D4.3 Inventory of inspection strategies using robots

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Samenvatting

Dit rapport markeert de voltooiing van Deliverable 4.3 'Inventarisatie van inspectie strategieën met robots' 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 waves* 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.
Het ontwerp van een DVM-meting omvat de locatie van akoestische bronnen en de regio waar een akoestisch signaal moet worden opgenomen. Als richtlijn is een akoestische bron nodig voor elke 1 à 2 m² en is er minstens één bron nodig op elk paneel. Deze bronnen kunnen in de toekomst automatisch worden geplaatst met behulp van een cobot (KLM en Suzlon use-case) of met een lineaire actuator (GTM use-case). Elke meting wordt bij voorkeur uitgevoerd door het sensorkop langs een rechtlijnig pad te scannen. Bij voorkeur loopt dit pad in de richting waar het te scannen object de minste kromming heeft (bijvoorbeeld langs de romp voor de vliegtuiginspectie). Het meest veelbelovende concept voor de KLM- en Suzlon-use-cases is het scannen van het oppervlak met een robot (industrieel of cobot) op een rail. De inspectie van zonnepanelen kan worden uitgevoerd door een sensorhoofd op een lineaire as, gecombineerd met een transportband voor het transporteren van de zonnepanelen onder deze as.

Deze meetstrategieën en systeemconcepten vloeien voort uit de algemene richtlijnen voor DVM-metingen en de specifieke uitdagingen van de drie use-cases. Het zijn realistische concepten waarmee de use-cases kunnen worden afgedekt.

Summary

This report marks the completion of Deliverable 4.3 'Inventory of inspection strategies using robots' 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 object 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 objects and detect defects in objects. In the presence of support structures behind the object, 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.
For a DVM measurement, the design of the measurement comes down to deciding where to place the acoustical sources and where to record the acoustical signal by a scan with a sensor head. As a guideline, an acoustical source is needed for every 1 to 2 m^2 and at least one source is needed on each panel. In the future, these can be placed automatically using a cobot (KLM and Suzlon use-case) or with a dedicated linear actuator (GTM use-case). Each measurement is preferably done by scanning the sensor head along a rectiliniear path. This path should be along the direction of the sample with the least curvature (e.g. along the hull for the aircraft inspection). The most promising concept for the KLM and Suzlon use-cases scan the surface using an robot (industrial or cobot) on a rail. The solar panel inspection can be performed by a sensor head on a linear stage, combined with a conveyer belt for transporting the solar panels.
This report thus describes concrete measurement strategies and system concepts, that implement the general guidelines for DVM measurements to the three use-cases.

Contents

Abbreviations

Abbreviation	Meaning
ADL	Allowable Defect Limit
CFRP	Carbon Fiber Reinforced Plastic
DVM	Direct Velocity Mapping
MEMS	Micro-Electrical Mechanical System
MRO	Maintenance, Repair and Operations
NDI	Non-Destructive Inspection
NDT	Non-Destructive Testing
QA	Quality Assurance
SNR	Signal to Noise Ratio
US	UltraSound

1   Introduction

The inspection method described in this report, require scanning of the object under inspection in relatively close proximity. This report provides methods and strategies for performing such a scan for the three use-cases that are identified in the project NXTGEN-ZERO-D, 'NXT-GEN High Tech Composiet 03: Efficient & Proven Zero Defect Robotic Manufacturing "ZERO-D"', work package 4 'Inspection robots'.

1.1   Objective and structure of report

The objective of this report is to evaluate suitable inspection strategies and develop a test plan for more complex structures using the NXT-GEN High Tech ZERO-D use-cases. The three use-cases are described in detail in D4.1 and summarized in Chapter 2, with a focus on the factors that influence the positioning of the measurement strategies. One use-case is focusing on in-service inspection or Maintenance, Repair and Operations (MRO). The other two use-cases are dedicated to quality assurance (QA) inspection during production.
Two types of inspection can be differentiated, superficial techniques that provided information about the surface of the structure under inspection and sub-surface analysis, where information below the surface can be obtained. Superficial techniques, such as visual inspection, spectroscopy, IR cameras, 3D camera, can be used to inspect superficial damage. These damages are for instance indents, oxidation, coating quality, cracks. Superficial inspection can be performed at high accuracy when inspected closely. Sub-surface inspection is needed to inspect the mechanical integrity of the structure. Commonly used techniques for sub-surface inspection are for instance shearography, thermography, X-ray and ultrasound (US).

Most of the inspection techniques described above can ideally be performed with a robotized system, where the sensor is moved closely over the structure under inspection.
In the NXTGEN-ZERO-D deliverable D4.2 [6], Appendix A and Volker et al [1], the DVM inspection method is described. DVM is an inspection technique that combines ultrasonic and optical inspection methods. The DVM sensor head can be mounted on a robot system. Chapter 3 focusses on the inspection method and Chapter 4 on positioning concepts that allows automatic inspection of the large structures as defined in the use-cases of NXTGEN-ZERO-D, as described in D4.1 [5].

Section 3.1 first introduces Direct Velocity Measurement (DVM), an acoustical technique for the inspection of panels or structures used in the three uses-cases. In Section 3.2 DVM is illustrated with some results from other projects. In Section 3.3 several guidelines are derived to perform a DVM measurement successfully. These are then applied to the use-cases of Chapter 2 to arrive at scanning strategies presented in Chapter 4.

2 Use-case construction details

This chapter provides a short summary of the most relevant aspects of the three use-cases from the perspective of the scanning strategies using robots. For more detailed use-case descriptions, the reader is referred to the NXTGEN-ZERO-D deliverable D4.1 'NDT Requirements' [5].

2.1 In-service composite aircraft inspections (KLM)

The introduction of composite aircraft, such as the Boeing B787 and Airbus A350 (see Figure 2.1) to the fleet of KLM, poses new challenges for in-service inspections as the damage mechanisms of composites differ from more traditional materials like aluminum. For composites, the most frequent causes of damage are impact damage and lighting strike which could occur at any given time during the lifetime of an aircraft. This leads to a more frequent inspection of damage prone areas such as the crown section, the top of the aircraft, due to lightning strike and hail and door surround areas where handling mistakes may lead to impact damage. For impact damage, the following estimation of the total area applies:

⟩ 4x passenger door surround: circumference 6m x 1m: 24m^2
⟩ 2x cargo door surround: circumference 8m x 1m: 16m^2
⟩ Additional areas of service equipment: 30m^2

For hail strike damage, the following estimation of the total area applies:
⟩ Fuselage crown section: 60m length, 2m width: 120m^2

All these inspection surfaces are curved, with a radius of curvature of typically 4m, that is much smaller in one direction than in the other.

B787
Length: 60-70m   Fuselage L: 50-60m
Height: 17m (tail)   Fuselage H: 6m
Wingspan: 60m   Fuselage W: 5.8m

A350
Length: 67-75m   Fuselage L: 50-60m
Height: 17m (tail)   Fuselage H: 6.1m
Wingspan: 65m   Fuselage W: 5.9m

Figure 2.1: B787 (left) and A350 (right) example details.

At the A- and B-checks, which occur roughly every 200-300 flights and every 6 to 8 months respectively, the above-mentioned areas need to be inspected. At the less frequent C- and D-checks, the inspection areas are larger and can even cover the entire aircraft exterior. During A-D-checks, the aircraft is out of operation and placed in a hanger, making MRO a mandatory and expensive procedure. Efficient inspection during MRO can result in high operational flight time and thus in a cost reduction. Currently, MRO costs are 10% of the TCO of an airplane and even 46% of all ground operational expenses [7].
It is important to note that during all checks, the inspection system must reference its measurements to the aircraft coordinate system (e.g. centered at the pitot tube).
This use-case poses the following challenges regarding the inspection strategy (i.e. the scanning with NDT technologies):
〉 curved inspection areas;
〉 large inspection areas of up to 60 meters in length;
〉 the need to reference to the aircraft coordinate system;
〉 not damaging the aircraft or endangering maintenance personnel;
〉 high coverage of automated inspection of the desired areas.

Figure 2.2: Example of fuselage inspection with the aid of two cobots [8].

2.2 QA inspections of wind blades (Suzlon)

Suzlon produces wind turbines with blade lengths of over 80 m. A wind turbine blade generally is made out of a root, two halve blades and a girder. The root is bolded to the rotating hub and the two halves blades are joined together with the girder in a separate production step, see Figure 2.3 and Figure 2.4. To reduce the production time of these blades, this use-case involves reducing the inspection of such a halve blade from 8 hours to 1 hour.

Figure 2.3: Joining of two halves of a wind turbine blade.

The NDT inspection would typically take place after completion of the curing cycle of half of an 80m+ wind turbine blade. In an ideal situation, the joining of the girder would be inspected while still located in the mold, making it potentially easier to repair any defects. The shape of the blade varies along its length. Typically, the blades are 3+ m in width and 80+ m in length. Similar to the KLM use-case, the wind blades are produced in a large factory hall, where the environmental conditions are poorly defined.

Some of the main challenges of this use-case with respect to the inspection strategy are:
❭ the large surface area and long length that needs to be scanned;
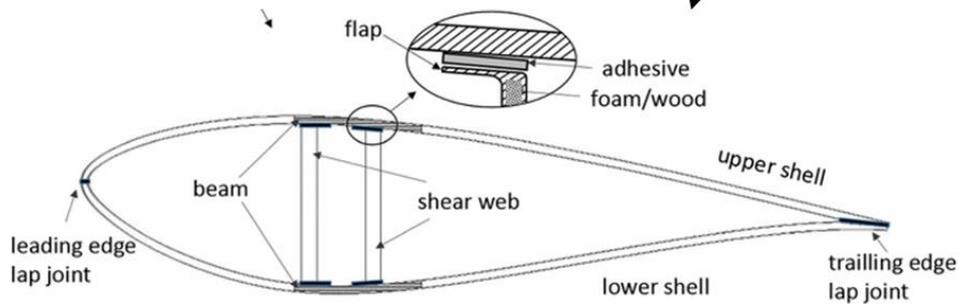❭ the curvature of the blade.

Figure 2.4 : Top. a Suzlon wind blade, made of a lower and upper shell joint together with girders to improve the mechanical stiffness of the blade [9]. Bottom, a typical cross-section of a wind blade [9].

2.3   QA inspections of solar cells (GTM)

GTM produces solar panels for space applications. The panels are bonded on different types of substrates. To offer clients improved quality assurance (QA), the GTM use-case involves testing of the bonding in an inspection cell part of their production line. QA of the bond lines, especially on the detection of enclosed air pockets, which can result in potential damage when the solar enters the space low-pressure environment, needs to be performed.
The inspection system must be able to inspect panels automatically with a surface area of up to 2m by 3m in a target takt time of 15 minutes. This may take place in a dedicated inspection cell and should be integrated in the assembly line at GTM.
Some of the main challenges of this use-case with respect to the inspection strategy are;
❭ the stringent takt time;
❭ a high level of required automation (e.g. regarding positioning the solar panels and the acoustical sources of the DVM inspection method).

Compared to the previously described use-cases, the benefit of the solar cell inspection is that it takes place in a controlled and enclosed area and that the inspection structure is flat but complex.

Figure 2.5: Example of an automated and robotized assembly line for solar cell manufacturing [11].

3 Acoustic based techniques

3.1 DVM NDI technology description

Direct Velocity Mapping or DVM is a non-destructive inspection (NDI) technique, suitable for high-speed inspection of large aerospace structures. Appendix A provides a brief description of the DVM NDT technique. A more in-depth explanation can be found in Volker et al [1]. Approximately one ultrasound source per 1 to 2 m^2 is currently manually positioned on the structure. Automatic placement of the source will be investigated in this NXTGEN-ZERO-D project. The source will generate a Lamb wave, a class of dissipative surface waves, in the structure [2][3][4]. Due to the out-of-plane motion of the wave, ultrasonic waves are radiated into the surrounding air. The speed of sound of the surface wave is determined by the material properties and the geometry of the structure. Defects will affect the speed of sound locally. A sensor head is moved over a planar surface 10 to 30 cm above the structure under inspection and will register the radiated waves. The movement of the sensor head over the structure can be performed by a scan table, or a robot/cobot as discussed in D4.2 [6]. By signal processing, a speed of sound map can be reconstructed at the surface of the structure under inspection. From the material properties and geometry, this speed of sound map can be converted into a thickness map. Defects in the structure or in welds will manifest as deviation in the local thickness. The sizes of the detected defects will be compared with the ADL, and the structure can be approved by the operator.
TNO is working on a DVM system that is able to inspect 1-2 m^2 per minute. DVM does not use water as a coupling medium and enables single sided inspection. DVM is perfectly suitable for aerospace structures such as thin metal panels, metal-metal bonded panels or composite panels. With a proper positioning system, as described in D4.2 [6], the DVM measurements can be performed fast, safe and automated. Automated inspection will lower the load on scarse personnel, and will result in high quality MRO and QA testing by the partners of the three use-cased in NXTGEN-ZERO-D.

3.2 Experiences of previous measurements

Recent years, the DVM techniques evolved to a robust inspection tool for the inspection of aeronautic panels. In several projects prior to and in parallel to NXT-GEN-ZERO-D different types of test panels were successfully inspected.
As an example, an inspection result of a test panel is given in Figure 3.1. The test panel is a stepped metal-metal bonded panel with artificial defects. The defects are Teflon inserts that act as disbonds. DVM can be used to detect the size and depth of these disbonds in a production setting. If the detected size and depth of the defects are above the Allowable Defect Limit (ADL), the panel must be repaired or scrapped. Typical ADL sizes in the aerospace industry are 10 mm. Metal-metal bonded panels have successfully been inspected using DVM.
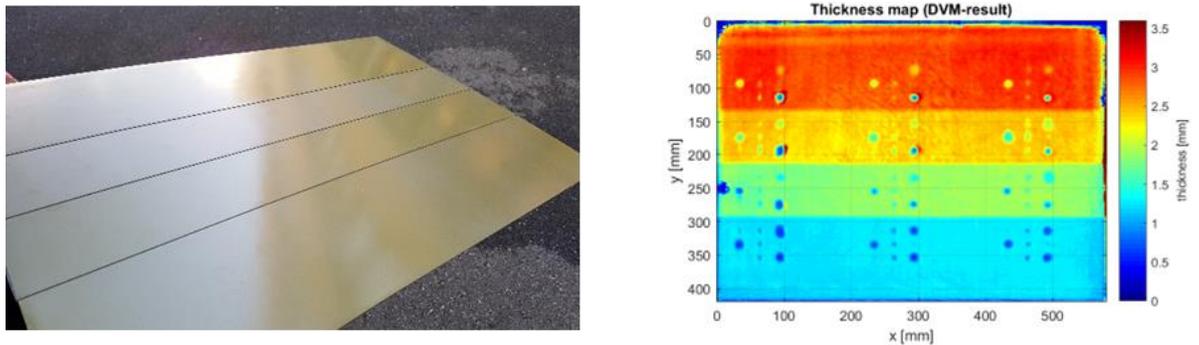
Figure 3.1: DVM results of a stepped metal-metal panel with artificial defects.

Similar to metal-metal bonded panels, the issue of disbonds will also occur in composite panels. In Carbon Fiber Reinforced Plastic (CFRP) panels such delamination defects have similar ADL sizes of 10 mm. DVM has been demonstrated to detect such delaminations. However, composite panels are more complex due to fiber orientation and lay-up, resulting in anisotropy and a higher number of delamination locations.

The DVM NDT capability of detecting disbond and delamination type defects is also effective to inspect the quality of a bonded or welded joint such as a stringer on a panel. Figure 3.2 shows how a DVM measurement of an omega stringer welded on a CRFP panel, with two locations of unsuccessful welding.
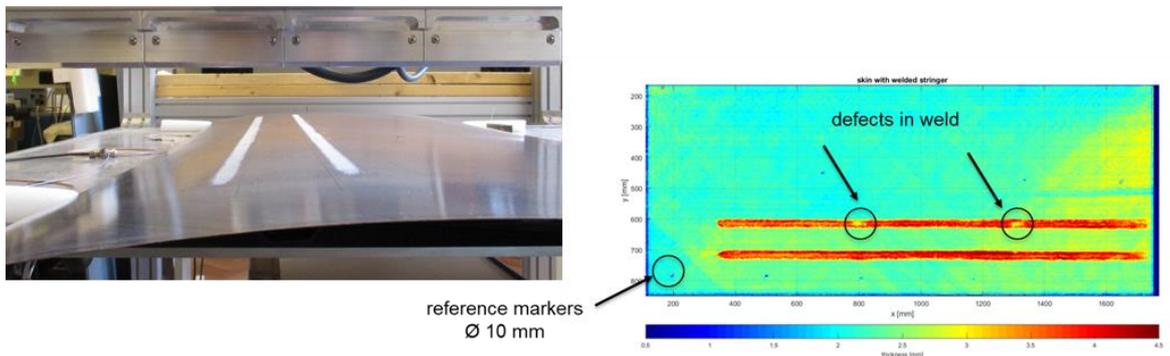

Figure 3.2: DVM results of welding inspection of two omega stringers welded on Thermoplastic (CFRP) panel. These measurements were performed under the project PENELOPE.

Since DVM measures the thickness of a panel, it can also detect areas where the panel thickness is lower than required. A test system that will measure the panel thickness of coated aluminum panels after blending, corrosion removal, is currently under development. The test system will be used in an in-service inspection setting.

With these and other previous measurements it was demonstrated that DVM is a capable method for the detection of sub-surface defects, weld quality, and panel thickness.

3.3 Guidelines for measurements

The aim of this report is to develop suitable inspection strategies for an NDT measurement using DVM. The key parameters one can adjust for a DVM measurement are the scan path of the sensor head and the location of the acoustical sources. This section will provide general guidelines for the scan paths and acoustical source location. It will also discuss the influence

of the sample material and the influence of support structures behind the surface that is being measured.

3.3.1 Scan paths

The area in which the sensor head records the acoustical signal is referred to as the 'sensor scan area'. This sensor scan area has a preferred stand-off distance of 10 cm to the sample. In post-processing, the acoustical waves are projected to the sample surface by means of backpropagation [1]. In this way, the origin of the sound on the sample surface is calculated. Effective back-propagation requires that the sensor scan area is a planar surface. The Lamb waves travel along the surface of the sample, due to the difference in speed of sound of the Lamb wave at the surface of the sample and the speed of sound in air, the sound waves radiate from the sample surface to the sensor head under an angle up to 45° with respect to the surface normal. Since the orientation of the source with respect to the sensor head varies during the measurements, the sensor scan area needs to be larger than the 'acoustical full data area' as depicted in Figure 3.3. After projection, the DVM algorithm is able to accurately determine the thickness of the sample in that region. The sensor scan area and acoustical full data area are schematically depicted in Figure 3.3 for a flat sample.
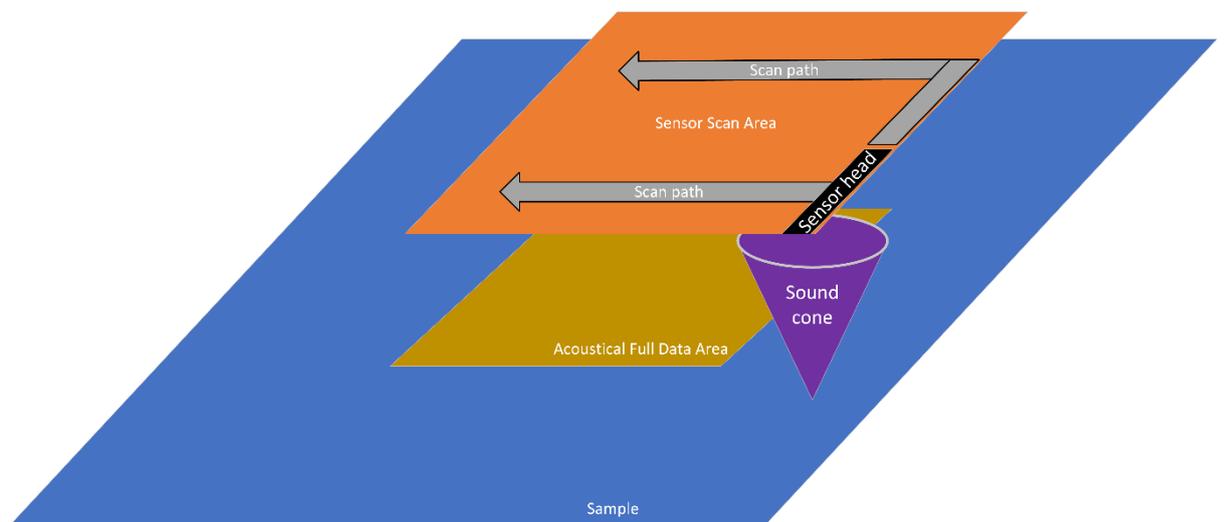

Figure 3.3: The scan regions of a DVM measurement. The sound is radiated in a cone away from the sample.

To prevent disturbing acoustical reflections from the sensor head, the sensor head should have a parallel offset from the sample in the range of 10 to 30 cm. Increasing this distance leads to a smaller acoustical full data area with the same scan area and to a longer acquisition time. Therefore, the sensor area should preferably be around 10 cm away from the sample.

At this distance, the acoustical full data area is about 10 cm smaller on each side than the sensor scan area, if the sample is parallel to the sensor scan area. A tilt between the sensor scan area and the sample, will further reduce the size of the acoustical full data area. For flat samples, it is therefore recommended to record the acoustical data in a plane parallel to the sample.

For curved samples, there are two feasible strategies. First, one can follow the curved contour of the sample with the scan head. This results in a curved sensor scan area. Secondly, one can divide the sample area into smaller regions, such that for each sub-region the sample does not deviate much from a plane.

The first strategy, contour following, has multiple challenges. First of all, positioning the sensor head at the right positions with the right orientation on a curved path will be a challenging task for the positioning system. Secondly, data projection algorithm to the surface of the structure is significantly more complex compared to a planar sensor scan area surface. If the surface is curved, the complexity of the data projection algorithmic increases drastically.

Therefore, the second strategy, scanning multiple smaller regions, is the preferred strategy as long as the radii of curvature of the sample are not too small (see Figure 4.1).

In Deliverable 4.2, multiple scan strategies were mentioned. In single lane scanning, each rectilinear scan path is processed individually. In multi-lane scanning, the data from multiple neighboring scan paths are first combined into one data set and then processed. Single lane scanning offers the advantage of reduced requirements on the positional accuracy of the positioning system. The downside is, that the acoustical full data area is approximately 20 cm narrower than the scanned lane. A single scan with a 40 cm wide sensor head, will thus result in a 20 cm wide acoustical full data area. For a multi-lane scan, this effect is less dramatic. The full data area after three scans with a 40 cm wide sensor head will be 100 cm wide when using multi-lane scanning and only 60 cm wide when using consecutive single lane scans.

Due to the very challenging requirements on positional accuracy, single lane scanning is the preferred despite its lower efficiency.

In summary, the following guidelines should be followed:
⟩ the sensor head should scan at a minimum distance of approximately 10 cm from the sample;
⟩ each rectilinear path should be processed individually, corresponding to the single-path scanning of D4.2;
⟩ the material thickness can be calculated in a region of the sample that is approximately 10 cm smaller on each side that sensor scan area;
⟩ its preferably to have the sensor scan area parallel to the sample;
⟩ a curved sample surface should be measured using multiple scans, such that within each sub-scan, the sample can be approximated to be close to planar.

3.3.2 Source positions

The acoustical source generates an ultrasonic lamb wave that propagates over the surface of the structure. The surface wave radiates an ultrasonic wave in air, which is measured using the sensor head. The projected amplitude of the ultrasonic wave in the structure, needs to be sufficiently strong for a proper thickness measurement. As a rule of thumb, a minimum signal to noise ratio (SNR) of 30 dB is required. On the other hand, to prevent measurement errors and can eventually damage to the structure by the generation of heat into the structure, the maximum strength of the acoustical source is limited.

With the current source attached to a uniform plate of a few millimeters thick, an area of roughly 1 to 2 m^2 can be measured. A larger area can be scanned by distributing multiple sources over the sample and using them in parallel, or by repositioning the source(s) after a single-path scan is completed.

Several factors reduce the strength of the acoustical signal. In a structure consisting of multiple joined plates, which is quite common in aerospace structures, the acoustical signal is strongly attenuated at the joints between the plates. It is therefore recommended to position an acoustical source on each plate. Thickness variations in a structure, in particular abrupt changes from a thin to a thick section, will cause reflection and therefore attenuate the propagating wave. It is therefore best to place the source on the thickest part of the structure and to have a maximum propagation distance of the lamb wave of 1 to 1.5 m.

Stiffened panels are typical aerospace construction types and consist of a relatively thin plate supported by stiffeners that can be an integral part of the structure or joined by bonding, riveting or welding. These stiffening structures will absorb acoustical energy, thereby reducing the area that can be measured using a single source location. It is best to place sources at least 20 cm away from support structures, to reduce the amount of energy that is dissipated into them.

Currently, the acoustical source is attached to the sample using suction cups [1]. Mechanical clamping of the source onto the panel is feasible as well. In principle, both methods would allow for the automatic placement of sources.

Another factor to consider where the acoustical source must be placed, is that the measurement is compromised in the vicinity of the source. Thickness maps cannot be created in a 'dead zone' of a few centimeters around the source. Additionally, the acoustical source should never be between the sample and the sensor head. Therefore, it is best to place the acoustical source outside the measurement area.

In NXT-GEN-ZERO-D, a source location strategy for the three use-cased needs to be developed together with an automated placing method of the sources on the surface.

In summary, the following guidelines should be followed:

〉 a source is needed at least every 2 m²;
〉 a source should be placed on each plate;
〉 the source is preferably positioned on the thickest section of a sample;
〉 sources should preferably be at least 20 cm away from support structures;
〉 sources should preferably be placed outside of the measurement area.

3.3.3 Influence of material

The sample geometry and material properties influence the inspection strategy in that it influences the signal attenuation. The thicker the material, the harder it is to measure its thickness using DVM. Additionally, the resolution of the thickness map is lower in thick than in thin materials, due to the frequency and thickness relation of the dispersion curves of the material [1]-[4]. The material type will also affect the measurement since it influences the coupling from the acoustical source into the sample and the propagation of the Lamb waves through the sample. In case of composite materials, the fiber orientation will cause these properties to be directionally dependent. All these factors influence the optimal position for acoustical sources.

Additionally, the sample construction greatly influences the relationship between the Lamb wave mode, its velocity and the plate thickness. This relationship depends, amongst other things, on the material type, the presence of adhesives and coatings, and for composites on the layer structure and fiber orientation. Although these factors do not directly influence the inspection strategy, they pose challenges for the DVM post-processing algorithms.

3.3.4 Influence of support structures

Aerospace structures are commonly based on thin panels on support structures to reach mechanical integrity at low mass. Figure 3.4 schematically shows two typical configurations; C and omega stiffeners. Since most mechanical connections are also acoustical connections, these contact areas in contact with the panels of these support structures are visible in a DVM measurement by means of an increase in thickness. The remaining part of the support structure cannot be measured, when the sensor head is positioned at the panel side.
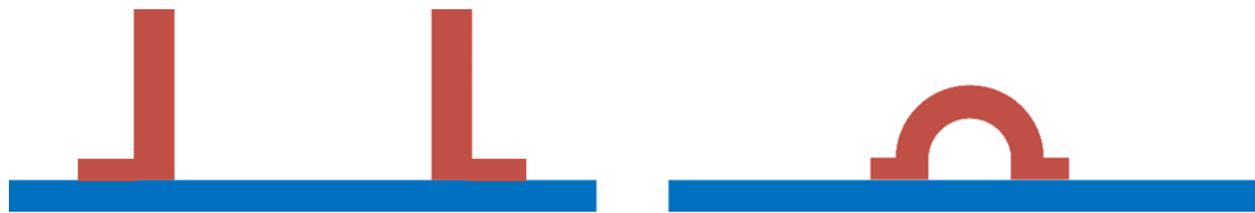
Figure 3.4: Two examples of support structures (in red) attached to thin panels (in blue). Left, representing L, C, I stiffeners and right and omega stiffener.

The ability of DVM to check the thickness of the panel and the mechanical connection between the panel and the support structure, is an additional useful feature of this inspection technology. The presence of the support structure is not expected to cause any issues, although it will lead to a slight reduction in the area that can be inspected using a single source location (see Section 3.3.2).

4 Potential inspection strategies

In this section, scan strategies for the three use-cases (presented in Chapter 2) are presented. They are based on the general guidelines for measurements provided in Section 3.3.

Throughout this section, it is important to consider that the DVM scans a planar surface above the structure under inspection. By moving the current DVM scan head above the surface, planar strips of 20 cm wide of the structure can be inspected.

4.1 In-service NDT inspection of composite aircraft

The vast majority of the surfaces for the three use-cases as defined in Chapter 2, that require frequent inspection are either approximately flat (e.g. the top of the wings) or only significantly curved in one direction (e.g. the fuselage or the wing blade). For the inspection of large curved areas with the DVM sensor head, the curved inspection surface can be divided into smaller sections, as described in Section 3.3.1. The inspected strips can be oriented such that the movement will follow the surface with large radius of curvature. In the direction with high curvature, the scanning surface can be divided into a subset of 20 cm wide strips (Figure 4.1). The length of each strip is limited by the curvature in the long direction and the range of the positioning system. The stand-off distance between the surface and the sensor head is typically 10 cm, which limits the scanning length of the strip if a curvature in the long direction is present. The range of the positioning system prevents scanning long surfaces. In that case, the positioning system has to be moved along the direction of the large radius of curvature as depicted in Figure 4.1.
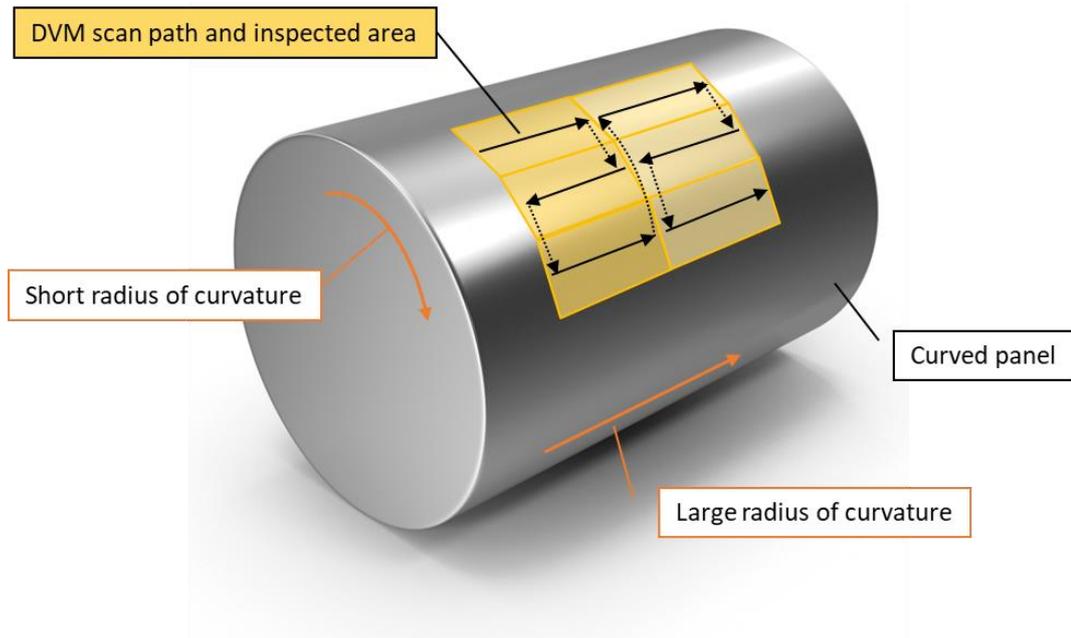
Figure 4.1: Scan paths for 1.5D curved panels.

The strategy of dividing the inspection area in smaller sections will even work for sections of the aircraft that are strongly curved in one or two directions. As discussed in Section 3.3.1, the stronger the curvature though, the larger the scan area will be with respect to the inspected surface area.

A second challenge in the aircraft use-case, is the size of the area that needs to be inspected. The crown section of the fuselage requires a flexible scanning system that can move the sensor head parallel to the surface over a range of about 2 meters by 60 meters. The width of the DVM trajectories is limited by the width of the sensor head, typically 40 cm, whereas the length of the DVM trajectories are limited by the positioning system (Figure 4.2). In case of an industrial robot, the range of the end-effector is typically 2-4m. In case of a cobot, this is limited to 50-100 cm and in case of a scan table, the length is typically 1-4m. A gantry typically has a scan range of 10m.

Figure 4.2: Different robot systems with different range, accuracy and payload.

None of these positioning systems have the ability to scan an entire fuselage crown or wind blade. It is however possible to combine a robot system and a linear rail (Figure 4.3 and Figure 4.4). The linear rail will be positioned parallel to the length of the structure. The cobot

or robot system will then be able to scan several planar trajectories, parallel to the curved structure (Figure 4.1). By moving the robot along the rail, the entire structure can be inspected with a relatively compact robot solution.

Figure 4.3: Example of a robot on a rail to measure long structures (image from: LR-2000-P | MABI Robotic).

The rail can be mounted on the floor or on the ceiling (Figure 4.4 and Figure 4.5). With this robot on a rail, the DVM scan head can be positioned, such that high coverage of large structures can be realized with maximum flexibility and minimum safety measures.
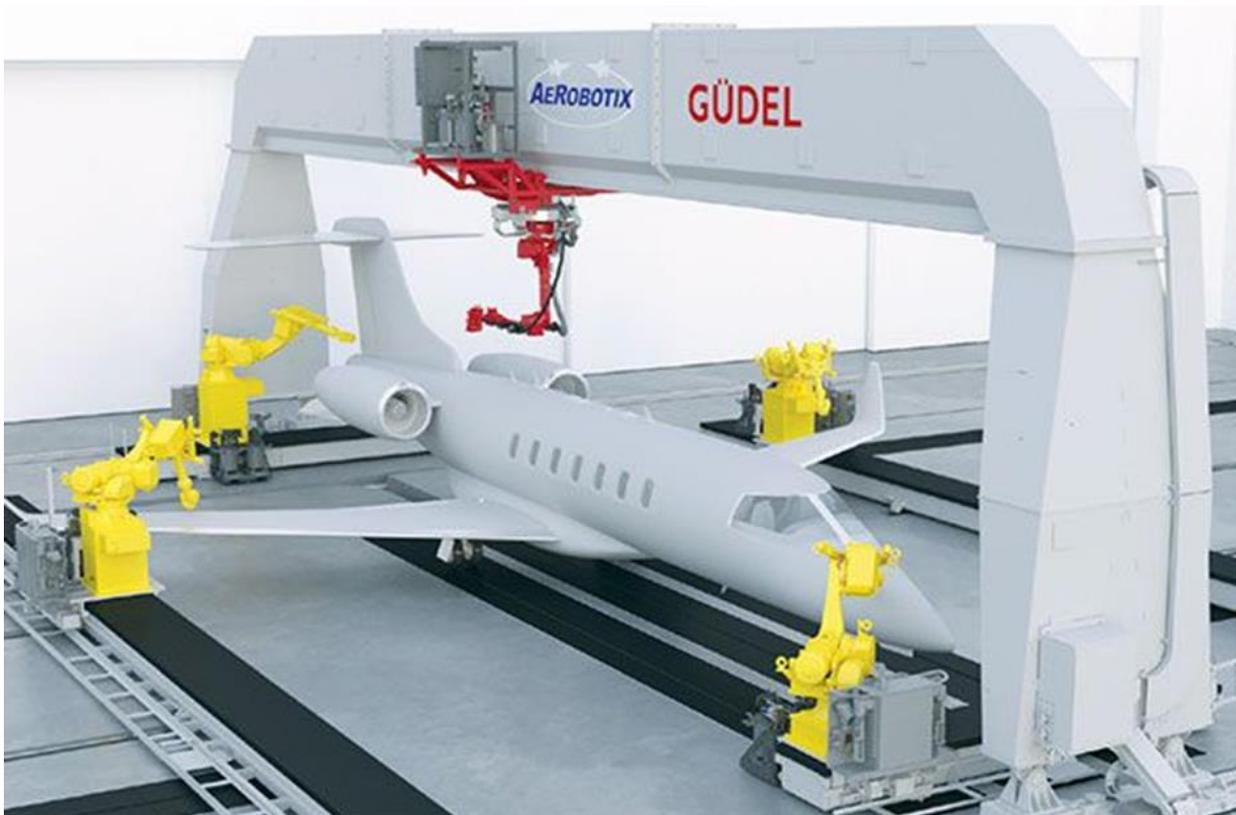

Figure 4.4: Example of MRO inspection with robot and gantry systems (image from: https://aerobotix.net/resources/case-studies/).

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Figure 4.5: Example of a robot on a service-car for local inspection (from:
https://www.compositesworld.com/articles/nondestructive-inspection-better-faster-and-cheaper)

The third challenge in the aircraft and wind blade use-cases, is that the position of the measurement must be known with respect to the aircraft (e.g. with respect to the aircraft pitot tube). This linkage between the coordinate system of the measurement system and of the aircraft can be achieved using of the shelf 3D measurement system like laser scanners or photogrammetry. This can be aided by placing markers on the measurement system and the aircraft or wind blade.

Finally, the inspection of the aircraft should not damage the aircraft or injure people. This can be achieved by a including situational awareness to the positioning system (e.g. using 3D scanners placed on or near the measurement system, or coupling to configuration data). Safety standards might still impose restrictions on the usage of industrial robots, even with situational awareness. In that case, cobots might be an alternative solution. Cobots are designed such that the exert very small forces upon impacts with objects or people. This makes them safe to use even when people or fragile objects are present within their range. A downside of cobots is that they offer a reduced range and positional accuracy compared to industrial robots (See Figure 4.2 and deliverable D4.2 [6]).

With the concepts and strategies outlined in this section, it is feasible to scan the main areas of interest (described in Section 2.1) of a composite passenger aircraft located in a hangar.

4.2 In-line NDT inspection of wind blades

The inspection of wind turbine blades poses similar challenges as the previously described aircraft inspection. Both involve the inspection of very large, curved areas.

Therefore, the previously described concept of a robot on a rail (see Figure 4.3) combined with the strategy of dividing the measurement area in small strips (see Figure 4.1), would also be a suitable solution for this use-case. The rail can be integrated in the housing of the mold (Figure 2.3).

The wind turbine blades use-case does however differ from the aircraft use-case in a number of significant ways: It poses much higher requirements on scan speeds but offers the benefit of a standardized (production) environment which can be free of people and a well-defined scanning trajectory can be pre-defined in a configuration datafile.

An industrial robot or cobot on a long rail can be integrated in the support structure of the production mold of the wind blade (Figure 4.6). The use-case involves scanning an entire half blade, of over 80 meters in length and several meters wide, within an hour. The inspection area of the blade is in the order of 400 m². The DVM system under development will offer scan speeds of up to 1 to 2 m² per minute. This throughput demands the use of several robots with sensor heads in parallel to reach full inspection within 1 hour. By using multiple industrial robots or large cobots on the same rail enables parallel inspection and thus a decrease in scanning time.

Figure 4.6: Example of the production of a half blade in a mold. A DVM positioning system can be integrated in the support structure of the mold (image from REPL_2012_04_Siemens_feature[1].pdf)

4.3 In-line NDT inspection of solar cells

To provide quality assurance in the production of solar cells, the DVM inspection system needs to be fully integrated in a production line with a takt time of about 15 minutes. The solar panels are flat and have a maximum size of 2 m by 3 m but can have smaller dimensions as well.

To perform in-line NDT inspection of solar cells, the DVM sensor head can be mounted to a single scanning axis with a stroke of at least 2.2m inside an inspection cell. The solar panel can be placed on a conveyer belt or linear axis that moves the panel forward by roughly

twenty centimeters after each scan. An entire panel of 2m by 3m can be inspected in 15 scans of 2.2 m. To achieve the required throughput, each scan can take up to a minute, which seems feasible with the current DVM.

4.4 Positioning strategies of the source

As described in Section 3.1, DVM inspection requires one or more ultrasound source(s) that will be mounted on the structure under inspection prior to scanning. Two important aspects need attention: the location of the sources and the method by which the sources are mounted and dismounted.
These two challenges need to be addressed in the second stage of the NXT-GEN-ZERO-D project.

Regarding the source location, the guidelines in Section 3.3.2 need to be considered. Each use-case brings additional practical consideration. In principle, the source can be mounted on both sides of the structure. For in service inspection however, the inner side is hardly accessible. In some cases, for QA inspection during production, dedicated flaps are available for handling the structure. In most cases these flaps can ideally be used for mounting the source onto the structure.

4.4.1 In-service composite aircraft inspections (KLM)

Regarding the use-cases of KLM, the aircraft inspection will require the source to be mounted on the outside of the aircraft. For smaller inspection regions, e.g. surrounding the aircraft doors, this can be done manually. For inspection of the fuselage crown section, an automated placement is preferable to enable fully automated inspection. An additional cobot, mounted on the same rail as the inspection robots, could be dedicated to the placement of acoustical sources. Alternatively, a dedicated source placement system can be developed that can be mounted close to the sensor head. If the system is dedicated to a specific inspection (i.e. of the fuselage crown), a dedicated solution can be simpler and cheaper.

4.4.2 QA inspections of wind blades (Suzlon)

The wind blade inspection will require the automated placement of sources due to the high throughput requirement. To scan a half blade within an hour, sources need to be mounted at a rate of more than one a minute. Again, either a cobot or a dedicated placement system could offer this functionality. Since the use-case is in a controlled environment and the variation between the inspection samples is low, a dedicated placement system could be the preferred way to go. This system should be mounted on the same translation system as the scanning system.
If the robot or large cobot for scanning the DVM sensor head and the cobot for placing the sources are both located on a rail, their relative movements and ranges are limited. The acoustical sources can in most situations always be mounted close to the edge of the mold just outside of the scan area.

4.4.3 QA inspections of solar cells (GTM)

The concept for the scanning system of the solar cell consists of a single scanning axis and a conveyer belt or a second linear axis. The benefit of this scanning system is that it always scans at the same location. As a result, the acoustical sources can always be mounted at the same position. One or two sources can be mounted just outside the scan area. They can

be positioned using a linear translation system, e.g. piston-based. The current acoustical sources are attached to the sample using a suction cup, but for this concept the source can be attached to the panel by using the force of the linear translation system or by clamping. If the sources need to be placed on handling flaps of the solar cell, the source mounting system will require two additional translation stages for movements in the plane of the solar cell.

4.4.4 Source location

It must be noticed that for QA inspection, the location of the sources is known upfront. For MRO, the source locations have to be chosen such that a good SNR of the ultrasonic waves after projection to the entire surface of the sample under inspection is achieved of at least 30 dB. It will be very challenging to create an algorithm that automatically chooses the source locations, since this requires additional information about the inspected area (e.g. regarding the expected thickness distribution, the presence of support structures, and the location of plate boundaries). A human operator is likely to be able to make an informed guess on these topics, especially if configuration data is available upfront. This only needs to be done once per measurement sample, which significantly reduces the workload for the wind blades use-case and the inspection of the fuselage crown (only two aircraft types will be inspected). For the solar cell use-case, the samples are uniform enough to allow choosing the source locations automatically.

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Appendix A
DVM NDT-system description

This appendix provides a copy of the DVM NDT system description as provided in D4.1. 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]-[4]. The latter is typical for anisotropic composite plates. Detecting irregularities in Lamb wave velocity and/or amplitude as a result of damage is the principal 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.
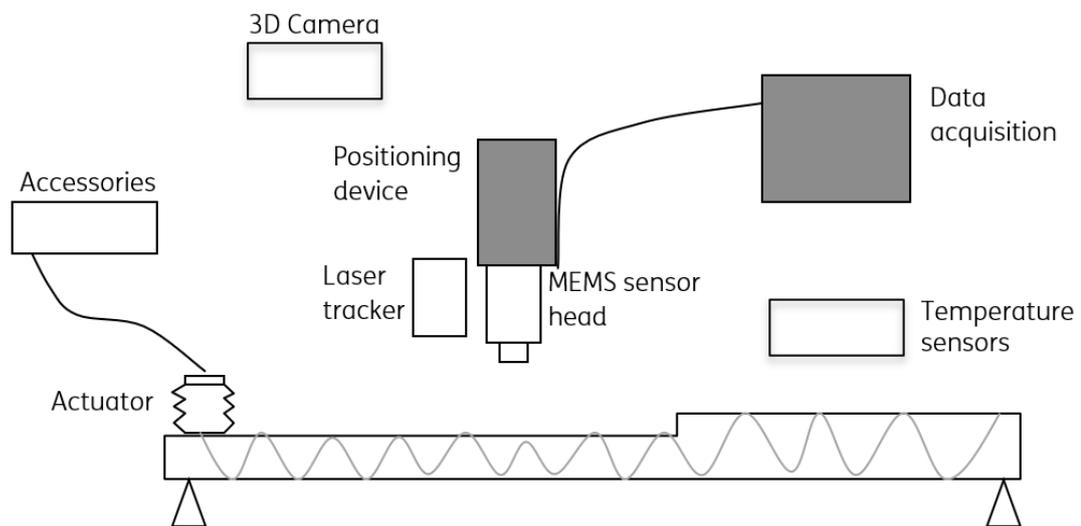

Figure A.1: Schematic overview of the Direct Velocity Mapping NDT system.

Figure A.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.