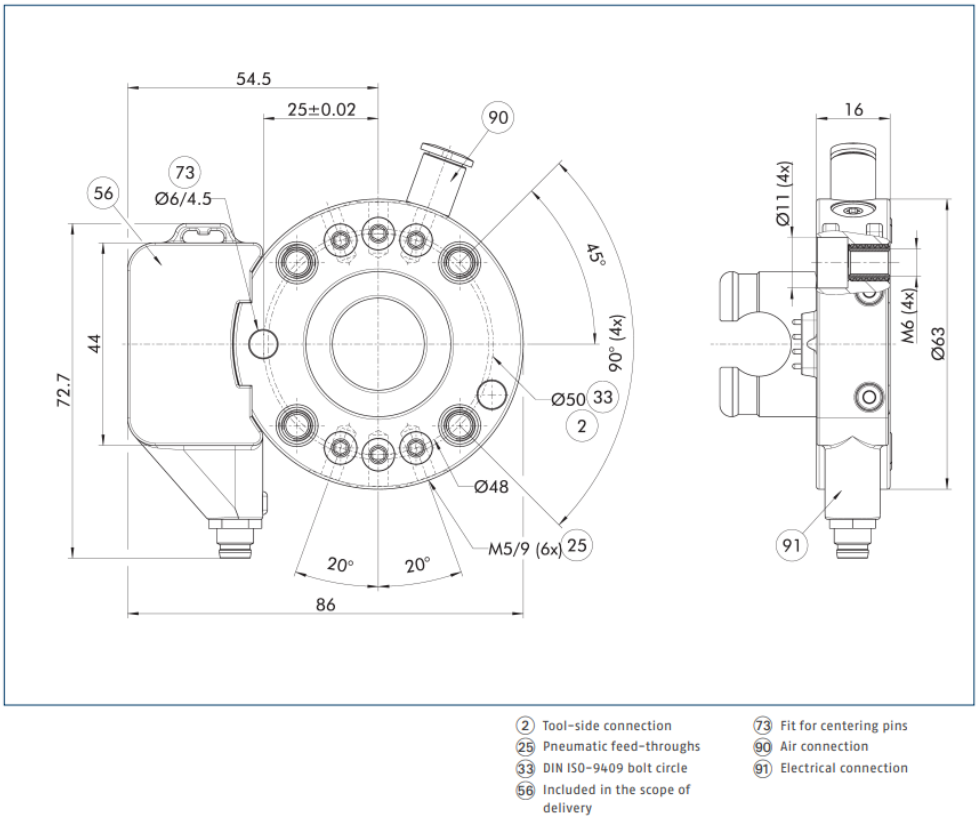


Figure 4.8: Mechanical drawing of the counterpat of the schunk SMS interface.

4.3.3 EROWA quick release mounting plate

The Erowa QuickChuck 100p is an alternative for manual exchange of end-effectors on robots (150800 Buch.indb (erowa.com)). The Erowa has a high repositioning accuracy, enabling high accuracy tool re-exchange without losing alignment and calibration. Currently, the large DVM setup uses this as mechanical interface at the end effector (Figure 4.9).

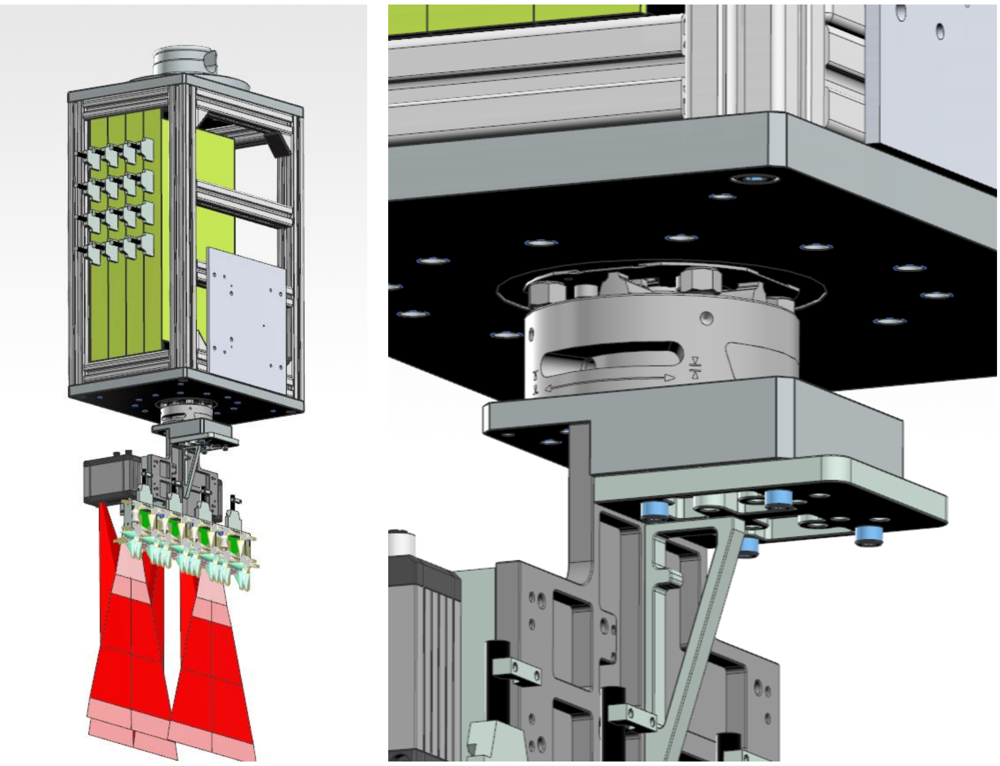


Figure 4.9: The erowa interface is currently used in the large DVM sensor head as a quick release interface between the MEMS array+ profilometers (bottom part) and the acquisition system (upper part).

4.4 Other interfaces

4.4.1 Environmental (flow and temperature)

Besides the hard interface, the DVM sensor head also interfaces with the environment. Especially temperature and humidity fluctuations within the measurements are important. These parameters are out of scope for this document.

4.4.2 DVM Source

Although the source is not part of the positioning system, it needs to be positioned on the panel.
A source can roughly cover a panel area of 1 to 4 m^2. For NDI during production, the location of the source is known prior to the measurement, based on experience. For MRO, the location of the source is close to, but outside, the ROI. In case multiple panels need to be inspected, each panel will have its own source.
The cable and vacuum tube needs to be outside the inspection area, preferable on the backside of the panel. If the cable and tube interfere with the acoustic path, it will result in distortion of the acoustic signals and thus degradation of the resulting thickness map.

5 Critical aspects and improvement directions

The most critical requirement on the positioning system regards the positional accuracy needed for DVM measurements. The currently used MEMS array has a MEMS sensor pitch of 3 mm, whereas the DVM technology requires a sampling interval of 1 mm. As a result, an interleaved scanning strategy is employed. This means that the same lane is scanned three times with an offset of 1 mm between the scans. The required positional accuracy is very demanding and can only be met by the purpose-build scan frames. The same is true for scanning multiple lanes and stitching the acoustical data to a single large acoustic measurement surface. Because the scan frames slightly bend under the weight of the sensor head, even the purpose-build scan frames do not fully meet these requirements. However, in practice, the data from such measurements proved to be adequate.

To reduce the requirements on the positioning system, a 1mm pitch MEMS array is currently under development. The positional requirements for single-lane scanning with a 1mm pitch array are significantly less stringent. The 1mm pitch array does however require a very accurate alignment between the sensor head and the scan axis of the positioning system. It is expected that for all types of positioning systems described in this document, versions exist that can meet those requirements.

To allow the usage of generic positioning system, like robots, a communication interface between the positioning system and the rest of the DVM system is required. The DVM system will request the positioning system to scan a certain area, whereafter the positioning system is responsible for the path planning, collision avoidance, and triggering the acquisition system. This document outlines the requirements on such a communication protocol.

In summary, a new sensor head is under development that relaxes the requirements on positional accuracy of the positioning system to reasonable values. The development of this sensor head and the interfaces defined in this document, would allow DVM measurements with varying purpose-build and generic positioning systems.

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