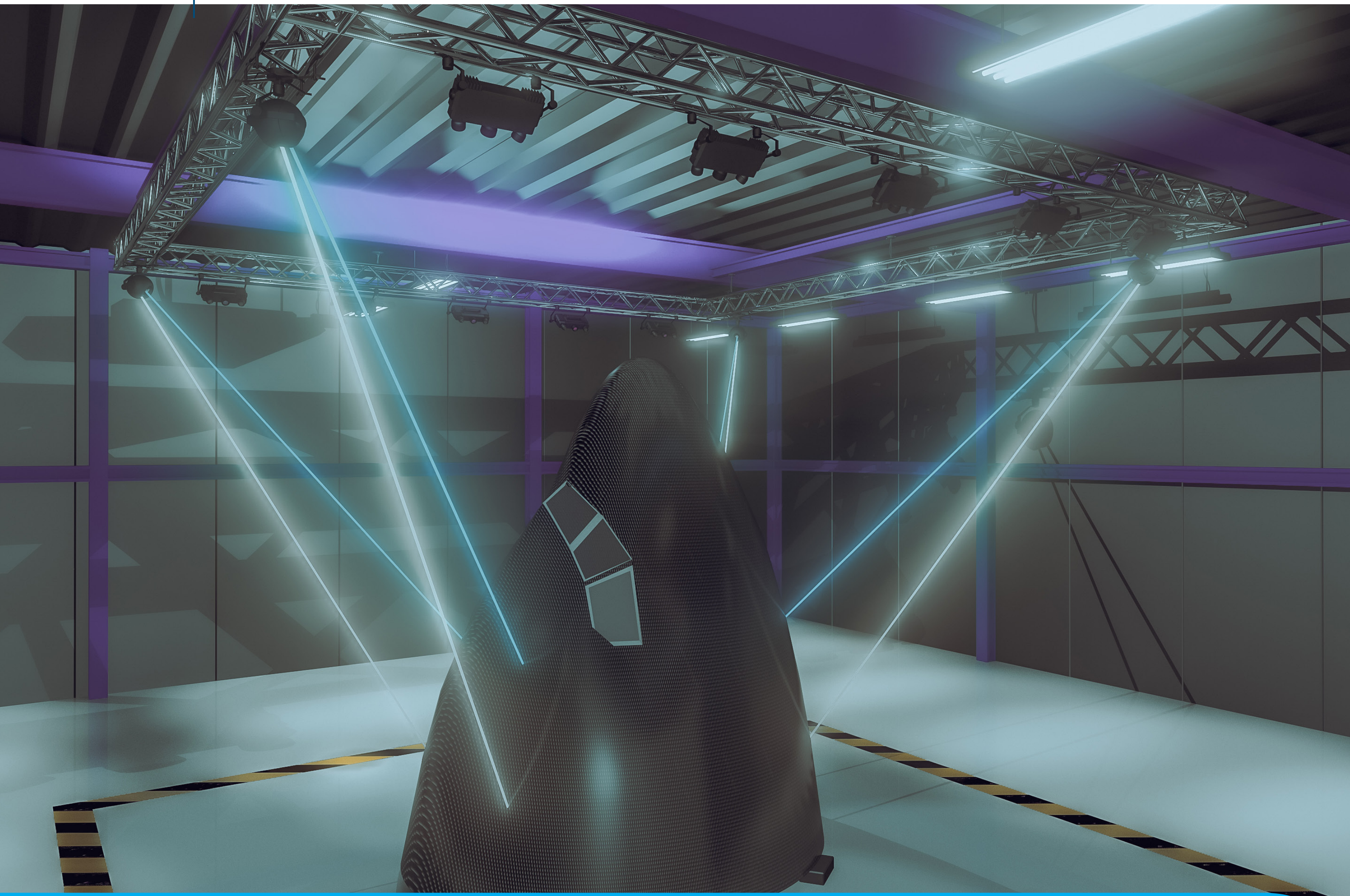
Accelerating the future of aerospace

Quality Assurance Cell

Multi-domain Non-Destructive Testing for Digital Quality Assurance

AUTHORS

J.S. Hwang
D.B. Deutz
M. Nawijn
B. van Elburg
H.P. Jansen



Conventional Non-Destructive Testing (NDT) of aerospace structures can be a labour-intensive process: often, small probes are used on the area of interest, manually placing this on the surface (ultrasonic inspection, eddy current inspection etc.). Furthermore, the human factor is a large contributor to the probability of detection, meaning that the experience of an inspector plays a significant role in the quality of the inspection. This uncertainty has to be accounted for in the design of aerospace vehicle structures, leading to potential over-dimensioning. Considering the development that in the future there will be fewer qualified inspectors with experience, NDT can become a bottleneck for the manufacturing and MRO industries, leading to reduced fleet availability and reduced revenues.

Introduction

Aerospace structures must undergo non-destructive Testing (NDT) after manufacturing. NDT is a necessary process to ensure the quality of the primary structures, looking for possible defects in the product. Moreover, NDT is also performed on in-service aircraft structures in order to guarantee its continuing airworthiness. Various NDT methods, each with their strengths and weaknesses, are in place enabling the maintainers to verify structural integrity.

The transition to more sustainable aviation has led to aircraft structures adoptings lighter and stronger structure design by employing composite materials. An increasing amount of composite materials is being used and, because of ever improving manufacturing techniques, the shape and structural configuration of the resulting lightweight structures are becoming more complex.

QUALITY ASSURANCE CELL CONCEPT

NLR has been developing new methods to control the quality of composite structures after manufacturing. To manage the challenges imposed by more complex and large composite aerospace structures, a new Quality Assurance Cell (QAC) concept is proposed (Front page). The QAC is the last step in the manufacturing process in which the final product is submitted to NDT for any defect. The QAC is a well-defined space that does not require the engagement of a human inspector.

The QAC concept consists of four pillars:

Pillar I: Contactless NDT
Pillar II: Automation
Pillar III: Synthesis by means of a Digital shadow
Pillar IV: Automatic quality assurance

Figure 2. The four pillars of the Quality Assurance Cell concept.

The purpose of the QAC is to offer the user a qualified finished product with its digital shadow. The digital shadow of each individual product may contain information such as the manufacturing process parameters and the NDT results, providing added value to the user of the product. The manufacturer of the aircraft part attains quality assurance of its product automatically, efficiently and in a more agile way. To realize the QAC concept, those building blocks are essential. Non-contact NDT enables the inspector to obtain NDT data with great flexibility and efficiency. Automation of the inspection process will improve work force efficiency as well as the consistency of data quality. The digital shadow will be the focal point where all data relevant to the quality of product will be collected. Synthesis of the digital shadow is based on the data coming from the automated NDT process. Based on the digital shadow, various machine learning techniques can be employed to execute automatic defect recognition and quality assurance.

Pillar I: Contactless NDT

Contactless NDT means that there is no physical contact between the sensor and/or probe and the object to be inspected. Typically, conventional NDT techniques requires contact between the probe and the object (ultrasonic techniques, eddy current, for example). In case of ultrasonic techniques, a coupling substance is required between the probe and the object surface to ensure proper transfer of ultrasonic energy in and out of material. This has some practical drawbacks: often, water is used as a couplant, which means that the object is submerged in a water tank or water is squirted into the space between the probe and the object. This implicates a logistic burden. Furthermore, liquid contact with the composite product may be prohibited for certain applications. In general, a contactless NDT method does not require a couplant to perform inspection.

NLR has built up experience with various novel contactless NDT methods:

1. 3D optical measurements: see for reference [1], [2]
2. Shearography: see for reference [3]
3. Thermography: see for reference [4], [5], [6]
4. Laser ultrasonic inspection: see for reference [7], [8]

Figure 3. NLR has built knowledge of contactless NDT methods for composite structures inspection. Combining these various methods has led to the so-called "multi-domain inspection".

These contactless NDT methods have the following advantages:

- Large areas can be covered with one measurement. However, as with all NDT methods, there is trade-off between the desired resolution and inspection speed.
- There is more tolerance for the misalignment of sensors with respect to the object to inspect.
- Faster inspection time is achievable compared to conventional NDT methods.

These novel NDT methods also have their limitations. One of the limitations is that there is no single NDT method that can cover all defect types in the composite material. Therefore, depending on the configuration of the final product, multiple NDT methods have to be employed and combined for a complete inspection. NLR uses the term “multi-domain inspection” to point out that multiple NDT methods are required to assess the integrity of the object to be inspected.

Two examples where NLR has contributed to the inspection of large aircraft parts with multi-domain inspection are the European Projects PENELOPE [9] and FasterH2 [10]. The production of large Carbon-Fiber Reinforced Polymer (CFRP) aircraft parts is a complex process where defects can have significant consequences. Ensuring precision and quality control is challenging due to the intricate nature of these components, resulting in scrap rates of up to 20%. Current quality control systems lack fast and automated inspection capabilities, allowing defects to propagate to later stages of production.

NLR has contributed to these projects by employing optical sensors, such as 3D surface scanning, active Infrared Thermography (IRT) and laser shearography for the detection of defects in composite parts [1]. By combining these methods, the structural integrity of an aircraft's outer surface can be quickly assessed, reducing inspection costs and downtime during production and maintenance. Figure 4 shows the demonstration of this concept, gathered as part of the FasterH2 EU project. Here, the overlap joint of the Multifunctional Fuselage Demonstrator (MFFD), an 8 m long by 4 m diameter thermoplastic CFRP part, manufactured under the lead of Airbus [11] is inspected with thermography. While the active time needed to inspect this 8 m overlap joint at a resolution of 0.9 mm/pixel is only 12 minutes, evaluating the thermography inspection data and manually repositioning the inspection jig can take significantly more time. In the next sections, the automation and the synthesis of digital shadow are highlighted to showcase how these technologies help to realize multi-domain inspection in a practical way.

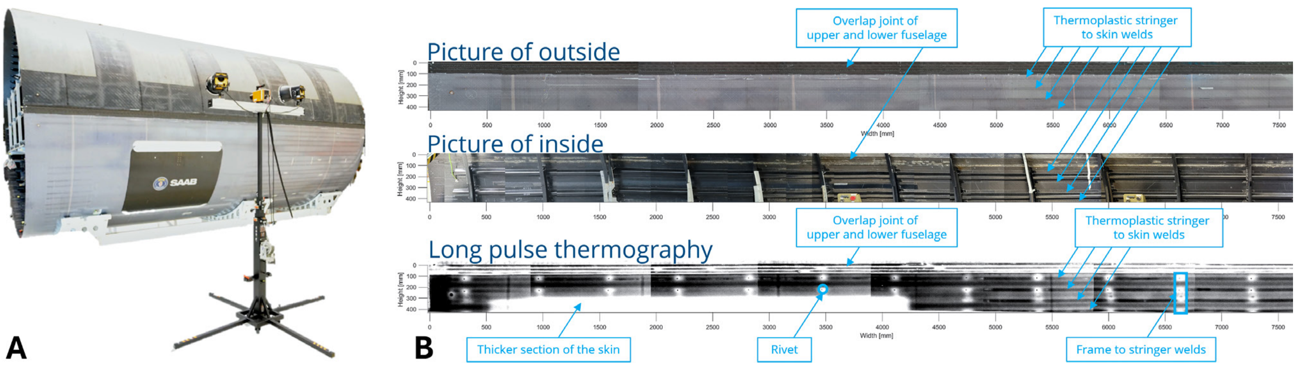


Figure 4. Demonstration of NDT at large scale [5]. Thermography inspection of the overlap joint on the right hand side (RHS) of the Multifunctional Fuselage Demonstrator (MFFD) with (a) a picture of the set-up at Airbus ZAL, Hamburg, Germany, and (b) LPT inspection and corresponding pictures of the inside and outside

Pillar II: Automation

Manufacturing industries increasingly employ automation techniques in their processes to reduce labor costs. In the aviation industry, manual labor is still required in a large part of the manufacturing process, especially in the final product check. This has to do with the relatively low quantity and often highly complex geometry of the product. A shortage of qualified personnel compels industries to adopt automation solutions. However, there are more reasons to implement automation in the inspection process.

Automation of the inspection process is an essential part for the QAC for multiple reasons. Automation takes out the human influence on the inspection process, resulting in more consistent data quality while the inspection time can be reduced. Furthermore, multi-domain inspection requires multiple NDT setups to be employed on a product. With automation, the workload for setting up the sensors and gathering the required data can be lowered. NLR has built knowledge in automation over the years, focusing on the application of the automation technologies, digitalization and qualification of automated inspection for aviation use cases.

In the aforementioned PENELOPE project, NLR has used multi-domain inspection techniques in which automation played a key role in reducing the inspection burden. In this EU project – in which NLR, TU Delft and TNO participated among other partners – NLR has built a pilot automated inspection setup within the SAM XL gantry in Delft, the Netherlands, to inspect CFRP panels in the 8 m long by 4 m wide half-pipe fuselage assembly jig. To simulate full-scale production, three panels were installed in the lower half-pipe fuselage assembly jig. Figure 5 shows a demonstration, see [12] for the online video. The thermography inspection system could be programmed to automatically scan any location in the jig and provide annotated results, which can be fed back into the digital production pipeline. This integrated setup enabled the rapid inspection of large parts. As an example: a 50 m² lower fuselage section can be inspected in just 1.5 hours, which is approximately 10 times faster than using ultrasound C-scan at equivalent resolution which would take around 14.5 hours.

In pillar IV "Automatic Quality Assurance", this use case is further elaborated.

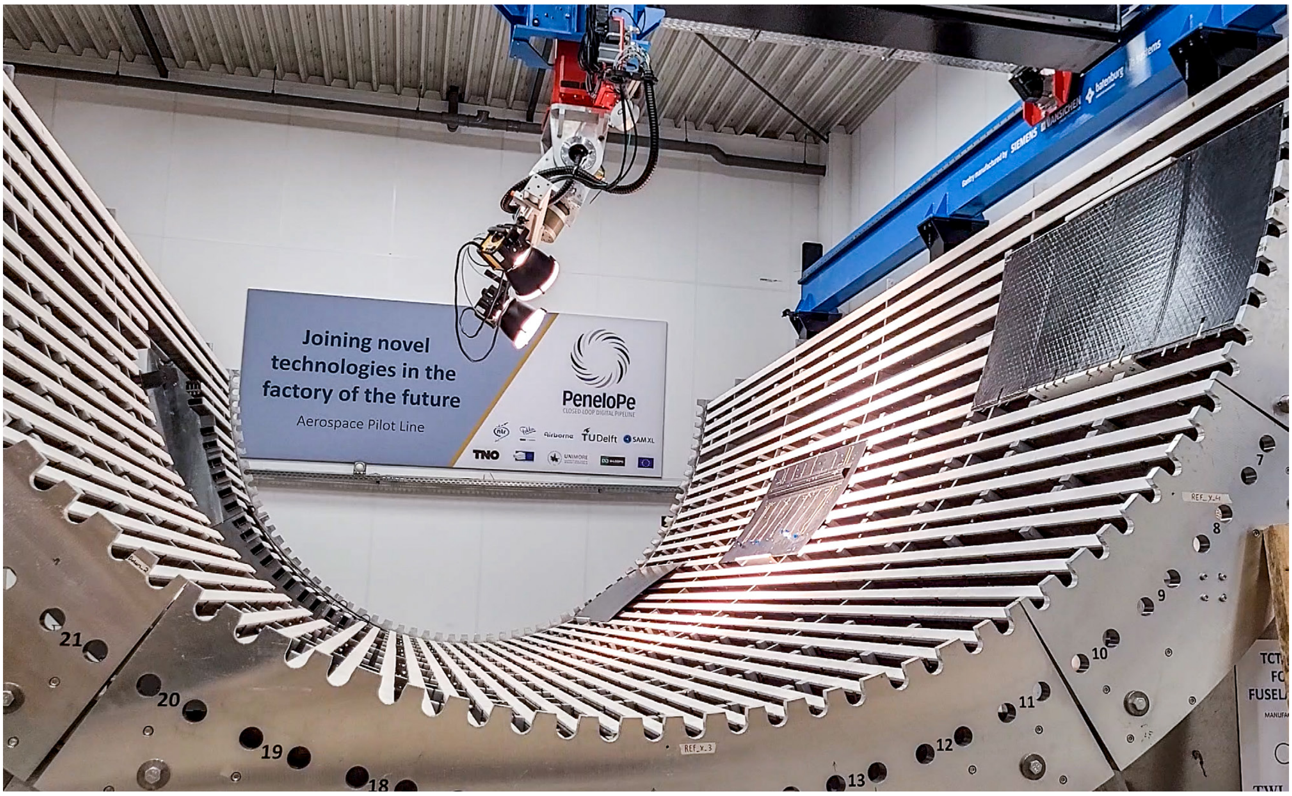


Figure 5. Demonstration of the automated large-scale thermography inspection in the assembly jig of the lower fuselage of the MFFD at SAMXL, Delft [5].

Within the project Automatic Robot for Aircraft Inspections (ARAI), NLR has developed an automated contactless inspection solution for long-shape aircraft structures [13], based on 3D structured light, shearography and thermography. This project aimed to create an automatic, and eventually an autonomous, robotic system capable of inspecting aircraft for damage or wear, reducing the need for manual inspections and increasing efficiency in maintenance operations. Figure 6 shows a demonstration of the ARAI system in which the wing of NLR's Pipistrel electric aircraft is inspected (top two pictures). For an online video, see [14].

ARAI showcases how automation can help inspectors to perform multiple NDT techniques simultaneously without the need to setup the NDT equipment individually. ARAI has been further developed for a customer to replace tap-testing for composite honeycomb-core structure. This is shown in the two bottom pictures of Figure 6, below. Notably, automated active infrared thermography has recently been successfully qualified for this specific application.

In pillar III “Synthesis of Digital Shadow”, this use case is further elaborated.

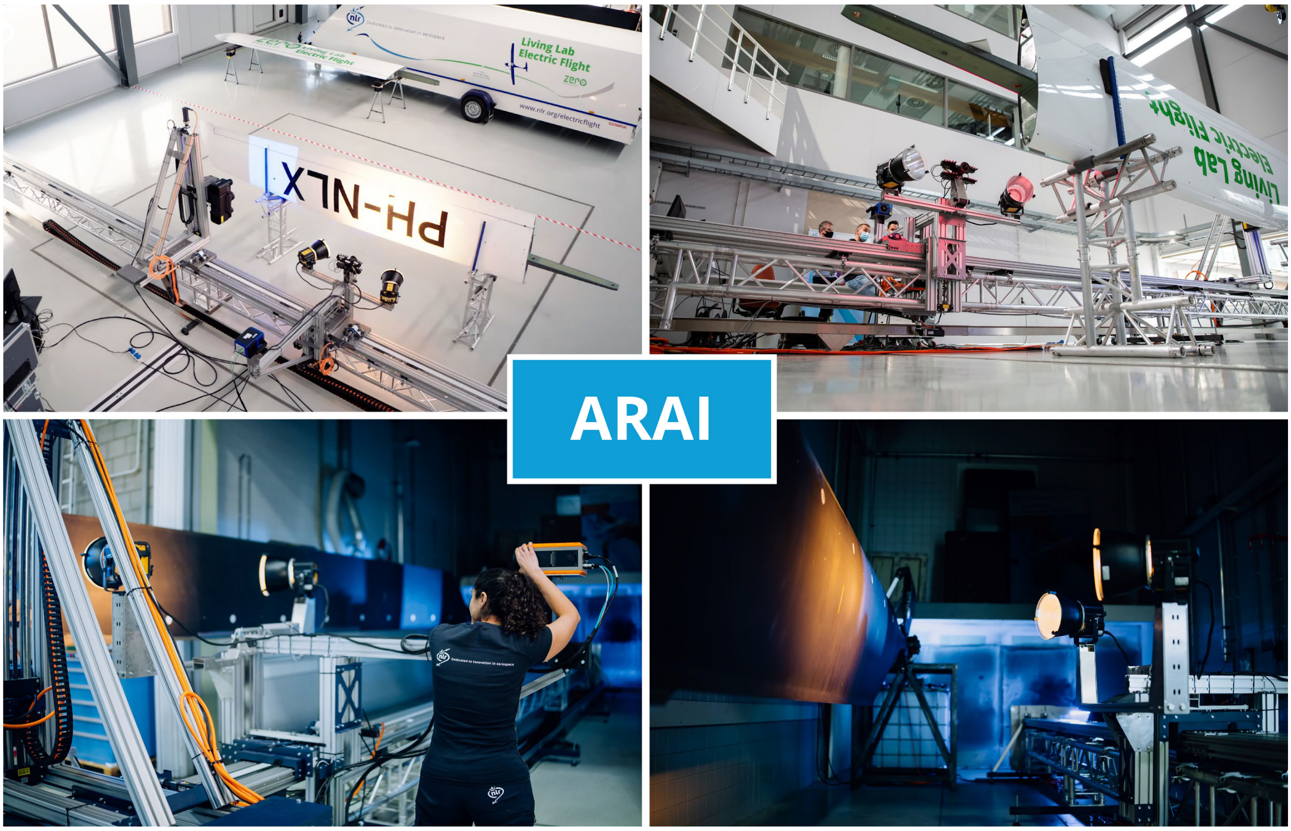


Figure 6. The ARAI. In the above photos ARAI is inspecting the wing of the NLR Pipistrel [13] with an integrated 3D structured light scanner, thermography and shearography. Below, ARAI is shown as developed for a customer.

Within the NXTGEN Hightech project, NLR has developed an automated contactless inspection system for complex-shaped composite structures based on 3D structured light and Laser Ultrasonic Testing (LUT), see [15] for the publication and [16] for the online video. Whereas traditional ultrasonic (UT) systems need an alignment of the transducer with respect to the component’s surface which is accurate to 0.5 degrees, the LUT system can scan at angles of incidence up to 10 degrees. While this 10 degree alignment angle is an improvement over UT, this still limits the applicability of LUT on the many curved components that are used in the aircraft industry. To address this challenge, NLR developed an integrated system consisting of a LUT, a rotation table and a 3D structured light scanner. This integrated system ensures that the angle of incidence of the LUT laser is aligned perpendicularly to the surface of the component at all times. The NLR LUT can automatically acquire a 3D model of a curved component and then obtains the internal structure of the component at multiple angles by scanning the LUT laser across it. This automation allows both the internal structure and the external geometry to be acquired in one swift measurement procedure.

In pillar III “Synthesis of Digital Shadow”, this use case is further elaborated.

Figure 7. The NLR integrated LUT system with the following components from left to right: PC with software, the Zeiss Atos 5 3D scanner, a curved component standing on the marked rotation table and the laser ultrasonic scanner [15].

Pillar III: Synthesis of Digital Shadow

The first two pillars of the QAC concept have shown how the inspection process can be automated using multiple contactless NDT methods. The third pillar is about how the data coming from the previous pillars can be combined together to form a digital shadow of the final product. In this context, a digital shadow is defined as a digital representation of the final product that allows rendering the NDT data and showing the relevant history of manufacturing parameters. The digital shadow can be utilized by aircraft operators as input for their asset management process. Moreover, the digital shadow can also be a means to serve as a central hub where the various data and information coming from sensors, structural design, manufacturing parameters, load and usage information etc. can be merged during its complete life cycle. After data processing, the relevant stakeholders can access any useful information of the product at any time. This section describes NLR's experience on the synthesis of digital shadow.

The project Automatic Robot for Aircraft Inspection (ARAI) showcases how data from multiple NDT methods are integrated into a digital shadow.
The project has yielded a tool to build a digital shadow of the aircraft structure in a consistent manner, enabling maintainers to assess structural integrity, analyse large datasets, and manage assets efficiently. This tool is demonstrated on the NDT inspection data of the wing of the NLR Pipistrel in Figure 8.
Here photos of the exterior of the wing, thermography inspection data and shearography inspection data are projected onto the acquired 3D oriented mesh of the wing. In Figure 8B an exploded view of the NDT data is shown. The ARAI project has the potential to significantly impact the aerospace industry by reducing inspection times, improving accuracy, and enhancing overall aircraft safety, while also providing a unique tool for maintainers to optimise their workflows.

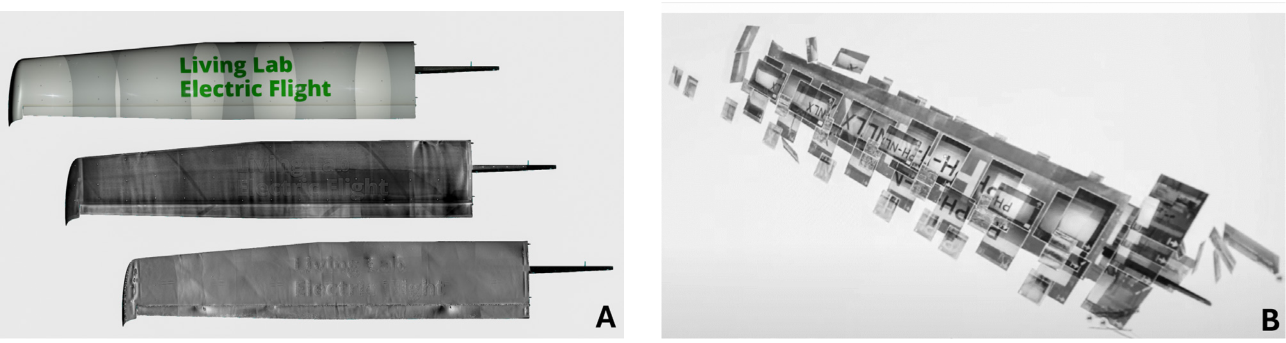


Figure 8. Demonstration of the digital shadow tool developed for the ARAI. (A) NDI inspection data (from top to bottom: photos, thermography and shearography) of the ARAI inspection of the NLR Pipistrel projected onto a 3D mesh of the wing, and (B) Exploded, 3D view of the NDT inspection data.

In the aforementioned NXTGEN Hightech project, NLR has developed an automated approach for the integration of two different types of NDT data into a digital shadow. To enable the integration, a rotation table with unique markers is used when gathering the NDT data, see Figure 9A. The integrated NLR LUT system first generates a digital representation of the surface of the component, see Figure 9B, using a 3D scanner. This 3D digital representation can be checked against previous scans or a CAD model to inspect for surface defects, such as dents. Next, the internal structure of the component is scanned using a LUT, while the system uses the markers on the rotation table to immediately project the inspection data in the 3D oriented mesh environment. A demonstration is given in Figure 9C, where the LUT inspection results show subsurface artificial defects spelling out the words 'NLR NXTGEN' on the interior of the curved component [15].

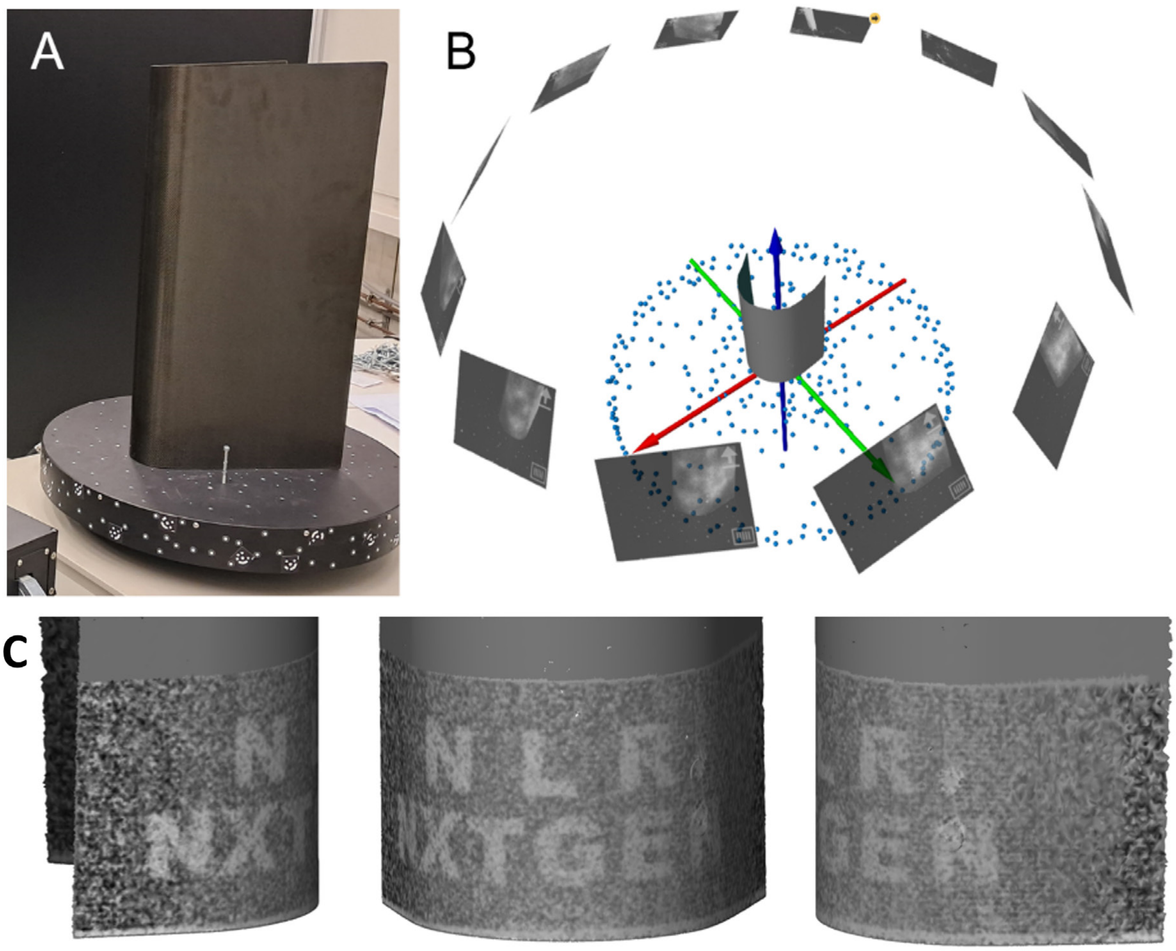


Figure 9. Automated integration of two types of NDT data in the NLR LUT system, with (A) a curved component on the rotation table with unique reference markers, (B) 3D digital representation of the surface of the curved component, and (C) LUT inspection result projected onto the 3D mesh acquired in (B).

The combination of data from different NDT methods into a digital shadow makes it easier to identify and classify different defect types. Another example where NLR is working towards a 3D oriented mesh environment of an object, enhanced with NDT data, providing sub-surface damage information is shown in Figure 10.

A major advantage of mapping the data on the 3D mesh is that the results of the different NDT methods can be easily compared. For example, the depth and location of a dent can be extracted from the 3D scan, while damage inside of the skin can be detected using thermography. Shearography can then be used to detect damage in the skin, skin to honeycomb core disbond as well as damage inside of the honeycomb. If there is no indication in the thermographic data, but there is an indication in the shearography data, damage in the skin can be excluded. This shows the strength of having the same data at the same location. The NDT data shown here is ideally suited for a digital shadow in which all data of a component can be stored.

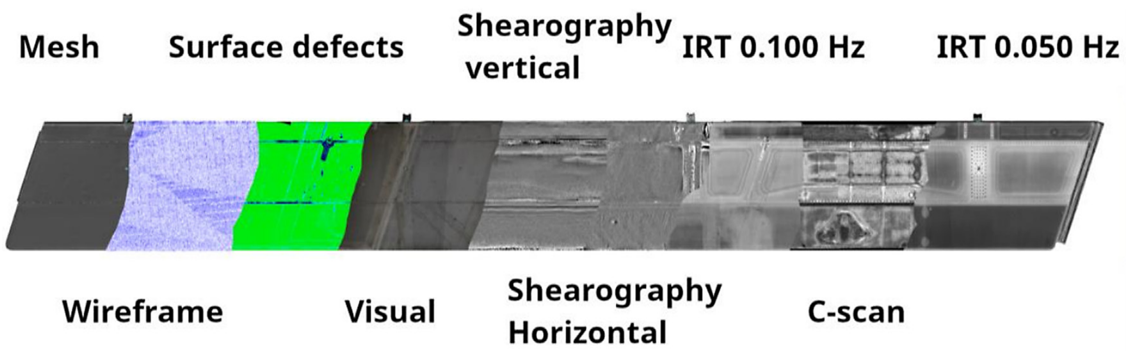


Figure 10. Results of the mapped data of the 747-400 flap showing the bottom side. From left to right, mesh, wireframe, surface defects, visual images, shearography vertical, shearography horizontal, IRT 0.100 Hz, C-scan and IRT 0.050Hz [2].

Pillar IV: Automatic Quality Assurance

The fourth pillar focuses on the final quality check of the final product based on the information gathered from the previous three pillars. This pillar is perhaps least evolved compared to other three. Automatic Defect Recognition (ADR) plays a vital role in the broader framework of QAC for structures. Quality assurance encompasses not only the detection of defects but also the evaluation of their size, quantity, and other relevant factors against predefined rejection criteria or requirements. ADR is a critical component of this process, as it enables the accurate identification of defects, which are then assessed in the context of QAC to determine their impact on the structure's integrity and functionality. By integrating ADR into the QAC, it is possible to automate the evaluation of inspection data, ensuring that structures meet the required standards and specifications, and thereby guaranteeing their safety and reliability.

Artificial intelligence (AI) and machine learning (ML) are increasingly used in ADR to improve the accuracy and efficiency of defect detection. AI algorithms can be trained on large datasets to recognize patterns and anomalies, allowing for automated detection of defects. NLR's expertise in ADR and AI is focused on developing and applying advanced algorithms and techniques to analyze NDT data, such as visual, ultrasonic testing and thermography data. Within the PENELOPE project, NLR has developed a data pipeline to enable AI-based Automatic Defect Recognition (ADR) in composite structures, leveraging machine learning and computer vision techniques, see [17] and [18]. Within the PENELOPE project, NLR explored the use of thermography for defect detection, developing pre-processing methods to remove disturbances and

heuristics for automatic defect detection, see Figure 11. The results show promise, but also highlight the need for additional data annotation and geometry information to improve accuracy.
To address this, NLR investigated the use of simulation-based methods, such as thermal finite element modelling, to generate additional training data and optimize lock-in thermography parameters. This approach has been successfully verified and can be used to extend training and validation datasets for AI development. By integrating AI and data analytics into quality assurance processes, NLR's work in ADR can help improve the efficiency and accuracy of defect detection, ensuring the quality and reliability of composite structures. With its expertise in data pipeline development and AI-based ADR, NLR can support the implementation of automated defect recognition in various industrial settings.

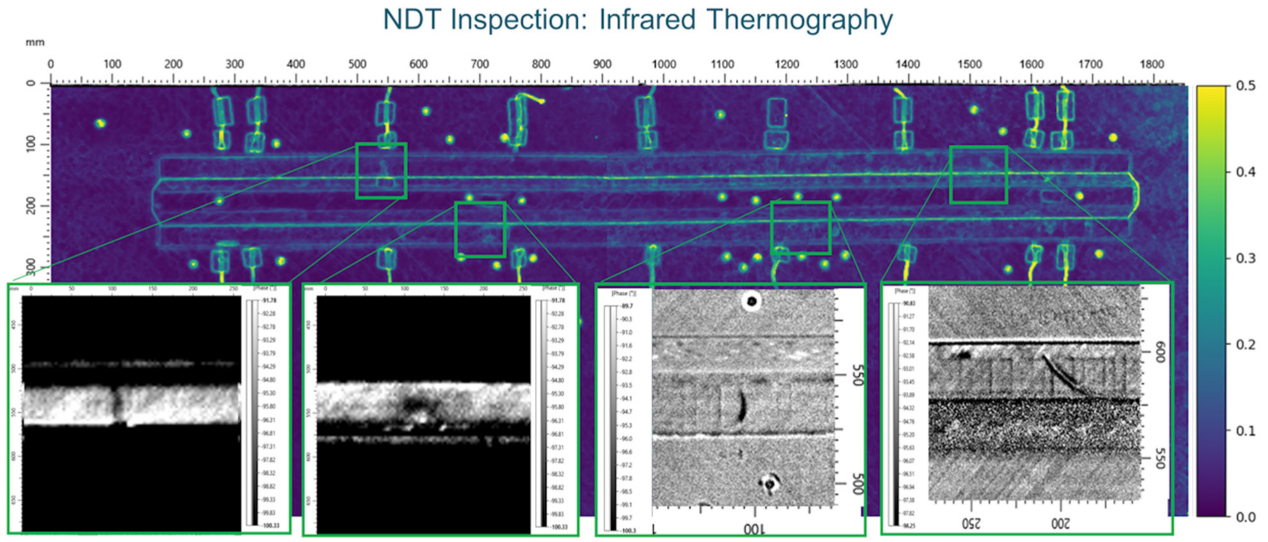


Figure 11. AI-supported detection image of a CFRP panel [17], with zoomed in greyscale IRT results.

Conclusion

NLR's Quality Assurance Cell (QAC) concept offers a comprehensive and scalable solution for ensuring the quality and reliability of composite structures in aerospace applications. By combining contactless Non-Destructive Testing (NDT) methods, automation, synthesis of a digital shadow, and automatic quality assurance, QAC provides a robust framework for detecting defects and ensuring structural integrity.

The four pillars of QAC have been demonstrated through various research projects and industrial collaborations, showcasing NLR's expertise in developing innovative solutions for quality assurance. From contactless NDT methods such as 3D optical measurements, shearography, and thermography, to automation solutions like ARAI, NLR has developed a range of technologies that can be integrated into QAC.

The synthesis of digital shadow enables the combination of multiple NDT data sources into a single digital representation of the final product, providing valuable insights for asset management and maintenance operations. Finally, automatic quality assurance through Artificial Intelligence (AI) and Machine Learning (ML) algorithms enables real-time defect detection and evaluation, ensuring that structures meet required standards and specifications.

The QAC concept has far-reaching implications for the aerospace industry, enabling faster inspection times, improved accuracy, and enhanced safety and reliability. By adopting the QAC concept, manufacturers and maintainers can reduce costs associated with manual inspections, minimize downtime, and optimize their workflows.

As aerospace structures become increasingly complex and demanding, NLR's QAC concept provides a vital and viable solution for ensuring quality and reliability. With its expertise in data pipeline development, AI-based Automatic Defect Recognition (ADR), and automation solutions, NLR is well-positioned to support industry partners in implementing the QAC concept and achieving their quality assurance goals.

In future work, NLR aims to further develop and refine the QAC concept through continued research and industrial collaborations, exploring new applications and technologies that can enhance its capabilities. By working together with industry partners and stakeholders, NLR can help shape the future of quality assurance in aerospace and contribute to a safer, more efficient, and more sustainable aviation industry.

References

[1] H. P. Jansen, D. J. Platenkamp and J. S. Hwang, "Hybrid Inspection Method using Three Dimensional Scanning Lock-in Thermography and Laser Shearography", in Proceedings of the WCNDT, Seoul, South Korea, 5 2024. doi: https://doi.org/10.58286/29892.

[2] H. P. Jansen, D. J. Platenkamp and A. F. Bosch, "Multi-domain contactless NDI approach: Data fusion of structural light scanning with thermography and shearography", in Proceedings of the ECNDT conference, Lisbon, Portugal, 7 2023.

[3] Rademaker, E.R., Jansen, H.P. and Lambrichs, R.B.R.T., "Evaluation on In-Service Laser Shearography for Composite Structures", NLR, Marknesse, Netherlands, NLR-CR-2019-513-RevEd-1, 7 2023.

[4] D. J. Platenkamp, "Evaluation of in-service active thermography for composite structures", Royal Netherlands Aerospace Centre NLR, NLR-CR-2018-365.

[5] D. B. Deutz, A. F. Bosch, D. E. Baptista, E. S. Van Veen, D. J. Platenkamp and H. P. Jansen, "Non-contact NDT methods for large-scale CFRP aircraft parts", Engineering proceedings, 2025, 90(1), 25.

[6] D. B. Deutz, A. F. Bosch, D. E. Baptista, E. S. Van Veen, D. J. Platenkamp and H. P. Jansen, "Non-destructive inspection of large, thin-walled CFRP aircraft parts with infrared thermography", presented at the Measuring by Light Conference, Delft, the Netherlands, 2025.

[7] Rademaker, E.R., Platenkamp, D.J. and Hwang, J.S., "Round Robin Test Results of Laser Ultrasonic Systems on Composite Panels", NLR, Marknesse, Netherlands, NLR-CR-2019-100-RevEd-1, 7 2023.

[8] NLR, "NXTGEN HIGHTECH AVIATION - Laser ultrasonic testing", NLRMedia. accessed: 07-Mar-2025. [Online]. Available at: https://www.youtube.com/watch?v=xwZvjxdgXL4

[9] Deutz, D.B., Jansen, H.P. and Bosch, A.F., "PENELOPE - Zero Defect Manufacturing", NLR, Marknesse, Netherlands, NLR-CR-2022-435, 6 2024.

[10] D. B. Deutz, B. van Elburg, W. Kramer, A. Volker, H. P. Jansen and C. de Miguel, "FasterH2 - D6.2.3-4: Benchmarking of NDI methods", NLR, Marknesse, Netherlands, Clean Aviation project CR-2023-171, 2025.

[11] Y. C. Roth et al., "CleanSky2/Clean Aviation large passenger aircraft for more sustainable commercial fuselage technologies – Major achievements", in Proceedings of the ICAS conference, Florence, Italy, 9 2024. [Online]. Available at: https://www.icas.org/icas_archive/icas2024/data/preview/icas2024_0091.htm

[12] NLRmedia, PENELOPE project. accessed: 16-Oct-2025. [YouTube Channel]. Available at: https://youtu.be/fKudfVvA0oY?si=tnZ1Nu5kU_vSE5qr

[13] NLR, "Robots coming to the aid of aircraft technicians". accessed: 07-Feb-2025. [Online]. Available at: https://www.nlr.org/mro/autonomous-robot-for-aircraft-inspections/

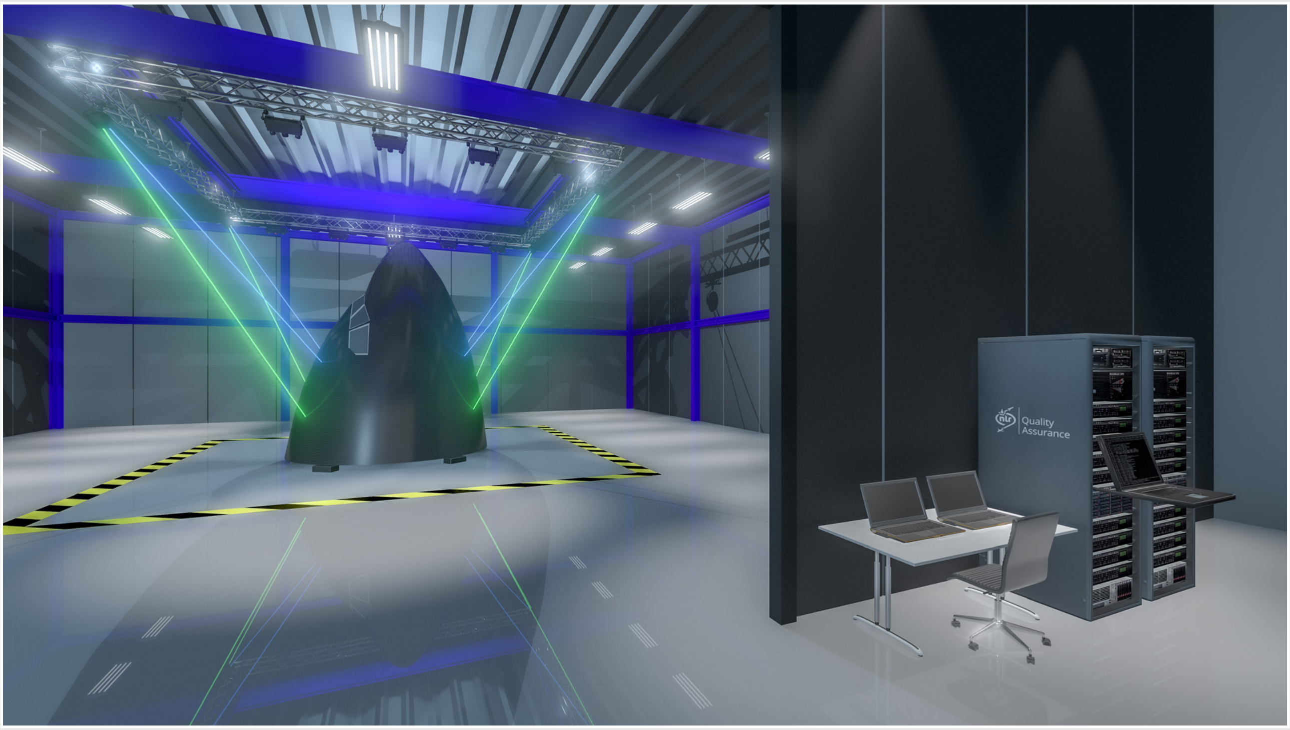
[14] NLRmedia, Autonomous Robot for Aircraft Inspections (ARAI). [YouTube Channel]. Available at: https://youtu.be/JGrOXqHDxSc?si=giaso8HELgvXusI7

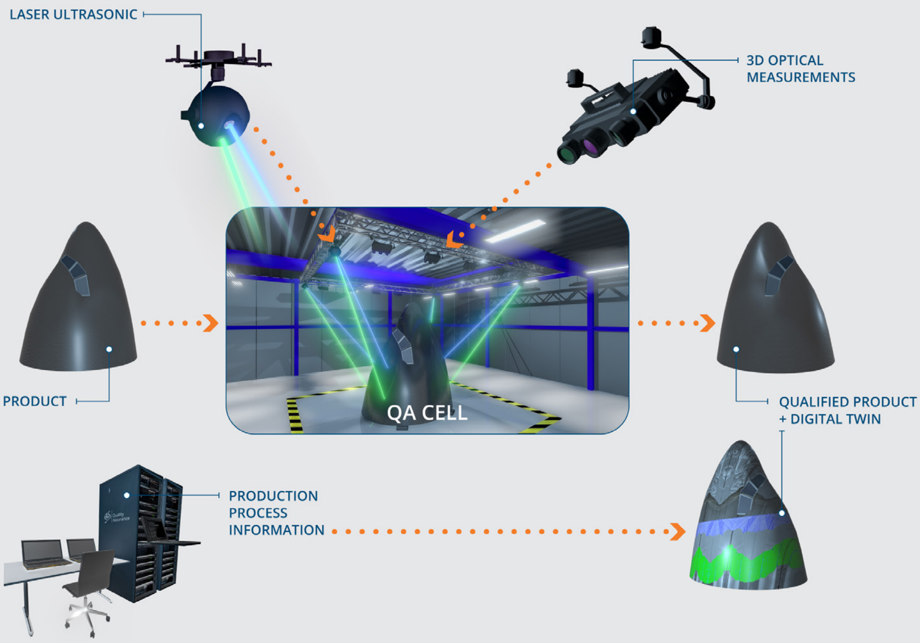
[15] B. van Elburg, W. Kramer, D. J. Platenkamp and H. P. Jansen, "Comparison of Laser Ultrasonic Testing using a Q-switched laser and LDV against traditional Ultrasonic Testing", presented at the Measuring by Light Conference, Delft, the Netherlands, 01-Apr-2025

[16] NLRmedia, NXTGEN HITECH AVIATION - Laser ultrasonic testing. accessed: 16-Oct-2025. [YouTube Channel]. Available at: https://youtu.be/xwZvjxdgXL4?si=aX0Xp0i2GBSPkxi4

[17] Tecnalia, "PeneloPe Work Package 4 Zero-Defect Manufacturing and Cognitive Factory", Grant agreement nr. 958303, Deliverable D4.4, 9 2024.

[18] F. Vidal et al., "PENELOPE White Paper: Novel AI-Based Machinery Certification Methodology", in Zenodo. https://doi.org/10.5281/zenodo.15270158





An impression of the Quality Assurance Cell concept.

Postal address
PO Box 90502
1006 BM Amsterdam, The Netherlands
info@nlr.nl www.nlr.org

Royal NLR
Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
+31 88 511 3113

Voorsterweg 31
8316 PR Marknesse, The Netherlands
+31 88 511 4444

E2176-01