CONCEPT FOR DIGITALISATION OF AN INSPECTION PROCESS USING HYBRID TRACKING OF PART AND PROBE FOR FUTURE MAINTENANCE AND DIGITAL TWINS

A. Wilken*, F. Heilemann*, L. Turgut*, G. Helfrich†

* German Aerospace Center (DLR), Institute of Maintenance, Repair and Overhaul, Hein-Saß-Weg 22, 21129 Hamburg, Germany

† Advanced Realtime Tracking GmbH Co. KG, Am Oeferl 6, 82362 Weilheim i.OB, Germany

Abstract

A transformation towards the digitalisation of maintenance is currently taking place, in which research is also being carried out in the area of inspection. Current literature shows efforts to track the path of an ultrasonic testing probe in various ways in order to link the recorded ultrasonic data with position information, i.e. coordinates.
In most cases, the data is correlated to a part-independent reference system. In this way, however, no direct reference to the part coordinate system is established, which means that a future utilisation potential, e.g. in digital twins, is not fully exploited. In order to use the part itself as a reference, a hybrid tracking system is developed in this work, in which the part is tracked without markers, whereas an ultrasonic testing probe is equipped with passive reflection markers. This makes it possible to assign the sensor data of an ultrasonic inspection directly to the position of origin without having to equip the part with optical markers.
Initial work is being done for the set up and the software development of the system. An experimental evaluation shows the general applicability. In addition, a method for visualising the recorded ultrasonic data using augmented reality is presented.

Keywords

Ultrasonic inspection; Markerbased tracking; Markerless tracking; Hybrid tracking; Maintenance; Digitalisation; Localisation; Automation; Augmented Reality

NOMENCLATURE

Symbols

fps	Frames per second
${}^{0}R_{B}$	Rotation matrix
${}_{(0)}r_{B}$	Translation vector
${}^{0}T_{B}$	Homogeneous transformation matrix

Indices

cam	camera
part	inspected part
probe	UT probe
smarttrack	Smarttrack 3
tree	target tree with passive markers

Abbreviations

6DoF	Six degrees of freedom
AR	Augmented reality
CAD	Computer-aided design
CMM	Coordinate measuring machine
CS	Coordinate system
dnn model	model of a deep neural network
GUI	Graphical User Interface
MBT	Markerbased tracking
MLT	Markerless tracking
NDT	Non-destructive testing
UDP	User Datagram Protocol
US	Ultrasonic signal
UT	Ultrasonic testing

1. INTRODUCTION

The maintenance of tomorrow will be more and more a digitised maintenance. The diagram in Fig 1 from a Scopus analysis shows how up-to-date this issue is. From 2016 onwards, the number of publications is increasing rapidly in the areas of maintenance and digitalisation. Therefore it is important to connect the real

and the digital world in a proper way. Data consistency and data linkage go hand in hand with this intention. Different systems, for example inspection systems, have to be integrated into one data system to make communication between them possible. This is also required for the ongoing digitalisation and automation. This work wants to ensure, that different systems in a maintenance or repair process know the exact defect location on a processed part. The information of where the defect is located on the regarded part is the key in this intention. The manual ultrasonic inspection is chosen to research how an inspection process can be used to generate the important information about the location. This inspection method is highly useful for this purpose, as it is frequently used for inspection in aircraft maintenance.
An example of a future automated repair process is described below. A defect on a part is found by a manual ultrasonic inspection. The generated data and report are stored in a database, potentially in a digital twin of the part. After an automated assessment, a robot or machine has to repair the defect automatically. For this, the information of where the defect is located on the part is needed.

Basically, there are three options to get the location:

- The robot or machine is teached or placed by a human worker
- The robot or machine inspects and measures again by itself
- The location is already saved in the database

The first two options appear to be time-consuming, because an already done process has to be completed or repeated. This paper now examines the third option.

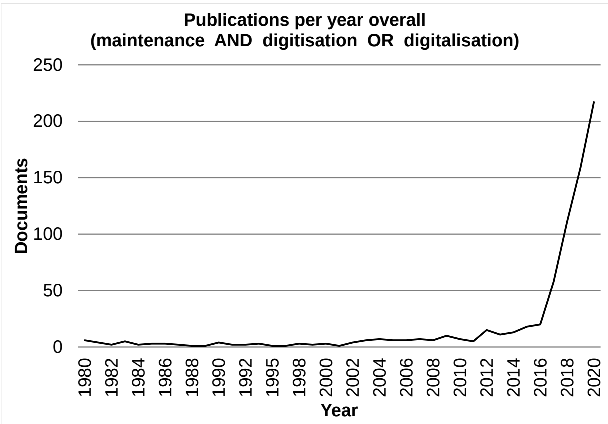

FIG 1. Publications per year

2. STATE OF THE ART

Current literature shows efforts to track the path of an ultrasonic testing (UT) probe in various ways in order to link the recorded ultrasonic data with position information, i.e. coordinates and orientation. First the question has to be answered, where the position of the UT probe can be referenced to. Fig 2 shows common methods of data referencing.

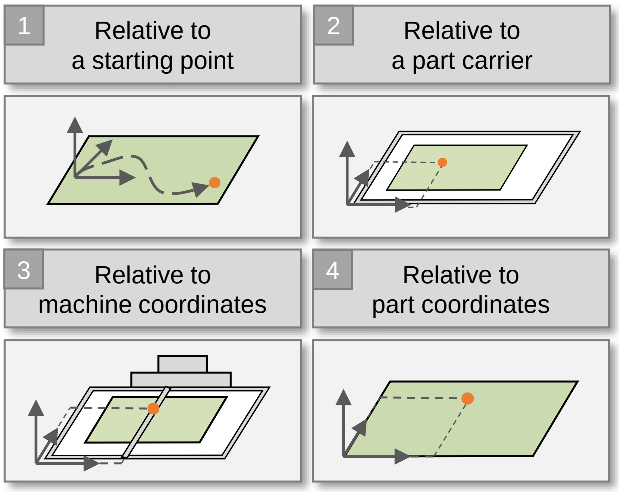

FIG 2. Different methods of data referencing

According to [1] indoor localisation technologies can be categorised by measured physical quantity and used hardware technology. Correspondingly, the methods shown for data referencing can also be described in more detail. For method one, an inspection tool can be localized by using cameras or by using mechanical encoders like wheels or rollers, see [2]. The starting point itself has to be referenced or documented in a proper way.
Method two can be better used for series inspection, because the inspected part is fixed in an individual part carrier. For this method, the UT probe and the part carrier have to be localised and positioned relative to each other. For example, in [3], [4], [5], [6] and [7], a phased array ultrasonic sensor is equipped with passive or active markers to track its pose (6DoF - six degrees of freedom) by an infrared camera system. The part carrier is also equipped with passive or active markers and tracked by an infrared system. Only the system from [8] uses a marker that can be tracked by using visible light.
In [5], which later became the commercial product called WiiPA, the position data is converted into electrical signals to emulate a conventional mechanical encoder. The converted position data is then synchronised with the ultrasonic data. Another way is chosen by [6]. There, a method is shown how a data fusion is carried out with a previously calculated time stamp and interpolations for the position data.
In the shown method three of Fig 2 the ultrasonic data is referenced relative to a machine coordinate system (CS). In [9] a coordinate measuring machine (CMM) is combined with an UT probe. The same principle is used by a 2-axis encoder, see [2] or [10].
All of the shown three methods track the inspection tool and combine the generated data with its position. But none of these methods are able to reference the inspection data relative to a part CS. The resulting major disadvantage becomes clear when the inspected

part is moved or replaced, because the data does not move with the part and remains in place. Only method four can handle this disadvantage, because tracking of the part is executed by a camera system and the inspection data can be referenced relative to the part CS. Therefore, a markerless or feature-based tracking system is needed.

3. HYBRID TRACKING SYSTEM FOR NDT

In the presented approach, capabilities of marker-based tracking of the UT probe are combined with capabilities of markerless tracking of the part. Marker-based tracking (MBT) of the UT probe is fast, robust and with high precision, but without further knowledge about the inspection tool. The MBT system only knows the pose of the tracked body. Here, the tracked body is a self-designed marker tree, which serves as a mount for the used UT probe. Furthermore, the location of the probe contact surface relative to the marker tree has to be calibrated before use. In contrast, the markerless tracking (MLT) is more flexible, because position of the local CS is known after a proceeded training. Another benefit is, that the part does not have to be equipped or modified with markers.
Fig 3 and Fig 4 show the structure and the real setup of the hybrid tracking system used in this approach. Item one shows the markebased tracking system Smarttrack 3, which is an out-of-the-box tracking system, see [11]. In addition, the software DTrack provides position and orientation of the tracked body via a UDP signal.
Item two shows the markerless tracking system CAPTA, which uses a 5 MP industrial camera, see [12]. An additional controler with high performance is needed for processing computer vision algorithms. Position and orientation of the tracked body are also provided via a UDP signal. Both tracking systems are products of the company Advanced Realtime Tracking GmbH & Co. KG.
Item three is the inspected part and item four is the used UT probe, combined with a marker tree of passive markers. The UT probe is connected to the ultrasonic frontend PCUS pro Single by Fraunhofer IKTS (item five). With the support of a LabVIEW VI the ultrasonic data is provided via a UDP signal.
The software DTrack and the LabVIEW VI are running on the laptop item six. All data streams are received, processed and visualised by a software written in Python.

4. ACCESS TO THE LOCAL PART COORDINATE SYSTEM

For accessing the local part CS a CAD model of the inspected part is required, because markerless or feature-based tracking needs to be trained with this information about the CAD model. Nowadays, MLT is state of the art. For exemplary recent publications in this area, see [13] and [14]. This work applies

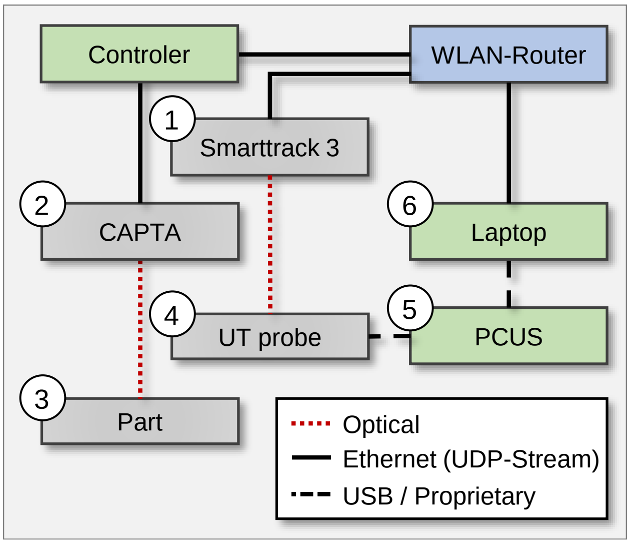

FIG 3. Structure of the hardware setup

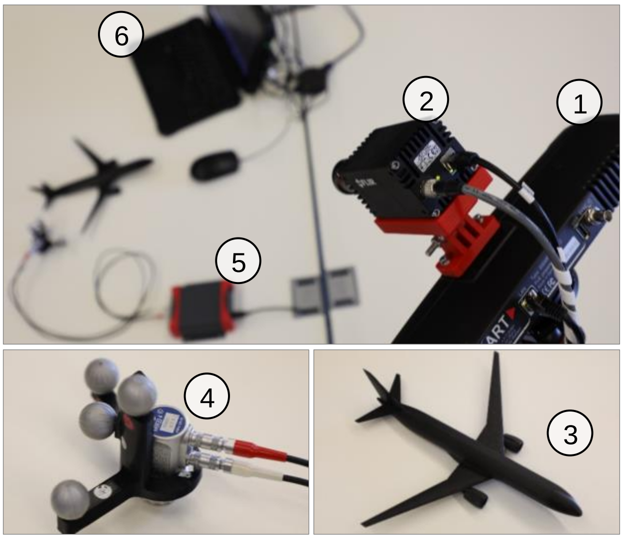

FIG 4. Setup of the hybrid tracking system

the markerless tracking CAPTA, which proceeds a deep-learning based detection and tracking. Technical details are described in [15] (chapter 4.1.1). A requirement for tracking with CAPTA is the presence of a trained deep neural network model (dnn model) and an edge model. To generate these, a CAD model in .stl or .obj format is needed as input. The latter one is needed, if the texture shall be used for training in addition to the geometry. For this status of the project, a 3D model of an aircraft was chosen, whose real part is available by 3D printing, see Fig 5. In this development stage, it is not feasible to generate UT data on this 3D printed aircraft, but the basic functionality of the developed system can be demonstrated.
For localising the UT probe relative to the part CS, transformations and registrations are required. Fig 6 illustrates the necessary steps.
The most important is the registration of the Smarttrack 3 CS ($CS_{smarttrack}$) to the camera CS (CS_{cam}) of the CAPTA system. This is done by a hand-eye calibration. Firstly, the interior orientation of the cam-

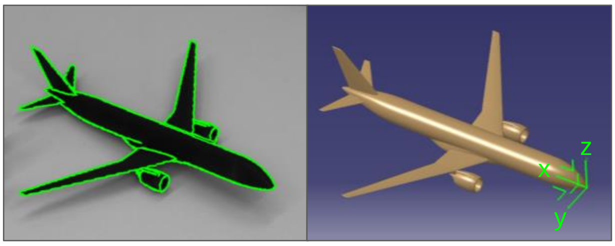

FIG 5. Tracked part (left) and its CAD model (right)

era is determined from a suitable set of images from a Charuco board. Afterwards, the room calibration of the Smarttrack 3 can be registered to the calibrated camera. Finally, the CS of both tracking systems are in the same place.
As already mentioned, the location of the UT probe contact surface relative to the marker tree has to be calibrated. This is implemented by a static transformation from the origin of the marker tree CS (CS_{tree}) to the centre of the UT probe contact surface (CS_{probe}). Needed values for x-, y- and z-translation are measured from a CAD model. Later, a generic calibration must be developed in order to be able to use UT probes of other dimensions. Poses of the UT probe and the inspected part are tracked dynamically, so the following transformation also has to be calculated dynamically. With the help of homogeneous transformation matrices ${}^{0}T_{B}$ (known from robotics), equation (1) can be formulated. In result it describes the pose of (CS_{probe}) in the CS of the part (CS_{part}). Equation (3) shows the structure of a homogeneous transformation matrix, whereby the location of the coordinate system CS_B is described in the coordinate system CS_0. The rotation matrix ${}^{0}R_{B}$ is calculated from euler angles with a xyz-rotation. ${}_{(0)}r_{B}$ is the translation vector. The lowermost line serves for homogenisation of the matrix.

$$(1)\quad {}^{part}T_{probe} = ({}^{part}T_{cam}) \cdot ({}^{cam}T_{tree}) \cdot ({}^{tree}T_{probe})$$

with

$$(2)\quad {}^{part}T_{cam} = ({}^{cam}T_{part})^{-1}$$

and

$$(3)\quad {}^{0}T_{B} = \left(\begin{array}{ccc|c} & {}^{0}R_{B} & & {}_{(0)}r_{B} \\ \hline 0 & 0 & 0 & 1 \end{array}\right)$$

5. SOFTWARE ARCHITECTURE AND DATA VISUALISATION

The software of the Hybrid Tracking System for NDT is realised by using Python 3.8 and PyQt5. As mentioned before, all three data streams were provided via a UDP signal by the individual software. To receive these streams, a UDP server has to be written for each client in separated threads. In PyQt5 it is possible to have these threads working in so called worker threads. Fig 7 shows the architecture of the presented software solution. The three UDP server threads each execute a preprocessing of the received data to send single data sets to the main thread, in which a GUI is integrated. During receiving, each data set gets a timestamp. The sending frequency to the main thread depends on the sending frequency of the data source. Furthermore, no additional filtering is necessary, as the position data and ultrasonic data are already provided preprocessed by the data source.

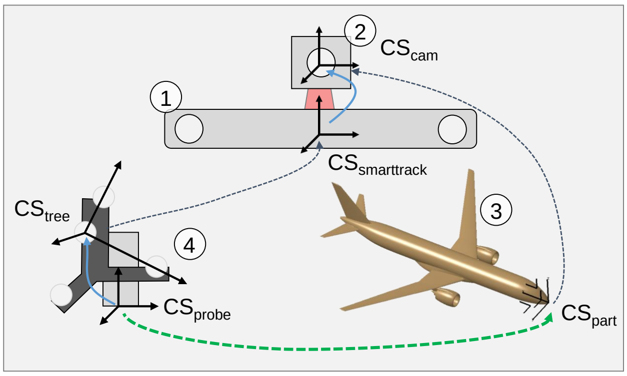

FIG 6. Illustrated transformations in the Hybrid Tracking System for NDT

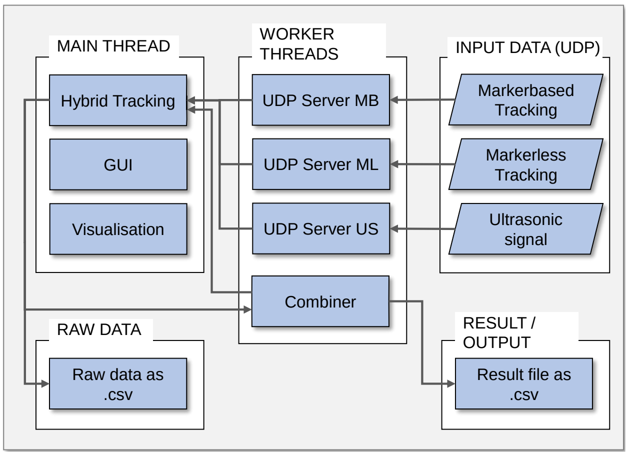

FIG 7. Structure of the written software in Python

In the main thread, a data visualisation is performed in two ways: Display of the received raw data in text fields and visualisation of the position and ultrasonic data on the 3D model of the inspected part. In addition, the raw data of each UDP stream is saved in a .csv file. Each data set is then sent to an additional worker thread, called "Combiner", where the three data sets are synchronised and combined. The slowest part (the markerless tracking system with approximately 10 fps) determines the overall speed of synchronisation. Every time a data set of the markerless tracking system is received by the combiner thread, the most recent data set from the markerbased tracking system and the ultrasonic system are taken to combine them to one single data set, which is sent back to the main thread. Now the combined data set is saved in a .csv file and the

data is visualised in the GUI. For future development steps, an advanced data structure than that of a .csv file can be considered.
The scatterplot in Fig 8 visualises the inspection data that is now mapped to the surface of the aircraft with respect to the aircrafts coordinate system CS_{part}. During this experiment, the UT probe was guided along the wing leading edges and the roof of the aircraft. It can be seen, that the data is now aligned with the aircrafts wing and fuselage. This position data is the result of the several transformations described before in chapter 4. The next step is to record UT data on metal parts and to visualise the data in the same plot. This however requires a 3D model of the inspected part for markerless training.
The output file contains a timestamp, the transformed position (x, y, z), all nine values of the transformed rotation matrix, the header and the samples (for A-scan) of the UT data.

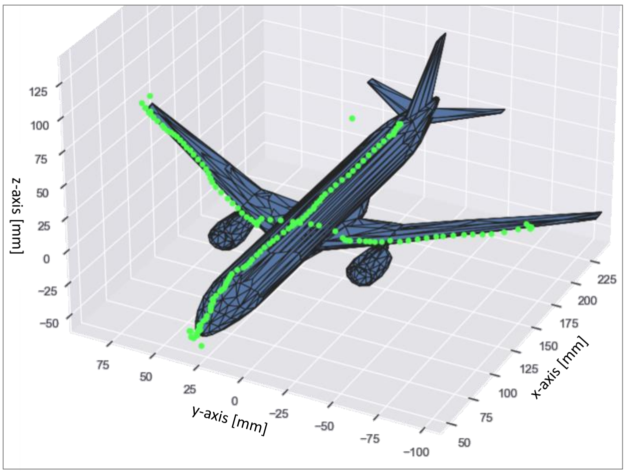

FIG 8. 3D model of the inspected part overlaid with position data of the UT probe

6. FIRST VALIDATION OF THE TRACKING PRECISION

In order to give an accuracy statement, the developed system has been evaluated with respect to repeatibility. The accuracy and the precision of the tracking performance is significant for the quality of the localised data. Thus a validation process has to be carried out, which is executed in accordance to [16]. For this work, the robot UR10e serves as a linear axis, because of its high repeatability accuracy of $\pm$ 0.05 mm. The tracked body within the robot gripper is placed in the center of the tracking systems field of view and with a distance of about 1 m to the tracking systems. The test setup is shown in Fig 9.
One test run is executed for each tracking system (markerbased and markerless). The tracked bodies are the UT probe marker tree for MBT and the 3D printed aircraft for MLT. The robot arm moves the gripper with the tracked body 25 times in a linear translation of 300 mm in every direction of the x-, y-

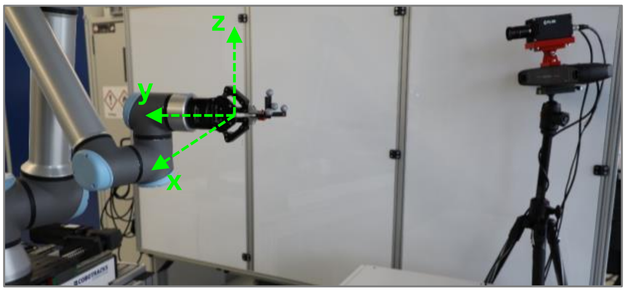

FIG 9. Test setup for validation of the tracking precision

	UT probe marker tree			
Axis	UR10e	MBT	[Diff.]	MBT-STD
+x	300.01	300.71	0.69	0.02
-x	300.00	300.78	0.78	0.02
+y	300.00	300.82	0.82	1.05
-y	300.01	300.44	0.44	0.04
+z	300.01	300.59	0.58	0.04
-z	300.00	300.59	0.59	0.03
Mean	300.01	300.66	0.65	0.20

TAB 1. Distances and standard deviation of the MBT of the UT probe marker tree in mm

and z-axis. The averaged results are shown in Tab. 1 for the MBT and in Tab. 2 for the MLT.
The start and end point of the UR10e are read from the robot, so that the distance can be calculated. They show a high accuracy and reliability. Values of the MBT and MLT are calculated from the position data, sent over UDP to a test software.
For the MBT in Tab. 1 a mean difference of 0.65 mm over all axes is reached, which is quite good for an optical tracking system. Note that the tracked UT probe marker tree has a maximum distance of around 45 mm between two marker balls. So it is a small object, which is difficult to track for the tracking system, compared to commercial marker trees. The values for standard deviation are not above 0.04 mm, with one exception for the positive y-direction (away from the tracking system), which shows a deviation of around 1 mm.

	Inspected part (aircraft)			
Axis	UR10e	MLT	[Diff.]	MLT-STD
+x	300.01	299.39	0.62	0.20
-x	300.00	300.10	0.10	0.06
+y	300.01	304.74	4.73	0.54
-y	300.01	307.64	7.62	0.39
+z	300.00	300.48	0.48	0.07
-z	300.01	300.91	0.90	0.10
Mean	300.01	302.21	2.2	0.23

TAB 2. Distances and standard deviation of the MLT of the inspected part in mm

For the MLT in Tab. 2 a mean difference of 2.2 mm over all axes is reached. It is noticeable that the maximum deviations of around 4.5 and 7.5 mm arise in the y-axis (increasing and decreasing distance to the tracking system). This seems to be a weakness of the monocular camera system of the MLT, but the exact cause of this inaccuracy has to be researched. By leaving the values of the y-direction away, the mean deviation improves to around 0.53 mm, which is a better result as of the MBT.
These values are only one element in the hole chain of error, which needs to be analysed in more detail.

7. VISUALISATION WITH AUGMENTED REALITY

Before developing the hybrid tracking system, a tracking system to localise ultrasonic data with reference to a part carrier was realised. For that purpose, a part carrier was equipped with passive markers. The inspected part is a rectangular acrylic glass plate with a DLR logo engraved. The UT probe has the same marker tree as mentioned before. Part and probe positions are tracked by the markerbased tracking system Smarttrack 3. Transformation and data combination allow to reference the position of the UT probe relative to the part carrier coordinate system. The position is then combined with ultrasonic data. This system is comparable to the mentioned references from method two in chapter 2 and can be seen in Fig 10.
After localising the ultrasonic data, the data stream is sent via WLAN and UDP to the augmented reality (AR) device MS HoloLens 2. This allows an overlay of the part with its inspection data. One example of a D-Scan can be seen in the upper right corner of Fig 10. This D-Scan is live displayed in the MS HoloLens 2 and illustrates the thickness of the part by converting the ultrasonic measurements into a colored visualisation. By using an augmented reality device, there is a high potential for a better data interpretation, because of the overlay of the part with the generated measured values. Complete coverage of the part can also be ensured better in this way, because the UT probe path is visualised. Another example of a head mounted display integrated in a localisation system is presented in [7]. But in this example, the localised data is referenced to a virtual coordinate system.
Because the MS HoloLens 2 has its own inside-out tracking, it is challenging to integrate this device into an external outside-in tracking system like the Smarttrack 3. Thus, the holographic visualisation via AR is positioned with the help of a QR code, like it is done in [10]. The next steps are to integrate the MS HoloLens 2 into the external tracking system by equipping the device with a marker tree. In addition, the QR code for positioning the visualisation should be removed by integrating the AR visualisation into the hybrid tracking system.

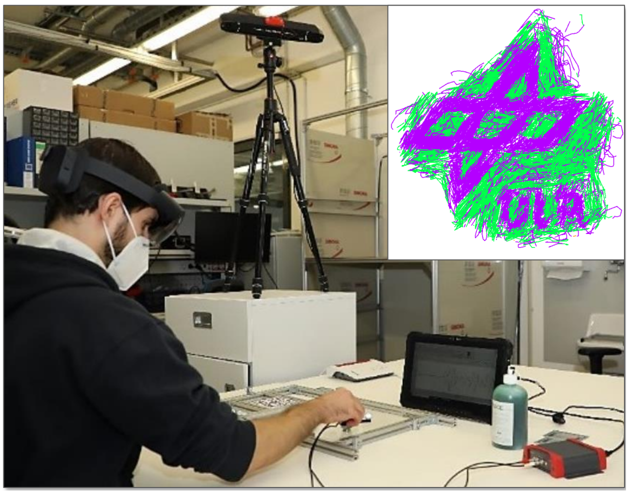

FIG 10. Visualisation of ultrasonic data

8. EXEMPLARY FUTURE APPLICATIONS

The presented hybrid tracking system for localising ultrasonic data offers various potentials for future applications.

8.1. Integration into digital twins

At the DLR, research to develop a digital twin of an aircraft is carried out. Digital twins are a digital representation of a physical or logical object. In [17], an exemplary repair process of a CFRP structure is presented as a basis for the development of a vision for a digital twin.

This repair process contains the following steps:
- Damage detection
- Damage inspection
- Damage assessment
- Repair planning
- Repair execution
- Documentation

In this context, the presented hybrid tracking system can be considered primarily as a measurement system for localised inspection data whose information should be stored. By storing the generated information on a layer of the digital twin, it is possible to make further use of it for advanced assessments, planning, documentation, improvements, etc. An application layer of the digital twin then will enable interaction between real-world objects and virtual ones. For future damage analysis, information about damage type, size, position and geometry can be stored and used.

8.2. Automated defect assessment and repair planning

Automatic damage analysis is another field of application of localised inspection data. For example, the hybrid tracking system can be integrated as an inspection tool in the described process of [18]. There, a new way of damage characterisation and assess-

ment is carried out by predicting structural load and by analysing residual load carrying ability of CFRP structures. In a first step, after detection, the damage is mapped and its contour is localised virtually on the part by its pose. The exact position is important, because the results of the following damage assessment strongly depend on structural features like materials, stiffeners, material thicknesses, holes, and so on. Therefore, an exact damage characterisation is equally important.
For positioning the damage, the hybrid tracking system can be used. In this way, the stored data is localised and referenced to the local part coordinate system. Simulative analyses in this way do not require any further positioning or transformation of the inspection data. However, a requirement is to perform training for markerless tracking of the part. Thus, a 3D model of the inspected part is needed.
Another advantage is the possible superimposition with other inspection data. In [19], another localisation system for inspection data is shown. But this system is used on two different inspection methods on the same part: on the one hand thermography techniques and on the other hand ultrasonic inspection. By combining these two kinds of inspection data, damage characterisation could be more precise.

8.3. Inspection of wall thickness on turbine blades

When maintaining turbine blades of aircraft engines, many process steps have to be carried out. This example deals with the first-stage turbine blades, which have a complex system of coatings and cooling air ducts, because they have to withstand enormous thermal and mechanical loads. The repair and inspection of these parts is therefore just as complex. One inspection step is the measurement of remaining wall thickness on the leading edge, suction and pressure side of the airfoil.
This is done mostly manually by a human worker using an ultrasonic device. A measuring mask is put over the blade to indicate the measuring points with the help of openings in the mask. Still it is challenging to interpretate the measurement results correctly, because turbulators, cooling holes or cooling air ducts can lead to a higher or lower indicated wall thickness. Fig 11 shows a x-ray image of an exemplary turbine blade.
The wall thickness is measured several times during the repair process. By localising the measurements with the hybrid tracking system, it is possible to display changes in wall thickness during the repair progress. This can allow for a better understanding for single repair steps, for example for the manual blending process of the leading edge. Furthermore, the data serves to build up a documentation.
Another great benefit would be a live visualisation of the ultrasonic data by using an augmented reality device. The ultrasonic data can be visualised directly on the part and similar to it, a 3D model of the inspected part ca be visualised overlaid to the real part, which allows an inside view. Thus a much better interpretation of the ultrasonic signal is possible and the measuring mask can be omitted if applicable.

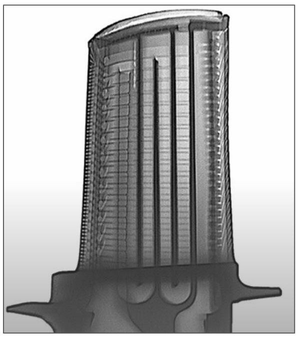

FIG 11. Turbine blade with cooling air ducts [20]

8.4. Collaborative work with mobile robots

The last example in Fig 12 shows the hybrid tracking system in a stationary way mounted on the ceiling, and illustrates the collaborative work of a human and a mobile robot. The human worker wears an AR device and executes a visual inspection of a part. After detecting a visible defect, he can flag the region with a markerbased tracked measurement tool on the markerlessly tracked part. So the flagged defect position is localised relative to the local part CS and can be stored on a proper data platform.
An inspection command can now be sent to a mobile robot, that is also operating in the hybrid tracking system. In this way, the robot knows the defect position on the part without an individual teaching or placing step and can execute the inspection. The recorded data is also localised and can be stored in the same data platform. In this way, a damage history of the part can be generated, as a digital twin would make it possible. At this point, there is an intersection to the automated defect assessment and repair planning example. The repair execution and final inspection can be proceeded by the robot in the same way as described before.

9. CONCLUSION AND OUTLOOK

A novel inspection concept and system for localisation of ultrasonic data was developed and presented. It combines markerbased and markerless tracking capabilities to allow inspection data referencing relative to the local part coordinate system. It is possible to set up a smaller mobile system for smaller parts or to use a stationary ceiling system for bigger parts. Basic functionality of the localisation method was proven and a first validation of the accuracy of the tracking systems was carried out. A data visualisation by using an augmented reality device was shown on a preliminary stage of the current hybrid tracking system.
Four examples with a high application potential for the presented hybrid tracking system were examined.

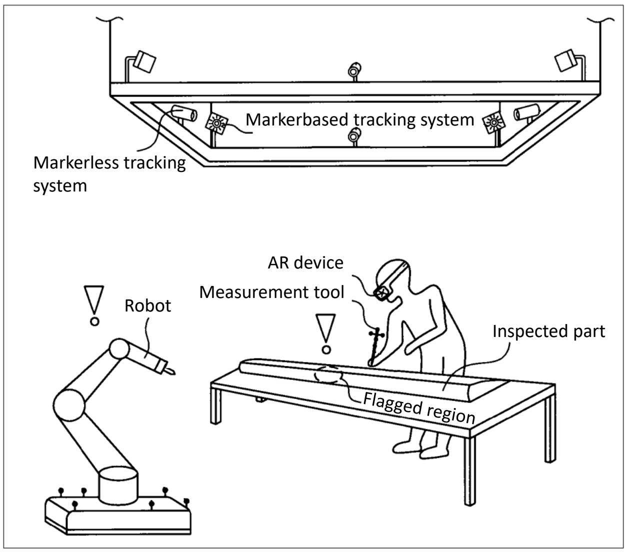

FIG 12. Collaborated work with a mobile arm robot [21]

Both the use in future digital twins, as well as the application of the generated inspection data for automated defect assessment and repair execution show a high applicability for the maintenance of tomorrow. An assistance for manual ultrasonic inspections is an additional benefit that can be realised by the presented inspection system.

Further research and development will improve the current system. The most important step is to train further parts for markerless tracking to record ultrasonic data on real parts. One of them will be a part for validating the localisation accuracy. It will have drilling holes with exactly defined positions, diameters and depths. Also a parametric study about the tracking accuracy will be carried out with the help of the presented robot. It is further necessary to examine whether industrial requirements with regard to accuracy are fulfilled by the system presented.
The chain of error, system requirements, risks and benefits will be analysed in more detail. In addition a user study will evaluate the applicability and usability of the system.
The presented exemplary applications will be analysed and described in more detail and the transferability of the hybrid tracking system to other inspection methods will be examined. Afterwards, the construction and evaluation of a future repair process with the hybrid tracking system has to be carried out. Parameter like process time, applicability, profits about the extended data basis, etc. will be examined.

Contact address:

andreas.wilken@dlr.de

References

[1] Jorge Torres-Solis, H. Tiago Falk, and Tom Chau. A review of indoor localization technologies: towards navigational assistance for topographical disorientation. In Felix Jesus Villanueva Molina, editor, *Ambient Intelligence*, pages 51–84. IntechOpen, 2010. DOI: 10.5772/8678.

[2] Martin Schickert, Christian Koch, and Frank Bonitz. Augmented-reality-visualisierung von abbildungsergebnissen an betonbauteilen – implementierung und ausblick. *DGZfP MTHz 2019*, 2019.

[3] André Lamarre and Jason Habermehl. Dynamic tracking or ultrasonic probe and real-time volumetric ray-tracing as a support to manual phasedarray inspection of complex components. *11th European Conference on Non-Destructive Testing,*, 2014.

[4] Borja Lopez. Camera encoded phased array for semi-automated inspection of complex composite components: Camus 3d. *Nondestructive Evaluation of Aerospace Materials & Structures 2018 (ASNT)*, 2018.

[5] Fernando Lasagni, Santamaria, Maria de la Luz, Francisco Alarcon, Javier Aldea-Arevalo, Sergio Hernandez-Ruiz, Sebastian Hernandez-Serrano, Antonio Jimenez, and Antidio Viguria. C-scan ultrasonic generation using wireless encoder based on passive markers. *6th International Symposium on NDT in Aerospace*, 2014.

[6] Robert Schmitt, Philipp Nienheysen, Nico Lehmann, Hamid Jahangir, Martin Peterek, and Thomas Neuenhahn. Digitalized ultrasonic inspection by optical tracking. *2019 IEEE/SICE International Symposium on System Integration (SII)*, 2019.

[7] Robert Deppe, Oliver Nemitz, and Jens Herder. Augmented reality for supporting manual non-destructive ultrasonic testing of metal pipes and plates. *Virtuelle und Erweiterte Realität – 15. Workshop der GI-Fachgruppe VR/AR*, 2018.

[8] 3d-smartinspect: Intelligente prüfüberwachng und -dokumentation durch optisches trackingsystem für ultraschall- und wirbelstromprüfung. `https://www.izfp.fraunhofer.de/content/dam/izfp/en/documents/2017/3D-SmartInspect-en.pdf`, 2017.

[9] Us 7921575b2 method and system for integrating ultrasound inspection (ut) with a coordinate measuring machine (cmm). US 7921575B2, 12.04.2011.

[10] Jean Meyer, Jörg Rehbein, Jens de Freese, and Jens Holtmannspötter. Visualisation of ultrasonic testing data using augmented reality. *7th International Symposium on NDT in Aerospace*, 2015, 2015.

[11] Smarttrack3 | advanced realtime tracking gmbh & co. kg. `https://ar-tracking.com/en/product-program/smarttrack3`, 2021.

[12] Products in connection with the software capta | advanced realtime tracking gmbh & co. kg. https://ar-tracking.com/en/product-program/products-connection-software-capta, 2021.

[13] Manuel Stoiber, Martin Pfanne, Klaus H. Strobl, Rudolph Triebel, and Alin Albu-Schaeffer. A sparse gaussian approach to region-based 6dof object tracking. *ACCV 2020*, 2020.

[14] William Tarimo, Moustafa M.Sabra, and Shonan Hendre. Real-time deep learning-based object detection framework. *2020 IEEE Symposium Series on Computational Intelligence (SSCI)*, pages 1829–1836, 2020. DOI: 10.1109/SSCI47803.2020.9308493.

[15] Werner Schreiber, Konrad Zürl, and Peter Zimmermann. *Web-basierte Anwendungen Virtueller Techniken*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2017. ISBN: 978-3-662-52955-3. DOI: 10.1007/978-3-662-52956-0.

[16] Qianqian Cai, Chang Peng, Juan C. Prieto, Alan J. Rosenbaum, Jeffrey S. A. Stringer, and Xiaoning Jiang. A low-cost camera-based ultrasound probe tracking system: Design and prototype. *2019 IEEE International Ultrasonics Symposium (IUS)*, pages 997–999, 2019. DOI: 10.1109/ULTSYM.2019.8925631.

[17] Robin Schmücker, Hendrik Meyer, and Florian Raddatz. Digitalization and data management in aircraft maintenance based on the example of the composite repair process. *DLRK 2021*, 2021.

[18] Christoph Paul Dienel. *Damage Assessment for Composite Structures based on Individual Residual Strength Prediction*. Dissertation, Technische Universität Braunschweig, Braunschweig, 05.09.2019.

[19] Samuel Soldan, D. Ouellet, P. Hedayati, H. Bendada, D. Laurendeau, and Andreas Kroll. Mapping non-destructive testing data on the 3d geometry of objects with complex shapes. *12th International Conference for Quantitative InfraRed Thermography (QIRT 2014))*, 2014.

[20] Yxlon - luft- und raumfahrt. https://www.yxlon.de/de/applikationen/luft-und-raumfahrt, 2021.

[21] Andreas Wilken and Florian Raddatz. Verfahren und system zum registrieren eines konstruktionsdatenmodells in einem raum: Offenlegungsschrift. DE102019110185A1, 2020.