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3D-Forensics/FTI –
Mobile high-resolution 3D-Scanner and 3D data analysis for forensic evidence fast track to innovation

Developmental Validation of the 3D-Forensics system

Document Information	
Authors:	S. Crabbe – Crabbe Consulting Ltd (CCLD) M. Lucas – LUCAS instruments GmbH (LUC) R. Ramm – Fraunhofer IOF (IOF) M. Sgrenzaroli – Gexcel Srl (GEX)
Lead by:	CCLD
Prepared by:	ALL
Reviewed by:	ALL
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PP = Restricted to other programme participants (including the Commission Services).
RE = Restricted to a group specified by the consortium (including the Commission Services).
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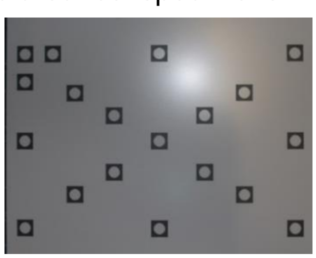
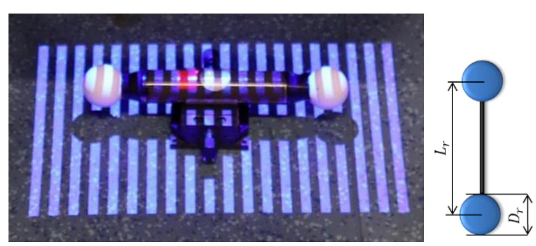
SUMMARY: This report contains the final results on developmental validation in the 3D-Forensics/FTI project. These results were carried out by the consortium and members of the associated EETG (External Expert Tester Group).

Document Evolution			
Revision	**Date**	**File Reference**	**Reason of change**
Rev. 1_0	08/04/2020	3DFFTI_RPT_DV_V1_0	Initial creation based on internal D4.3 report.
Rev. 1_1	04/09/2020	3DFFTI_RPT_DV_V1_1	Additional clarifications, added to pages 25, 90, 161 and 162.

Contents

1 Terms and definitions

Term	Definition
3D point cloud	A large set of 3D points each with X, Y, and Z component, in this context an ordered 3D point cloud is captured which means that the 3D points are ordered in rows and columns.
Accuracy	Agreement between accepted and obtained values, here in the context of distance measurements.
Authentication	The data is an accurate presentation of what it purports to be.
Calibration (in context of 3D sensors)	Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties. In the context of multi camera based 3D sensors the calibration includes the intrinsic characteristics of the optical elements (magnification, distortion, decentering) and the external relative orientation between the cameras (translation, rotation). In this 3D-Scanner the two stereo cameras and the external photo apparatus are calibrated elements.
CJS	Criminal Justice System.
Colour mapping	The photo is projected onto the 3D data by geometrical constraints.
DV	Developmental validation.
Examination / Observation	Specification can be validated through: ▪ Reference to the properly implemented design definition; and/or ▪ Implementation of already established/validated methods which are referenced; and/or ▪ Visual (generally) validation. Validation is based on human factors, or uses very common and passive means like microscope, gauge, …
Integrity	The data (image etc.) presented is complete and unaltered since time of acquisition.
Length measurement error (LME)	Evaluation of 3D accuracy in terms of distance error of known points with calibrated test specimens:  Circle board Positional deviations of circle centres  Ball distance normal Distance between sphere centres

Term	Definition
Measurement uncertainty	Variance of measurement results, typically expressed as standard deviation Measurement uncertainty is given by confidence interval for p = 0.95 Equation: ±U = ±tα * s Where: tα is the Student-factor considering the number of measurements e.g. for 10 measurements (with p=0.95) it is 2.228; and s is the standard deviation over the number of measurements. We always assumed that the measured values followed a Gaussian normal distribution. The confidence interval for p = 0.95 implies that 95% of observations fall within the range ±U and about 5% should be expected to be outside. This means that if a certain length (e.g. shoe size) was measured in the 3D data to see whether it matches with a certain reference length, and the true value of the length was outside that range, although unlikely, an outright exclusion of such an outlier would probably be incorrect. Using a larger confidence interval increases the probability, e.g. Six Sigma (6 times the standard deviation) would increase it to 99.99966%. Also performing repeated measurements of the same issue would increase the likeliness.[1] Applying the above by way of example, in the “Test Case 9 Measurement Reproducibility” reported in section 9.4.2, 10 users measured the same length in the analysis software. For all of the ten individual measured lengths, the range given by the individual measured length +/- 0,391mm was 95% likely to include the “true” length. In the results, the “true” univocal length was within the range of all the 10 individual measurements +/- 0,391mm. In the case that the distance measurement would be performed 100 times, measurement uncertainty predicts about 5 of those measurements would not include the “true” length within the ranges given by each of those 5 individual measurements +/- 0,391mm. (*This test case tested the users’ capabilities to measure length and not the intrinsic accuracy of the software to measure. This was also tested and is reported in section 9.4.1.)*
Meshing	The single points in the 3D point cloud are connected by small triangles to create a closed surface. In ordered point clouds this process is supported by the known neighbour relationships between the points.
Precision	Consistency of measurements.
Probing Error	Evaluation of 3D accuracy in terms of form error to calibrated test specimen

[1] See also Forensic Science Regulator, *Guidance: Validation* p41 (FSR, Issue 1, 2014) (Available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/375285/FSR-G-201_Validation_guidance_November_2014.pdf> last accessed 19 July 2018).

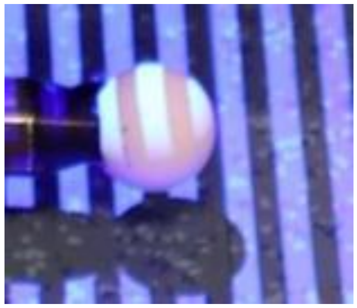
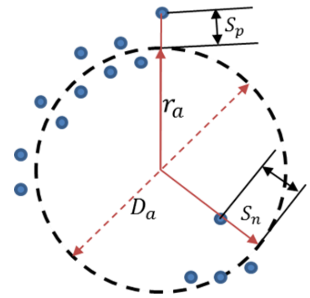
Term	**Definition**
	geometry e.g.:   Form deviation relative to ideal sphere
Range *Lower / upper limit of detection*	Range in which measurement values can be obtained, here in the context of distance range / depth of focus of the 3D-Scanner (ca. 405 … 505 mm).
Registration	Two (or more) 3D datasets are aligned to each other by ICP algorithm (Iterative closest points).
Repeatability	Repeatability measurement precision under a set of repeatability conditions of measurement (same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time).
Reproducibility	Reproducibility measurement precision under reproducibility conditions of measurement (different locations, operators, measuring systems, and replicate measurements on the same or similar objects).
Resolution	Smallest distance needed between two edges to be resolved as separate edges.
Robustness	Efficiency of method to small variations in parameters.
Round robin (in forensic context)	Verification of performance and reproducibility of results.
Specificity	Ability to detect features in presence of other components.
Test	Validation of functional characteristics that can be measured. Test equipment / set-ups are generally required to perform tests.
Validation (in forensic context)	Demonstrate that the technique is fit for purpose.

Table 1: Terms and definitions

2 Introduction

This report describes the 3D-Forensics/FTI system developmental validation carried out by the consortium partners and the associated External Expert Tester Group (EETG) up to the end of June 2019.

Chapter 3 describes framework conditions derived from relevant guidelines and their application for the planning and implementation of the 3D-Forensics/FTI system validation.

Chapter 4 – Chapter 9 describe for the six main system tool functionalities subject to developmental validation:

- The technical principle and reference publications
- Performance limitations, interferences and countermeasures
- Reviewed end user requirements, related specifications and acceptance criteria
- Developmental validation test results – summarised in overview
- Developmental validation assessment for the functionality
- Advice for the implementation of the system tool

The developmental validation results include validation activities carried out by EETG members for reproducibility testing (“Round robin tests”).

Chapter 10 provides conclusions.

Annex 1 describes the system user requirements, specifications as defined at the beginning of the previous FP7 project (2014) and their review culminating in the preparation for developmental validation.

Annex 2 described the 3D-Forensics system’s product specifications as of June 2019.

Annex 3 describes the tests specimens used for developmental validation.

Annex 4 provides the detailed test scenarios and full and final developmental validation results.

3 Validation strategy and procedure

3.1 International and national guideline framework conditions for validation

The goal of validation is to demonstrate and document that the results from the 3D-Forensics/FTI system can be relied upon in forensic science activities connected with footwear and tyre impressions. It is “the process of providing objective evidence that a method, process or device is fit for the specific purpose intended.”[2] Reliability is crucial as the system is to be used in criminal investigations which should lead to the solving of crime and also prosecutions. Without proof of reliability, police organisations are unlikely to adopt the system in any meaningful way and evidence based on it, if submitted to court, risks being judged inadmissible or at the very least of low probative value.

How validation is to be demonstrated and documented for individual organisations varies across the world, also within Europe. It is not the case that all forensic organisations carrying out forensic science activities, and particularly connected with footwear and tyre impressions, must be accredited following international standards. In general, it is however to be recognised that there is an increasing move towards ensuring the quality of forensic science activities through accreditation to international standards.

The international standards most relevant to 3D-Forensics/FTI are ISO/IEC 17020[3] and ISO/IEC 17025.[4]The International Laboratory Accreditation Cooperation (ILAC) provides guidelines on the application of these standards to forensic processes.[5] The United Kingdom’s Forensic Science Regulator (FSR) implements these guidelines in further guidance.[6,7]

The 3D-Forensics/FTI Description of the Action (DoA) indicated that the project would refer to both the guidelines from ILAC and the UK FSR in planning and preparing its validation activities. Further research and analysis, including discussions with members of the EETG and other forensic users, has confirmed this approach remains valid. By targeting the requirements for validation within an accredited process, 3D-Forensics/FTI should satisfy the most stringent validation criteria within any organisation providing forensic services.

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[2] Ibid. p3.
[3] BS EN ISO/IEC 17020:2012, Conformity assessment - Requirements for the operation of various types of bodies performing inspection. <http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=52994> last accessed 18 February 2019).
[4] BS EN ISO/IEC 17025:2017, General requirements for the competence of testing and calibration laboratories (Available at: <http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=39883> last accessed 18 February 2019).
[5] International Laboratory Accreditation Cooperation, *Modules in a Forensic Science Process* (2014) *(*Available at: <http://ilac.org/?ddownload=805> last accessed 18 February 2019).
[6] Supra: FSR/Validation.
[7] Forensic Science Regulator, *Codes of Practice and Conduct for forensic science service providers and practitioners in the Criminal Justice System*, Vers. 4.0 October 2017 (FSR 2017) (Available at: <https://www.gov.uk/government/publications/forensic-science-providers-codes-of-practice-and-conduct-2017> last accessed 18 February 2019) and supra: ILAC/G19 Annex A.

The analysis of the ILAC and UK FSR guidelines identified a number of framework conditions of particular pertinence for the project. These are provided below and were key for the project's validation planning and preparation:

- "Validation is the confirmation by examination and the provision of objective evidence that the particular requirements for a specific intended use are fulfilled"[8]
- "Validation involves demonstrating that a method used for any form of analysis is fit for the specific purpose intended, i.e. the results can be relied upon"[9]
- "Validation is performed against specific and measurable, testable or observable acceptance criteria" (FSR/Validation s.5.5.1)"[10]
- "It is generally the method, the use that something is put to, that can truly be validated rather than any sub-processes, component parts, devices or tools"[11]
- "… it is only those features that have an impact on the result that are likely to be required to be included in the validation"[12]
- "Developmental validation is the acquisition of objective evidence of the fitness of purpose for a new or novel methodology often performed by the developer or manufacturer"[13]
- "Methods that involve the application of commonly accepted scientific theories/principles in an area where it is relatively routine will require far less assessment than methods that apply a new scientific model/theory or apply an existing model/theory in a novel area"[14]
- Footwear impressions comparison to evidential standards is a recognised forensic science activity[15]
- Both the FSR and ILAC identify that manufacturers can carry out validation[16] (*but there is no an indication that validation requirements are then different to what a forensic unit needs to do)*
- FSR says responsibility for validation stays with forensic unit and cannot be transferred to manufacturer, but manufacturer (and other agencies) can produce objective evidence to show method can be relied upon[17]
- FSR and ILAC indicate that "when a method has been validated in another organisation the forensic unit shall review the validation records to ensure that the validation performed was fit for purpose. It is then possible for the forensic unit to only undertake *verification* for the method to demonstrate that the unit is competent to perform the test/examination"[18]

[8] Supra: ILAC/G19 s2.22.
[9] Supra: FSR/Validation s1.1.2.
[10] Ibid. s5.5.1.
[11] Ibid. s3.3.1.
[12] Ibid. s3.3.2.
[13] Ibid. ss4.2.7.
[14] Ibid. s4.4.11.
[15] FSR/Codes Table 1, p7 and supra: ILAC/G19 Annex A.
[16] Supra: FSR/Codes s20.2.1 and ILAC/G19.
[17] Supra: FSR/Validation s1.13.
[18] Supra: ILAC/G19 s3.10 and FSR/Validation s1.1.5.

- "In considering the scientific model/theory in terms of its validity and the limits of applicability, publications in respected scientific journals can usually be relied on."[19] It is "not a requirement that a validation study is published"[20] "Published work deemed relevant and reliable can be used to supplement the performance criteria derived from the end-user requirement/ specification that need to be verified to show a method works in the provider's hands."[21]
- "Methods may be validated by comparison with other established methods using certified reference materials (where available) or materials of known characteristics"[22]
- "If a method is required to use portable equipment for any reason, the validation study shall include any additional aspects that may impact on the tests (e.g. temperature, humidity, surfaces, cross reactivity, lighting)"[23]
- *For validation of measurement-based methods*, "The functional and performance requirements, and the relevant parameters and characteristics for measurement-based methods that shall be considered include the: a. competence requirements of the user, b. environment constraints, … l. results are consistent, reliable, accurate, robust, and with an uncertainty measurement, m. compatibility of results obtained by other analysts using different equipment and different methods; and n. limitations of applicability."[24]
- "An interpretive method shall require only the relevant subset of the parameters and characteristics for measurement-based methods to be determined."[25]
- "Some examples of portable equipment used at the scene that needs calibration or checking according to a prescribed maintenance program before taken to the scene are the following: Digital cameras (white balance calibration)…. Measurement devices for recording distances and dimensions"[26]
- Same or similar procedure can be used to check the calibration and recalibrate the 3D-Scanner regularly in the laboratory[27]
- None exclusive list of issues which may need to be determined when validating test methods include (see Figure 1):

[19] Supra: FSR/Validation s4.4.2.
[20] Ibid. s4.4.6.
[21] Ibid. s4.4.9.
[22] Supra: ILAC/G19 s3.10.
[23] Supra: FSR/Codes s20.1.4.
[24] Ibid. FSR/Codes 220.2.34.
[25] Ibid. FSR/Codes 220.2.36.
[26] Supra: ILAC/G19 s4.4.5.
[27] Ibid. s3.10.

Scope of the method
- Intended purpose and limitations

Sampling
- sampling strategy

Sample preparation
- sample homogeneity

Testing
- accuracy
- precision
- measurement uncertainty
- matrix effects
- interference
- limit of detection
- limit of quantification
- linearity range
- stability of measured compounds
- specificity and selectivity
- repeatability
- reproducibility
- robustness

Interpretation
- Reproducibility
- Robustness
- Performance characteristics
- Hypothesis and/or scenarios
- Databases
- Statistical Evaluation
- Limitations of conclusions
- Scientific Literature

Figure 1 None exclusive issues which may need to be determined when validating test methods

- Regarding the actual procedure to be followed for validation the FSR is more prescriptive than ILAC, indicating the following steps:
    a. "determining the end-user's requirements;
    b. determining the specification;
    c. risk assessment of the method;
    d. a review of the end-user's requirements and specification;
    e. setting the acceptance criteria;
    f. the validation plan;
    g. the outcomes of the validation exercise;
    h. assessment of acceptance criteria compliance;
    i. validation report;
    j. statement of validation completion; and
    k. implementation plan"[28]

[28] Supra: FSR/Codes s20.2.5.

- “There should be a clear separation between development and validation to ensure that the final version of a method is the subject of the validation study”,[29] “validation should be of the final method rather than an extension to method development.”[30]
- “The correct operation of a method is the sum-of-its-parts, so modifying any aspect of a method may influence several seemingly unconnected performance parameters. Once a performance parameter has been characterised, modifying a method/instrument to fix underachievement for subsequent performance characteristics may nullify all the previous testing.”[31]
- “The risk assessment process during validation is not about managing out and/or mitigating all the risks inherent in a method, as the method development stage should have largely dealt with this. It is about understanding the risks to ensure that the validation study correctly assesses whether the risk mitigation put in place works. There may be risks that cannot be managed out of the analytical stage, but many of these can be dealt with by the more human aspects of secondary checks, as required in the validation of interpretive methods.”[32]
- “Before verification of performance, the provider must review/assess/verify that the external/developmental validation:

  a. was relevant to the way that the provider intends to use the method (e.g. covering the equivalent end-user requirements and to being used in the same manner); and

  b. had been conducted in a scientifically robust manner.

  Internal validation is probably a better term, as it is less likely to be misconstrued. This is in contrast to the larger more in-depth study, which is sometimes called a developmental validation.[33]
- “The requirements are for validation, internal validation may be demonstrating that established methods and procedures are relevant and perform as expected in the laboratory but may also need to cover aspects of the underlying fitness for purpose.”[34]

3.2 Application of international and national guidelines to 3D-Forensics/FTI validation

The application of the key framework conditions identified in the guidelines presented in the previous section led to the following conclusions and decisions for 3D-Forensics/FTI validation:

- 3D-Scan by fringe projection is already a standard technique in industrial quality control and other areas. Some crime scene investigators are already familiar with 3D-Scanning with laser

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[29] Supra: FSR/Validation s5.1.4.
[30] Ibid. s5.7.4.
[31] Ibid. s5.1.5.
[32] Ibid. s5.4.2.
[33] Ibid. s4.2.6-4.2.7.
[34] Op.cit.

scanners (e.g. Landeskriminalamt[35] (LKA) Hamburg has also validated its usage). While still carrying out validation tests we should also identify and document that 3D-scanning is a standard method adapted to capture traces at crime scenes.

- Forensics units should have already validated their workflow of recording and analysing footwear imprints and impressions with state of the art (i.e. photography/plaster casting/expert visual analysis and comparison).
- 3D-Forensics/FTI (consortium and forensic units) should only concentrate on validating what we add / update in the forensic workflow of recording and analysing footwear imprints and impressions e.g. recording of traces as 3D point clouds with the 3D-Scanner, mapping of colour data from an external digital camera to the 3D point clouds, visualisation of 3D point clouds on PC, registration of 3D point clouds, meshing of 3D points, camera re-calibration, a number of analysis and reporting tools for the experts.
- Validation can be done independently for each step in this workflow
- We need to demonstrate the results (i.e. recorded data and visualisation/measurement etc. tools) provided by the 3D-Scanner and 3D analysis software can be relied upon with any caveats regarding e.g. performance limitations; required quality controls, including calibration; required competence/training, …
- Relevant validation methods are examination/observation (E/O) and test (T) (see Table 2).

Validation methods	
Method	**Comments**
Examination / Observation (E/O)	Specification can be validated through: ▪ Reference to the properly implemented design definition; and/or ▪ Implementation of already established/validated methods which are referenced; and/or ▪ Visual (generally) validation. Validation is based on human factors, or uses very common and passive means like microscope, gauge, …
Test (T)	Validation of functional characteristics that can be measured. Test equipment / set-ups are generally required to perform tests.

Table 2: Validation methods

- In consortium developmental validation testing, we orientated our planning and reporting on the FSR validation process for the issues which needed to be determined with validation data.[36]

[35] Landeskriminalamt = State Office of Criminal Investigations.

- Linking to FSR - our "issues" were in principle our reviewed "key" specifications
- We focused on specifications that have impact on the results. The main ones were: resolution, accuracy, robustness, reproducibility, repeatability, integrity, authenticity, measurement uncertainty, interference.
- We focused the "Round robin" on a sub-set of the issues/specifications as identified in Table 3.
- The "Round robin" scans were performed in the standard scan mode "Quad", in which the 3D-Scanner is used on a quadpod (or in another stationary scan position) and in the alternative scan mode "Hand", in which the 3D-Scanner is held by the user during the scan acquisition.

Focus of "Round robin" validation tests	
Issues/specifications	**Comment**
Reproducibility measurement precision (of resolution and accuracy)	▪ Replication of data by Crime Scene Investigators (3D-Scanner) ▪ Replication of analysis data by footwear examiners (3D analysis software)
Robustness (of resolution and accuracy)	▪ Efficacy of methods to small variations in parameters (*such as working distance and angle of measurement*) ▪ Influence of scan mode

Table 3: Focus of "Round robin" validation tests

- Certified reference materials were applied and developed informed with test samples such as ball bars, reference planes, reference edges used by VDI 2634 and in discussion with EETG members[37]
- The risk of updates and improvements to the 3D-Scanner and 3D analysis software were assessed with regards to the continued validity of previously obtained developmental validation results.

[36] None exclusive Issues are those stated in ILAC/G19 in s3.10 and referenced to by FSR in FSR/Validation s5.3.5.
[37] Verein Deutscher Ingenieure (VDI) (Association German Engineers), *VDI-Richtlinie: VDI/VDE 2634 Blatt 1 Optische 3D-Messsysteme – Bildgebende Systeme mit punktförmiger Antastung/ Optical 3D measuring systems Imaging systems with point-by-point probing* (2014), (Available at: <https://www.vdi.de/nc/richtlinie/vdivde_2634_blatt_1-optische_3d_messsysteme_bildgebende_systeme_mit_punktfoermiger_antastung/> accessed 18 February 2019).

- Under user validation, the users, informed with the developmental validation test results and any earlier testing of the 3D-Forensics/FTI system, must decide what needs to be done for validation/verification within their organisations.

These conclusions and decisions led to the implementation of the developmental validation procedures described in the next section. User validation approach was determined by the users themselves, primarily to date, as far as reported, through pilot testing to assess requirements considered particularly important for their organisations.

3.3 Developmental validation procedure

As stated in 3.2, T4500 (consortium developmental validation testing) was orientated on the FSR validation process described in 3.1:

a. "determining the end-user's requirements;
b. determining the specification;
c. risk assessment of the method;
d. a review of the end-user's requirements and specification;
e. setting the acceptance criteria;
f. the validation plan;
g. the outcomes of the validation exercise;
h. assessment of acceptance criteria compliance;
i. validation report;
j. statement of validation completion; and
k. implementation plan"[38]

It was recognised that not all aspects were applicable to the consortium as developers but that this approach would enable also the end users to determine which issues they would need to verify and or validate independently from the consortium.

The application of the process is shortly described below.

a. <u>Determining the end-user's requirements</u>

These were defined already in the earlier FP7 project in 2013 with an update in 2014 (deliverable <u>D1.1 System parameter requirements</u>). The primary forensic end user input was provided by the Politie Zeeland-West Brabant in the Netherlands. They are included in Annex 1 to this report.

b. <u>Determining the specifications</u>

These were defined already in the earlier FP7 project in 2014 (deliverable <u>D2.1 Technical design of the Sensor)</u>. They are included in Annex 1 to this report.

[38] Supra: FSR/Codes s20.2.5.

Both requirements and also the specifications have been continually reviewed both within the FP7 and present FTI projects for relevance and accuracy with input from the EETG, further end users and consortium developmental and testing experience.

c. Risk assessment of the method

During the system development risks inherent to the functionalities implemented were identified and mitigation methods were defined. Considering the application, the main risks to the Criminal Justice System (CJS) would be if data is not recorded (resolution) and/or is not recorded or presented accurately and/or users are not aware of potential limitations. In preparation of the developmental validation these risks and mitigation methods were evaluated to ensure that the validation investigations would assess whether the proposed risk mitigations work.

Sections 4.2, 5.2, 6.2, 7.2, 8.2, 9.2 report on performance limitations, interferences and countermeasures for each of the six main system tool functionalities subjected to developmental validation.

Sections 4.5, 5.5, 6.5, 7.5, 8.5, 9.5 which report on the developmental validation for each of the six main system tool functionalities subjected to developmental validation also highlight limitations in connection with for example, scan mode, substrate and structure, which users must consider in evaluating the information provided by the system.

Most of the methods used in the 3D-Forensics system are in their principle already established methods in other fields, such as industrial quality control. In this report, the technical principles behind the applied tools are described and reference publications are listed in the sections 4.1, 5.1, 6.1, 7.1, 8.1, 9.1. The references give a link to advanced technical background and concrete applications of the methods. Through this, the users can verify that the applied tool is already established in other non-forensics fields.

The risk assessment directly informed which of the end-user's requirements and specifications needed to be subject to specific developmental validation tests.

d. A review of the end-user's requirements and specifications

In preparation of the developmental validation, the end user requirements and specifications were reviewed considering the knowledge gained since 2014 and the risk assessment. We took as a basis the end user requirements and specifications as defined in 2014 and commented, updated and/or extended them to reflect the actual level of knowledge at that time. Additional more detailed (sub-) specifications were added to higher level specifications as determined. This was primarily a result of considering the aspects identified by both ILAC and the FSR in Figure 1 above and the risk assessment e.g. precision, repeatability, reproducibility, robustness and measurement uncertainty. They are included in Annex 1 to this report.

It must be mentioned that the reported end-user's requirements and specifications were defined to the best of our knowledge. The past contacts with many different forensic organisations showed that each has its own perspective and own priorities. The consortium tried to be in accordance with all received feedback. When users do their own "user" verification or validation of the system, they should add, remove or change specifications as relevant.

e. Setting the acceptance criteria

The reviewed end-user's requirements and specifications were evaluated to determine which needed to be subjected to a validation method (Examination/Observation or Test – see Table 2 above). This was determined by assessing which features are new or novel for the forensic application and which have an impact on the reliability of the results displayed by the system.

This process led to the setting of the developmental validation for the six main system tool functionalities subjected to developmental validation described in this report in chapters 4-9.

3D-Forensics system tools subject to developmental validation		
	Added / updated forensic tool	**Replaced tool**
3D-Scanner		
1	Recording of traces as 3D point clouds with the 3D-Scanner	Recording of traces as 2D photos with a digital camera or as "3D" plaster casts
2	Mapping of external colour images onto 3D point clouds	None (new tool)
3D analysis software		
3	Visualisation of 3D point clouds on a PC	Visualisation of 2D images on a PC
4	Registration of 3D point clouds	None (new tool)
5	Meshing of 3D points	None (new tool)
6	Capability to measure in data accurately	Rulers

Table 4: Forensic tools provided by the 3D-Forensics system subject to developmental validation

The decision to group specifications around the six main system tool functionalities was taken to be able to developmentally validate each functionality separately and for breaking down the complication in test planning, implementation, assessment and reporting.

The acceptance criteria for these six main system tool functionalities was for the developmental validation the meeting of the relevant specifications as listed in the sections 4.3, 5.3, 6.3, 7.3, 8.3, 9.3.

f. The validation plan

We assessed for each relevant specification (as mentioned above: sections 4.3, 5.3, 6.3, 7.3, 8.3, 9.3) of the six main system tool functionalities which validation method was appropriate i.e. examination/observation or test (as described in Table 2 above). (The methods implemented for each specification during developmental validation are reported in the sections 4.5, 5.5, 6.5, 7.5, 8.5, 9.5. reporting on the developmental validation assessments.)

For those specifications requiring test equipment / set-ups the test specimens were chosen and/or designed and manufactured and test set-ups designed also considering the statistical significance of the tests, but also the resources available in the project. The VDI guideline uses at least 7 scans of sphere distance normal and at least 10 scans of spheres.[39] Annex 3 reports on the test specimens and in Annex 4 the test setups with the specimens are described in detail for each of the different test scenarios. The timing of testing and evaluation was implemented adaptively within the consortium and with end users for reproducibility testing.

g. The outcomes of the validation exercise

As noted above, the user requirements and specifications had been reviewed to consider aspects identified by both ILAC and the FSR in Figure 1 above and the risk assessment e.g. precision, repeatability, reproducibility, robustness and measurement uncertainty. These specifications were key to designing the developmental validation study represented in the validation plan.

The validation exercise was performed with the goal to have standards that ensure that the results are of a sufficient quality to establish the reliability of a method, if necessary, in court, paying due regard to any limitations in the tools.

h. Assessment of acceptance criteria compliance

The results of the validation exercise were assessed against the acceptance criteria (as described above, the specifications). This assessment is provided for each of the six main system tool functionalities in the developmental validation assessment sections 4.5, 5.5, 6.5, 7.5, 8.5, 9.5. Reminders on performance limitations, interferences and countermeasures (described in sections 4.2, 5.2, 6.2, 7.2, 8.2, 9.2) are also included here.

The actual system product specifications achieved and/or assessed by the developers, considering also developmental validation as of June 2019 are reported accordingly in Annex 2.

We provide directions for the end users with regards to required quality controls during operation and recommended user competencies and training levels in the sections 4.6, 5.6, 6.6, 7.6, 8.6 and 9.6.

i. Validation report

This document includes the developmental validation report (and feedback from users on their validation activities / assessments).

[39] Supra: *VDI-Richtlinie 2634 – Blatt 2.*

j. Statement of validation completion

This was out of scope of the developmental validation but its contents were considered in formulating the conclusions in chapter 10.

k. Implementation plan

This was out of scope of the developmental validation.

4 3D-Scanner: Recording of traces as 3D point clouds with the 3D-Scanner

4.1 Technical principle and reference publications

The 3D scanning technique is based on “fringe projection”, in a more general framework also known as “stereo-based pattern projection” or “structured light 3D scanning”. In the 3D-Forensics’ 3D-Scanner a sequence of fringe patterns is projected onto the scene by a digital projector while two cameras capture them from slightly different positions. The calibrated stereo cameras allow through triangulation the determination of 3D coordinates for each surface point visible from both views. This technical approach enables the calculation of a highly resolved 3D point cloud of the scene in a similar way as capturing a photo.

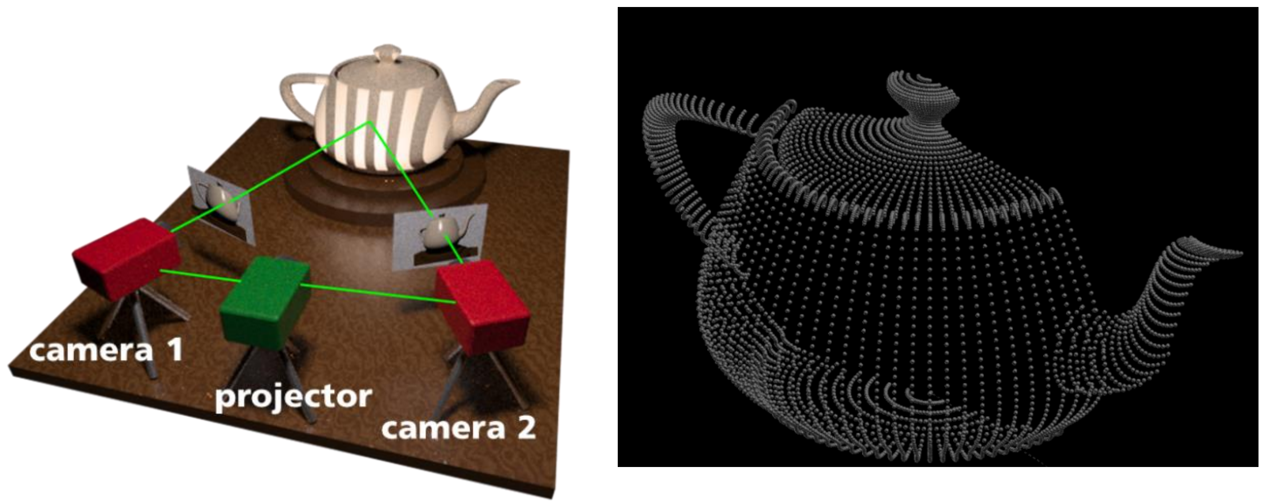


Figure 2: Technical approach of the stereo based pattern projection

The technical principle is well known for more than twenty years. It has established applications in industrial quality control, medicine and cultural heritage. A broad overview of the technology can be found in:

`T. Luhmann, S. Robson, S. Kyle: Close-Range Photogrammetry and 3D Imaging. 2nd Edition, 2013, De Gruyter`

4.2 Performance limitations, interferences and countermeasures

Limitation / interference	**Countermeasure**
Measurement volume	If the object is larger than a single field of view, it is possible to make a set of multiple overlapping 3D scans (recommendation >30% overlap) and use the registration tool of the analysis software to stitch them together (distantly related to a panorama photo).

Limitation / interference	**Countermeasure**
Limited inclination angle	Surfaces with very steep edges cannot be captured in one single scan from top. If the steep edges contain important information, additional inclined scans can be captured. The scans can be merged by using the registration tool.
Time to scan (with handheld usage.)	The handheld usage of the 3D-Scanner is similar to a photo apparatus. When starting the 3D scan the user needs to keep the device as still as possible. Additional noise is caused by shaking. (The standard scan mode is with the quadpod. The quadpod allows a quick realization of scans with a fixed setup. It also allows the application of improved photo settings. Alternatively the 3D-Scanner can be used in combination with an appropriate tripod. Appropriate means it must be at least able to support the weight of the 3D-Scanner i.e. without falling over and to enable a field of view over the measurement scene to be scanned)
Direct sunlight	Too strong direct sunlight leads to large dropouts in the 3D point cloud. Direct sunlight shining onto the measurement surface must be shielded. Indirect sunlight is no problem.
Transparent / translucent objects (e.g. slushy snow)	The 3D scan of transparent and high translucent object surfaces leads to large dropouts in the 3D point cloud. The 3D scan of low translucent object surfaces lead to 3D points which are slightly shifted relative to the real surface. Transparent / translucent surfaces like slushy snow need to be coated with e.g. Snow Wax spray. This was not covered by developmental validation testing to date.
Specular reflecting objects (e.g. mirrors or very wet surfaces)	The 3D scan of high specular reflecting object surfaces leads to dropouts in the 3D point cloud. High specular reflecting surfaces such as very wet surface scan to be coated with e.g. Snow Wax spray or chalk spray. As above, not covered by developmental validation testing to date.
Low reflecting (dark) objects	Objects with an extremely dark surface may not reflect enough of the fringe patterns. This leads to large dropouts in the 3D point cloud. Very low reflecting surfaces can be coated with e.g.

Limitation / interference	Countermeasure
	Snow Wax spray or chalk spray. As above, not covered by developmental validation testing to date.
Dark and bright objects in one scene	Object surfaces with very dark and very bright regions in one scene may not be captured with one single brightness settings. It results in dropout in one or the other region. The user can do multiple scans with two or more different brightness settings and use the registration tool of the analysis software to stitch them together.
Artefacts on the border of the field of view.	The 3D data can be corrupted by small artefacts directly on the border of the field of view, due to limitations of the pattern projection unit. This effect occurs mainly when the 3D-Scanner is used handheld. When it comes to the further processing and analysis of the 3D data in a 3D analysis software, the user can mask points on the border of the field of view using manual or automatic selection tools.
Spike artefacts in the scan data	Above mentioned limitations (e.g. small specular reflecting objects in the scene), can cause local artefacts in the form of spikes. These are clearly separable from the valid scan data. The user should check the data visually for any kind of artefacts. The analysis software allows to mask the regions.

4.3 Reviewed end user requirements and related specifications

The standard mode to use the 3D-Scanner is by putting it on the associated quadpod or fixing it on a tripod. This use mode achieves the best results. If the circumstances do not allow the usage of the quadpod or a tripod (e.g. through limited space at the crime scene), the 3D-Scanner can be used handheld. Handheld scans have typically a lower quality in terms of resolution and accuracy because shaking by the user causes additional noise in the 3D data. The scanner control software provides a distinct scan mode, with slightly different parameter settings for the handheld scan and 3D data reconstruction that mitigate shaking errors. The specifications, that “affect the result”, were tested primarily in the standard mode. The influence on scan results by handheld use was also investigated for most specifications as well.

	End user requirement - description	Specification
[1.1]	Local resolution - ability to resolve identification characteristics found in footwear / tyre impressions as good as plaster casting (or better)	< 200 µm

[1.2]	Accuracy LME and Accuracy PE - ability to measure distances in the outsole / profile	< 50 µm
[1.3]	Robustness resolution, - resistance of the resolution to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner, brightness setting).	Small variations without influence Effects of larger variations must be known
[1.4]	Robustness accuracy - resistance of the accuracy to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner, brightness setting).	Small variations without influence Effects of larger variations must be known
[1.5]A	Repeatability resolution - scan results should be stable / precise. (Measurement uncertainty / standard deviation of resolution)	<±50 µm
[1.5]B	Repeatability accuracy - scan results should be stable / precise. (Measurement uncertainty / standard deviation of accuracy)	<±20 µm
[1.6]A	Reproducibility resolution - scan results should be independent from user. (Measurement uncertainty / standard deviation of resolution)	<±50 µm
[1.6]B	Reproducibility accuracy - scan results should be independent from user. (Measurement uncertainty / standard deviation of accuracy)	<±20 µm
[1.7]	Range of inclination angle - capturing steep boundaries of deep impressions	0 … 60°

Other end user requirements do not directly have an “effect on the result”, but define relevant limitations, interferences and necessary user competences:

	End user requirement	**Specification**
[1.8]	Range - Field of View / Measurement volume	≥ 300 x 200 x 50 mm³
[1.9]	Working distance	> 300 mm (contactless)

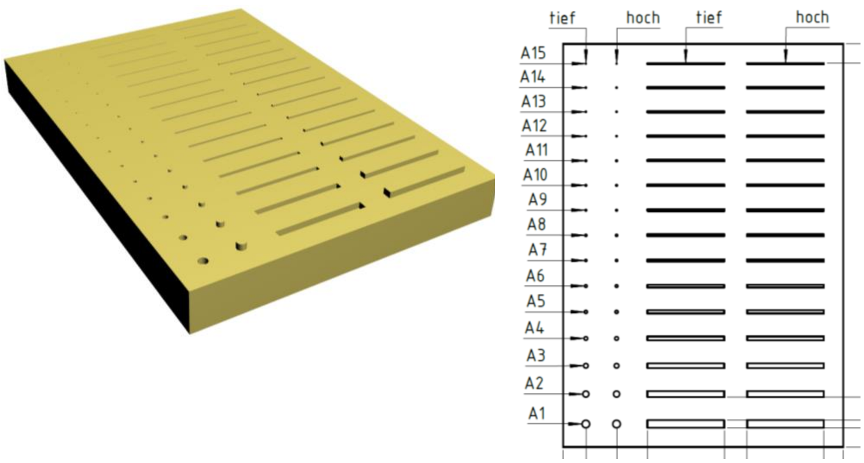
	End user requirement	Specification
[1.10]	Brightness setup - ability to measure on any kind of underground in which impression traces can occur (snow, mud, etc.)	brightness pre-settings
[1.11]	Usability - easy handling of the 3D-scanner means in simple words to “measure with one touch of a button” and to provide an output result that is understandable for a layman	Scan starts with one button (measurement modes and brightness pre-settings)
[1.12]	Use feedback - preview of 3D-patch and the colour photo is shown, the user has to evaluate the quality, e.g. holes	Projection of a green or red box by projector (PRO) signals a technical successful scan 3D-patch preview Photo preview
[1.13]	Mobility - main application field of the 3D-scanner is outdoor measurements in arbitrary surroundings using it as a hand-held sensor head	Handheld 3D-Scanner No (or easy-to-use) additional equipment
[1.14]	Time to scan - quick enough to allow handheld scans	≤ 200 ms
[1.15]	Thermal robustness - usability at typical outdoor conditions	-10 – 40°C working temperature
[1.16]	Moisture - usability at typical outdoor conditions	< 80% air moisture
[1.17]	Moisture/dust - usability at typical outdoor conditions	IP44
[1.18]	Shock resistance - Usability at typical outdoor conditions	IK04
[1.19]	Surrounded light - usability at daytime	< 10,000 lux (cloudy day, shadow, not in direct light)
[1.20]	Maintenance - long-life device with stable functional parameters	> 1 year
[1.21]	Quality control - verify the functionality of the device at the crime scene	Test specimen (to be used at crime scene)

4.4 Developmental validation test results – summarised overview[40]

4.4.1 Limit of resolution and repeatability measurement precision[41]

To investigate the resolution and repeatability measurement precision of the 3D-Scanner a specimen was manufactured in Rescor ceramic “Dark” material which is similar to a dark matt surface, representing an ideal surface for optical 3D scanning regarding reflection characteristics.

The test specimen has embossed and indented bar and dot structures varying in width and depth/height in 15 steps (Figure 3).



Nr.	Durchmesser / Breite	Tiefe / Höhe
A1	1.0	0.75
A2	0.8	0.6
A3	0.6	0.45
A4	0.5	0.38
A5	0.4	0.3
A6	0.35	0.26
A7	0.3	0.23
A8	0.275	0.21
A9	0.25	0.19
A10	0.225	0.17
A11	0.2	0.15
A12	0.18	0.14
A13	0.16	0.12
A14	0.14	0.11
A15	0.12	0.09
T	±0.005	±0.01

Figure 3: 3D resolution specimen layout[42]

Using standard operational parameters indoors (specimen located in centre of field of view at nominal working distance, brightness is set to an appropriate value), 1 engineer experienced in using the 3D-Scanner made 10 quadpod scans of the specimen. Results are provided in Figure 4.

[40] Full results in Annex 4.
[41] *Test case series: 3DFFTI_TC_1a.*
[42] Tief=depth, hoch=height, Durchmesser=diameter, Breite=breadth, Tiefe=depths, Höhe=heights.

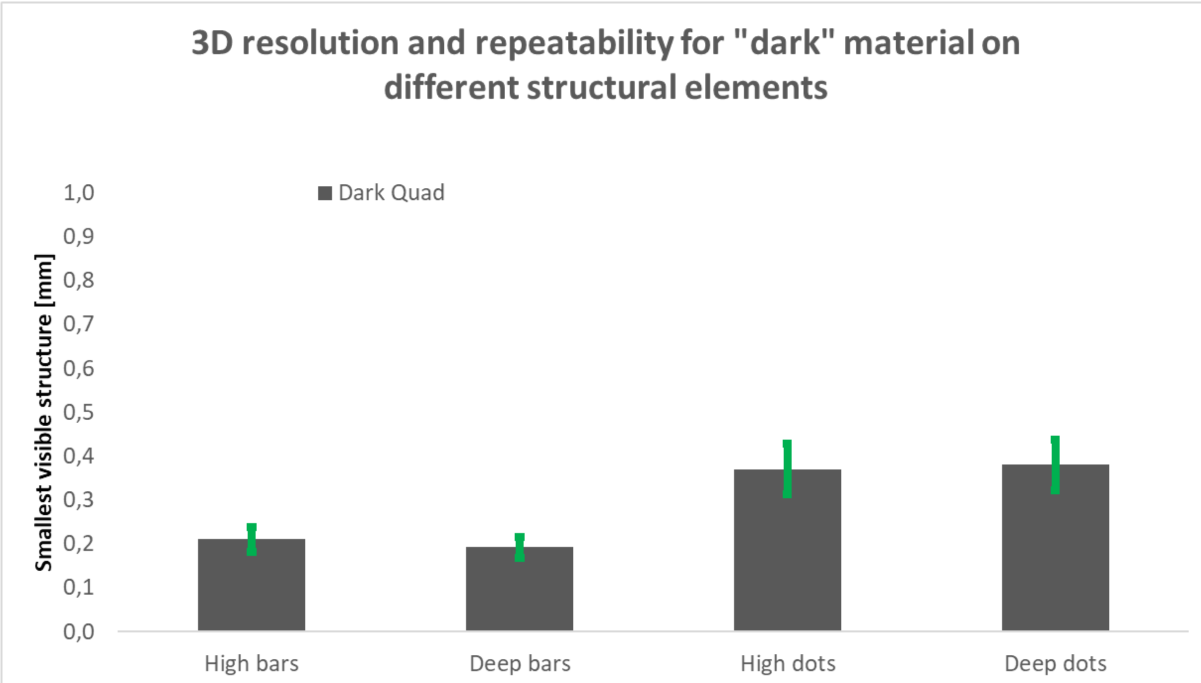


Figure 4: 3D resolution and repeatability as range between best and worst value for Rescor ceramic "Dark" material on different structural elements

The highest and lowest measured resolutions of each material are presented in Table 5.

Scan mode and highest / lowest resolution (structure)	Structure	Arithmetic mean (mm)	Uncertainty p=95% (mm)	Best value of 10 [mm]	Worst value of 10 [mm]
Highest resolution	Indented bars	0.192	± 0.023	0.180	0.200
Lowest resolution	Indented dots	0.380	± 0.058	0.350	0.400

Table 5 Highest and lowest resolutions achieved with "Dark" specimen

4.4.2 Limit of inclination angle for recording data[43]

To investigate the range of inclination angle for recording data with the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 1 quadpod scan test of a special specimen (sphere normal, diameter 80 mm). All other operational parameters were standard.

[43] *Test case series: 3DFFTI_TC_2.*

Figure 5: Enrolled view of the measured sphere in sphere coordinate system

The minimum inclination angle which could be captured was ≥64.4°. Most parts of the sphere are captured with an even larger inclination angle. The 64.4° is the worst case. The limit of the inclination angle is majorly determined by the positions of the stereo cameras in the 3D-Scanner, which are defined by design. Thus, the variance between specific devices is here negligible.

4.4.3 3D accuracy and repeatability measurement precision

4.4.3.1 Test 1 – Circle board[44]

To investigate the 3D accuracy in terms of length measurement error (LME) and probing error (PE) and corresponding repeatability measurement precision, 1 engineer experienced in using the 3D-Scanner made 10 quadpod scans of the 3D-Scanner's calibration circle board (Figure 6). All other operational parameters were standard.

The positional deviations relative to the centre circle were extracted out of the 3D data for the remaining 18 circles. The averaged deviations representing the 3D accuracy in terms of LME are provided in Figure 7. The uncertainty for LME represents the stability (standard deviation) of the measured circle positions over 10 measurements.

In a homogenous region of ca. 40 x 40 mm² of the circle board (see Figure 6) the 3D accuracy in terms of PE was determined by evaluating the standard deviation of the 3D points relative to the plane (planarity of the circle board is <5 µm). The uncertainty for PE represents the stability of the measured plane deviation over 10 measurements.

[44] *Test case series: 3DFFTI_TC_3a.*

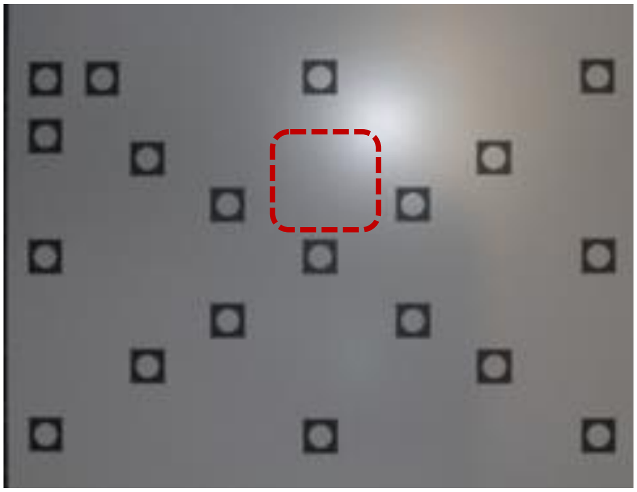


Figure 6: 3D-Scanner calibration board (red area – evaluation of PE)

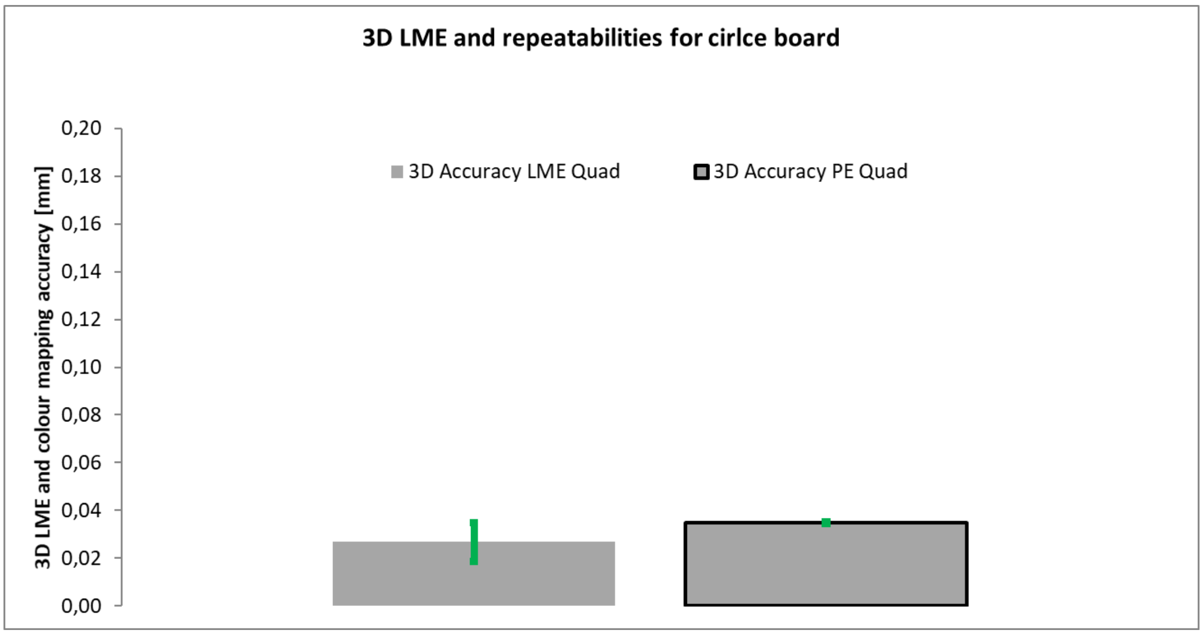


Figure 7: 3D LME, PE and repeatability with range derived from measurement uncertainty for circle board

Average length measurement error LME and average probing error PE are less than 0.05 mm.

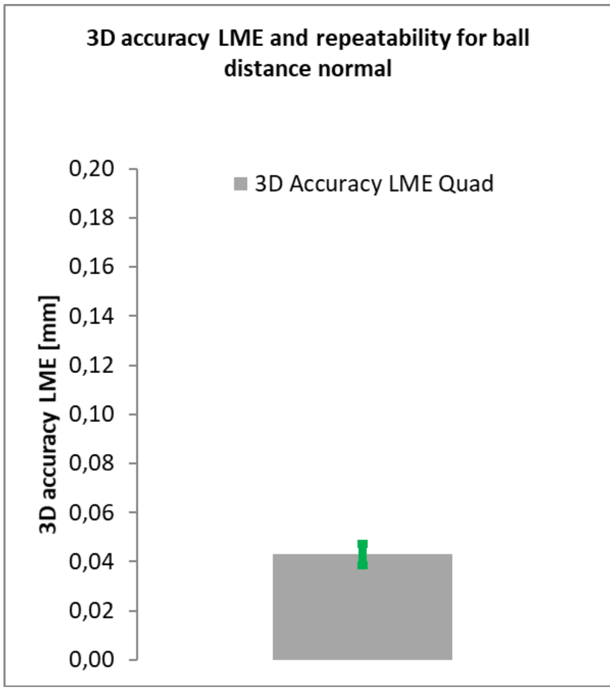
4.4.3.2 Test 2 - Ball sphere distance normal test[45]

To investigate the 3D accuracy in terms of length measurement error (LME) and probing error (PE) and corresponding repeatability measurement precision, 1 engineer experienced in using the

[45] *Test case series: 3DFFTI_TC_4a.*

3D-Scanner made 10 quadpod scans of a special specimen (ball/sphere distance normal, distance of sphere centres ca. 200mm). All other operational parameters were standard.

Two spheres are fitted into the 3D data. The PE is determined by the form deviation of the 3D points to the ideal spheres (standard deviation). The LME is determined by calculating the distance between the two sphere centre points. Results are provided in Figure 8.



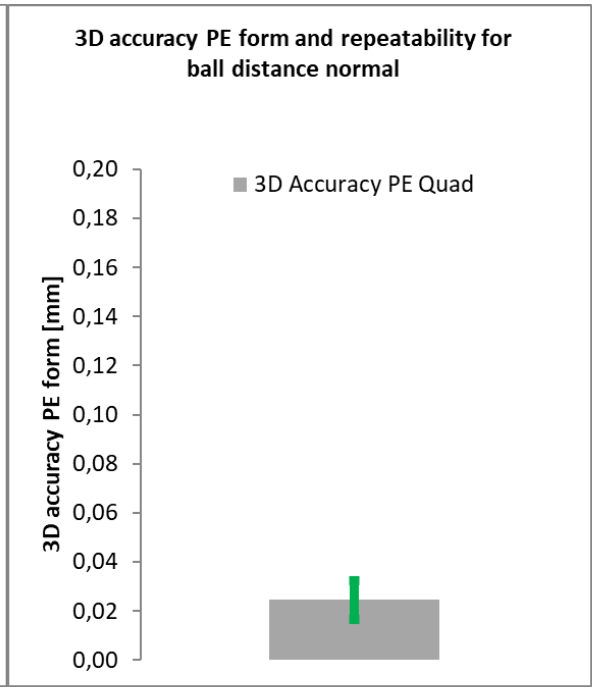


Figure 8: 3D accuracy LME and PE and repeatability with range derived from measurement uncertainty for ball distance normal

Average length measurement error LME and average probing error PE are less than 0.05 mm.

4.4.4 Influences on the 3D measurement (robustness)

4.4.4.1 Challenging materials / surface characteristics

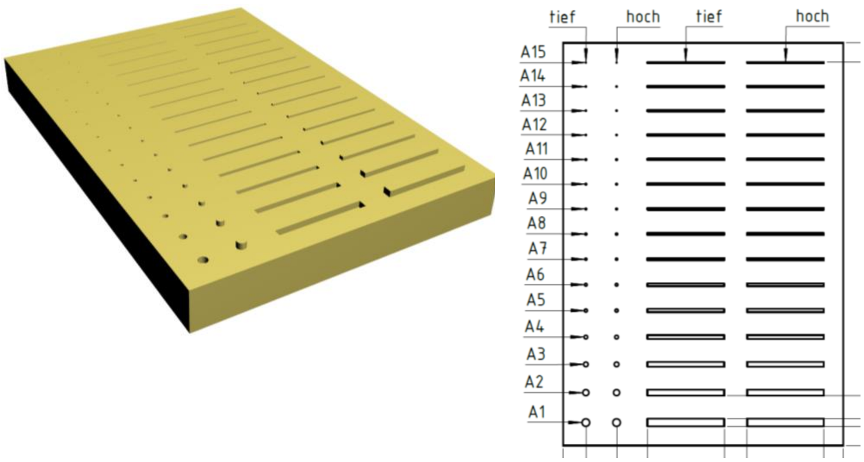
4.4.4.1.1 Limit of resolution and repeatability measurement precision[46]

To investigate the resolution and repeatability measurement precision of the 3D-Scanner for challenging materials / surface characteristics two specimens were manufactured in materials with representative reflection properties:

- Macor ceramic “White”, which is translucent, has similar reflectivity/diffraction as snow (not ideal for optical 3D scanning)
- Aluminium “Metallic”, which is reflective, imitates a wet shiny surface (not ideal for optical 3D scanning)

[46] *Test case series: 3DFFTI_TC_1a.*

Each of the test specimens has embossed and indented bar and dot structures varying in width and depth/height in 15 steps (**Figure 9**, below, *the same as for the tests in section 0 and Figure 3 above*).



Nr.	Durchmesser / Breite	Tiefe / Höhe
A1	1.0	0.75
A2	0.8	0.6
A3	0.6	0.45
A4	0.5	0.38
A5	0.4	0.3
A6	0.35	0.26
A7	0.3	0.23
A8	0.275	0.21
A9	0.25	0.19
A10	0.225	0.17
A11	0.2	0.15
A12	0.18	0.14
A13	0.16	0.12
A14	0.14	0.11
A15	0.12	0.09
T	±0.005	±0.01

Figure 9: 3D resolution specimen layout[47]

Using standard operational parameters indoors, 1 engineer experienced in using the 3D-Scanner made 10 quadpod scans of each of the two specimens. Results are provided in Figure 10.

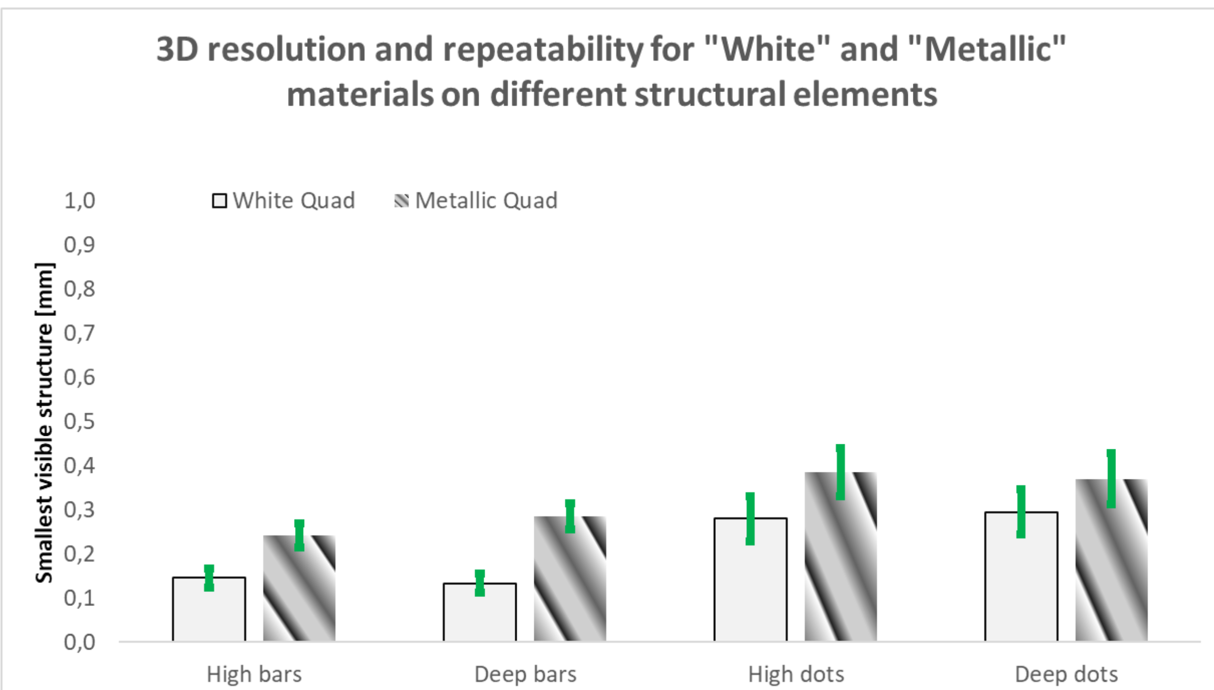


Figure 10: 3D resolution and repeatability as range between best and worst value for Macor ceramic "White" and Aluminium "Metallic" materials on different structural elements.

[47] Tief=depth, hoch=height, Durchmesser=diameter, Breite=breadth, Tiefe=depths, Höhe=heights.

The highest and lowest measured resolutions of each material are presented in Table 6 and Table 7.

Scan mode and highest / lowest resolution (structure)	Structure	Arithmetic mean (mm)	Uncertainty p=95% (mm)	Best value of 10 [mm]	Worst value of 10 [mm]
Highest resolution	Indented bars	0.134	± 0.022	0.120	0.140
Lowest resolution	Embossed dots	0.295	± 0.051	0.275	0.350

Table 6 Highest and lowest resolutions achieved with "White" specimen

Scan mode and highest / lowest resolution (structure)	Structure	Arithmetic mean (mm)	Uncertainty p=95% (mm)	Best value of 10 [mm]	Worst value of 10 [mm]
Highest resolution	Embossed bars	0.243	± 0.027	0.225	0.250
Lowest resolution	Embossed dots	0.385	± 0.054	0.350	0.400

Table 7 Highest and lowest resolutions achieved with "Metallic" test specimen

4.4.4.2 User / device – reproducibility measurement precision

4.4.4.2.1 Resolution[48]

To investigate the resolution and reproducibility measurement precision of the 3D-Scanner the 3 specimens described above were also used. Using standard operational parameters indoors, after a short training, 9 Crime Scene Investigators and 1 experienced engineer from 4 organisations in 2 different countries made 1 quadpod scan of each of the 3* specimens (**8 (rather than 9) Crime Scene Investigators and 1 experienced engineer for the Macor "White" specimen*). During the tests 3 different 3D-Scanners were used. Results are provided in Figure 11.

[48] *Test case series: 3DFFTI_TC_1b.*

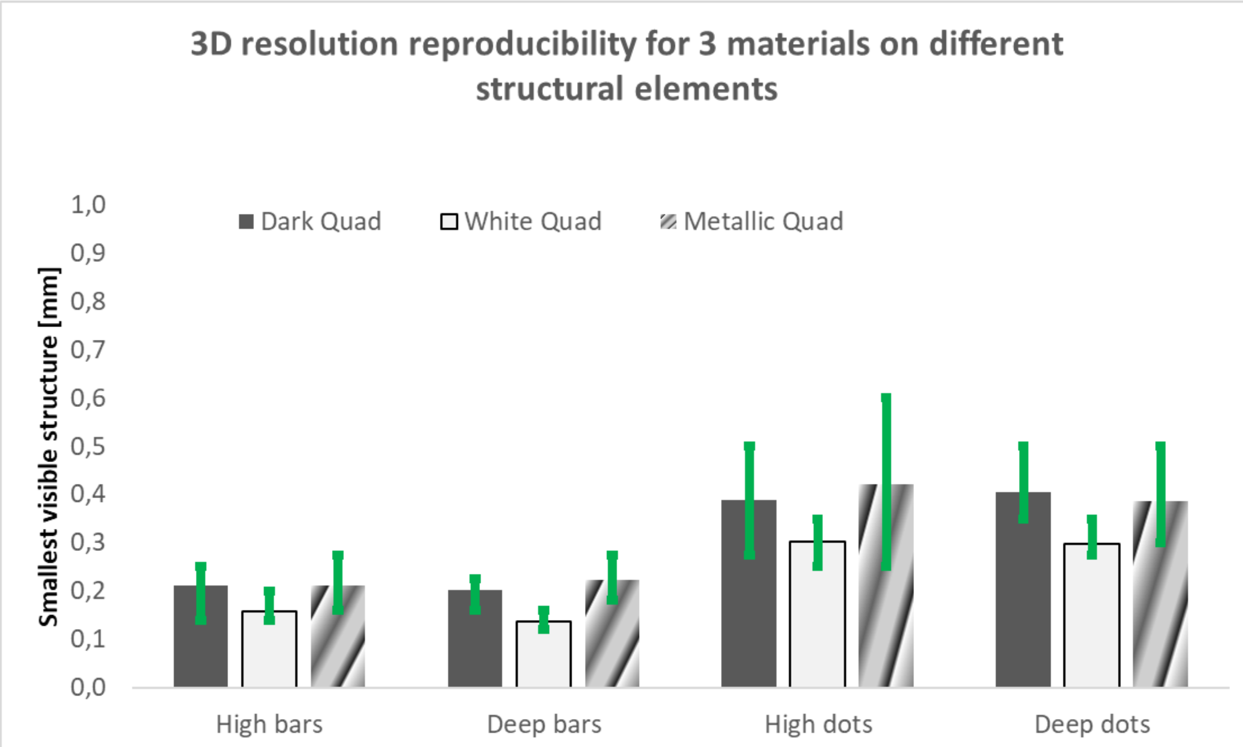


Figure 11: 3D resolution and reproducibility as range between best and worst value for 3 undergrounds on different structural elements with seven users

The highest and lowest measured resolutions are presented in Table 8, Table 9 and Table 10.

Scan mode and highest / lowest resolution (structure)	Structure	Arithmetic mean (mm)	Uncertainty p=95% (mm)	Best value of 10 [mm]	Worst value of 10 [mm]
Highest resolution	Indented bars	0.202	± 0.046	0.160	0.225
Lowest resolution	Indented dots	0.405	± 0.082	0.350	0.500

Table 8 Highest and lowest resolutions achieved with “Dark” specimen (9 CSI + 1 engineer)

Scan mode and highest / lowest resolution (structure)	Structure	Arithmetic mean (mm)	Uncertainty p=95% (mm)	Best value of 10 [mm]	Worst value of 10 [mm]
Highest resolution	Indented bars	0.138	±0.041	0.120	0.160
Lowest resolution	Embossed dots	0.303	±0.090	0.250	0.350

Table 9 Highest and lowest resolutions achieved with “White” specimen (9 CSI + 1 engineer)

Scan mode and highest / lowest resolution (structure)	Structure	Arithmetic mean (mm)	Uncertainty p=95% (mm)	Best value of 10 [mm]	Worst value of 10 [mm]
Highest resolution	Embossed bars	0.211	±0.088	0.160	0.275
Lowest resolution	Embossed dots	0.420	±0.230	0.250	0.600

Table 10 Highest and lowest resolutions achieved with "Metallic" test specimen (9 CSI + 1 engineer)

4.4.4.2.2 3D accuracy, Test 1 – circle board[49]

To investigate 3D accuracy in terms of length measurement error (LME) and probing error (PE) corresponding reproducibility measurement precision of the 3D-Scanner, 9 Crime Scene Investigators and 1 experienced engineer from 4 organisations in 2 different countries made 1 quadpod scan of the calibration circle board. All other operational parameters were standard.

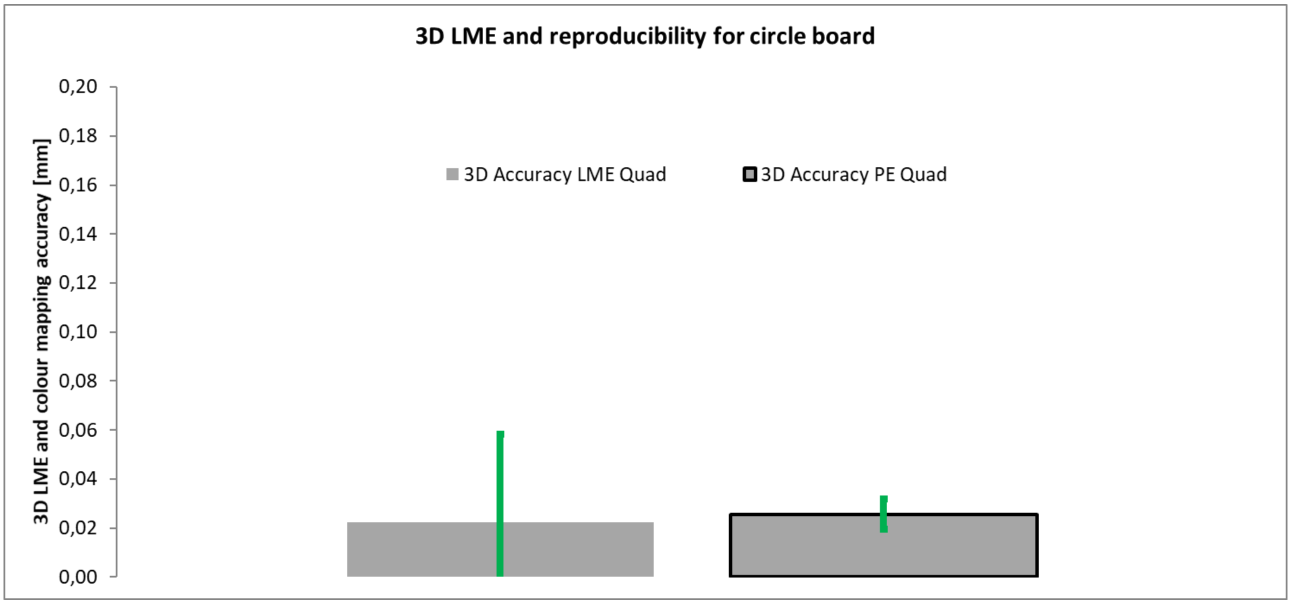


Figure 12: 3D LME, PE and reproducibility with range derived from measurement uncertainty for circle board for 10 users

Settings			**Accuracy Quad**	
User-ID	**Device**	**Mode**	**3D accuracy LME [mm]**	**3D accuracy PE [mm]**
IOF1	006	Quad	0.020	0.020
YHP1	006	Quad	0.014	0.027

[49] *Test case series: 3DFFTI_TC_3b.*

YHP2	006	Quad	0.016	0.024
YHP3	006	Quad	0.015	0.028
LKASA1	007	Quad	0.021	0.023
LKASA2	007	Quad	0.019	0.026
LKASA3	007	Quad	0.021	0.027
LKAMV1	008	Quad	0.021	0.026
LKAMV2	008	Quad	0.037	0.025
LKAMV3	008	Quad	0.038	0.031
3D accuracy LME [mm]			0.022	0.026
Reproducibility [mm] / [mm]			0.036	0.006

Table 11 3D LME, PE and reproducibility for circle board and quadpod scanning with 10 users

Averaged accuracy in terms of LME for the 10 users had a measurement error less than 0.025 mm for LME.

4.4.4.2.3 3D accuracy, Test 2 - MikroTrack™ / Shoe sole[50]

To investigate 3D accuracy in terms of probing error (PE) and reproducibility measurement precision, 10 Crime Scene Investigators and 1 experienced engineer from 5 organisations in 3 different countries made 1 quadpod scan of a footwear impression recorded in MicroTrack™ and 1 quadpod scan of a shoe sole. It is to be noted that deformation of the MikroTrack™ between the reference scan and users' scans was apparent during tests – probably through movement of the MicroTrack™ and the reference scan was apparent. All other operational parameters were standard. Averaged results together with minimum and maximum deviations are provided in Figure 13.

[50] *Test case series:3DFFTI_TC_5b.*

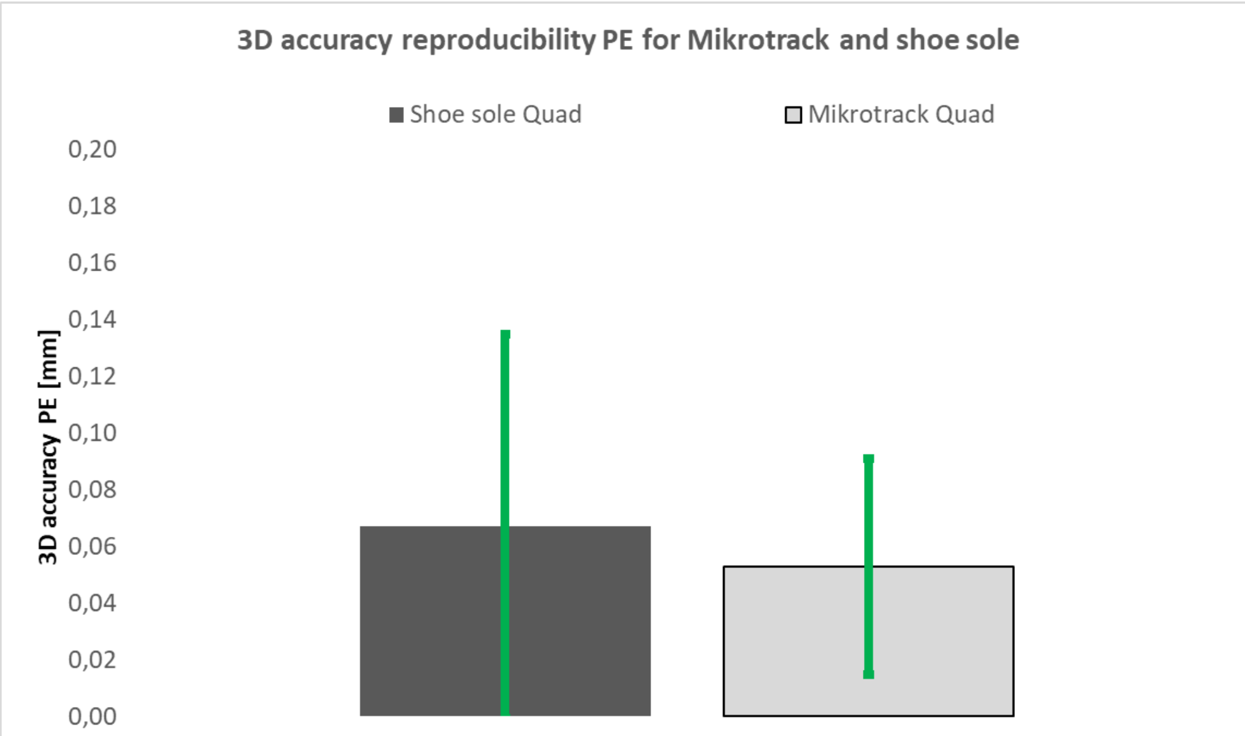


Figure 13: 3D accuracy reproducibility PE for MikroTrack™ and shoe sole as range between best and worst value

4.4.4.3 Handheld scan mode

4.4.4.3.1 Resolution[51]

To investigate the influence of the handheld scan mode on the resolution, repeatability and reproducibility measurement precision of the 3D-Scanner the 3 specimens described above were used. Using standard operational parameters indoors 1 experienced engineer made 10 handheld scans and, after a short training, 10 Crime Scene Investigators and 1 experienced engineer from 4 organisations in 2 different countries made 1 handheld scan of each of the 3 specimens. During the tests 4 different 3D-Scanners were used. Results are provided in Figure 14 and Figure 15.

[51] *Test case series: 3DFFTI_TC_1aH, 3DFFTI_TC_1bH.*

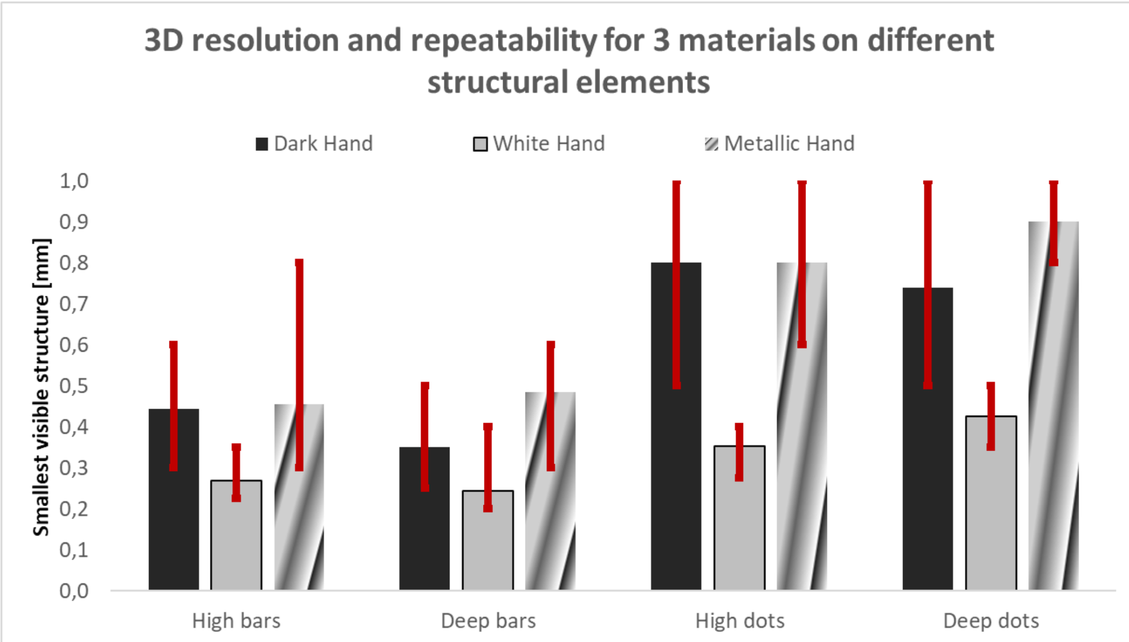


Figure 14: 3D resolution and repeatability as range between best and worst value for 3 undergrounds on different structural elements

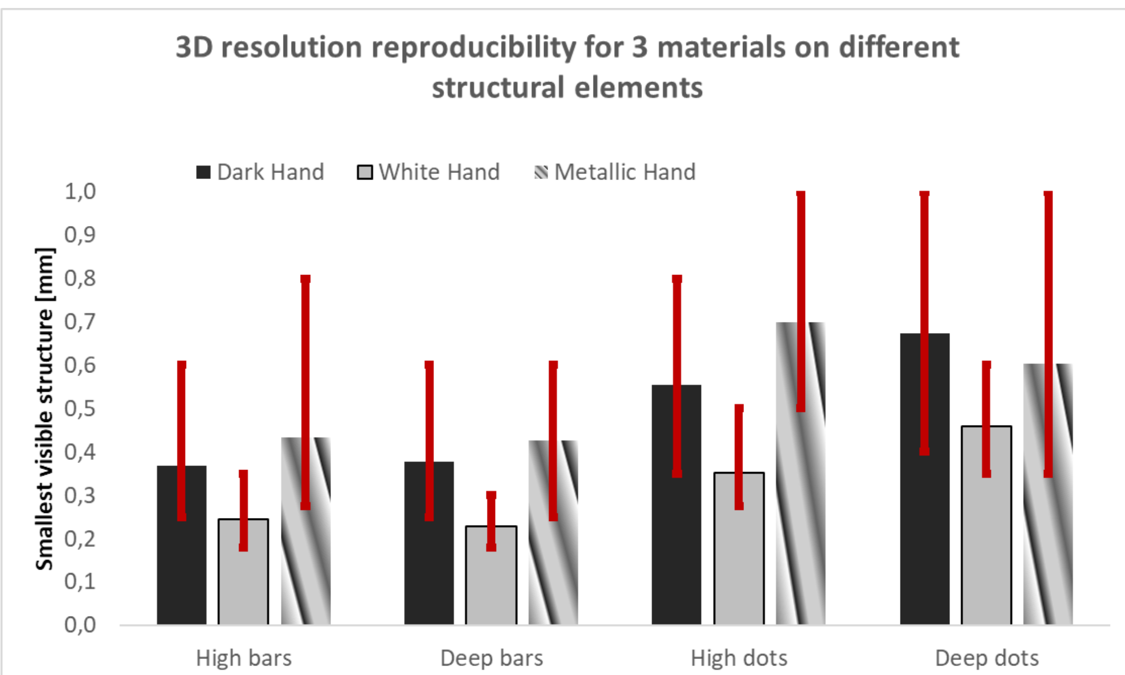


Figure 15: 3D resolution and reproducibility as range between best and worst value for 3 undergrounds on different structural elements with ten users

The 3D scan resolution and its variance is increased by factor 1.5 … 2.0 in the handheld use mode compared to the standard use mode (quadpod). The resolution is between 0.245 mm (intended bars of “White” specimen) and 0.9 mm (intended dots of “Metallic” specimen).

4.4.4.3.2 3D accuracy, Test 1 – circle board[52]

To investigate the influence of the handheld scan mode on the 3D accuracy in terms of length measurement error (LME) and probing error (PE) corresponding repeatability and reproducibility measurement precision of the 3D-Scanner 1 experienced engineer made 10 handheld scans and 9 Crime Scene Investigators and 1 experienced engineer from 4 organisations in 2 different countries made 1 handheld scan of the calibration circle board. All other operational parameters were standard.

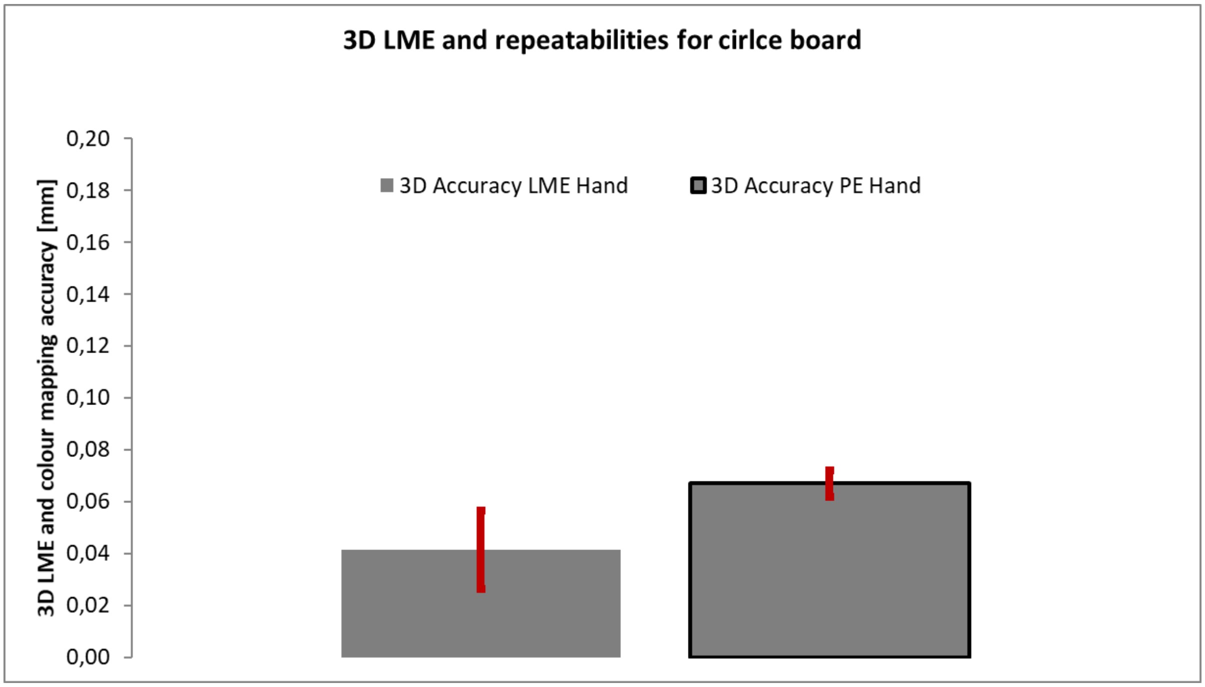


Figure 16: 3D LME, PE and repeatability with range derived from measurement uncertainty for circle board

[52] *Test case series: 3DFFTI_TC_3aH, 3DFFTI_TC_3bH.*

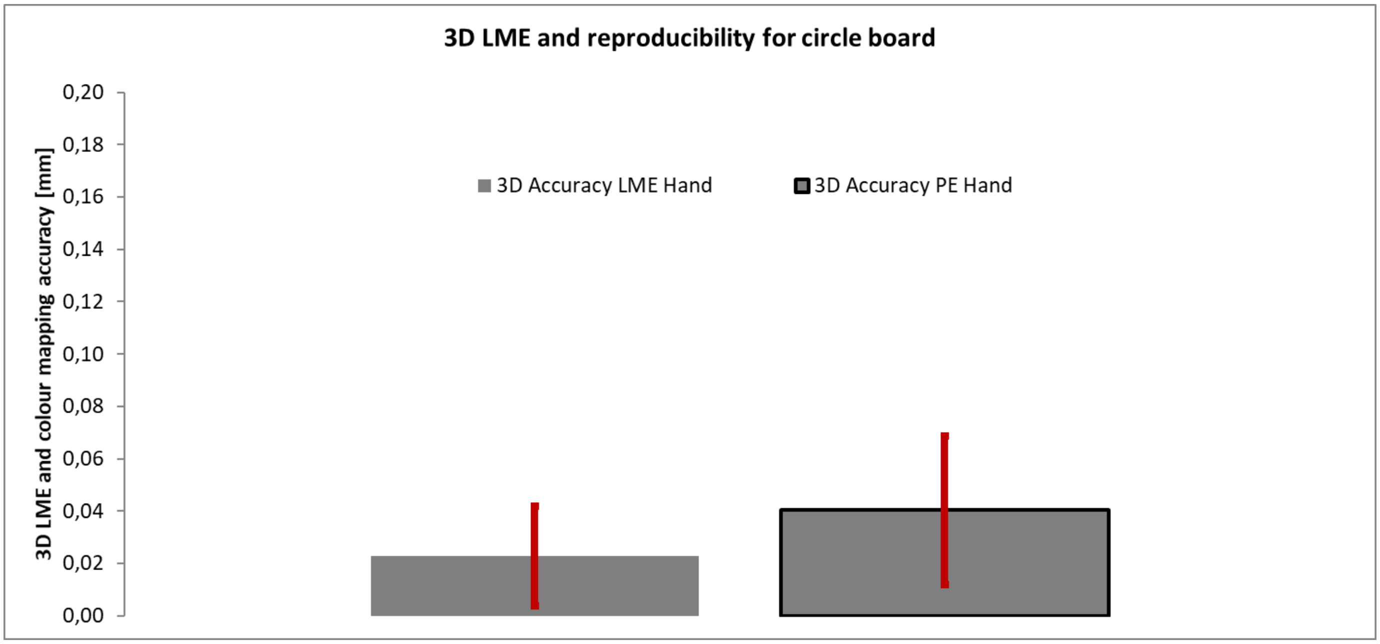


Figure 17: 3D LME, PE and reproducibility with range derived from measurement uncertainty for circle board for 10 users

The 3D LME is on the same level for handheld use mode compared to the standard use mode (quadpod). The PE is increased by factor 2 compared.

4.4.4.3.3 3D accuracy, Test 2 - MikroTrack™ / Shoe sole[53]

To investigate the influence of the handheld scan mode on 3D accuracy in terms of probing error (PE) and repeatability and reproducibility measurement precision, 1 experienced engineer made 10 handheld scans and 10 Crime Scene Investigators and 1 experienced engineer from 5 organisations in 3 different countries made 1 handheld scan of a footwear impression recorded in MicroTrack™. It is to be noted that deformation of the MikroTrack™ between the reference scan and users scans was apparent during tests – probably through movement of the MicroTrack™ and the reference scan was apparent. All other operational parameters were standard. Averaged results together with minimum and maximum deviations are provided in Figure 19.

[53] *Test case series:3DFFTI_TC_5aH, 3DFFTI_TC_5bH.*

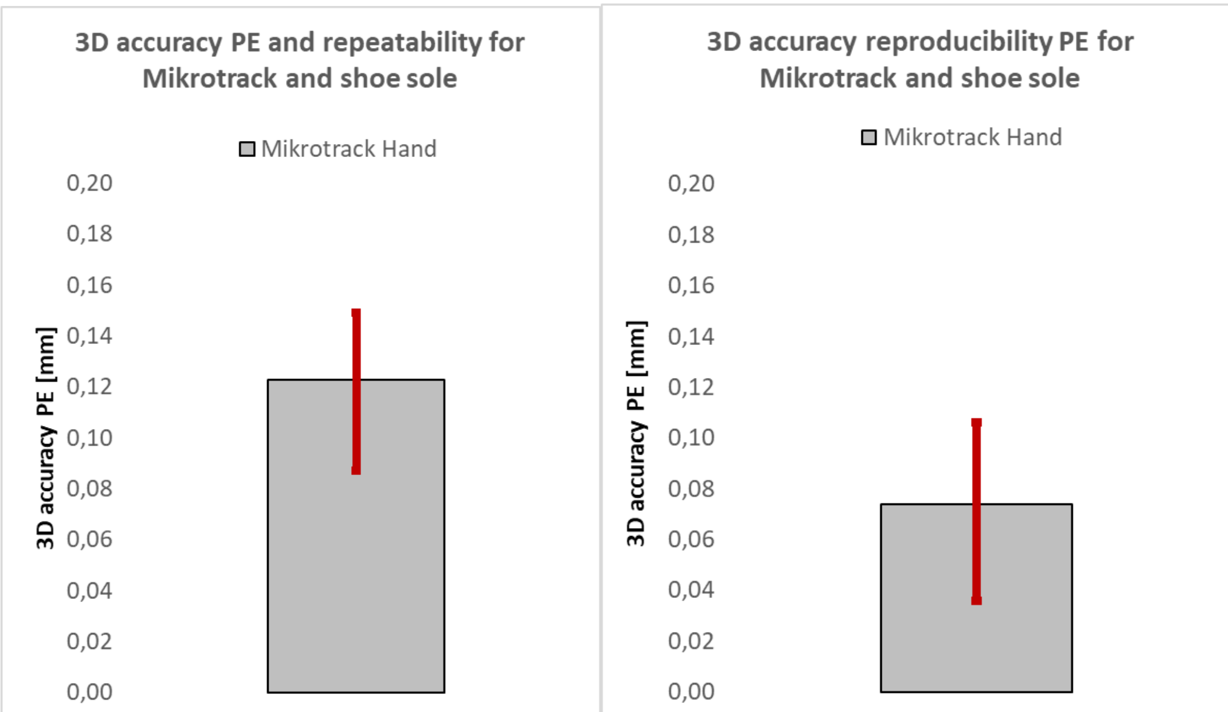


Figure 18: 3D accuracy repeatability and reproducibility PE for MikroTrack™ as range between best and worst value

The 3D accuracy in terms of PE, its repeatability and reproducibility are increased by factor 2 for the handheld use mode compared to the standard use mode (quadpod).

4.4.4.4 Position of field of view

4.4.4.4.1 Resolution[54]

To investigate the <u>robustness of recording resolution with regards to the field of view</u> of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 5 quadpod scans of the “Dark” rescor specimen described above in the centre and the corners of the field of view. All other operational parameters were standard. Scans were made indoors. Results are provided in Figure 19.

[54] *Test case series: 3DFFTI_TC_1d1.*

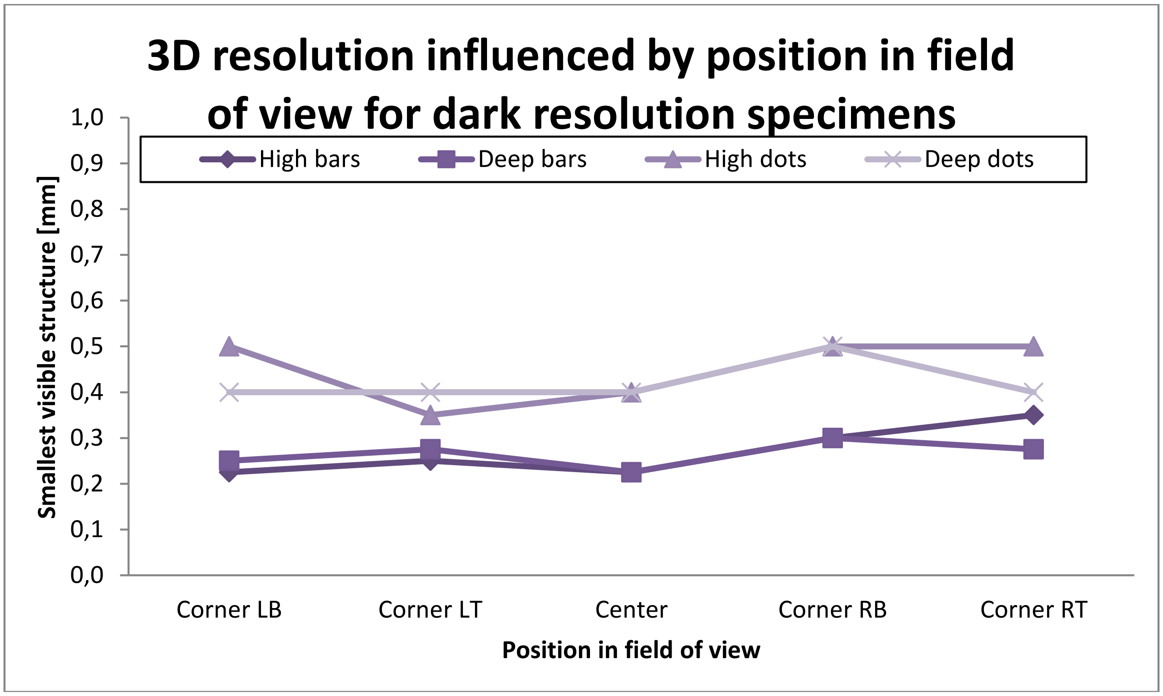
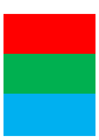


Figure 19: 3D resolution influenced by position in field of view for dark resolution specimens

Resolution is slightly reduced in the right hand corners.

4.4.4.4.2 3D accuracy, Test 1 – circle board[55]

To investigate the robustness of 3D accuracy in terms of length measurement error (LME) with regards to the position within the field of view of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 10 quadpod scans of the circle board described above. All other operational parameters were standard. For the 19 circles on the board systematic positional deviations from the intended reference position were evaluated by calculating their average distance to the centre circle over the 10 scans.



circle is more than 0.04 mm too far away from center

circle is more than -0.04 mm too far away from center

[55] *Test case series: 3DFFTI_TC_3c3.*

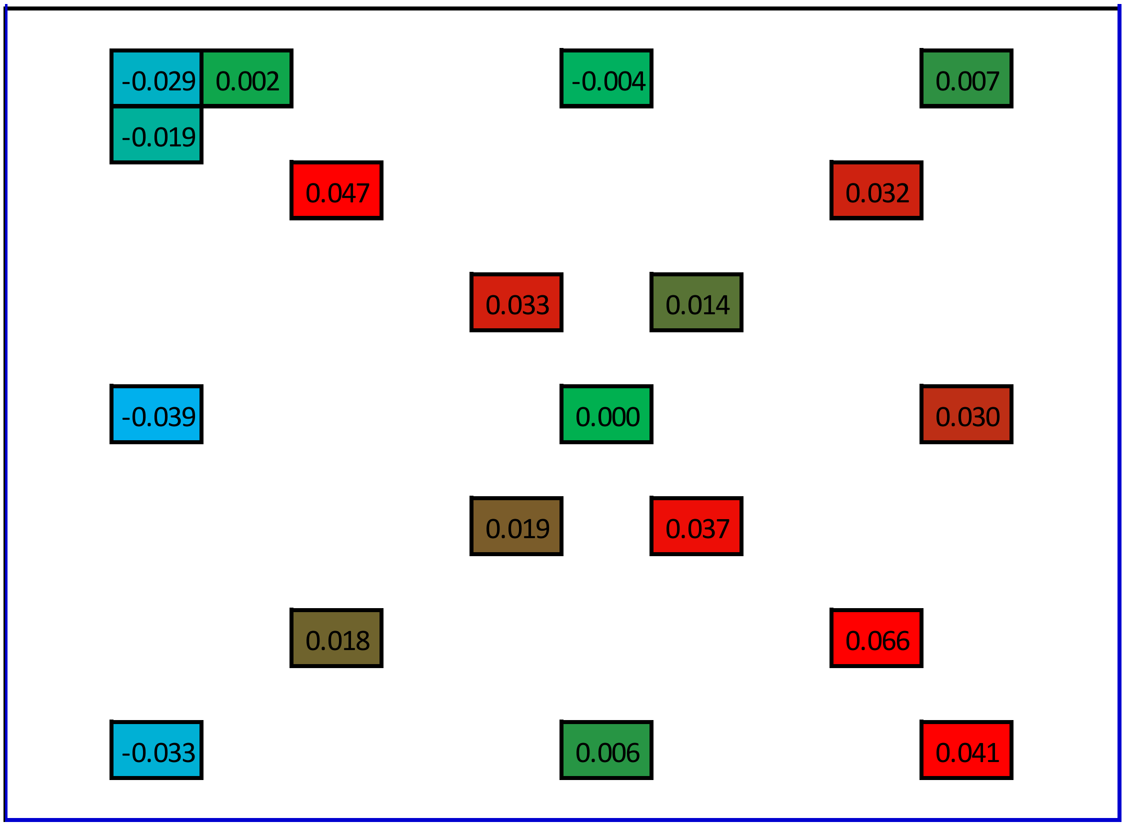


Figure 20: 3D LME and colour mapping accuracy and repeatability for circle board

Tests indicate that the lower right corner of the field of view distances are measured slightly too large while the left side of the field of view distances are slightly too small.

4.4.4.4.3 3D accuracy, Test 2 - ball/sphere distance normal[56]

To investigate robustness of 3D accuracy in terms of length measurement error (LME) and probing error (PE) with regards to position in field of view, 1 engineer experienced in using the 3D-Scanner made 10 quadpod scans of a special specimen (ball/sphere distance normal, distance of sphere centres 200mm) in different positions according to the German Society of Engineers Guideline VDI 2634. All other operational parameters were standard.

[56] *Test case series: 3DFFTI_TC_4b.*

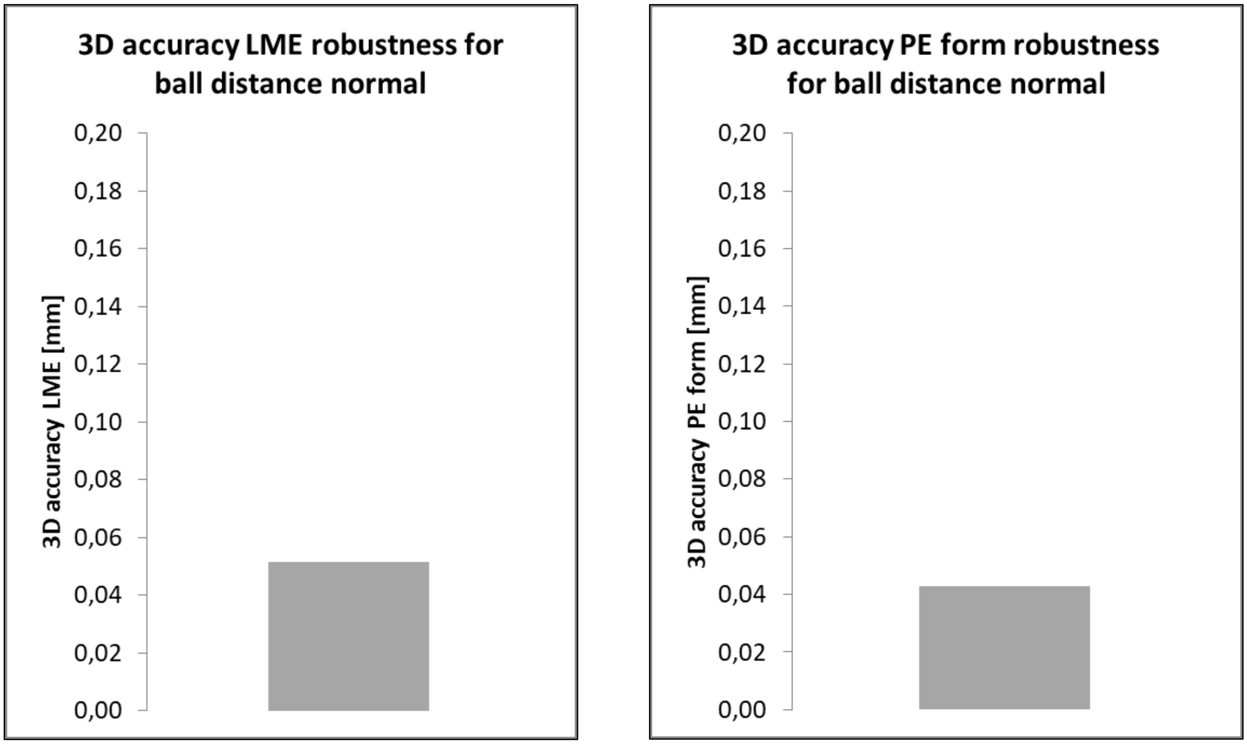


Figure 21: 3D accuracy LME and PE robustness for ball distance normal. The robustness is defined as the maximum error from all measured positions.

4.4.4.5 Working distance

4.4.4.5.1 Resolution[57]

To investigate the robustness of recording resolution with regards to variations in nominal working distance of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 5 quadpod scans of the “Dark” rescor specimen described above at the nominal working distance (455 mm) and at +/- 25mm and +/- 50mm. All other operational parameters were standard. Scans were made indoors. Results are provided in Figure 22.

[57] *Test case series: 3DFFTI_TC_1c.*

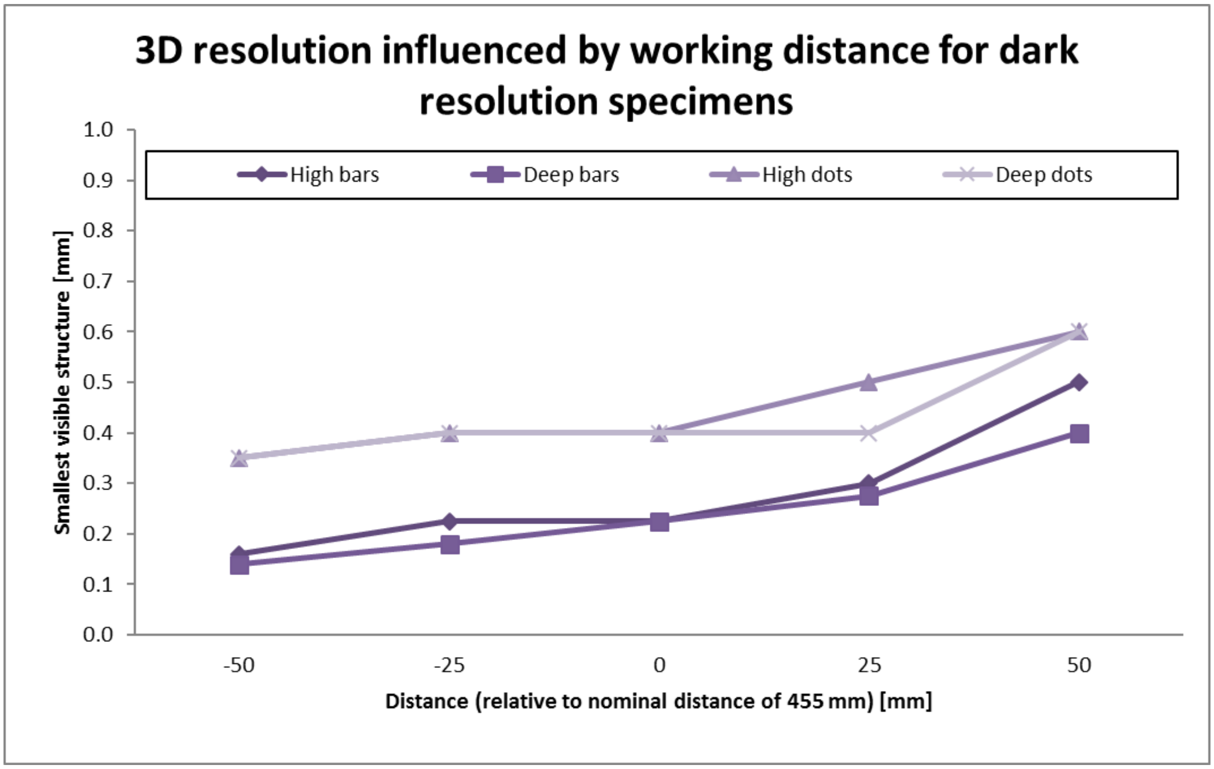


Figure 22: 3D resolution influenced by working distance for dark resolution specimens

Resolution is improved with decreased distance. At the same time the field of view is decreased with distance.

4.4.4.5.2 3D accuracy[58]

To investigate the robustness of 3D accuracy in terms of length measurement error (LME) and probing error (PE) with regards to variations in nominal working distance of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 5 quadpod scans of the calibration circle board described above at the nominal working distance (455 mm) and at +/- 25mm and +/- 50mm. All other operational parameters were standard. Scans were made indoors. Results are provided in Figure 23.

[58] *Test case series: 3DFFTI_TC_3c1.*

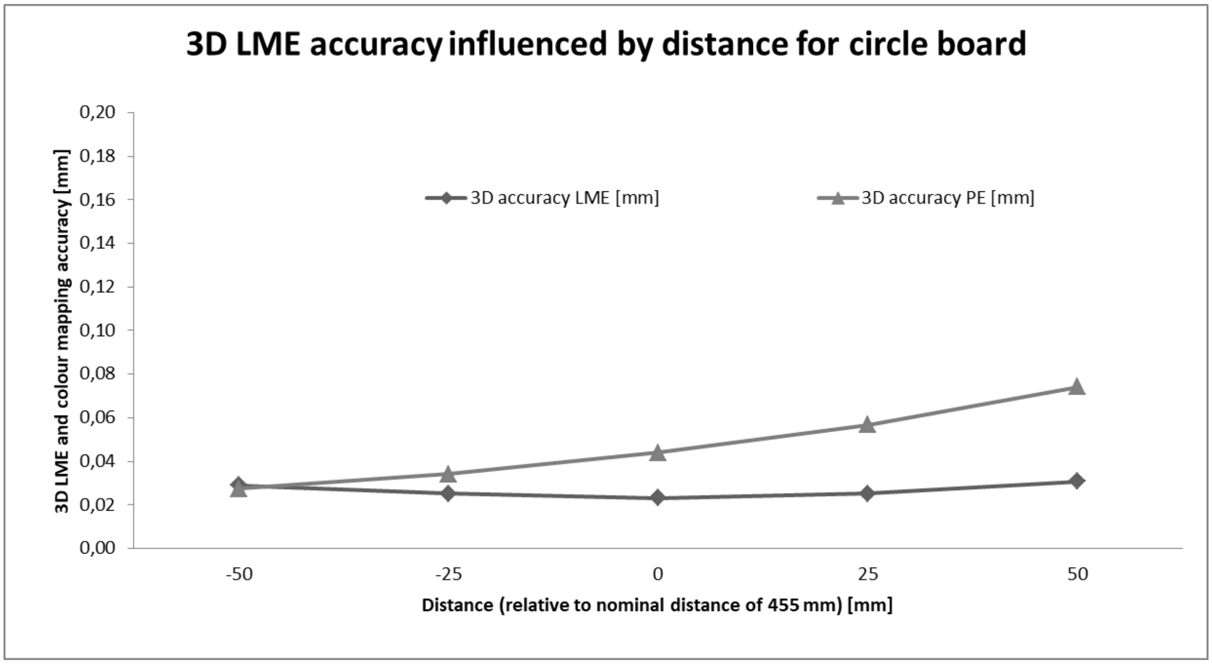


Figure 23 3D LME accuracy influenced by distance for circle board

The results indicate accuracy in terms of LME is not influenced by distance. The probing error PE is increasing with distance.

4.4.4.6 Tilting

4.4.4.6.1 Resolution[59]

To investigate the <u>robustness of recording resolution with regards to tilting</u> of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 5 quadpod scans of the “Dark” rescor specimen described above with no tilt and tilted at ca. 3-5° in the horizontal and vertical planes in both directions. All other operational parameters were standard. Scans were made indoors. Results are provided in Figure 24.

[59] *Test case series: 3DFFTI_TC_1d2.*

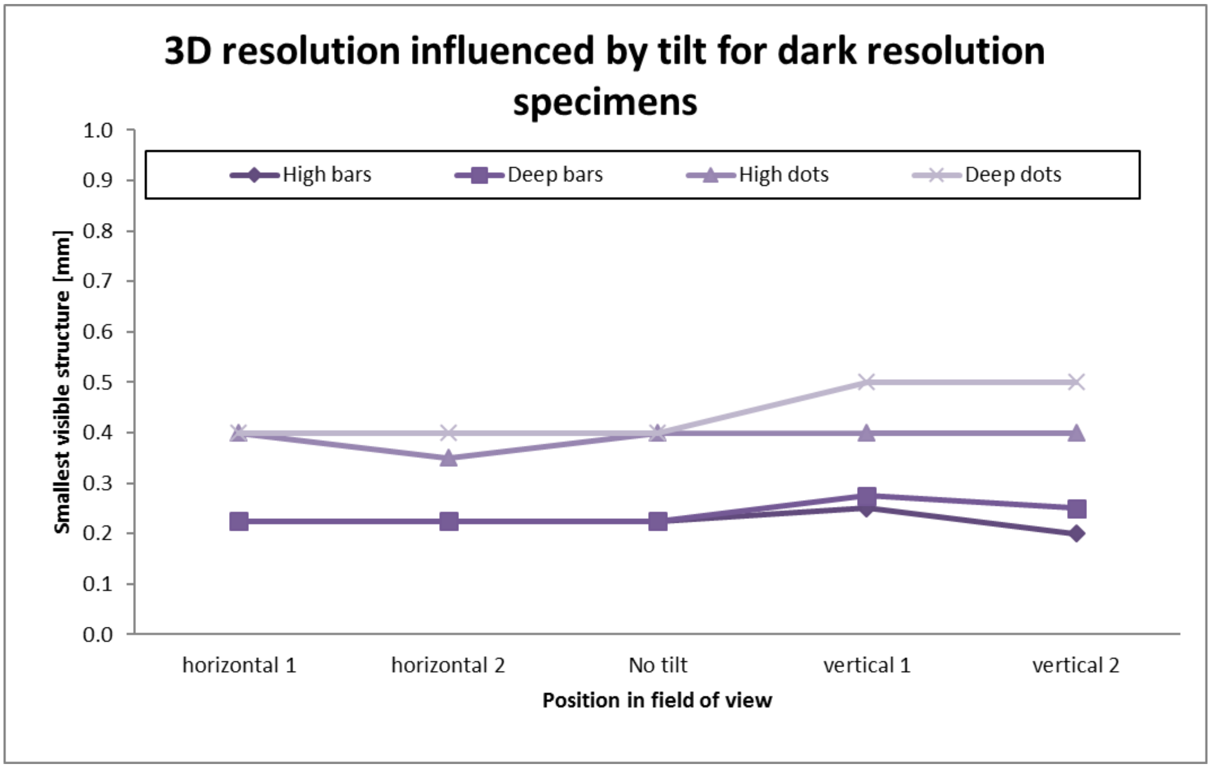


Figure 24: 3D resolution influenced by tilt for dark resolution specimens

The resolution deteriorates slightly when the structure being scanned is tilted in the vertical plane.

4.4.4.6.2 3D accuracy[60]

To investigate the robustness of 3D accuracy in terms of length measurement error (LME) and probing error (PE)with regards to tilting of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 5 quadpod scans of the circle board described above with no tilt and tilted at ca. 3-5° in the horizontal and vertical planes in both directions. All other operational parameters were standard. Scans were made indoors. Results are provided in Figure 25.

[60] *Test case series: 3DFFTI_TC_3c2.*

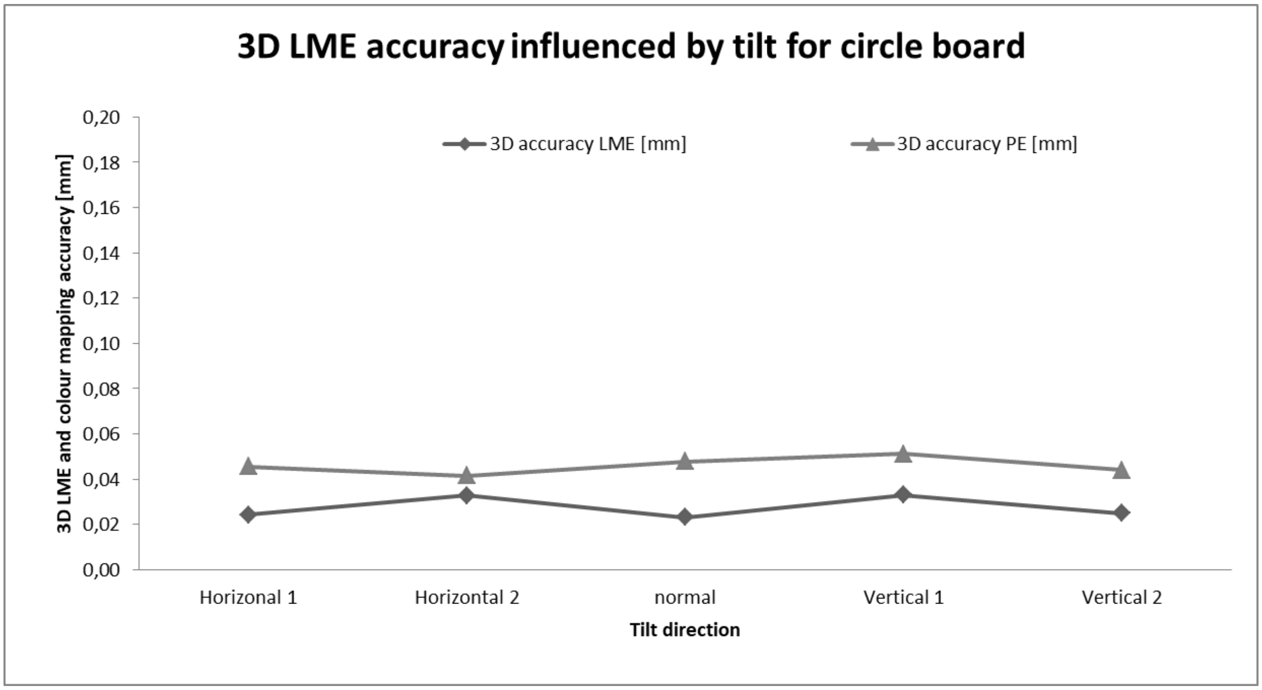


Figure 25: 3D LME accuracy influenced by tilt for circle board

The results indicate that the 3D accuracy LME is slightly influenced by tilting the circle board but with accuracy errors below 0.05 mm.

4.4.4.7 Orientation (influence on resolution)

4.4.4.7.1 Resolution[61]

To investigate the robustness of recording resolution with regards to orientation of the 3D-Scanner relative to the structure being recorded, 1 engineer experienced in using the 3D-Scanner made 6 quadpod scans of the “Dark” rescor specimen, 3 each for orientation of the specimen in the vertical and horizontal plane. All other operational parameters were standard. Scans were made indoors. Averaged results are provided in Figure 26.

[61] *Test case series: 3DFFTI_TC_1d3.*

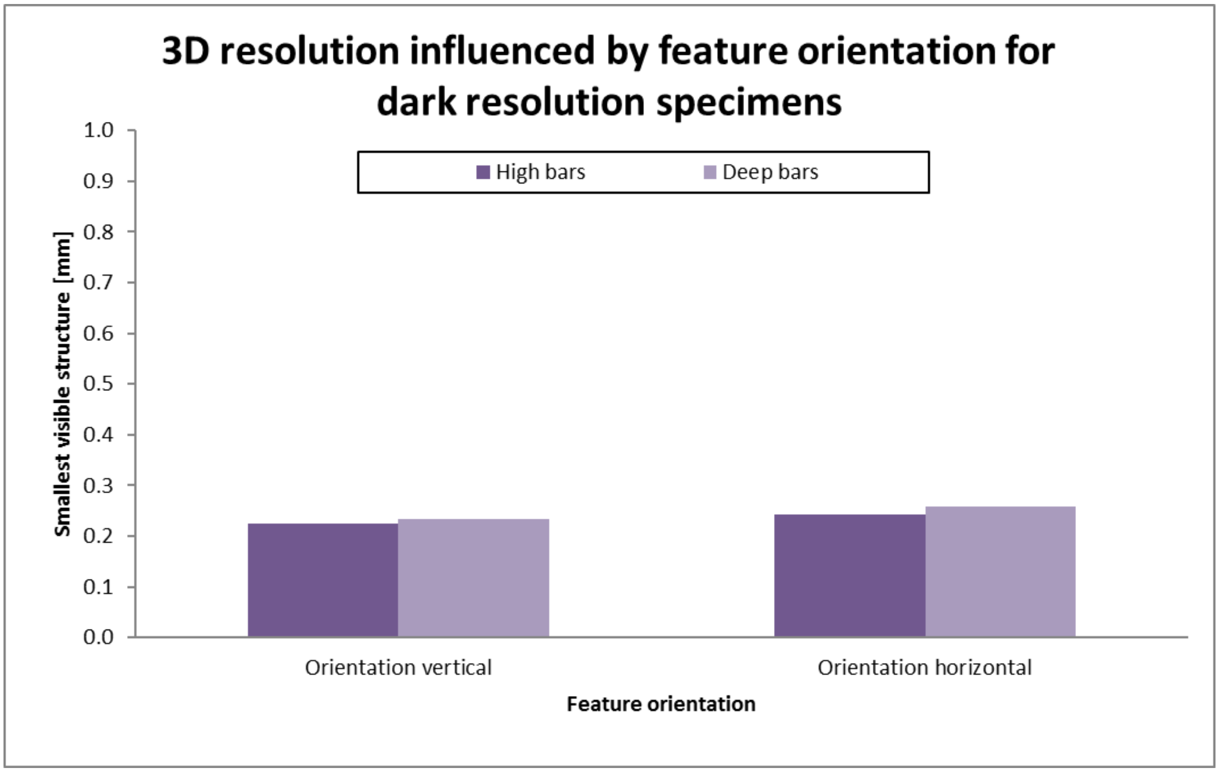


Figure 26: 3D resolution influenced by feature orientation for dark resolution specimens (for the dot structures the orientation is always same)

Tests indicate that the influence of the orientation on resolution performance is negligible.

4.4.4.8 Temperature

4.4.4.8.1 Resolution[62]

To investigate the <u>robustness of recording resolution with regards to temperature</u> with the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made quadpod scans of the "Dark" rescor specimen at different environmental temperatures. All other operational parameters were standard. Scans were made indoors and outdoors. Results are provided in Figure 27.

[62] *Test case series: 3DFFTI_TC_1e.*

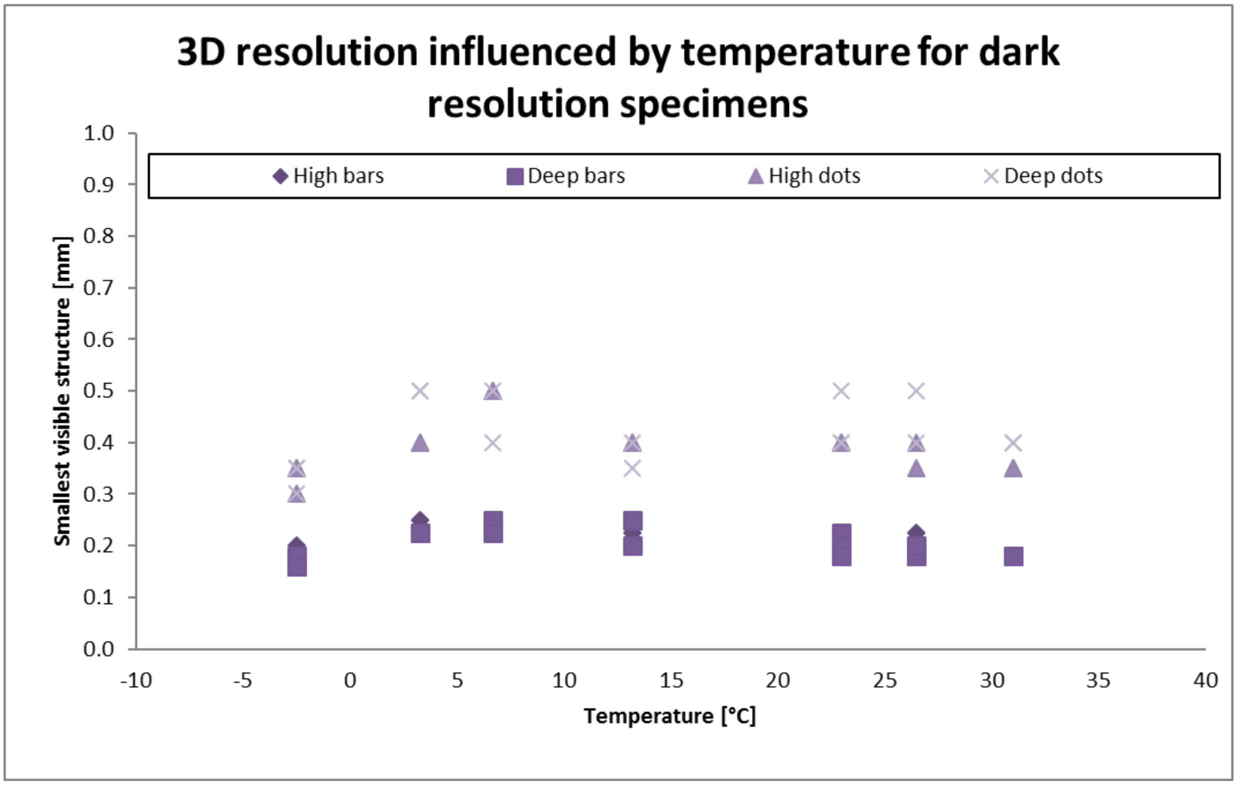


Figure 27: 3D resolution influenced by temperature for dark resolution specimens

Tests indicate the temperature influence is negligible regarding resolution.

4.4.4.8.2 3D accuracy[63]

To investigate the robustness of 3D accuracy in terms of length measurement error (LME) and probing error (PE)with regards to temperature with the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made quadpod scans of the circle board varying environmental temperature. All other operational parameters were standard. Scans were made indoors and outdoors. Results are provided in Figure 28.

[63] *Test case series: 3DFFTI_TC_3d.*

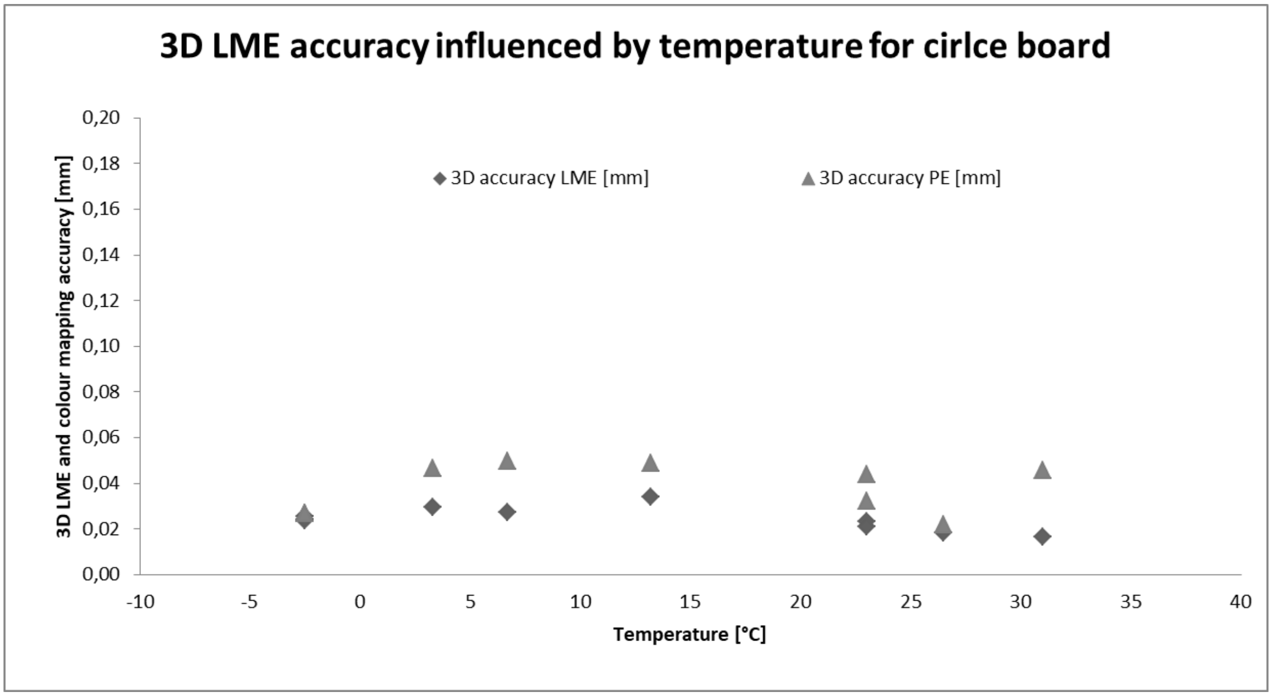


Figure 28: 3D LME accuracy influenced by temperature for circle board

Tests to date indicate 3D accuracy LME and PE is not influenced by temperature.

4.4.4.9 Sunlight

4.4.4.9.1 Resolution[64]

To investigate the robustness of recording resolution with regards to sunlight with the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner will make (tests not done yet) quadpod scans of the rescor specimen at different sun light intensities (specified in lux). All other tests made to date were with room light at approximately 500 lux if not stated otherwise. Results are provided in Figure 29.

[64] *Test case series: 3DFFTI_TC_1f.*

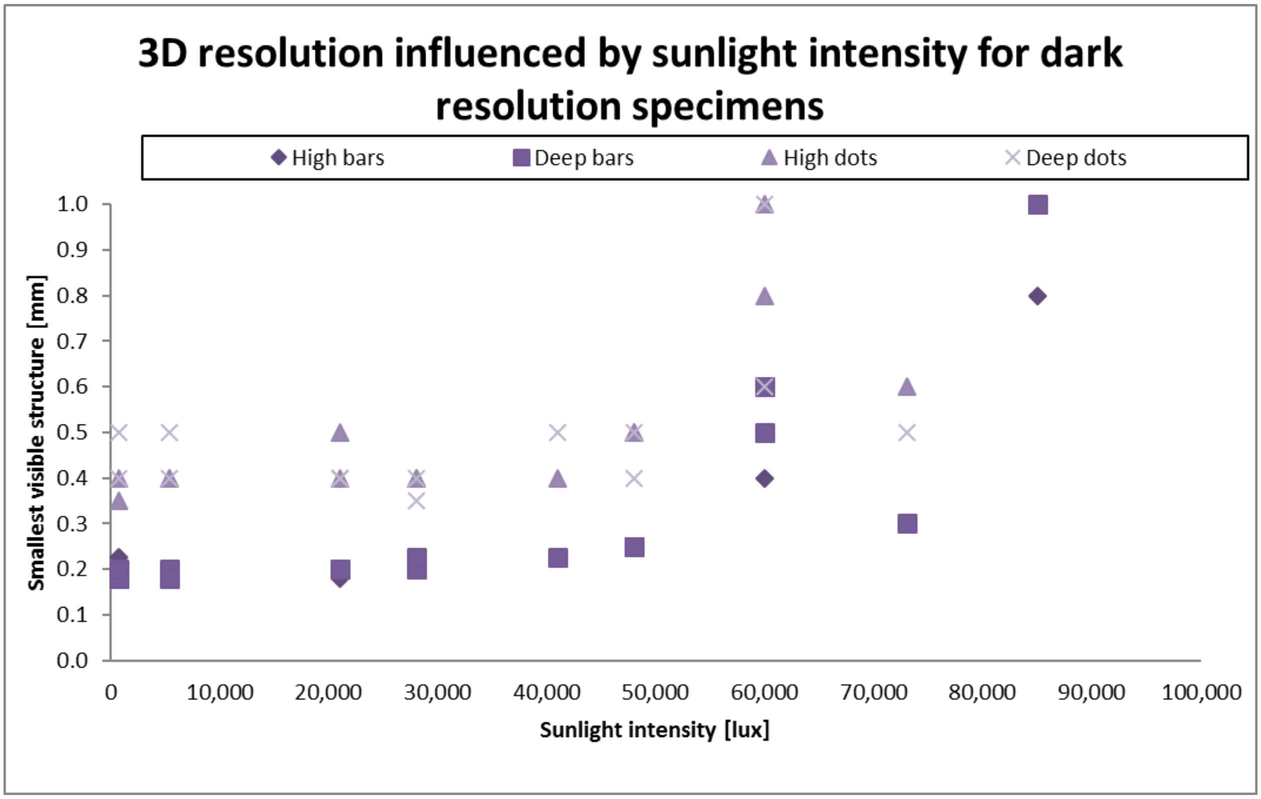


Figure 29: 3D resolution influenced by sun light for dark resolution specimens

Tests indicate the sun light is negligible regarding resolution for intensities <50,000 lux. For larger light intensities, which only occur in direct sun light, the resolution is reduced. Using a simple shielding for direct sun light reduces its intensity below 25,000 lux.

4.4.4.9.2 3D accuracy[65]

To investigate the robustness of 3D accuracy in terms of length measurement error (LME) and probing error (PE)with regards to sunlight with the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made quadpod scans of the of the circle board at different sun light intensities (specified in lux). *(All other tests made to date were with room light at approximately 500 lux if not stated otherwise.)* Results are provided in Figure 30.

[65] *Test case series: 3DFFTI_TC_3e.*

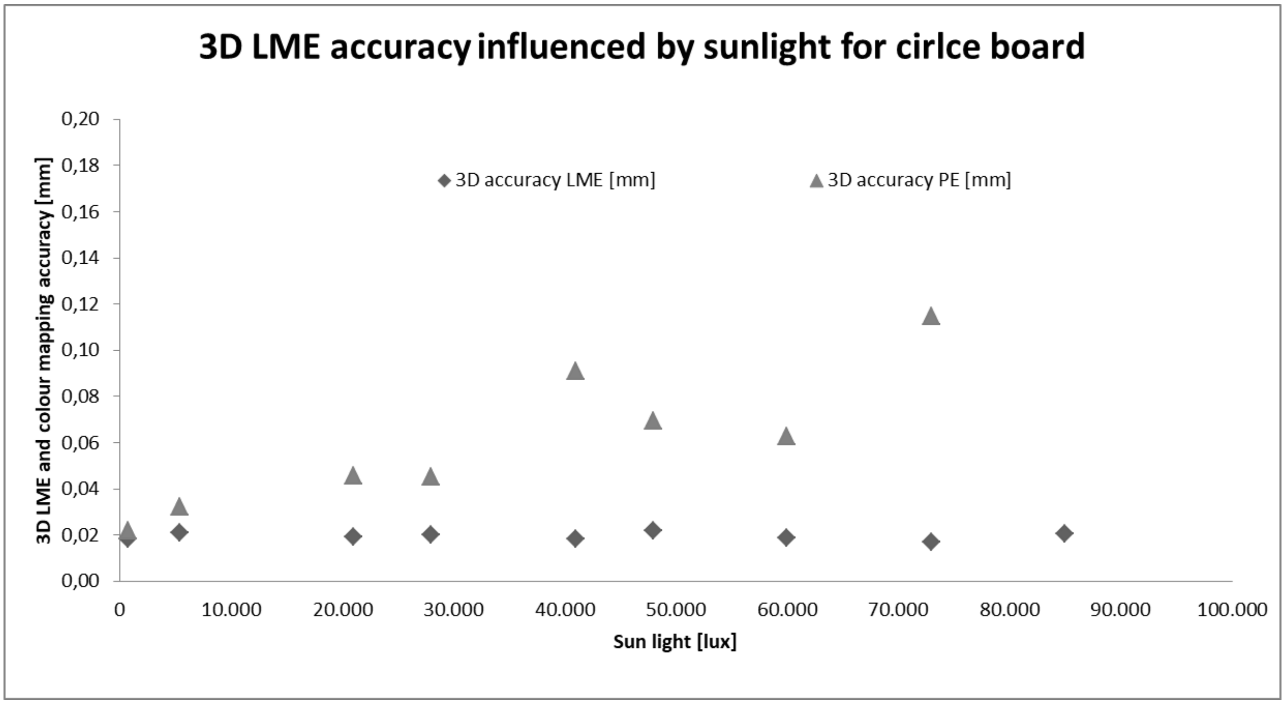


Figure 30: 3D LME accuracy influenced by sun light intensity for circle board

Tests indicate the sun light is negligible regarding length measurement error accuracy. The probing error is increasing at a sunlight intensity of ca. 40,000 lux.

4.5 Developmental validation assessment

	End user requirement	Specification	Test reference*	Assessment from developmental validation
[1.1]	3D Resolution - ability to resolve identification characteristics found in footwear / tyre impressions as good as plaster casting (or better)	< 200 µm	3DFFTI_TC_1a	The specified resolutions are achieved with the 3D-Scanner but recorded resolution can be lower depending on the properties of the substrate and / or the structure measured. Countermeasures such as snow wax spray or chalk spray can be used to improve results for the challenging substrates: ▪ Transparent / translucent objects (e.g. slushy snow) ▪ Specular reflecting objects (e.g. mirrors or very wet surfaces) ▪ Low reflecting (dark) objects (But, these were note covered by developmental validation testing to date.) Crime Scene Investigators (CSIs) and identification experts need to be aware of the potential limitations on 3D resolution connected with the handheld scan mode, substrate and type of structure. Manual and training must provide this information. It should be noted that the colour cameras available as an integral part of the system have the following resolutions: CANON EOS100D 28mm is 1px = 0.075mm and CANON Mark IV 50mm 1 px = 0.05mm. When working within the colour layer finer details may be resolved.
[1.2]	3D Accuracy - ability to measure distances in the outsole / profile	< 50 µm	3DFFTI_TC_3a 3DFFTI_TC_4a 3DFFTI_TC_5a	The specified accuracy was achieved with certified tests specimens and for investigations with MicroTrack™ and a shoe sole. Crime Scene Investigators (CSIs) and identification experts need to be aware of the potential limitations on 3D Accuracy connected with the handheld scan mode. Manual and training must provide this information.

[1.3]	3D Robustness resolution - resistance of the resolution to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner, brightness setting).	Small variations without influence Effects of larger variations must be known	3DFFTI_TC_1aH 3DFFTI_TC_1c 3DFFTI_TC_1d	The system's resolution is robust to variations in field of view, tilting, orientation of structures. The use of the handheld scan mode reduces the resolution by factor 1.5 … 2. Manual and training to highlight that the resolution can be increased by using the 3D scanner at a closer distance.
[1.4]	3D Robustness accuracy - resistance of the accuracy to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner, brightness	Small variations without influence Effects of larger variations must be known	3DFFTI_TC_3aH 3DFFTI_TC_3c 3DFFTI_TC_4b 3DFFTI_TC_5aH 3DFFTI_TC_5b 3DFFTI_TC_5bH	The system's accuracy is robust to variations in nominal working distance, field of view, tilting, and orientation of structures. The use of the handheld scan mode reduces the accuracy in terms of PE by factor 2.

	setting).			
[1.5]A	3D Repeatability resolution - scan results should be stable. (Measurement uncertainty / standard deviation of resolution)	<±50 µm	3DFFTI_TC_1a 3DFFTI_TC_3a 3DFFTI_TC_4a 3DFFTI_TC_5a	Resolution repeatability measurement precision (tests *3DFFTI_TC_1a)* was better than <±50 µm with an uncertainty (confidence interval 95%) of between 0.029mm and 0.058mm. For reflective surfaces (aluminium test specimen) and dot structures the standard deviation was above <±100 µm. Countermeasures such as snow wax spray or chalk spray can be used to improve results for the challenging substrates: ▪ Transparent / translucent objects (e.g. slushy snow) ▪ Specular reflecting objects (e.g. mirrors or very wet surfaces) ▪ Low reflecting (dark) objects Crime Scene Investigators (CSIs) and identification experts need to be aware of the potential limitations on resolution repeatability for handheld scans depending on substrate and type of structure. Manual and training must provide this information.
[1.5]B	3D Repeatability accuracy - scan results should be precise. (Measurement uncertainty / standard deviation of accuracy)	<±20 µm	3DFFTI_TC_1a 3DFFTI_TC_3a 3DFFTI_TC_4a 3DFFTI_TC_5a	3D accuracy repeatability measurement precision was within the targeted specifications. It was not above a standard deviation of 0.008mm.
[1.6]A	3D Reproducibility	<±50 µm	3DFFTI_TC_1b	Resolution reproducibility measurement precision (tests *3DFFTI_TC_1b)* varied for the bar structures between 0.036 mm and

	resolution - scan results should be independent from user. (Measurement uncertainty / standard deviation of resolution)		3DFFTI_TC_3b 3DFFTI_TC_5b	0.088 mm. Crime Scene Investigators (CSIs) and identification experts need to be aware of the potential limitations on resolution reproducibility depending on substrate and type of structure or in case the handheld scan mode is used. Manual and training must provide this information.
[1.6]B	3D Reproducibility accuracy – scan results should be independent from user. (Measurement uncertainty / standard deviation of accuracy	<±20 µm	3DFFTI_TC_1b 3DFFTI_TC_3b 3DFFTI_TC_5b	3D accuracy reproducibility measurement precision was within the targeted specifications (for the 9 valid user tests for the tests with the certified specimens). It was not above an uncertainty (confidence level 95%) of 0.036mm. For investigations with MicroTrack^{TM} and a shoe sole this was achieved only with the MicroTrack^{TM}. Results with MicroTrack^{TM} and shoe sole may be explained by the less accurate nature of the test.
[1.7]	3D Range of inclination angle - capturing steep boundaries of deep impressions	0 … 60°	3DFFTI_TC_2	Range of inclination angle is 0…>64.4°
[1.8]	Range	≥ 300 x 200 x 50	Observation	325 x 200 x 100 mm³

	(Measurement volume) - ability to capture a footwear impressions in one scan	mm^3		
[1.9]	Working distance	> 300 mm (contactless)	Observation	455 mm
[1.10]	Brightness setup - ability to measure on any kind of underground in which impression traces can occur (snow, mud, etc.)	Brightness pre-settings	Observation	7 exposure steps and 7 LED brightness settings
[1.11]	Usability - easy handling of the 3D-scanner means in simple words to “measure with one touch of a button” and to provide an output result that is understandable	Scan starts with one button (measurement modes and brightness pre-settings)	Observation	2 measurement modes

	for a layman			
[1.12]	User feedback after 3D-scan - preview of 3D-patch and the colour photo is shown, the user has to evaluate the quality, e.g. holes	3D-patch preview Photo preview	Observation	Quick and extended 3D-preview separate photo preview
[1.13]	Mobility / handling / scanner size - main application field of the 3D-scanner is outdoor measurements in arbitrary surroundings using it as a hand-held sensor head	Handheld 3D-Scanner No (or easy-to-use) additional equipment	Observation	Easy-to-use quadpod, 3D-Scanner also attachable on an appropriate tripod. As indicated above, appropriate means it must be at least able to support the weight of the 3D-Scanner i.e. without falling over and to enable a field of view over the measurement scene to be scanned Optionally handheld use mode no additional equipment Crime Scene Investigators (CSIs) and identification experts need to be aware of the potential limitations in case the handheld scan mode is used.
[1.14]	Time to scan - Quick enough to allow handheld scans	≤ 200 ms	Observation	≥ 133,3 ms
[1.15]	Thermal	-10 – 40°C	3DFFTI_TC_1e	System is robust to variations in environmental temperature.

	robustness - usability at typical outdoor conditions	working temperature	3DFFTI_TC_3d	*(Range not fully tested to date - but there was no indication that the system does not work within these specifications.)*
[1.16]	Moisture - usability at typical outdoor conditions	< 80% air moisture	Observation	< 80% air moisture
[1.17]	Protection class - usability at typical outdoor conditions	IP44	Observation	IP22 (*feedback from EETG members indicates that this is acceptable*)
[1.18]	Shock resistance - usability at typical outdoor conditions	IK04	Observation	IK04
[1.19]	Surrounded light - usability at daytime	< 10,000 lux (cloudy day, shadow, not in direct light)	3DFFTI_TC_1f 3DFFTI_TC_3e	System is robust to sunlight intensity below 50,000 lux. For larger intensities the user should use an auxiliary means to shield direct sun light.
[1.20]	Frequency of technical maintenance - long-life device with stable functional parameters	> 1 year	Observation	> 1 year– *based on development status/assessment in June 2019. Experience with first products will confirm and or update this specification.*

[1.21]	Quality control - verify the functionality of the device at the crime scene	Test specimen (to be used at crime scene)	Observation	Calibration board

* Test references are used in Annex4.

4.6 Advice for the implementation of the tool

Required quality controls:

- Verify the calibration at the crime scene using the dedicated calibration board
- Regular check all 3 months of the calibration in laboratory using the dedicated calibration board
- Regular maintenance once in a year and re-calibration by manufacturer

Required competence / training:

- Read and follow user manual
- Half-day training is recommended
- Necessary user competences:
    - Adjusting the working distance before scanning
    - Setting an appropriate brightness before scanning
    - Knowledge how (and in which situation) to make a set of multiple overlapping scans
    - Training / experience for assessing the scan quality in the 3D preview
    - Visually assess the objects' surface whether it falls into the category mentioned under limitations

5 3D-Scanner: Mapping of external colour images onto 3D point clouds

5.1 Technical principle and reference publications

Colour images are taken by an attached high resolution camera simultaneously with the 3D measurement. They can be later mapped onto the 3D point cloud to distinguish between characteristics in the impression trace and distortions such as small stones or leaves and to assess higher resolution details in the colour images. The external camera is calibrated relative to the 3D point cloud. This calibration can be updated automatically with the dedicated calibration board.

T. Luhmann, S. Robson, S. Kyle: Close-Range Photogrammetry and 3D Imaging. 2nd Edition, 2013, De Gruyter

5.2 Performance limitations, interferences and countermeasures

Limitation / constraint	Countermeasure
Non-coloured areas through parallax between 3D sensor and colour camera can occur in steep regions of the object	Multiple scans, including inclined scans, can be merged by using the registration tool.
Limited depth of focus	Adjustable through aperture size
Large shaking between 3D scan and photo capture with handheld use (also connected with Time to scan)	Use standard scan mode with quadpod or an appropriate tripod
Mechanical robustness of camera	Re-calibration through scanning the calibration board.

5.3 Reviewed end user requirements and related specifications

Digital photo capturing itself can be seen as validated, because it is widely used in crime scene investigation.

	End user requirement	Specification /
[2.1]	Accuracy - accurate alignment between colour photo and 3D data	< 1 3D point pitch (170 µm)
[2.2]	Robustness accuracy - resistance to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner).	Small variations without influence Effects of larger variations must be known
[2.3]	Repeatability (Accuracy) - alignment should be stable. (Measurement uncertainty / standard deviation of accuracy)	<±50 µm
[2.4]	Reproducibility (Accuracy) - alignment should be independent from user. (Measurement uncertainty / standard deviation of accuracy)	<±50 µm
[2.5]	Range (Field of view FOV) - ability to colour the complete 3D point cloud	≥ than FOV of 3D-Scanner

Other end user requirements do not directly have an “impact on the result”, but define relevant limitations, interferences and necessary user competencies:

	End user requirement	Specification
[2.6]	Time to scan - quick enough to allow handheld scans without a relevant misalignment between 3D scan and photo	20 ms (but improved photo settings are possible)
[2.7]	Thermal robustness - stability of camera alignment at typical outdoor conditions (in Europe)	-10 … +40°C
[2.8]	Quality control - verify the calibration of the camera alignment at the crime scene	Calibration board

5.4 Developmental validation test results – summarised overview

5.4.1 Colour mapping accuracy and corresponding repeatability measurement precision[66]

To investigate Colour mapping accuracy and corresponding repeatability measurement precision, 1 engineer experienced in using the 3D-Scanner made both 10 quadpod scans of the 3D-Scanner's calibration circle board (Figure 6). All other operational parameters were standard. The colour camera was the CANON Mark IV 50mm (1px ≙ 0.05mm).

The positional deviations between mapped circle centres from the colour image and the corresponding circle centre in the 3D data represent the colour mapping error. Results are provided in Figure 31.

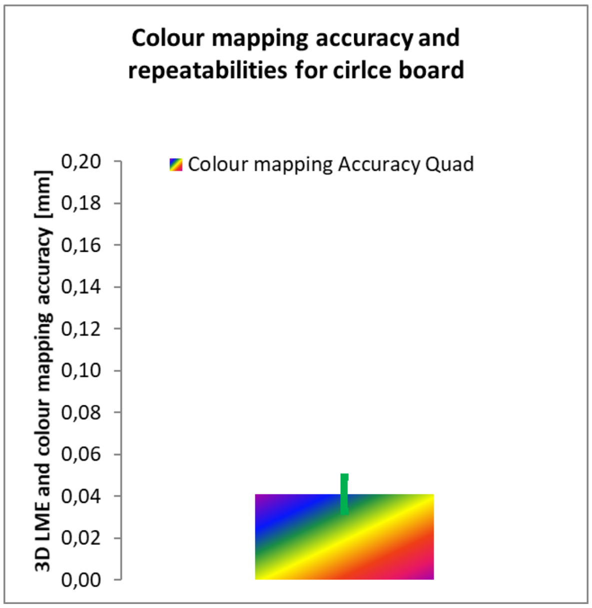


Figure 31: 3D LME and colour mapping accuracy and repeatability for circle board

Average colour mapping accuracy is clearly below the point pitch distance of the 3D scans of 0.17 mm so that no misalignment between 3D and colour data would be visible.

[66] *Test case series: 3DFFTI_TC_3a.*

5.4.2 Influences on colour mapping (robustness)

5.4.2.1 User / device

5.4.2.1.1 Colour mapping accuracy and reproducibility measurement precision[67]

To investigate colour mapping accuracy and corresponding reproducibility measurement precision of the 3D-Scanner, 9 Crime Scene Investigators and 1 experienced engineer from 4 organisations in 2 different countries made 1 quadpod of the calibration circle board. All other operational parameters were standard. 2 organisations used the CANON EOS100D 28mm colour camera and the other organisation the CANON Mark IV 50mm. The spatial resolution of the CANON EOS100D 28mm is 1px = 0.075 mm and for the CANON Mark IV 50mm it is 1px = 0.05mm.Results are provided in Figure 32.

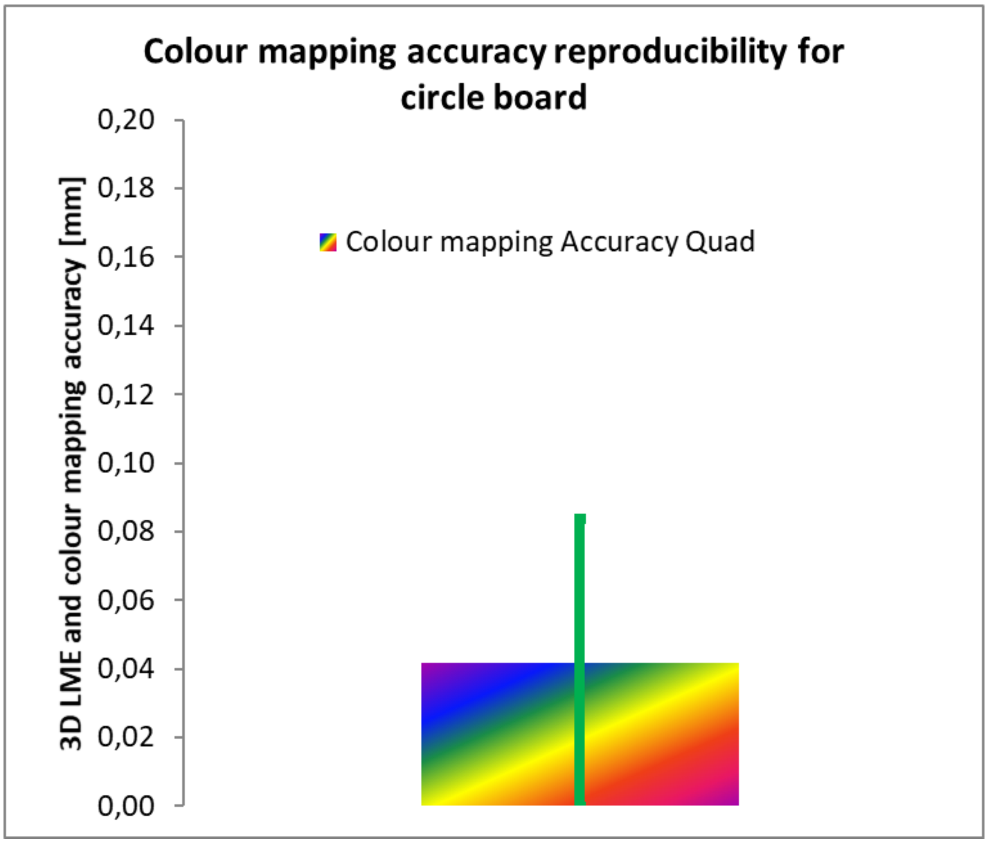


Figure 32: Colour mapping accuracy reproducibility for circle board for 10 users

[67] *Test case series: 3DFFTI_TC_3b.*

Settings			**Accuracy Quad**
User-ID	**Device**	**Mode**	**Colour mapping accuracy [mm]**
IOF1	006	Quad	0.032
YHP1	006	Quad	0.031
YHP2	006	Quad	0.028
YHP3	006	Quad	0.029
LKASA1	007	Quad	0.068
LKASA2	007	Quad	0.066
LKASA3	007	Quad	0.065
LKAMV1	008	Quad	0.035
LKAMV2	008	Quad	0.031
LKAMV3	008	Quad	0.032
Colour mapping accuracy [mm]			0.042
Reproducibility [mm]			0.042

Table 12 Colour mapping accuracy reproducibility for circle board and quadpod scanning with 10 users

Averaged accuracy for the 10 users had a measurement error less than 0.05 mm for colour mapping. As the point pitch distance of the 3D scan is ca. 0.17 mm no visible misalignment between colour photo and 3D data will appear.

5.4.2.2 Handheld scan mode

5.4.2.2.1 Colour mapping accuracy and reproducibility measurement precision[68]

To investigate the influence of the scan mode on colour mapping accuracy and corresponding repeatability and reproducibility measurement precision of the 3D-Scanner, 1 experienced engineer made 10 handheld scans and 9 Crime Scene Investigators and 1 experienced engineer from 4 organisations in 2 different countries made 1 handheld scan of the calibration circle board. All other operational parameters were standard. 2 organisations used the CANON EOS100D 28mm colour camera and the other 2 organisations the CANON Mark IV 50mm. The spatial resolution of the CANON EOS100D 28mm is 1px = 0.075 mm and for the CANON Mark IV 50mm it is 1px = 0.05mm.Results are provided in Figure 33.

[68] *Test case series: 3DFFTI_TC_3aH, 3DFFTI_TC_3bH.*

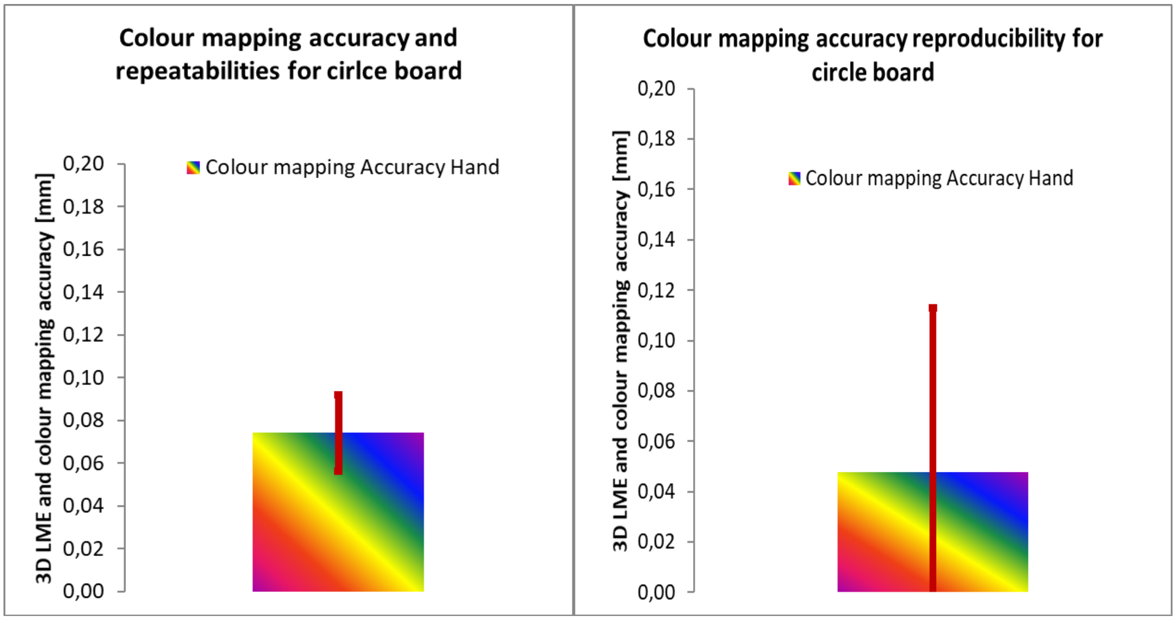


Figure 33: Colour mapping accuracy repeatability and reproducibility for circle board for 10 users

Averaged accuracy is increased compared to the results in standard scan mode. Different devices (with different photo cameras) show larger variance of the colour mapping accuracy. However there will still be no visible misalignment between colour photo and 3D data.

5.4.2.3 Position in field of view[69]

To investigate the robustness of colour mapping accuracy with regards to the position within the field of view of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 10 quadpod scans of the circle board described above. All other operational parameters were standard. For the 19 circles on the board systematic positional deviations between the circle centre positions in the 3D point cloud and the projected colour photo were evaluated by calculating their average distance to the centre circle over the 10 scans.

[69] *Test case series: 3DFFTI_TC_3b.*

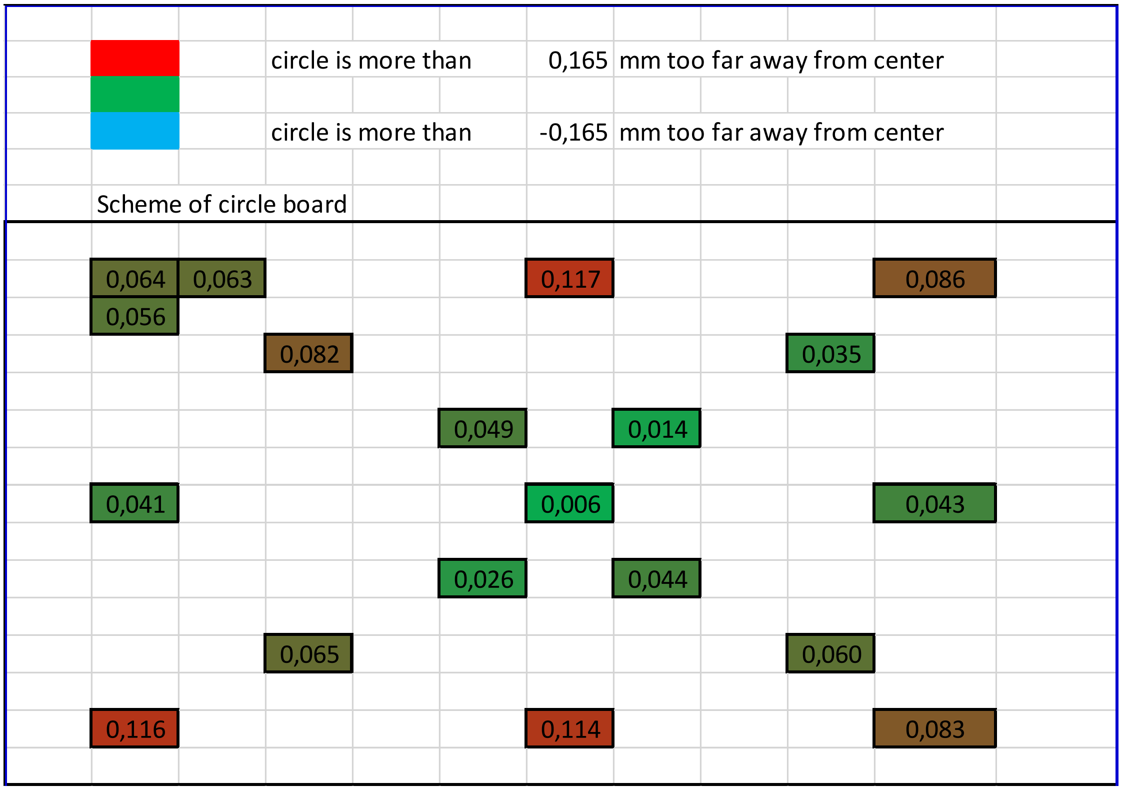


Figure 34: Colour mapping accuracy with regards to field of view for circle board

Tests indicate that the top and bottom side of the field of view deviations are measured slightly increased.

5.4.2.4 Working distance[70]

To investigate the robustness of colour mapping accuracy with regards to variations in nominal working distance of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 5 quadpod scans of the calibration circle board described above at the nominal working distance (455 mm) and at +/- 25mm and +/- 50mm. All other operational parameters were standard. The colour camera was the CANON Mark IV 50mm. Scans were made indoors. Results are provided in Figure 35.

[70] *Test case series: 3DFFTI_TC_3c1.*

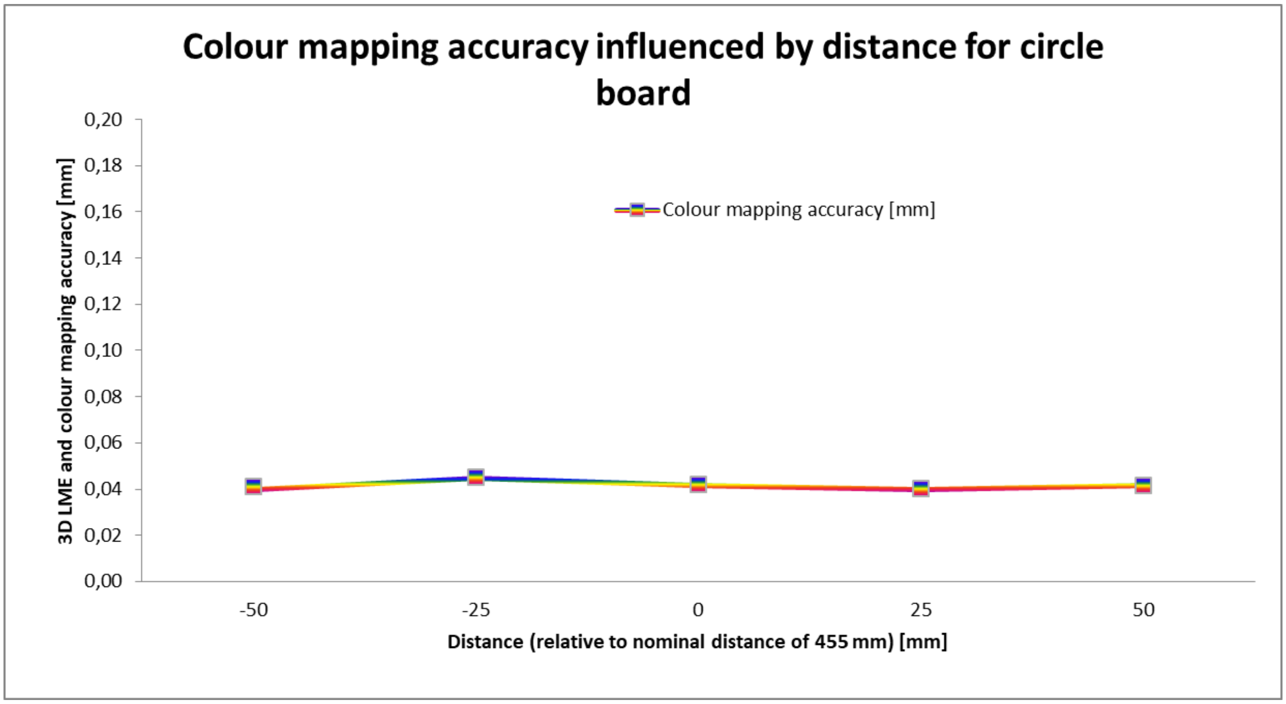


Figure 35: Colour mapping accuracy influenced by distance for circle board

The results indicate accuracy is not influenced by distance

5.4.2.5 Tilting[71]

To investigate the robustness of colour mapping accuracy with regards to tilting of the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made 5 quadpod scans of the circle board described above with no tilt and tilted at ca. 3-5° in the horizontal and vertical planes in both directions. All other operational parameters were standard. The colour camera was the CANON Mark IV 50mm. Scans were made indoors. Results are provided in Figure 36.

[71] *Test case series: 3DFFTI_TC_3c2.*

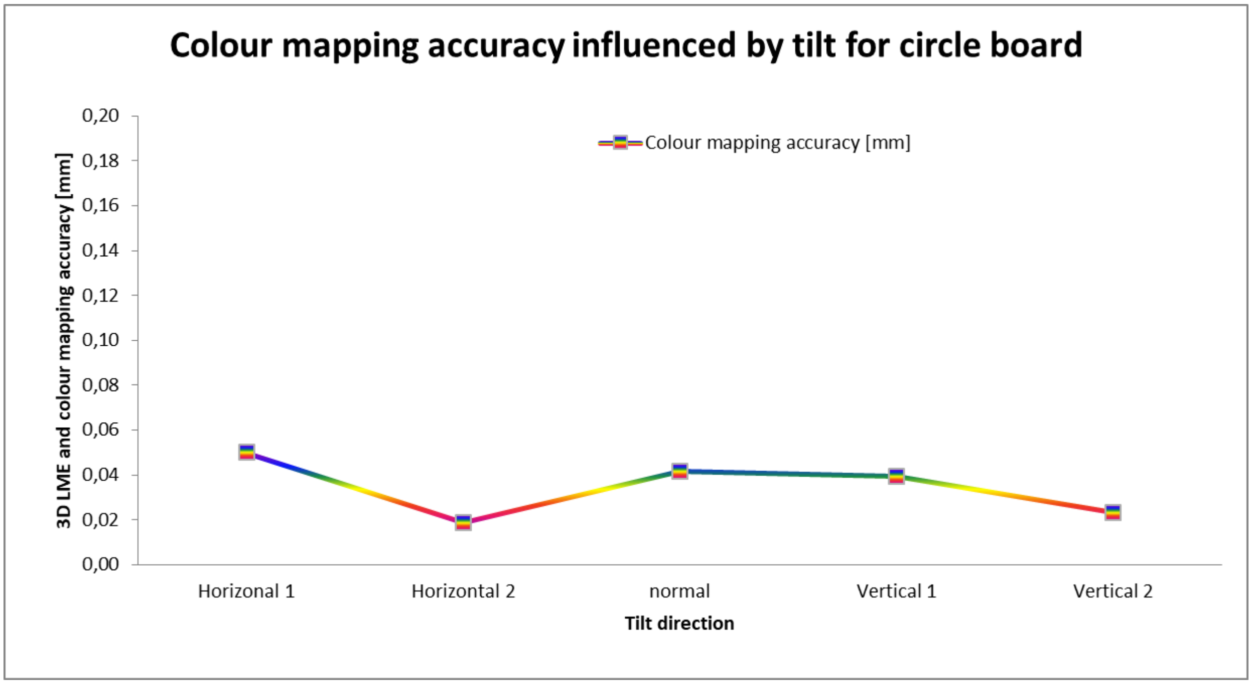


Figure 36: Colour mapping accuracy influenced by tilt for circle board

The results indicate that the colour mapping accuracy is slightly influenced by tilting the circle board but with accuracy errors below 0.05 mm.

5.4.2.6 Temperature[72]

To investigate the robustness of colour mapping accuracy with regards to temperature with the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made quadpod scans of the circle board varying environmental temperature. All other operational parameters were standard. Scans were made indoors and outdoors. Results are provided in Figure 37. .

[72] *Test case series: 3DFFTI_TC_3d.*

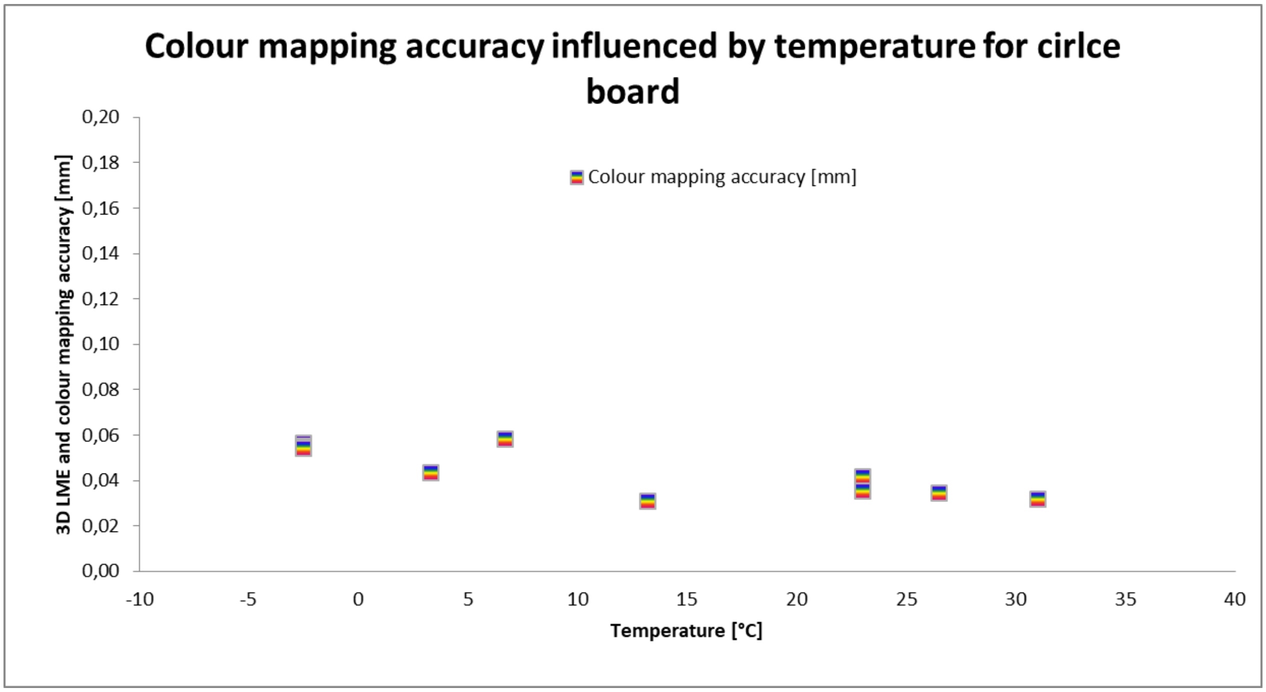


Figure 37: Colour mapping accuracy influenced by temperature for circle board

Tests to date indicate colour mapping accuracy is slightly influenced.

5.4.2.7 Sunlight[73]

To investigate the robustness of colour mapping accuracy with regards to sunlight with the 3D-Scanner, 1 engineer experienced in using the 3D-Scanner made quadpod scans of the of the circle board at different sun light intensities (specified in lux). *(All other tests made to date were with room light at approximately 500 lux if not stated otherwise.)* Results are provided in Figure 38.

[73] *Test case series: 3DFFTI_TC_3e.*

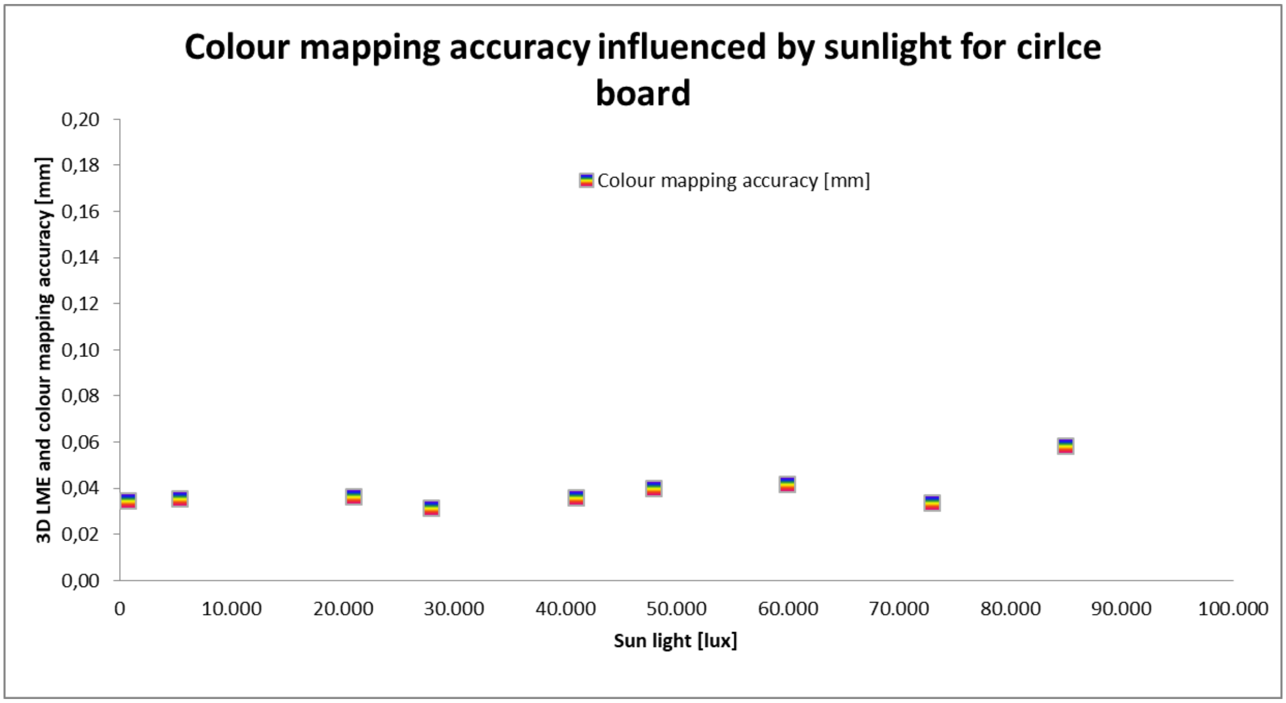


Figure 38: Colour mapping accuracy influenced by sun light intensity for circle board

Tests indicate the sun light is negligible regarding colour mapping accuracy.

5.5 Developmental validation assessment

	End user requirement	Specification	Test reference*	Assessment from developmental validation
[2.1]	Accuracy - accurate alignment between colour photo and 3D data	< 1 3D point pitch (170 µm)	3DFFTI_TC_3a	The results were all within the targeted specifications.
[2.2]	Robustness accuracy - resistance to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner).	Small variations without influence Effects of larger variations must be known	3DFFTI_TC_3c 3DFFTI_TC_3aH 3DFFTI_TC_3bH	System is robust to variations in working distance, tilting, and orientation of structures. Results in handheld scan mode were all within targeted specifications.
[2.3]	Repeatability (Accuracy) - alignment should be stable. (Measurement	<±50 µm (0,05mm)	3DFFTI_TC_3a	The results were all within the targeted specifications.

	uncertainty / standard deviation of accuracy)			
[2.4]	Reproducibility (Accuracy) - alignment should be independent from user. (Measurement uncertainty / standard deviation of accuracy)	<±50 µm (0,05mm)	3DFFTI_TC_3b 3DFFTI_TC_5b	3D accuracy reproducibility measurement precision were all within the targeted specifications (for the 10 valid user tests).
[2.5]	Range (Field of view FOV) - ability to colour the complete 3D point cloud	≥ than FOV of 3D-Scanner	Observation	340 x 250 mm³
[2.6]	Time to scan - quick enough to allow handheld scans without a relevant misalignment between 3D scan and	20 ms (but improved photo settings are possible)	Observation	Settable by user or Automatic mode

	photo			
[2.7]	Thermal robustness - stability of camera alignment at typical outdoor conditions (in Europe)	-10 … +40°C	3DFFTI_TC_3d	System is robust to variations in environmental temperature. *(Range not fully tested to date - but there was no indication that the system does not work within these specifications.)*
[2.8]	Quality control, verify the calibration of the camera alignment at the crime scene	Calibration board	Observation	Calibration board

* Test references are used in Annex4.

5.6 Advice for the implementation of the tool

Required quality controls:

- Regular check each 3 months of the calibration in laboratory using the calibration board
- Check of the calibration at the crime scene and recalibrate the external camera alignment
- Regular maintenance once in a year and re-calibration by manufacturer or by themselves

Required competence / training:

- Read and follow user manual
- Knowledge about appropriate camera settings for handheld photos
- Knowledge about relation between depth of focus and aperture size for camera

6 3D analysis software: Visualisation of 3D point clouds on a PC

6.1 Technical principle and reference publications

The rendering engine fully exploits the latest technologies in OpenGL based 3D rendering, maximizes the throughput in the full range of graphics cards available on the market. It also fully utilizes the modern opengl programmable pipeline to implement shaders which allow deferring computations onto the graphic card and minimizing the data exchange between CPU memory and GC memory.

* https://www.khronos.org/registry/OpenGL-Refpages/gl4/

6.2 Performance limitations, interferences and countermeasures

Limitation / constraint	**Countermeasure**
Artefacts in the original 3D or colour data	Visually control of the raw data by the user
Provide proper light to the rendered scene	Tool to adjust the light settings (1)

Note 1: light setting can be optionally applied by the user to emphasise details

6.3 Reviewed end user requirements and related specifications

	End user requirement	**Specification**
[3.1]	Resolution - ability to resolve specific geometric features in a point cloud	≤ resolution of 3D point cloud
[3.2]	Specificity 3D - only geometric features, which are present in the 3D point cloud, are emphasized	No artificial features are created

6.4 Developmental validation test results – summarised overview

6.4.1 Resolution and specificity[74]

In order to investigate resolution and specificity reproducibility a visualization test was made with simulated 3D point clouds of the resolution specimen with different point pitch distances. Different point pitch distances were used to simulate the data from different 3D sensors and demonstrate the same behaviour on different PCs of the rendering engine.

To run the test a project containing the following 6 point clouds was created, with 6 different point pitch distances as listed here below (Table 13):

[74] *Test case series: 3DFFTI_TC_6_1400_neigh100, 3DFFTI_TC_6_700, 3DFFTI_TC_6_350, 3DFFTI_TC_6_300, 3DFFTI_TC_6_250, 3DFFTI_TC_6_200.*

Name	**Point pitch distance**	
1400	37.5 µm	point pitch
700	75 µm	point pitch
350	150 µm	point pitch
300	175 µm	point pitch
250	200 µm	point pitch
200	260 µm	point pitch

Table 13 6 point clouds with 6 different point pitches

The 6 point clouds were rendered in 3 different computers with the following graphic cards (**Table 14**):

Computer	**Graphic card**
PC1	NVIDIA PRO 2000
PC2	GeForce 560 Ti
PC3	Quadro M2000M

Table 14 3 Graphic cards used

The 6 simulated scans were rendered with height colour layers to be independent from material reflectivity according to the colour classes reported in the following histogram (see Figure 39)

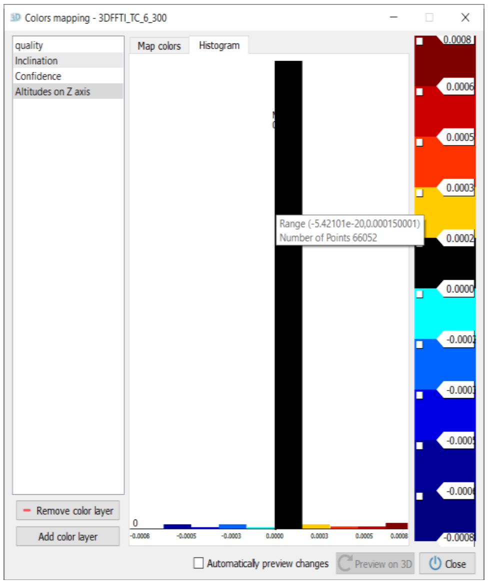


Figure 39: Histogram of the height colour map applied to the 6 simulated scans

During the rendering in the 3 independent PC, light effects were disabled in order to put all the users in the same conditions.

As reported in the test sheet in Annex 4, no significant differences between different PCs in the display of the same 3D clouds were detected. A statistical evaluation is not required.

As a clarification, the datasets 1400, 700, … 200 simulate datasets from different 3D-Scanners with different resolution (point pitch distances). The coarser point pitches do not allow the resolution of the smallest structures (because they were not captured by the scanner, not through a limitation in the software).

6.5 Developmental validation assessment

	End user requirement	Specification	Test reference*	Assessment from developmental validation
[3.1]	Resolution - ability to resolve specific geometric features in a point cloud	≤ resolution of 3D point cloud	3DFFTI_TC_6	Features in the size of the point pitch distance of the 3D data can be visualized. The ability to resolve specific geometric features is independent from the PC characteristics (Graphic card) where the 3D Forensic analysis software is installed.
[3.2]	Specificity 3D - only geometric features, which are present in the 3D point cloud, are emphasized	No artificial features are created	3DFFTI_TC_6	The usage of 3 different PC / graphic cards demonstrates that no artificial features are created.

* Test references are used in Annex 4.

6.6 Advice for the implementation of the tool

Required quality controls:

- None

Required competence / training:

- Some knowledge / experience concerning measurement artefacts

7 3D analysis software: Registration of 3D point clouds

7.1 Technical principle and reference publications

Scans registration is performed in a two steps procedure: i) a manual pre-registration to approximately overlap two scans, ii) cloud to cloud registration based on the Iterative Closest Point (ICP) algorithm (Besl, 92). It requires that an estimation of the relative position between two scans is known a-priori (manual pre-registration). Based on this estimation the algorithm searches for each point in one scan and the closest point in the other scan and uses the corresponding point pairs to compute a new relative position between the scans. This process is repeated iteratively until the relative position of the scans converges.

Besl, P. J. and McKay, N. D., 1992. A method for registration of 3-D shapes. IEEE Trans. Pattern Analysis and Machine Intelligence, 14(2): 239-256.

7.2 Performance limitations, interferences and countermeasures

Limitation / constraint	Countermeasure
Min. 35% overlap, sufficient geometric structure	Put target marks into the scene, if 35% overlap not possible Fine registration error given in the software to be checked to be < 0.05 mm (accuracy level of the scanner) Check the registration result visually for errors.
Manual pre-registration to initialize the ICP	Interactive tool to select min. 3 common point between two overlapping scans Pre-registration error given in software to be checked to be < 19.5 mm Fine registration error given in the software to be checked to be < 0.05 mm (accuracy level of the scanner) Check the registration result visually for errors.
Artefacts in the original 3D	Visual control of the raw data (and if necessary masking of artefacts)

7.3 Reviewed end user requirements and related specifications

	End user requirement	Specification
[4.1]	Accuracy - alignment of point clouds results in no visible transition border.	< accuracy of 3D-Scanner
[4.2]	Robustness - resistance to small variations in method parameters and environmental conditions (e.g.	Small variations without influence

	manual pre-alignment).	
[4.3]	Repeatability (Accuracy) - alignment should be stable. (Measurement uncertainty / standard deviation of accuracy)	< 50 µm
[4.4]	Reproducibility (Accuracy) - alignment should be independent from user. (Measurement uncertainty / standard deviation of accuracy)	< 50 µm
[4.5]	Range - point clouds require low overlapping area.	30-50%
[4.6]	Quality control - resulting deviation of the alignment is logged. / Error resistance	Output the alignment error

7.4 Developmental validation test results – summarised overview

7.4.1 3D accuracy and reproducibility measurement precision[75]

To investigate 3D accuracy and repeatability measurement precision 2 scans of a shoe impression (2 portions) with a ca. 50% overlap were imported into the 3D Forensic analysis software (not aligned) and pre-processed (see Figure 40).

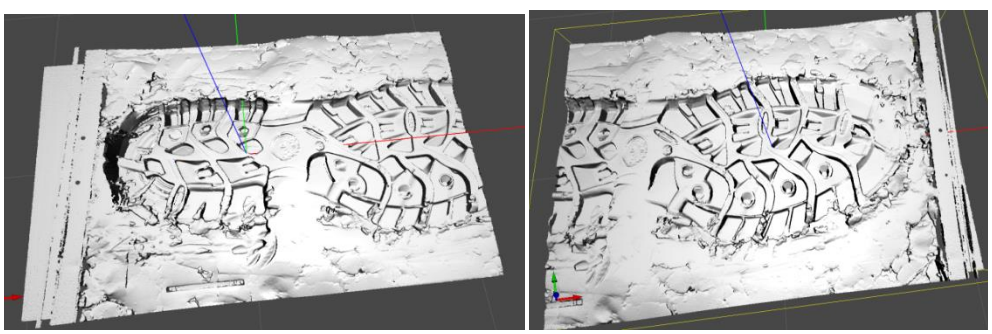


Figure 40: a) and b): show two overlapping scans covering a shoe impression

The investigation consisted of 4 independent tests carried out by 3 identification experts and 1 engineer in two steps:

[75] *Test case series: 3DFFTI_7_Registration_1 to 3DFFTI_7_Registration_4, 3DFFTI_TC7_Registration_Results.*

I. Manual preregistration by selecting 3 common points between the 2 clouds (Figure 41)

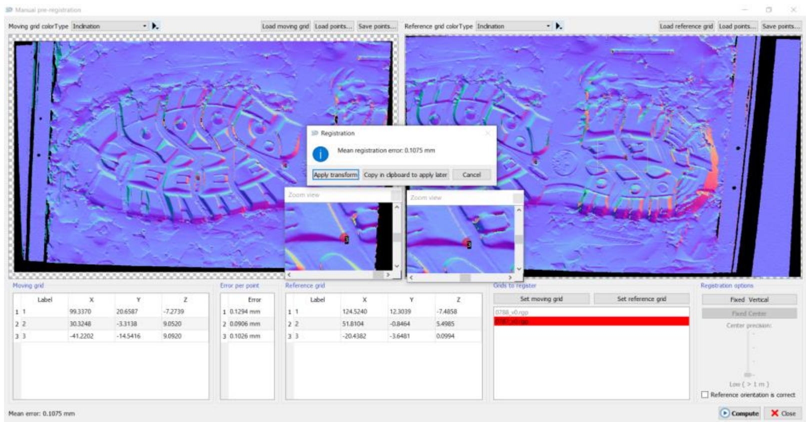


Figure 41: Manual pre-registration step

II. ICP automatic fine registration (see Figure 42)

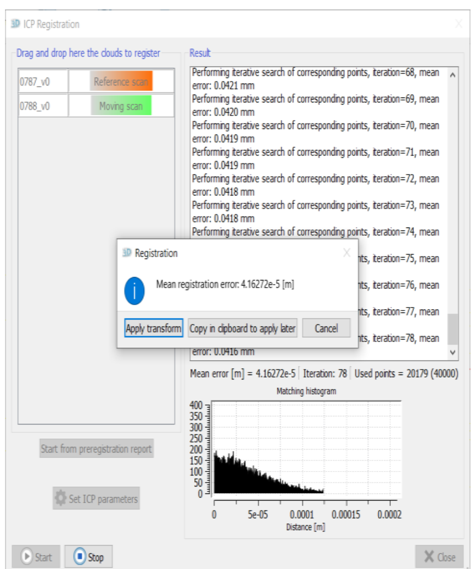


Figure 42: Automatic fine registration with IPC algorithm

As reported in the test sheet in Annex 4 the fine registration reaches a value between $4.16x10^{-2}$ mm and $4.29x10^{-2}$ mm which is the limitation through the noise in the 3D scan data (accuracy $\leq 5.0x10^{-2}$ mm).

The test results confirm that the alignment is stable. (Of course, 4 tests are not statistically significant, but the variance is extremely small.)

7.4.2 3D accuracy and robustness against preregistration error[76]

Using the same test procedure as described in 7.4.1, an engineer made 6 further tests with different pre-registration errors, which taking into consideration also the tests in 7.4.1 were ordered between a minimum of 0.1075 mm to a maximum of 19.523 mm. The fine registration converged to accuracy comparable to the scan accuracy between 4.06×10^{-2} mm and 4.99×10^{-2} mm.

The test results confirm the resistance to small variations in method parameters (such as the manual pre-alignment). In case of large manual preregistration error the user can easily verify the error and is able to improve the quality of this starting phase.

[76] *Test case series: 3DFFTI_7_Registration_5 to 3DFFTI_7_Registration_10, 3DFFTI_TC7_Registration_Results.*

7.5 Developmental validation assessment

	End user requirement	Specification	Test reference*	Assessment from developmental validation to date
[4.1]	Accuracy- alignment of point clouds results in no visible transition border.	< accuracy of 3D-Scanner	3DFFTI_TC_7	After the fine registration process the registration error is on the level of the accuracy of the scan data.
[4.2]	Robustness - resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).	Small variations without influence	3DFFTI_TC_7	Starting from larger pre-registration error (up to 19.523 mm) the fine registration converges to low values ($4.99x10^{-2}$ mm).
[4.3]	Repeatability (Accuracy) - (Measurement uncertainty / standard deviation of accuracy)	< 50 µm	3DFFTI_TC_7	Repeatability was not tested as it is expected to be better than reproducibility which has already an extremely small variance.

[4.4]	Reproducibility (Accuracy) - alignment should be independent from user. (Measurement uncertainty / standard deviation of accuracy)	< 50 µm	3DFFTI_TC_7	4 independent tests from different users converged to an average registration error of 4.23×10^{-2} $\pm 0.05 \times 10^{-2}$mm.
[4.5]	Range - point clouds require low overlapping area.	30-50%	Observation	Already after the preregistration step the overlap of the 2 scans can be checked. Direction to user is at least 35% overlap.
[4.6]	Quality control -resulting deviation of the alignment is logged. / Error resistance	Output the alignment error	Observation	The final registration error is displayed.

* Test references are used in Annex 4.

7.6 Advice for the implementation of the tool

Required quality controls:

- Intermediate preregistration error to be < 19.5 mm
- Final standard deviation between scans (alignment error) to be less than < 0.05 mm

Required competence / training:

- Users should be aware to acquire 3D scans with at least 35% overlap
- Read and follow user manual
- Knowledge for assessing strong misalignment

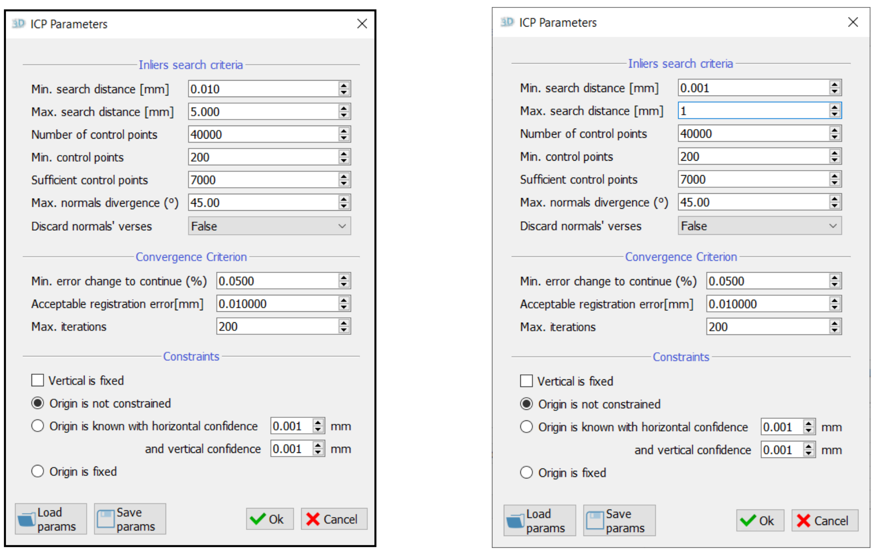


Figure 43: a) default parameters, b) suggested parameters for a second iteration

Notes: The ICP best fitting converges to the noise level of the 3D data. Occasionally, in the case of higher noise levels in the scans, the first ICP iteration can converge to a "mean registration error" higher than 50 µm. In this case it is suggested to run the ICP a second time using the parameters from Figure 55 (page 162).

For particular noisy scans, the mean error can be larger than 50 µm after the second ICP run. In this case the user should additionally check the scan alignment visually for correctness in the region of interest, e.g. by using the Screen Setting "Color by ID" or by displaying the two aligned scans in slice view (Figure 56, page 162). If visually the scans show no mismatch, also a larger mean error is acceptable.

Single scans can still be analyzed independently from the registration process to identify specific characteristics.

8 3D analysis software: Meshing of 3D points

8.1 Technical principle and reference publications

The adopted mesh technique is a per scan triangulation based on the 2D grid provided by the scanner. The neighbourhood relations are given by the 2D grid. The algorithm connects all the acquired points according to the 2D scan grid, without introducing geometrical simplifications; all the points in the original cloud are used for the mesh generation.

At the same time the scan depth discontinuities are taken into account to avoid artefact creation due to uncorrected filled gaps.

In case of a multiple scan impressions the final mesh is resulting from the sum of per scan triangulation.

Sequeira V., et al. - Automated Reconstruction of 3D Models from Real Environments, ISPRS Journal of Photogrammetry and Remote Sensing (Elsevier), vol. 54, pp. 1-22, 1999.

8.2 Performance limitations, interferences and countermeasures

Limitation / constraint	Countermeasure
Holes in 3D point cloud	Possible holes are closed at the level of the grid point cloud considering the neighbours in scan structure
False long triangles	Depth continuities are not meshed

8.3 Reviewed end user requirements and related specifications

	End user requirement	Specification
[5.1]	Accuracy - meshing of point clouds does not change the measurement data. (Deviation between mesh and point cloud is small)	< 1/10 of accuracy of 3D-Scanner
[5.2]	Specificity – only geometric features, which are present in the 3D point cloud, are also visible in the mesh.	No artificial features are created

8.4 Developmental validation test results – summarised overview

8.4.1 3D accuracy and specificity[77]

During the data preparation, a fundamental step is the conversion of the acquired scan from a point cloud format to a mesh model.

[77] *Test case series: 3DFFTI_TC_8_Meshing_1 to 3DFFTI_TC_8_Meshing_6.*

Six different 3D models have been selected to investigate the 3D accuracy and specificity of the meshing process. The six models are shown in the test sheet in annex 4 and listed in Table 15 below. They have been selected to have representative characteristics in terms of shape, discontinuities, 3D depth that could determine inaccuracies going from point cloud to mesh models.

Mesh models
3D scan of a tyre impression (portion) on sand
3D scan of a shoe impression on MikroTrack™
3D scan of a shoe profile
3D scan of a shoe impression on terrain
3D scan of a tyre portion
2 scans of 2 registered scans

Table 15 6 mesh models used

The 6 models (listed in Table 15), acquired as a 3D point cloud, were converted into mesh models.

Each resulting mesh has been compared with the original cloud using a tool that measures the distance (with sign) between each point and the closest mesh triangle.

The results of the distance measurements have been plotted in a histogram to analyse possible discrepancies between the mesh and the original cloud.

From the distance measurements results, no significant differences between the original scan data and the generated uniform mesh have been identified, as reported in the test sheet in Annex 4.

The meshing algorithm is fixed and leads always to exactly the same result for the same point cloud. There is no variance and thus a statistical evaluation is not required.

8.5 Developmental validation assessment

	Enduser requirement	Specification	Test reference*	Assessment from developmental validation
[5.1]	Accuracy - meshing of point clouds results does not change the measurement data. (Deviation between mesh and point cloud is small)	< 1/10 of accuracy of 3D-Scanner	3DFFTI_TC_8	Mean displacement value between point cloud and related meshes are in the order of 0.0019 mm i.e. within the specification of < 1/10 of accuracy of 3D-Scanner.
[5.2]	Specificity - geometric features, which are present in the 3D point cloud, are also visible in the mesh.	No artificial features are created	3DFFTI_TC_8	Colour coding the point clouds according to the differences between mesh and related point clouds, reveals that no artefacts are generated.

* Test references are used in Annex 4.

8.6 Advice for the implementation of the tool

Required quality controls:

- None

Required competence / training:

- None

9 3D analysis software: Capability to measure in data accurately

9.1 Technical principle and reference publications

The user can measure distances in the 3D models by picking manually 2 points in the 3D scene. When selecting the starting and ending point on the screen, the next full resolution point in the cloud is detected. The distance is calculated using the coordinates of the raw points in the scans.

The 3D measure between two picked points can be decomposed in x, y, z components according to the user coordinate system.

9.2 Performance limitations, interferences and countermeasures

Limitation / constraint	Countermeasure
Imprecise selection of the starting/ending point of a distance measure	Possibility to zoom the 3D point cloud to identify the right points
User dependent selection of points	Select points / measure distances by different users (Seek independent verification and/or peer review)

9.3 Reviewed end user requirements and related specifications

	End user requirement	Specification
[6.1]	Measurement accuracy and repeatability of the software itself - extract correct measure given the same starting and ending point	≈ 0 µm measure error
[6.2]	Measurement accuracy and reproducibility	< 1 mm

9.4 Developmental validation test results – summarised overview

9.4.1 Measurement accuracy and repeatability of the software itself[78]

To investigate the measurement accuracy the circle board was scanned and the acquired scan data was imported in the 3D-Forensics analysis software.

[78] *Test case series: 3DFFTI_TC_9_measure acc.*

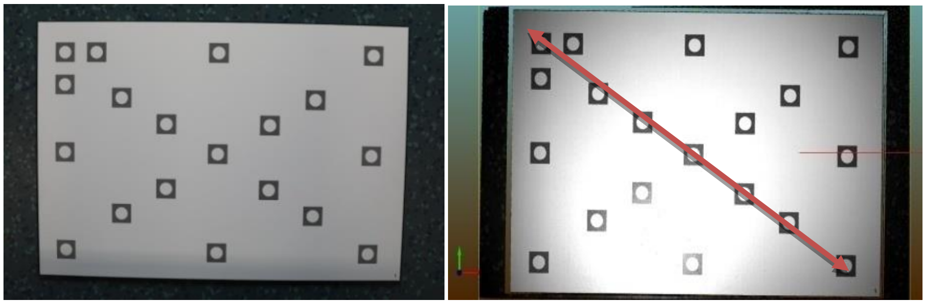


Figure 44 a) Circle board **b) Acquired scan imported in the 3D-Forensic software (the measured distance is marked)**

A start/end point was univocally identified in the point cloud (from top left corner of top square to bottom right corner of square in bottom right corner) and the same start and end point was used to extract the distance value for 10 independent measurements (see Figure 44).

Exactly the same distance of 306.453 mm was measured all 10 times (standard deviation is 0). The test demonstrates that the software itself measures distances perfectly accurately and with repeatability.

9.4.2 Measurement accuracy and reproducibility[79]

To investigate measurement accuracy and reproducibility, the same scan of the circle board was imported into the 3D-Forensic analysis software.

The 3D scan was rendered in 3D in an orthographic view. 10 users with different skills made the same measurement as in the investigation above with the zoom level and point cloud setting fixed (**Table 16**).

The users measurements were also compared to a reference measurement distance = 306.575 mm) calculated from the point cloud before the import in the analysis software.

User	Distance (mm)
User 1	306.6709
User 2	306.3039
User 3	306.7932
User 4	306.7932
User 5	306.7714

[79] *Test case series: 3DFFT_TC_9_measure repr.*

User 6	306.7932
User 7	306.8917
User 8	306.8917
User 9	306.8917
User 10	306.6709
Mean	306.747
Standard deviation	0.176
Measurement uncertainty	0.391

Table 16 Distances measured by 10 users, mean and standard deviation

The user's interpretation of starting and ending points causes a variance of 0.176 mm standard deviation and a measurement uncertainty of 0.391 mm. It is to be expected that this would be similar for distance measurements in other 3D or 2D analysis tools. Reproducibility is limited through the user capabilities.

9.5 Developmental validation assessment

	End user requirement	Specification	Test reference*	Assessment from developmental validation
[6.1]	Extract correct measure given the same starting and ending point	≈ 0 µm measure error	3DFFTI_TC_9	10 measurements = 0 µm measure error / variance.
[6.2]	Distance between the visual detectable start/ending points must be reproducible	< 1 mm	3DFFTI_TC_9	Variance (standard deviation) is 0.176 mm, measurement uncertainty is 0.391 mm, within specification -Max. displacement in 10 measures from the reference value (from another software) = -0.3167 mm Max. displacement of the mean value for 10 measures from the reference value (from another software) = -0.172 mm Reproducibility is limited through the user capabilities to select the same start and end points.

* Test references are used in Annex 4.

9.6 Advice for the implementation of the tool

Required quality controls:

- Select points / measure distances by different users (i.e. seek independent verification and/or peer review), depending on the level of reliance to be placed on measurements, particularly in sub-millimetre range.

Required competence / training:

- Read and follow user manual

10 Conclusions

The international standards most relevant to 3D-Forensics/FTI are ISO/IEC 17020[80] and ISO/IEC 17025.[81] The International Laboratory Accreditation Cooperation (ILAC) provides guidelines on the application of these standards to forensic processes.[82] The United Kingdom's Forensic Science Regulator (FSR) implements these guidelines in further guidance.[83,84] 3D-Forensics/FTI orientated its validation planning, implementation, assessment and reporting of on the FSR validation process for the issues which needed to be determined with validation data. This approach was presented to EETG members and was supported with no proposal to do it differently. By targeting the requirements for validation within an accredited process, 3D-Forensics/FTI should satisfy the most stringent validation criteria within any organisation providing forensic services. The process led to the setting and carrying out of the developmental validation tests for the six main system tool functionalities subjected to developmental validation described in this report in chapters 4 - 9 (see Table 17).

3D-Forensics system tools subject to developmental validation		
	Added / updated forensic tool	**Replaced tool**
3D-Scanner		
1	Recording of traces as 3D point clouds with the 3D-Scanner	Recording of traces as 2D photos with a digital camera or as “3D” plaster casts
2	Mapping of external colour images onto 3D point clouds	None (new tool)
3D analysis software		
3	Visualisation of 3D point clouds on a PC	Visualisation of 2D images on a PC
4	Registration of 3D point clouds	None (new tool)
5	Meshing of 3D points	None (new tool)
6	Capability to measure in data accurately	Rulers

Table 17: Forensic tools provided by the 3D-Forensics system subject to developmental validation[85]

[80] Supra: Conformity assessment - Requirements for the operation of various types of bodies performing inspection.
[81] Supra: General requirements for the competence of testing and calibration laboratories.
[82] Supra: ILAC/G19.
[83] Supra: FSR/Validation.
[84] Supra: FSR/Codes.
[85] Copy of Table 4 from above.

The decision to group specifications around the six main system tool functionalities was taken to be able to developmentally validate each functionality separately and for breaking down the complication in test planning, implementation, assessment and reporting.

Standard specimens were used when available to test specifications. However, no such specimens exist for important specifications such as 3D resolution and colour mapping accuracy. In such cases, specific specimens and approaches were worked out together with EETG members. The specimens used for testing are reported in Annex 3.

For each of these tools, the following information has been reported in chapters 4 -9:

- Technical principle and reference publications
- Performance Limitations, interferences and countermeasures
- Reviewed end user requirements and related specifications
- The developmental validation test results
- The developmental validation assessment
- Advice for the implementation of the tool

The major proportion of the tests were connected with the 3D-Scanner especially its resolution and accuracy. As the 3D-Scanner will be used outdoors, also environmental conditions such as temperature and sunlight were considered. Further the two scan modes “Handheld” and “Quadpod” were evaluated separately. Test results show clear differences, especially in terms of resolution. This led to declaring the standard scan mode to be “quadpod” and reporting the validation results accordingly. “Quadpod” means the system is in a fixed position and not susceptible to movement.

All 3D-Scanner tests connected with “Reproducibility” were executed together with users in the EETG. These tests were done with Yorkshire and The Humber Police (UK) and LKA Saxony (Germany) (Figure 45), RIS Carabinieri (Italy) and LKA Mecklenburg-Vorpommern (Germany).

Figure 45 Reproducibility testing with LKA Saxony (Germany) in January 2019.

The achieved 3D-Forensics system's product specifications as of June 2019 which the consortium is confident to report are included in Annex 2. These specifications are based on the developmental validation tests and/or internal assessment.

The key application for the 3D-Forensics/FTI system is to record and analyse footwear and tyre impressions as well as profiles left at crime scenes in 3D and colour with optical scanning technology.

Validation testing highlights the requirement for users (primarily, crime scene investigators for the 3D-Scanner and identification experts for the 3D analysis software) to be competent in the use of the system which includes understanding the limitations, interferences and countermeasures described.

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TABLE OF STANDARDS

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BS EN ISO/IEC 17025:2005, General requirements for the competence of testing and calibration laboratories (Available at: <http://www.iso.org/iso/catalogue_detail.htm?csnumber=39883> accessed 18 February 2019).

Annex 1: User requirements and specifications in answer to requirements

Explanation method to note and prioritise requirements and specifications

The user requirements and the specifications detailed in answer to the requirements are presented in tables following the template in Table 18. The *italics* provide a short clarification as to the content which is included.

Req.-ID	*Original requirement ID set in FP7 project in 2014*
Short name	*Short name as set in FP7 project in 2014*
Description	*Short description as set in FP7 project in 2014*
Priority	*As set in FP7 project in 2014:* • ***Essential*** *- This implies that a future 3D-Forensics product will not be acceptable unless these requirements are provided in an agreed manner.* • ***Conditional*** *- This implies that these are requirements that would enhance the product, but would not make the product unacceptable if they were absent.* • ***Optional*** *- This implies a class of functions that may or may not be worthwhile.*
Comment	Any comments relevant to transferring requirement in to specification
Specification	*Specification determined from requirement as set in FP7 project in 2014*
Output following review for DV	*Any revisions or clarifications to requirement and/or specification following review of end user requirements, specification and risk assessment, culminating in preparation for developmental validation (DV).*
DV content (Y/N), reason if relevant	*Whether specification subject to developmental validation (Yes/No) with reason / clarification.* *Determined primarily by considering whether feature has impact on the reliability of the result*
DV Req.-ID	*Derived developmental validation (DV) requirement/specification ID as listed in chapters 4 to 9.*

Table 18: User requirement and related specification template

3D-Scanner requirements / specifications list

Req.-ID	HW 1
Short name	Field of View / Measurement volume
Description	- Capture a single footwear impression in 1-2 shots to avoid registration artefacts of multiple scans with less overlap - Average shoe length for men is ca. 300 mm (average in Germany: EUR 44 \ UK 9½) - Capture the track width of a tire impression in 1 shot (PKW up to 240 mm width) - Measurement of “flat” impressions (depth < 50 mm) **≥ 300 x 200 x 50 mm²**
Priority	Essential
Comment	n/a
Specification	**≈325 x 200 x 50 mm³**
Output following review for DV	No update
DV content (Y/N), reason if relevant	Y (*Also note: positively tested already in FP7 project, no design changes affecting requirement*)
DV Req.-ID	[1.8]

Req.-ID	HW 2
Short name	Local resolution
Description	- The scan resolution will have to be small enough to visualize even small individual characteristics that are needed to make an identification (< 200 µm) - Too little detail leaves too many questions and will devaluate the system to merely a selection tool (class characteristics) **< 200 µm**
Priority	Essential
Comment	- There must be a trade-off between the large field of view and the limited resolution of state-of-the-art cameras
Specification	**≈170 µm**
Output following review for DV	Specification revised to original requirement i.e. < 200 µm Standard operating procedure with quadpod Determination of further detail requirements/specifications HW2.1-2.3, the DV requirements [1.3],[1.5]A,[1.6]A (*provided directly below*)
DV content (Y/N), reason	Y

if relevant	
DV Req.-ID	[1.1]

DV Req.-ID	**Name - description**	**Specification**
[1.3]	Robustness resolution - resistance of the resolution to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner, brightness setting).	Small variations without influence Effects of larger variations must be known
[1.5]A	Repeatability resolution - scan results should be stable / precise. (Measurement uncertainty / standard deviation of resolution)	<±50 µm
[1.6]A	Reproducibility resolution - scan results should be independent from user. (Measurement uncertainty / standard deviation of resolution)	<±50 µm

Req.-ID	HW 3
Short name	Accuracy
Description	- High measurement accuracy is necessary to allow a safe determination of class and individual characteristics **≈ 50 µm**
Priority	Essential
Comment	- The resulting accuracy arises from many different constraints in the scanner (local resolution, angle between cameras, projector noise, …)
Specification	**≈ 50 µm**
Output following review for DV	Standard operating procedure with quadpod Determination of further detail requirements/specifications HW3.1-3.3, the DV requirements [1.4],[1.5]B,[1.6]B (*provided directly below*)
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[1.2]

DV Req.-ID	**Name - description**	**Specification**
[1.4]	Robustness accuracy - resistance of the	Small variations without influence

	accuracy to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner, brightness setting).	Effects of larger variations must be known
[1.5]B	Repeatability accuracy - scan results should be stable / precise. (Measurement uncertainty / standard deviation of accuracy)	<±20 µm
[1.8]	Reproducibility accuracy - scan results should be independent from user. (Measurement uncertainty / standard deviation of accuracy)	<±20 µm

Req.-ID	HW 4
Short name	Working distance
Description	- A large working distance makes it easier to measure in difficult accessible or narrow environments **> 300 mm**
Priority	Essential
Comment	- the working distance is derived from the optical magnification of the cameras and projector (their lenses), their chip size and the achieved field of view
Specification	**≈480 mm**
Output following review for DV	Specification revised to original requirement i.e. > 300 mm
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[1.9]

Req.-ID	HW 5
Short name	Warm-up time / connection time
Description	- At a crime scene, the 3D-scanner should be ready for action in short time **≤ 5 min**
Priority	Conditional
Comment	n/a

Specification	**≤ 4 min**
Output following review for DV	No update
DV content (Y/N), reason if relevant	No, conditional and does not affect result
DV Req.-ID	**n/a**

Req.-ID	HW 6
Short name	Data storage volume
Description	- All 3D-scans that are made in one session (one crime scene situation) must be stored in one volume (typical < 20 scans)
Priority	Essential
Comment	- One 3D-dataset, including all raw and intermediate data, has a size of <500 MB - The storage could be made on the hard disk from the used laptop, USB-stick or SD-card. *Update 2019: The chosen design fully integrates a PC, there is no laptop.* - For security reasons the data should be stored encrypted
Specification	**> 10 GB**
Output following review for DV	No update
DV content (Y/N), reason if relevant	No, does not affect result (*Also note: positively tested already in FP7 project, no design changes affecting requirement*)
DV Req.-ID	n/a

Req.-ID	HW 7
Short name	Compatibility / 3D-data output formats
Description	- The outputted 3D point cloud should be compatible with 3D-software analysis products to enable the further analysis of the 3D-data
Priority	Conditional
Comment	n/a

Specification	- The 3D-scanner will provide a standard 3D-pointcloud file which could be imported by all 3D-analysis software: **ASCII-format** (text file containing XYZ-coordinates of all measured points)
Output following review for DV	No update
DV content (Y/N), reason if relevant	No, achieved by design and positively tested already in FP7 project, no design changes affecting requirement
DV Req.-ID	n/a

Req.-ID	HW 8
Short name	Brightness setup
Description	- The 3D-scanner should be able to measure on any kind of underground (snow, mud, etc.) - Due to the different reflectivity of the underground materials, it is necessary to adjust the brightness settings before a measurement - e.g. 3 – 5 pre-settings for brightness setup
Priority	Essential
Comment	- “Brightness” is determined by the luminosity of the projector as well as the integration time and gain factor of the cameras
Specification	- **7 pre-settings for brightness setup**
Output following review for DV	Specification update to “brightness pre-settings”
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[D1.10]

Req.-ID	HW 9
Short name	Usability / operator convenience
Description	- Easy handling of the 3D-scanner means in simple words to “measure with one touch of a button” and to provide an output result that is understandable for a layman - 3 – 5 measurement modes as pre-settings
Priority	Conditional
Comment	- The 3D-Forensics prototype will contain several standard measurement modes as pre-settings (containing different fringe pattern sequences)

	- Finally, the user has to choose the measurement mode and the brightness setup before starting a measurement, then - The measurement itself will be started by adjusting the working distance with the laserpointers and by pushing one start-button on the sensor head
Specification	- None pre-set settings must be adapted by the user in a simple user guidance
Output following review for DV	Specification updated to “Scan starts with one button (measurement modes and brightness pre-settings)
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[D1.11]

Req.-ID	HW 10
Short name	User Feedback after 3D-scan
Description	- Colour information (e.g. green or red) shows if a scan was successful (meaning that 3D-points were measured) - Preview of 3D-patch and the grey photo is shown, the user has to evaluate the quality, e.g. holes
Priority	Essential
Comment	n/a
Specification	- Projection of a green or red box by projector (PRO) signals a technical successful scan - Displaying of a rendered image of the 3D-scan for quality control by the user
Output following review for DV	Specification updated to: “Projection of a green or red box by projector (PRO) signals a technical successful scan”, “3D-patch preview”, “Photo preview”. This specification includes contributing to: ▪ Checking image quality to see if it is sufficient for a meaningful and reliable analysis[86]
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[D1.12]

[86] Forensic Science Regulator, *Forensic Image Comparison and Interpretation Evidence: Guidance for Prosecutors and Investigators* (FSR, Issue 1, 2015) p.10 (Available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/405528/Image_Comparison_and_Interpretation_Guidance_Issue_1_160115.pdf> accessed 13 July 2017).

Req.-ID	HW 11
Short name	Mobility / Handling outdoors / scanner size
Description	- Main application field of the 3D-scanner are outdoor measurements in arbitrary surroundings using it as a hand-held sensor head - The user handles only the compact sensor head to measure a scene, two handles are attached - An adapting plate offers the possibility to attach a tripod - The graphical user interface is provided by a Smartphone fixed with an armband which enables easy and fast setting of measurement parameters (brightness, measurement mode) - Laptop and battery are held in an extra bag or platform and do not need to be handled during the acquisition of 3D-scans **Size of the sensor head < 300 x 300 x 300 mm³** **Two handles on the sensor head, adapter plate for attaching a tripod** **Smartphone User Interface** **Extra platform for laptop and battery** **Skilled / trained user level**
Priority	Essential
Comment	- The mobility and handling of the 3D-scanner is defined by many constraints, but mainly by its size, its weight, the attached handles and the user interface realization - To minimize the size and weight compact, light components need to be chosen, and to be arranged in a compact way - Good handling is achieved when the user is able to concurrently hold the sensor and set the scan settings, and to start a scan with a button directly at the handles - Integrated (i) iPC and I display (DISP) would enhance the handling and mobility of the sensor head as long as an acceptable weight and size is not exceeded - External (e) PC and eDISP, which do not need to be held during the scanning, could be an alternative if the iPC and iDISP exceeds an acceptable weight and size of the sensor
Specification	Mobile and easy to handle device
Output following review for DV	Specification updated to: “Handheld 3D-Scanner (or easy-to-use) additional equipment” Standard scan mode is with quadpod.
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[D1.13]

Req.-ID	HW 12
Short name	Battery time

Description	- The battery time of the 3D-scanner must be enough to process on crime scene - The power consumption of the system will be about 100…150W **> 1 hour under working conditions** **> 6 hours in standby** **rechargeable within < 10 hours** (overnight)
Comment	- Battery time is defined by the power consumption of the 3D-scanner components and the chosen battery parameters
Specification	- Overall power consumption under working conditions: ≈ 100 W - Overall power consumption under standby: ≈ 20 W - Optimizations to decrease the power consumption will be implemented (e.g. to shut down the PRO between single measurements)
Output following review for DV	No update
DV content (Y/N), reason if relevant	N
DV Req.-ID	n/a

Req.-ID	HW 13
Short name	Measurement rate
Description	- A high measurement rate enables fast evidence collection at one crime scene - Determined by the processing time for one scan and the reset time of the 3D-scanner **> 3x 3D-scans / minute**
Priority	Conditional
Comment	- Measurement rate is defined by the duration of one scan, time for data transfer from camera over Sensor Head Base Board (SHBB) to iPC / ePC, the data processing time and the time needed to reset the system
Specification	**ca. 5x 3D-scans / minute**
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, conditional and does not affect result
DV Req.-ID	**n/a**

Req.-ID	HW 14
Short name	Time to scan (acquisition of the fringe images)
Description	- A long scanning time increases the 3D-point accuracy but could produce motion artefacts in hand-held measurements **150 – 700 ms** (long scanning times will necessitate the usage of a tripod)
Priority	Essential
Comment	- Time to scan is defined by the projection / acquisition frequency and the count of projected fringe patterns
Specification	Time to scan equals: **100 – 700 ms**
Output following review for DV	Specification updated to "≤ 200 ms"
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[1.14]

Req.-ID	HW 15
Short name	Time to final 3D-result
Description	- Processing time for calculating the 3D-object out of the scanned sequence and to provide it in a preview **< 10 sec** ("quasi" real time)
Priority	Conditional
Comment	- Processing time to calculate a 3D-pointcloud from a sequence of fringe images is primarily defined by the time to transfer the image data on the iPC / ePC and the processing performance
Specification	Time to final 3D-result **< 8.5 sec**
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, conditional and does not affect result
DV Req.-ID	n/a

Req.-ID	HW 16
Short name	Transportability

Description	**Covered transportation bag for the whole sensor equipment**
Priority	Optional
Comment	n/a
Specification	Appropriate transportation bag
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, optional and does not affect result
DV Req.-ID	n/a

Req.-ID	HW 17
Short name	Weight
Description	- A low weight of the sensor head is important for hand-held measurements to allow easy usage - The sensor head can also be adapted to a tripod **< 3 kg** (for the sensor head, which has to be held during a scanning procedure) <10 kg (for the whole equipment, which not necessarily has to be held during scanning)
Priority	Conditional
Comment	n/a
Specification	Weight of the sensor head of < 3 kg
Output following review for DV	Specification update: “4.3 kg (without battery)”, “5.1 kg (with battery)” Standard operating procedure with quadpod
DV content (Y/N), reason if relevant	N, conditional and does not affect result
DV Req.-ID	n/a

Req.-ID	HW 18
Short name	Thermal robustness
Description	- 3D-scanner is primarily for outdoor use and should work in an adequate temperature range - A cooling system will be implemented to avoid overheating **-10 – 40°C working temperature** (-40 – 60°C transportation and storage temperature)

Priority	Conditional
Comment	n/a
Specification	Working temperature between -10 – 40°C
Output following review for DV	No update
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[1.15]

Req.-ID	HW 19
Short name	Moisture / Dust robustness – protection class
Description	- 3D-scanner is primarily for outdoor use and should work under typical air moisture and dust conditions - Usage in strong raining conditions is only possible with additional water protection (umbrella) **< 80% air moisture** **Protection class IP 44** (protected against particles >1 mm and protected against spray water)
Priority	Conditional
Comment	- Moisture and dust robustness is defined by the robustness of the scanner housing
Specification	Air moisture robustness <80% and IP44 class
Output following review for DV	Separation of the two parts of the specification.
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[1.16] and [1.17]

Req.-ID	HW 20
Short name	Mechanical robustness – shock resistance
Description	- The 3D-scanner will be protected by a plastic housing - Strong mechanical vibrations and shocks should be avoided - For transportation the scanner equipment is put in a vibration protected bag **Protection class IK 04** (light shocks by hand, no drops) in vibration protected bag – protection class IK09

Priority	Conditional
Comment	n/a
Specification	Protection class IK04
Output following review for DV	No update
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[1.18]

Req.-ID	HW 21
Short name	Electromagnetic Compatibility
Description	**Class 2**
Priority	Optional
Comment	n/a
Specification	Electromagnetic compatible system of class 2
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, does not affect results.
DV Req.-ID	n/a

Req.-ID	HW 22
Short name	Surrounded light
Description	- The more surrounding light, the worse for the 3D-scan - 3D-scanner should work under average lightning conditions without additional equipment - Additional shadow box for strong sunlight is provided **< 1000 lx** (cloudy day), with increased light, usage of a shadow box
Priority	Essential
Comment	- Robustness against surrounded light is mainly defined by the brightness of the projector - Illumination of the projector depends on its working distance
Specification	- 3D-measurements with < 1000 lx lighting - For larger surrounded lighting a shadow box can be used
Output following review for DV	Update of specification to < 10,000 lux (cloudy day, shadow, not in direct light) (*Implementation of blue light, removal of use of shadow box*)
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[1.19]

Req.-ID	HW 23 Hardware costs – *commercial aspect – not relevant for this report*

Req.-ID	HW 24 Necessary Know-How for assembling – *commercial aspect – not relevant for this report*

Req.-ID	HW 25
Short name	Frequency of technical maintenance / change period of components
Description	**> 1 year**
Priority	Conditional
Comment	
Specification	Technical maintenance of > 1 year
Output following review for DV	No update
DV content (Y/N), reason	Y

if relevant	
DV Req.-ID	[1.20]

Req.-ID	HW 26
Short name	Sound intensity
Description	**< 40 dB**
Priority	Optional
Comment	n/a
Specification	Sound intensity of < 40 dB
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, does not affect results.
DV Req.-ID	[1.19]

Req.-ID	HW 27
Short name	Working Life
Description	**> 5 years**
Priority	Conditional
Comment	- the working life of the 3D-scanner is defined by the working life of the inner sensor components and the way and frequency of how the operator handles the system
Specification	Technical maintenance of > 1 year
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, does not affect results.
DV Req.-ID	n/a

Req.-ID	HW 28
Short name	Power Supply
Description	- Battery for autarchic work - Power supply for recharging **AC DC Adaptor (100~240 free voltage), 50/60Hz**
Priority	Essential
Comment	- 3D-scanner requires a hardware interface to a power supply with an AC DC Adaptor (100~240 free voltage), 50/60Hz
Specification	AC DC Adaptor (100~240 free voltage), 50/60Hz
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, does not affect results. Tested in FP7 project, no design changes affecting achievement.
DV Req.-ID	n/a

Req.-ID	HW 29
Short name	Pose acquisition
Description	- Add on of a navigation unit should be a possible enhancement option
Priority	Optional
Comment	n/a
Specification	Foreseeing of a software interface in the 3D-scanner control software
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, optional.
DV Req.-ID	n/a

Req.-ID	HW 30
Short name	Calibration / Accuracy verification
Description	- Guidelines in forensics mention that calibration or test measurement on specimens before every scan have to be made to approve the accuracy and transparency of the technique Test specimen will be provided to scan and verify before every measurement session
Priority	Essential
Comment	n/a
Specification	Providing of a certified test specimen from which the sensor noise and the 3D accuracy can be determined
Output following review for DV	Update requirement name "Quality control" Update of specification: "Test specimen (to be used at crime scene)" This specification includes: ▪ "Authentication" - "the data is an accurate presentation of what it purports to be."[87] ▪ Checking correct operation of equipment (e.g. operator adjustable settings)[88]
DV content (Y/N), reason if relevant	Y.
DV Req.-ID	[1.21]

Req.-ID	HW 31
Short name	Easy to clean
Description	- To avoid contamination of the crime scene a cleaning of the scanner is necessary - The scanner will be put in a special bag, so that it is not contaminated during storage Easy cleaning procedure will be defined
Priority	Essential
Comment	n/a
Specification	Description of appropriate cleaner and a cleaning guidance are provided
Output following review for DV	No update
DV content (Y/N), reason	N (Guidance provided in manual)

[87] Home Office Scientific Development Branch, *Digital Imaging Procedures* p.77 (v2.1 2007) (ISBN: 978-1-84726-559-3) (Available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/378451/DIP_2.1_16-Apr-08_v2.3__Web_2835.pdf> accessed 13 July 2017).
[88] Ibid. p.12

if relevant	
DV Req.-ID	n/a

Req.-ID	HW 32
Short name	Depth (angle)
Description	- Steep boundaries of depth impression are more difficult to measure than plane structures - Is verified by measuring a test specimen **> 60°** (steeper angles can be captured by multiple measurements of one scene from different view directions and alignment of these)
Priority	Conditional
Comment	- Maximum measurable surface angle is defined by the triangulation angle between the cameras and the roughness and reflectivity of the underground
Specification	Maximum measureable angle of > 60°
Output following review for DV	No update
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[1.7]

Req.-ID	HW 33
Short name	(Eye) safety
Description	- The projection unit of the 3D-scanner is an active light source - Directly looking inside the light spot is not dangerous for the eyes **Less dangerous than laser class 1M** (≤ 500 lumen, which equals 40W light bulb)
Priority	Conditional
Comment	- Eye safety is defined by the brightness of the projector
Specification	- Eye safety less than laser class 1M - Brightness of PRO: 500 lm (equals 60 W light bulb)
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, conditional does not affect the results.
DV Req.-ID	n/a

Req.-ID	HW 34
Short name	Textures \ Colour acquisition
Description	- The measurement of textures and colors additional to the 3D-information is necessary to consider leaves and twigs that distort the trace and should not be treated as any characteristic as well as to measure 2D-imprints - The 3D-scanner will contain an adapter for a photo apparatus that can be attached on the top of the 3D-scanner - The camera (and lens) of the photo apparatus will be calibrated to the 3D-scanner in a way that the RGB photos can be plotted onto the 3D point cloud **Adapted and calibrated photo apparatus on top**
Priority	Conditional
Comment	Following technical features lead to a possibility to measure texture / colour: - Selection of photo apparatus Canon 100D in conjunction with Canon EF 28mm f/2,8 IS USM (COL) as an add-on component to the 3D-sensor - Photo apparatus will be attachable onto the 3D-scanner - Software interface to the photo apparatus is implemented into the control software of the 3D-sensor
Specification	Adapted and calibrated photo apparatus on top
Output following review for DV	Extension to indicate colour camera compatibility: Canon EOS 100D/200D or Canon 5D Mark IV. Determination of further detail requirements/specifications HW34.1-34.8, the DV requirements [2.1]-[2.8] (*provided directly below*)
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[2.1]-[2.8]

DV Req.-ID	Name - description	Specification /
[2.1]	Accuracy - accurate alignment between colour photo and 3D data	< 1 3D point pitch (170 µm)
[2.2]	Robustness accuracy - the resistance to small variations in method parameters and environmental conditions (e.g. working distance, orientation of scanner).	Small variations without influence Effects of larger variations must be known
[2.3]	Repeatability (accuracy) - alignment should be stable. (Measurement uncertainty / standard deviation of accuracy)	<±50 µm

[2.4]	Reproducibility (accuracy) - alignment should be independent from user. (Measurement uncertainty / standard deviation of accuracy)	<±50 µm
[2.5]	Range (Field of View FOV) - ability to colour the complete 3D point cloud	≥ than FOV of 3D-Scanner
[2.6]	Time to scan - quick enough to allow handheld scans without a relevant misalignment between 3D scan and photo	20 ms (but improved photo settings are possible)
[2.7]	Thermal robustness - stability of camera alignment at typical outdoor conditions (in Europe)	-10 … +40°C
[2.8]	Quality control - verify the calibration of the camera alignment at the crime scene	Calibration board

Req.-ID	HW 35
Short name	Location and orientation registration
Description	- The location and the orientation of footwear and tyre impression could be an important part of the evidence (e.g. in what direction the suspect was walking) - This information could be captured by a GPS-sensor and compass sensor (both available as Smartphone Apps) **Location registration by GPS-signal** **Orientation registration by Compass sensor (e.g. Compass App for Smartphone)**
Priority	Conditional
Comment	- To analyze the location and orientation of a scanned footwear or tyre impressions special guidance or sensors have to be integrated in the scanner
Specification	- Numbering of scans in one scan session (one crime scene), so that the location of each scan is known specifically - Compass sensor (compact hall sensor) gets tested and integrated in the 3D-sensor, so that the orientation relative to the north (or south) vector can be calculated
Output following review for DV	Not implemented
DV content (Y/N), reason if relevant	N, conditional
DV Req.-ID	n/a

Req.-ID	HW 36
Short name	User manual
Description	- Training and look up material
Priority	Conditional
Comment	-
Specification	- Short instructions on leaflet in English and German - Long user manual in English and German
Output following review for DV	No update
DV content (Y/N), reason if relevant	N
DV Req.-ID	n/a

Req.-ID	HW 37
Short name	Usable data download
Description	The download of scan data should be user friendly and safe.
Priority	Conditional
Comment	-
Specification	- Encrypted download - Selection of scan projects to download - Progress bar - Control of space on memory stick - Robustness in case of abort (e.g. through empty batteries)
Output following review for DV	No update
DV content (Y/N), reason if relevant	N
DV Req.-ID	n/a

Req.-ID	HW 38
Short name	Set up for demonstrations and trainings
Description	Transportable setup and material for system demonstration during workshops,

	exhibitions or user trainings.
Priority	Optional
Comment	-
Specification	- Mobile setup and demonstration objects
Output following review for DV	No update
DV content (Y/N), reason if relevant	N
DV Req.-ID	n/a

3D analysis software requirements/specifications list

Req.-ID	SW 1
Short name	Usability
Description	The software design and development will focus on footwear and tyre impressions for “High Volume Crimes”. The high volume crime scenarios require well predefined and easy to use workflow with few clear steps in an intuitive and simplified interface. The workflow will be suggested to the user through a simplified interface that will guide the user in the following steps: - Data input - (Data stitching/alignment - if necessary) - (High resolution image overlapping - if acquired) - Support to *Class characteristics* identification - Support to *Individual characteristics* identification - Output result (printing, data viewing, data web sharing, data export in other software for further analysis)
Priority	Essential
Comment	n/a

Specification	- Dedicated workflow
	  - Raw data import (scan and images)
	  - Alignment of multiple scan related to the same impression (print)
	  - *Class characteristics* identification
	  - *Individual characteristics* identification
	  - *Characteristics* archived per print
	  - Search for "similar print" per project or within projects
	  - Print comparison
	  - Final report supported by measuring tools and exporting functions

Output following review for DV	Requirement is updated to not focus on “High Volume Crimes” but also “Serious Crimes” i.e. all crime scenes. Specification is not updated, but it is emphasised that the workflow is flexible and must not be seen as a series of steps, regarding analysis. This specification includes enabling: ▪ Checking image quality to see if it is sufficient for a meaningful and reliable analysis[89]
DV content (Y/N), reason if relevant	Y, indirectly for importing, alignment, meshing and measuring *Software design implements requirement/specification*
DV Req.-ID	[3.1]-[3.3], [4.1]-[4.6], [5.1]- [5.2], [6.1]-[6.2] (see below)

[89] Supra: FSR, *Forensic Image Comparison* p.10.

Req.-ID	SW 2
Short name	Necessary Know-How for usage
Description	The software GUI and processes steps will be designed so that analysis of measurements can be done by a person qualified to be a crime scene investigator. *Update 2019: “crime scene investigator” in above sentence should be replaced by “identification expert”.*
Priority	Conditional
Comment	n/a
Specification	Software workflow mimics the common operational methodology used by experts for identifying the presence of characteristics such as cuts, scratches, tears and holes in physical impressions, but the process is completely software based using electronically scanned data.
Output following review for DV	This specification includes enabling: ▪ Checking image quality to see if it is sufficient for a meaningful and reliable analysis[90]
DV content (Y/N), reason if relevant	N, connected with end user and their know-how *Software design implements requirement/specification* *Partly tested during round-robin tests.*
DV Req.-ID	n/a

Req.-ID	SW 3
Short name	Software platform performance
Description	- The software will be designed on a platform capable to handle large point cloud data sets. - The points will be imported directly from the sensor and converted in a level of detail structured for fast navigation also when large data sets are displayed - The software platform is scalable to be used with short range/highly accurate sensors and long range/middle accuracy sensors. - Workflows and processing tools will be designed to provide results in short time after raw data import from the sensor
Priority	Essential
Comment	n/a
Specification	Point cloud engine based on octree point database with unlimited point cloud rendering size
Output following review for DV	No update

[90] Op.cit.

DV content (Y/N), reason if relevant	*Software design implements requirement/specification.*
DV Req.-ID	n/a

Req.-ID	SW 4
Short name	Resources
Description	The software platform (including processing algorithm) will run on a “good” PC work station or on a high-performance laptop, all easily commercially available.
Priority	Essential
Comment	n/a
Specification	The following characteristic will be required - OS: Windows XP SP2 | Windows Vista | Windows 7 | Windows 8 - Graphics card: NVIDIA GeForce FX and onwards - PC recommended features: Multi-core processor | At least 4GB RAM | NVIDIA GeForce 500 with at least 512MB - 64 bit version
Output following review for DV	MINIMAL SOFTWARE REQUIREMENTS Processor: 64 bit single core. Main memory: 4 GB Graphics card that supports OpenGL 3.3. Windows 7 service pack 1. Mouse with two buttons plus a clickable scroll wheel. These requirements are the bare minimum to use 3D Forensic software, the software performance will be very limited. RECOMMENDED SOFTWARE REQUIREMENTS Processor: Intel Core i7/Xeon, 4 or 8 physical cores Main memory: 16 GB Graphics card that supports OpenGL 4.0 or higher, 4 GB dedicated GPU memory. Windows 10 Mouse with two buttons plus a clickable scroll wheel. Screen resolution: 1920x1080 or higher.
DV content (Y/N), reason if relevant	Y, *indirectly tested with DV tests for the data analysis software* *Platform requirements stated with software*
DV Req.-ID	[3.1]-[3.2], [4.1]-[4.6], [5.1]- [5.2]

Req.-ID	SW 5
Short name	Input formats - Points
Description	- Software will accept point clouds directly from the forensic sensor (with quality value for each point (0-255) and calibrated image from one camera) - The software will also accept as inputs 3D points from different range sensor or from photogrammetric data sources.
Priority	Essential
Comment	n/a
Specification	- Point cloud input from the 3D Forensic sensor - Scan and 3D point formats input from different range sensors or from calibrated cameras data sources: Optech ixf scan — *.ixf VIC pst point cloud — *.pst LAS point cloud — *.las LAS zipped point cloud — *.laz MDL point cloud — *.txt PTS point cloud — *.pts ZF laser scan — *.zfs FARO laser scan — *.fls; *.iQscan PTX point cloud — *.ptx PLY point cloud — *.ply
Output following review for DV	No update
DV content (Y/N), reason if relevant	N
DV Req.-ID	n/a

Req.-ID	SW 6
Short name	Input formats- Meshes
Description	Data inputs of "references models": point cloud or meshes of footwear and tyre impressions created with external modelling software or directly from scanning systems. The reference mesh model will be one for the input during the point to mesh comparison to verify compatibility between print and reference object. The following mesh format will be supported: - Stanford Triangle Format (Ply) - Autodesk DXF format - 3D Studio model format (3ds)

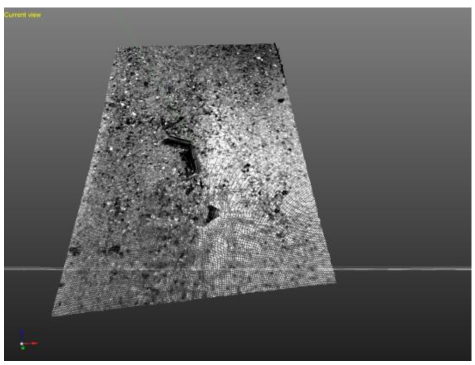
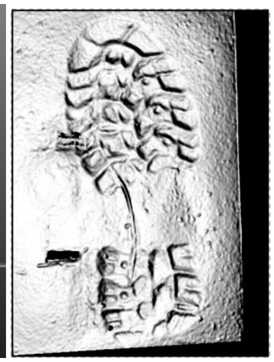
	- STL binary and ascii format - Alias Wavefront OBJ format
Priority	Essential
Comment	n/a
Specification	Following mesh formats are supported: Stanford Triangle Format *.ply Autodesk DXF format *.dxf 3D Studio model format *.3ds Reconstructor triangle meshes *.rtm STL ASCII format *.sta STL binary format *.stl OpenSceneGraph Archive format *.osga OpenSceneGraph extendable binary ... *.osgb OpenSceneGraph extendable format *.osg2 Psuedo OpenSceneGraph file loaded... *.osgs Alias Wavefront OBJ format *.obj OpenSceneGraph Ascii file format *.osg OpenSceneGraph extendable ascii fo... *.osgt OpenSceneGraph extendable XML fo... *.osgx
Output following review for DV	No update
DV content (Y/N), reason if relevant	N
DV Req.-ID	n/a

Req.-ID	SW 7
Short name	File size
Description	- The original file backup will be stored in compressed format in order to minimize size of the raw data storage. - Date compression is lossless and does not affect the quality
Priority	Conditional
Comment	n/a
Specification	Both octree data set and raw gridded files are saved and archived in data formats that internally uses compression capabilities preserving fast data access
Output following review for DV	No update
DV content (Y/N), reason if relevant	N *Software design implements requirement/specification.*
DV Req.-ID	n/a

Req.-ID	SW 8
Short name	Safe Storage of the original scans
Description	- The original scans and RGB photographs will be stored in a way that nobody can change these scans. A working, editable copy must be derived from the original scan to make selections and identification.
Priority	Essential
Comment	
Specification	- The project structure in the software preserve the raw data (3D points and images with calibration parameters) - The internal format for 3D points avoids points lost in case of user editing - The images are stored in standard formats (jpg, png, bmp)
Output following review for DV	No update
DV content (Y/N), reason if relevant	N *Software design implements requirement/specification.*
DV Req.-ID	n/a

Req.-ID	SW 9
Short name	Data export - Point and Mesh
Description	- The acquired dataset will be exportable (compatible) to regular 3D formats both as point cloud (txt,, pts, ptx, las, E57) and meshes (VRML, Obj, STL, Ply, Ascii, AOP, E57) This is necessary to perform different actions, combine complete 3D crime scenes, etc with other programs like Maya, 3DMax, Autocad, Cyclone, PointForce, Geomagic.
Priority	Conditional
Comment	n/a
Specification	The acquired scanner data (3D points) can be exported in the following standard formats: Point cloud export formats E57 point cloud *.e57 Text point cloud (x y z r[0-255]) *.txt VIC pst point cloud *.pst LAS point cloud *.las LAS zipped point cloud *.laz Solid image export formats Reconstructor 2 grid point cloud *.rgp E57 point cloud *.e57 PTX point cloud *.ptx The imported mesh model are in and out in the following standard formats Stanford Triangle Format *.ply Autodesk DXF format *.dxf 3D Studio model format *.3ds Reconstructor triangle meshes *.rtm STL ASCII format *.sta STL binary format *.stl OpenSceneGraph Archive format *.osga OpenSceneGraph extendable binary ... *.osgb OpenSceneGraph extendable format *.osg2 Psuedo OpenSceneGraph file loaded... *.osgs Alias Wavefront OBJ format *.obj OpenSceneGraph Ascii file format *.osg OpenSceneGraph extendable ascii fo... *.osgt OpenSceneGraph extendable XML fo... *.osgx The images are stored, used and exported in standard formats: jpg, png, bmp The listed formats are compatible, within many others i.e. the following software used worldwide: Rhino, Maya, 3D Studio Max, Autocad, Cyclone, Geomagic
Output following review for DV	No update

DV content (Y/N), reason if relevant	N, conditional, does not affect results. *Software design implements requirement/specification.*
DV Req.-ID	n/a

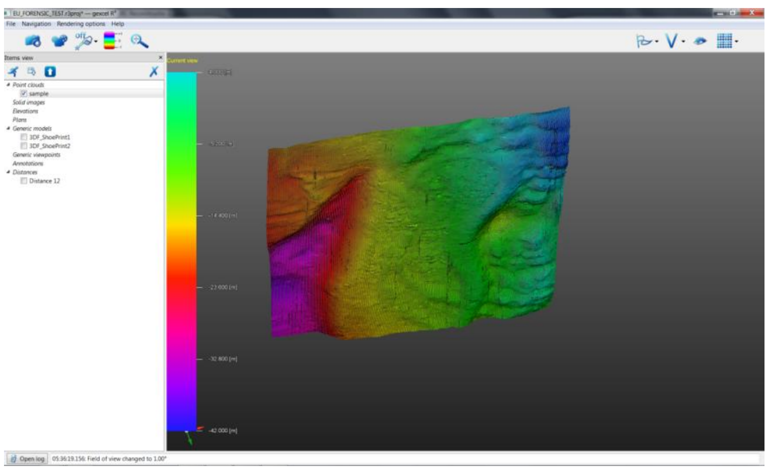
Req.-ID	SW 10
Short name	3D and 2D Navigation tools
Description	- Together simplified GUI the point/meshed navigation tool both for 3D and 2D data display will be designed to be intuitive and user friendly.
Priority	Conditional
Comment	n/a
Specification	The software supports both 3D point view and 2D (scan grid and images) display   3D view 2D view
Output following review for DV	Determination of further detail requirements/specifications SW10.1-10.2, the DV requirements [3.1]-[3.2] (*provided directly below*)
DV content (Y/N), reason if relevant	Y, DV indirectly *Software design implements requirement/specification.*
DV Req.-ID	[3.1]-[3.2], [4.1]-[4.6], [5.1]-[5.2]

DV Req.-ID	**Name - description**	**Specification**
[3.1]	Resolution - ability to resolve specific geometric features in a point cloud	≤ resolution of 3D point cloud
[3.2]	Specificity 3D, - geometric features, which are present in the 3D point cloud, are emphasized	No artificial features are created

Req.-ID	SW 11
Short name	Point to point alignment (stitching)
Description	Multiple 3D-scans of objects that did not match in one measurement, e.g. tyre impression, have to be stitched into one 3D-point cloud. The registration of several point clouds will be made in a semi-automatic way, with a two steps procedure i) Put the two dataset closer and ii) Automatically fit the two models in a single reference system for the next comparison steps Moreover a scan comparison between reference dataset and the measured one requires this easy to use alignment tool
Priority	Essential
Comment	n/a
Specification	The alignment functions works in two steps: 1) a first tool to put an impression close to another, moving one scan into the rough position of the reference scan 2) a second tool for a cloud to cloud best fitting that minimize the alignment errors In the first step external reference points can be used. The 2 steps can be performed between two scans acquired with the 3D Forensic scanner but also with other scanning systems.
Output following review for DV	Determination of further detail requirements/specifications SW11.1-11.6, the DV requirements [4.1]-[4.6] (*provided directly below*)
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[4.1]-[4.6]

DV Req.-ID	**Name - description**	**Specification**
[4.1]	Accuracy - alignment of point clouds results in no visible transition border.	< accuracy of 3D-Scanner
[4.2]	Robustness - resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).	Small variations without influence
[4.3]	Repeatability (accuracy) - alignment should be stable. (Measurement uncertainty / standard deviation of accuracy)	< 50 µm
[4.4]	Reproducibility (accuracy) - alignment	< 50 µm

	should be independent from user. (Measurement uncertainty / standard deviation of accuracy)	
[4.5]	Range - point clouds require low overlapping area.	30-50%
[4.6]	Quality control - resulting deviation of the alignment is logged. / Error resistance	Output the alignment error

Req.-ID	SW 12
Short name	3D Model comparison
Description	Once the measured points and the reference model are in the same reference system, a tool will allow the identifying and quantifying of the similarities. The comparison report with visible and numerical evidence will be a support for judicial acceptance of the collected evidences. 
Priority	Essential
Comment	n/a
Specification	Comparison tools include: - Function to merge in a single project, impressions coming from different crime scenes - Function to set one impression close to another for a comparison (SW 11) - Function to display 2 scans in 2 parallel windows for visual comparisons supported by the underlined blocks/lines/ or waves visible in the scan or in overlapped images (SW 16)
Output following review for DV	At the moment there is only a visual comparison tool with transparency changes. Feedback from users has indicated that this is acceptable. Requirement reassessed as “optional”. Determination of further detail requirements/specifications SW12.1-12.2, the DV requirements [5.1]-[5.2] (*provided directly below*)

DV content (Y/N), reason if relevant	Y, regarding generation of mesh model *Software design implements requirement/specification.*
DV Req.-ID	[5.1].[5.2]

DV Req.-ID	Name - description	Specification
[5.1]	Accuracy - meshing of point clouds does not change the measurement data. (Deviation between mesh and point cloud is small)	< 1/10 of accuracy of 3D-Scanner
[5.2]	Specificity - only geometric features, which are present in the 3D point cloud, are also visible in the mesh.	No artificial features are created

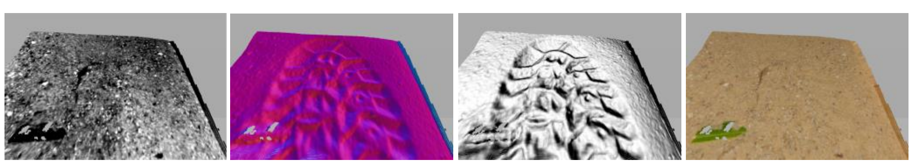
Req.-ID	SW 13
Short name	Camera projection - Fit of external images (HighRes RGB photograph)
Description	- The overlapping of a high-resolution RGB camera image over the 3D-point cloud would be a great help in considering the texture and distortions from a footwear or tyre impression - A software module will be developed to re-project calibrated images onto the 3D model of the scene using the intrinsic (internal calibration parameters) and orientation of the camera. The images from the camera inside the forensic sensor will be automatically positioned onto the related geometry. The images overlapped to points or meshes provide important complementary information to support measured extraction. - In case of traces with undetectable depth geometry, the image projection becomes fundamental to retrieve planar measure (distances, areas). If the system is provided with an external (high resolution) pre-calibrated camera connected to the scanner with a special mounting system, the software will use acquired images as described for the internal ones. - This capability will add high resolution colour information to the 3D model.
Priority	Essential
Comment	n/a
Specification	The importing function supports automatic 3D scan input with one or more images. The external camera is calibrated (inner and outer parameters) according to the scanner head; the calibration parameters are directly readable by the software. The calibrated image can be overlaid in real time on the 3D point cloud.
Output following review for DV	Determination of further detail requirements/specifications SW13.1, the DV requirements [3.3] (*provided directly below*) *Calibration dependent on calibration data provided with 3D-Scanner*
DV content (Y/N), reason if relevant	Y (with 3D-Scanner)

DV Req.-ID	[2.1] [2.5]

Req.-ID	SW 14
Short name	Class characteristics: data input from database manufacturers
Description	- For the class characteristics (profile elements and size) step, a guided procedure will help the user to import shoes or tyre models from external manufacturers' databases and to compare them with the survey. - Manufacturers' 3D models and 2D print will be importable as mesh model or 2D pictures respectively and usable with the comparison tools.
Priority	Conditional
Comment	n/a
Specification	A tool allows: - to import 2D images coming from external manufacturers databases or dedicated forensic archives - to scale and position the 2D image according to the 3D footprint If 3D mesh models of the reference tires or shoe is available, it can be imported in standards mesh formats (SW 9).
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, not directly affecting result *Software design implements requirement/specification.*
DV Req.-ID	n/a

Req.-ID	SW 15
Short name	Class characteristics: comparison tools
Description	- Imported manufacturer' 3D models after point to point alignment (stitching), will be compared with scanned prints and provide a compatible numerical report. - For 2D print comparison, an easy-to-use manual procedure will allow to overlap a 2D projection of the scanned print (with photo if available) with the 2D manufacture and to visually point out discrepancy and similarities. This procedure will be applicable if manufacturer's prints will be provided with the corrected scale (show size, tire corrected size) - Additional manual drawing tools will be provided to support class characteristics for diverse profiles (blocks/lines/waves/etc).
Priority	Conditional
Comment	n/a
Specification	A tool allows overlapping the imported and scaled 2D images over the scans and helps the expert to verify compatibility with the reference manufacturer's characteristics. When size and type are identified, these class characteristics are archived in the project as

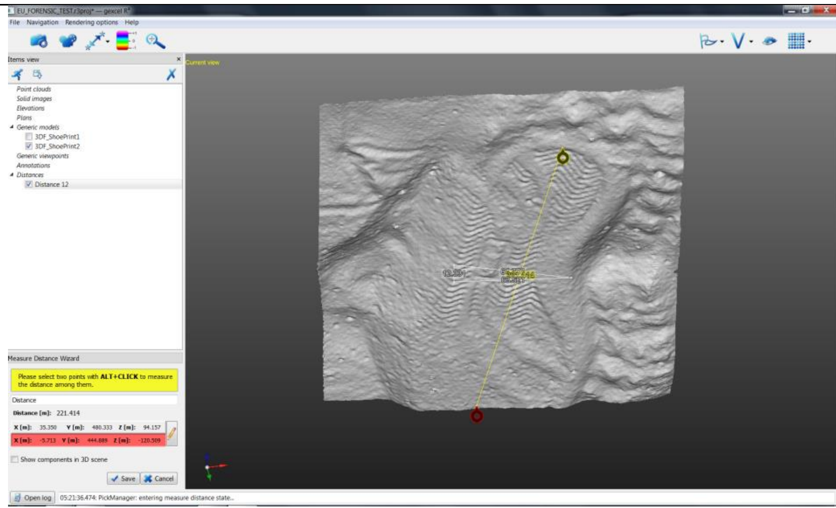
	specific annotations for the analysed print. In case of 3D meshes form a 3D reference manufacturer model, the pre-alignment tool can be used to set the 3D meshes in the same reference system of the scanned print (SW 11). The 3D model comparison tool (SW 12) supports the user to visually compare the reference model with the scanned model.
Output following review for DV	No update *(Note: with reference to the requirement numerical reports are created by users if their Criminal Justice system approves this evidential approach. There are no automatic tools for numerical analysis, except the distance, area etc. measurement tool.)*
DV content (Y/N), reason if relevant	N, not directly affecting result *Software design implements requirement/specification.*
DV Req.-ID	n/a

Req.-ID	SW 16
Short name	Tool to support identification
Description	- For the identification process (individual classification) steps drawing and measurement tools will be provided to point out deviations, damages, etc. of the class characteristics and support the user to determine the individual characteristics
Priority	Essential
Comment	n/a
Specification	A drawing tool allows the user to underlay visible deviations or damages (cuts, scratches, tears and holes etc). The drawing tool works using the 2D scan view but having the 3D coordinates as background information. In this way all the extracted lines or segments are measurable in 3D (3D length) and can be archived in the project as specific annotation for the analysed impression. Drawing tool is supported by overlapping different colour layers (external images, inclination, distance map) that help the user to visually emphasize deviations or damages.  Model slice (section can be extracted) for local profiles visual inspections
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, not directly affecting result *Software design implements requirement/specification.*

DV Req.-ID	n/a

Req.-ID	SW 17
Short name	Annotation tool and drawing
Description	- During the field campaign and the following data analysis, the measured evidence needs a dedicate tool to insert annotation as well as ancillary data (photos, videos, etc). - With the dedicated annotation tool all the collected evidence will be organized and spatially located having a common reference geometrical model. - An additional easy to use drawing tool will be provided to support class characteristics comparisons and individual characteristics identification
Priority	Essential
Comment	n/a
Specification	- During the field campaign each impression (from a single or multiple scans) is identified with a unique ID; this ID is preserved during the importing phases - All the drawings (SW 16) are archived as specific annotations linked to the referenced scan - Customizable (with an external *.csv file) annotation tool with rapid short cuts allows the user to insert annotation picking points in 3D.
Output following review for DV	Update regarding insertion of ancillary data (photos, videos, etc) – it is possible at the moment is to insert an annotation point and Hyperlink to external file (imaged, docs, videos)
DV content (Y/N), reason if relevant	N, not directly affecting result *Software design implements requirement/specification.*
DV Req.-ID	n/a

Req.-ID	SW 18
Short name	Measuring tool
Description	The operator will have dedicated measuring tools to selected points and mesh key points and extract the relevant print measured (length, size, area, depth). The measuring tool will be a fundamental basic tool to provide a numerical report during the analysis step.

	
Priority	Essential
Comment	n/a
Specification	- Tool to measure the linear distances between points - Tool to measure the lentgh of drawing (SW 16) - Tool to measure local areas
Output following review for DV	Determination of further detail requirements/specifications SW18.1-18.2, the DV requirements [6.1]-[6.2] (*provided directly below*) *Calibration dependent on calibration data provided with 3D-Scanner*
DV content (Y/N), reason if relevant	Y
DV Req.-ID	[6.1]-[6.2]

DV Req.-ID	Name - description	Specification
[6.1]	Measurement accuracy and repeatability of the software itself - extract correct measure given the same starting and ending point	≈ 0 µm measure error
[6.2]	Measurement accuracy and reproducibility	< 1 mm

Req.-ID	SW 19
Short name	Printing images / scans / reports
Description	The software will have printing capabilities for images, files and reports.
Priority	Conditional

Comment	n/a
Specification	- Screen shot from the visualized models exportable as standard image - Ortho-graphic views exportable as scaled measurable 2D images compatible with CAD or image processing software for scaled prints - 2.5D measurable images (Solid images) exportable in CAD with a dedicated plug in - Annotation exportable as standard *.csv - 3D scene video recording according to user defined trajectories exportable in *.avi format
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, not directly affecting result, conditional *Software design implements requirement/specification.*
DV Req.-ID	n/a

Req.-ID	SW 20
Short name	Scans web sharing
Description	The software platform is designed to display point clouds stored on a local PC or stored on a web server. The web sharing capability will offer to the forensic operators (experts, lawyers, magistrates etc) the possibility to show and evaluate the results of forensic activity from different locations accessing the same data set.
Priority	Optional
Comment	n/a
Specification	After authentication on a dedicated web page a user can upload a 3D cloud on a web protected server. The user can publish only the desired 3D point cloud with other user controlling the accessing time and closing the connection if necessary.
Output following review for DV	At the moment this sharing functionality is not directly offered to the user in the last version of the software. The web-sharing infrastructure is strongly dependent from internal web infrastructure of the forensic police. The RIS Carabinieri works on PCs that are not web connected at all. Requirement/Specification was optional.
DV content (Y/N), reason if relevant	N, not directly affecting result, optional
DV Req.-ID	n/a

Req.-ID	SW 21
Short name	Error resistance
Description	The software will be designed and tested to be resistant against failure by user with some

	recoverable, functionalised and back up tools.
Priority	Conditional
Comment	n/a
Specification	The dedicated workflow (SW1) helps the user to avoid procedural errors If a crash occurred all the data, raw and processed are saved in the project structure to prevent data lost
Output following review for DV	No update
DV content (Y/N), reason if relevant	No
DV Req.-ID	n/a

Req.-ID	SW 22
Short name	Accuracy
Description	The user will have a report concerning the accuracy during the comparison steps and the preparing processing steps.
Priority	Conditional
Comment	n/a
Specification	During the alignment process and measuring process the user can display accuracy parameters in terms of alignment errors and pixel resolution when drawing or measures are extracted
Output following review for DV	This specification includes: ▪ “Authentication” - “the data is an accurate presentation of what it purports to be.”[91]
DV content (Y/N), reason if relevant	Y, regarding alignment and measuring
DV Req.-ID	[4.1]-[4.6] and [6.1-6.2] (*described above*)

[91] Supra: Home Office, *Digital Imaging Procedures* p.77.

Ensuring admissibility in court as evidence requirements / specifications list

Req.-ID	CC 1
Short name	Transparency
Description	The complete sequence: from scanning until identification must be transparent and reproducible. The system will be able to output any intermediate data that was produced in the analysis. It must be possible to give the original data to an independent third person for contra-expertise.
Priority	Essential
Comment	n/a
Specification	- Detailed documentation of all functionalities in the scanning and analysing process - Possibility to output every intermediate data in the analysis process - Workflow in the 3D-analysis will be guided by the software to achieve reproducible results
Output following review for DV	This specification includes: ▪ Integrity - "the data (image etc.) presented is complete and unaltered since time of acquisition." (p.7) (e.g. Secure copy, master/working copy, audit trail)[92] ▪ "Authentication" - "the data is an accurate presentation of what it purports to be."[93]
DV content (Y/N), reason if relevant	Y, reproducibility
DV Req.-ID	[1.5]A, [1.5]B, [2.4], [4.4], [6.2] (*described above*)

Req.-ID	CC 2
Short name	Accreditation/Validation anticipation
Description	The following international standards have been identified: ISO17025 for laboratory work, and ISO17020 for crime scene work. In addition it is noted that CEN activities started in 2013 to develop a CEN crime scene standard. National countries can also have their own codes of practice and conduct for forensic service providers and practitioners supporting standards. Analysis within the partner countries to date identifies that compliance with standards and/or codes is not a precondition for acceptance in court, though it may certainly help to facilitate acceptance in court. Accreditation and validation can however be a requirement requested by police forces for the provision of forensic services and/or equipment and/or prosecution authorities. However, for example, PZ states that it can and will use the 3D-Forensics system to prepare evidence for court without accreditation/validation if it is satisfied with its performance. (*Text relevant to earlier FP7 project deleted*)

[92] Supra: Home Office, *Digital Imaging Procedures* p.7
[93] Ibid. p.77.

Priority	Conditional
Comment	n/a
Specification	- The usage of the system does not constrain an accreditation - The project activities, specifically in WP7 “Forensic Test and Scientific Evaluation”, will prepare the way towards potential future accreditation / validation processes *Note 2019: Specification specific to FP7 project, present FTI project has present WP4 activities connected with pushing validation further.*
Output following review for DV	No update to requirement, specification is still to push validation, both developmental validation and validation/verification by end users
DV content (Y/N), reason if relevant	Y, DV supports validation.
DV Req.-ID	ALL

Req.-ID	CC 3
Short name	Uniqueness of the trace
Description	Each trace must bear a unique code to track: the time, location, number of traces and person that recovered the traces
Priority	Essential
Comment	n/a
Specification	- Additional time stamp is saved for each scan as part of the file- or directory-name - Additional information, such as number of traces, name of the crime scene and system user, can be added to each scan or scan session (all 3D-scans at one crime scene) by the user
Output following review for DV	This specification includes: ▪ “Authentication” - “the data is an accurate presentation of what it purports to be.”[94]
DV content (Y/N), reason if relevant	N, 3D-Scanner and 3D analysis software design implements requirement/specification.
DV Req.-ID	n/a

Req.-ID	CC 4
Short name	Simplicity and output easy to understand
Description	The output should be understandable for a layman. The people who have to understand the procedure and the techniques are often non-technical

[94] Op.cit.

	(judges/lawyers/jury). The results will be reported by the software in a format that will be comprehensible.
Priority	Essential
Comment	n/a
Specification	- Detailed documentation of all functionalities in the scanning and analysing process - Detailed documentation of the final analysis results in the software
Output following review for DV	No update
DV content (Y/N), reason if relevant	N, connected with laymen and their know-how *3D analysis software design implements requirement/specification, tools provided for reporting, user responsible for providing understandable content.*
DV Req.-ID	n/a

Req.-ID	CC 5
Short name	Safe storage of the original scans.
Description	The original scans and RGB photographs should be stored in a way that nobody can change/manipulate these scans. A working, editable copy must be derived from the original scan to make selections and identifications. After data collection all measured datasets are moved from the 3D-scanner to an USB stick in a protected encrypted archive. The encrypted data archive (e.g. ZIP-file) is transported on the USB-stick to the analysis PC in the office, while the password is transported on a separate device. The analysis software PC in the police office is under supervision of the police network. During the importing phase the analysis software PC requires that the data on the USB stick gets decrypted. The measurement data is consistent with the raw data. A local copy of the raw data is automatically made during the importing phase to the office PC, providing for safe storage on the police office PCs. Data integrity is guaranteed during the processing phase: the user has the possibility to start or re-start the processing and analysis from the raw data.
Priority	Essential
Comment	n/a
Specification	- The original measurement data consists of the 3D point cloud and the colour map - Directly when scanning, the data is stored encrypted on the PC, that is integrated in the 3D-scanner - When analysing (and editing) the data, the original files are stored write-protected, the user works with an editable copy

Output following review for DV	This specification includes: ▪ Integrity - “the data (image etc.) presented is complete and unaltered since time of acquisition.“ (p.7) (e.g. Secure copy, master/working copy, audit trail)[95]
DV content (Y/N), reason if relevant	N *3D-Scanner and 3D Software design implements requirement/specification*
DV Req.-ID	n/a

Req.-ID	CC 6
Short name	Prevent data manipulation
Description	The data structure and project structure will be in the logic to prevent data manipulation during the chain of custody. For example the final results can be delivered in a project structure that becomes unreadable if some component of the dataset is modified.
Priority	Essential
Comment	n/a
Specification	- Directly when scanning, the data is stored encrypted on the PC, that is integrated in the 3D-scanner - The analysis of the data will be made on a PC in the police office, which is secured by the system of the police - The original scan data cannot be manipulated by anyone (only system administrator) - The working copy can only be edited by authorized users - The project structure will enable that each intermediate step in the analysis can be undone to prevent unwanted data manipulations
Output following review for DV	This specification includes: ▪ Integrity - “the data (image etc.) presented is complete and unaltered since time of acquisition.“ (p.7) (e.g. Secure copy, master/working copy, audit trail)[96]
DV content (Y/N), reason if relevant	N *3D-Scanner and 3D Software design implements requirement/specification*
DV Req.-ID	n/a

[95] Supra: Home Office, *Digital Imaging Procedures* p.7.
[96] Op.cit.

Annex 2: 3D-Forensics system's product specifications (June 2019)

The following tables provide the 3D-Forensics system's "high-level" product specifications (June 2019) with full consideration of the "developmental validation" results. "High level" means they do not go into all the detail as included in Annex 1. However the fuller specifications connected with the "developmental validation" will be available for user review.

3D-Scanner

3D-Scanner specifications	
Field of view	325 x 200 mm^2 (single field)
Measurement height	100 mm
Working distance	455 mm
Resolution	Lateral: 0.17 mm (point pitch distance) / Vertical: 0.04 mm
Accuracy	< 0.05 mm
Weight	3.7 kg (without camera, without battery) 0.8 kg (battery) 0.6 kg (200D *camera*) or 1.1 kg (Mark IV *camera*)
Size	350 x 240 x 260 mm^3 (without external camera)
Sound intensity	< 30 dB
Battery time	> 2 h (recording ca. 1 scan per minute) < 4 h (running device, without recording) ca. 2 h (recharging)
Time to scan	<200 ms
Processing time	4 - 6 secs
Colour camera	Canon EOS 100D/200D or Canon 5D Mark IV
Brightness settings	7 exposure steps, 7 LED brightness settings
Temperature	-10°C … 40°C
External light	< 40,000 lux
Start-up time	35 sec
Data storage	ca. 3,000 3D scans + photo

Output format	.rgp, .txt, .ply (.E57, .las,. obj,. .stl, .wrml from the 3D Forensic software)
Eye safety	≙ laser class 1 (no danger for eyes)
IP class	IP22

3D analysis software

3D analysis software specifications	
Import 3D Point clouds	• Import 3D Forensic scans in native formats • Imports point clouds from LiDAR, UAV, total station in open formats (.txt, .las, .laz, .e57, .ptx, .pts, .asc, .ply, .csv)
Import meshes, CAD/BIM models and polylines	• Imports meshes, CAD models and polylines (.dxf, .ifc, .stl, .wrl, .vrml, .3ds, .ply, .obj, .dae)
Import 2D images	• Import high resolution image from 3D Forensic scanner • Calibration check and recalibration function included
Import/merge of multiple projects	• Multiple project can be merged in one for comparison purposes
Export point clouds in open formats	• Export point clouds (.txt, .las, .laz, .e57, .ptx, .pts, .asc, .ply, .ptc, .ixf)
Export 3D mesh models in open formats	• Export 3D mesh models (.dxf, .stl, .wrl,. 3ds, .ply, obj, .dae)
3D data visualization and navigation	• 3D rendering and navigation of 3D point clouds and meshes
Point Cloud Filtering & Editing	• Point clouds noise removal • Point clouds normal calculation • Point clouds quality assessment • Point clouds editing and clustering
3D Models registrations	• Manual registration of models • Cloud to cloud ICP registration • Scan registration with circular targets
Automatic meshing	• per scan triangulation mesh with no artefact or accuracy loss
Automatic mesh texturing	• 3D mesh texture mapping based on calibrated images from the 3D forensic scanner

Camera calibration	• Internal and external camera calibration (perspective, ortho and spherical cameras) using 3D points from point clouds or meshes: chessboard internal calibration included.
Analysis tool: dedicated tool to analyse class and specific characteristics and do comparisons	• Class characteristic visual identification comparing 3D scan with 2D shoes images (from external data set); scaling and measuring tools included • Specific characteristic visual identification thanks to measuring, profile and annotation tools; per impression characteristics are save in an internal DB • Comparison between impressions or with suspect shoes thanks to overlapping tool with transparency settings
3D distances	• Extract and export distances (with components in current UCS) between points and planes
Angle measure	• Calculate angles between points and planes
Area calculation	• Calculate area under a point cloud or a mesh
Segment and polylines	• Manual extraction of 3D segment and polylines from picked points
Orthophotos from point clouds and meshes	• Interactive tool to create orthophotos given a point clouds or a meshes
Orthophotos viewer	• Interactive tool visualize orthophotos and extract measures
Video recording	• Generate and export fly-through video in standard formats
Save high resolution snap	• Extract high resolution images for user defined views of 3D models

Annex 3: Development validation test specimens

Overview specimens used to test specifications and related test references

An overview of the specimens used to test specifications and related test references are described in the following tables. In Annex 4 test scenarios connected with the test references are described in detail and the full and final results of the developmental validation are given. Under terms of "Reproducibility", the full and final results of the round robin tests are given.

	Specimen	**Tested specifications**	**Test references**
1)	**3D resolution specimen**	Tool 1: Resolution	3DFFTI_TC_1a
		Tool 1: Repeatability of resolution	3DFFTI_TC_1a
		Tool 1: Reproducibility of resolution	3DFFTI_TC_1b
		Tool 1: Robustness of resolution	3DFFTI_TC_1c/d
		Tool 1: Thermal robustness of resolution	3DFFTI_TC_1e
		Tool 1: Surrounded sunlight	3DFFTI_TC_1f
		Tool 1: Handheld scan mode	3DFFTI_TC_1aH 3DFFTI_TC_1bH
2)	**Sphere normal**	Tool 1: Range of inclination angle	3DFFTI_TC_2
3)	**Calibration board**	Tool 1: Accuracy	3DFFTI_TC_3a
		Tool 1: Repeatability of accuracy	3DFFTI_TC_3a
		Tool 1: Reproducibility of accuracy	3DFFTI_TC_3b
		Tool 1: Robustness of accuracy	3DFFTI_TC_3c
		Tool 1: Thermal robustness of accuracy	3DFFTI_TC_3d
		Tool 1: Surrounded sunlight	3DFFTI_TC_3e
		Tool 1: Handheld scan mode	3DFFTI_TC_3aH 3DFFTI_TC_3bH
		Tool 2: Accuracy	3DFFTI_TC_3a
		Tool 2: Repeatability of accuracy	3DFFTI_TC_3b
		Tool 2: Reproducibility of accuracy	3DFFTI_TC_3c
		Tool 2: Thermal robustness of accuracy	3DFFTI_TC_3d
		Tool 2: Handheld scan mode	3DFFTI_TC_3aH 3DFFTI_TC_3bH
		Tool 2: Surrounded sunlight	3DFFTI_TC_3e

4)	**Sphere distance normal**	Tool 1: Accuracy	3DFFTI_TC_4a
		Tool 1: Repeatability of accuracy	3DFFTI_TC_4a
		Tool 1: Robustness of accuracy	3DFFTI_TC_4b
		Tool 1: Handheld scan mode	3DFFTI_TC_4aH
5)	**Realistic objects**	Tool 1: Accuracy	3DFFTI_TC_5a
		Tool 1: Repeatability of accuracy	3DFFTI_TC_5a
		Tool 1: Reproducibility of accuracy	3DFFTI_TC_5b
		Tool 1: Handheld scan mode	3DFFTI_TC_5aH 3DFFTI_TC_5bH

Table 19: Specimens to validate the 3D-Scanner performance

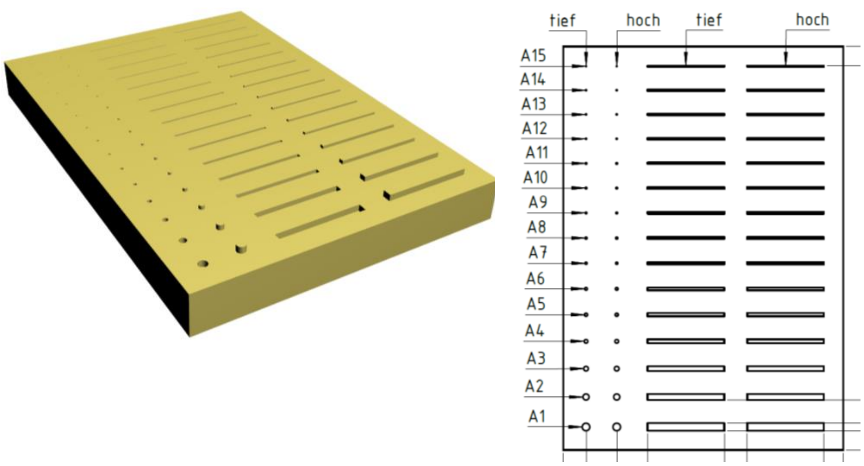
To validate the 3D analysis software, a set of specific scan datasets and simulated datasets are used as specimen:

	Specimen	Tested specifications	Test references
1)	**3D point cloud visualisation specimen**	Tool 3: Resolution	3DFFTI_TC_6
		Tool 3: Specifity 3D	3DFFTI_TC_6
		Tool 3: Specifity colour	3DFFTI_TC_6
2)	**Overlapping 3D scans specimen**	Tool 4: Accuracy	3DFFTI_TC_7
		Tool 4: Robustness of accuracy	3DFFTI_TC_7
		Tool 4: Repeatability of accuracy	3DFFTI_TC_7
		Tool 4: Reproducibility of accuracy	3DFFTI_TC_7
		Tool 5: Accuracy	3DFFTI_TC_8
		Tool 5: Specificity	3DFFTI_TC_8
3)	**3D scans with different shape, depth, discontinuities**	Tool 5: Accuracy	3DFFTI_TC_8
		Tool 5: Specificity	3DFFTI_TC_8
4)	**3D scan of calibration board**	Tool 6: Accuracy	3DFFTI_TC_9

Table 20: Specimens to validate the 3D analysis software performance

3D resolution specimen

For the end users the 3D resolution is the most critical specification of the 3D-Scanner, because this specification determines the usability of the data for identification purposes. There were no specimens for the evaluation of a 3D sensor resolution available, because the resolution of 3D sensors have a wide range and the accuracy has a higher value for many applications. Thus, a self-designed specimen was used which was agreed with EETG members. The specimen contains a sequence of embossed and imprinted bars and dots, which mimic tiny shoe or tyre marks.



Nr.	Durchmesser / Breite	Tiefe / Höhe
A1	1.0	0.75
A2	0.8	0.6
A3	0.6	0.45
A4	0.5	0.38
A5	0.4	0.3
A6	0.35	0.26
A7	0.3	0.23
A8	0.275	0.21
A9	0.25	0.19
A10	0.225	0.17
A11	0.2	0.15
A12	0.18	0.14
A13	0.16	0.12
A14	0.14	0.11
A15	0.12	0.09
T	±0.005	±0.01

Figure 46: 3D resolution specimen layout

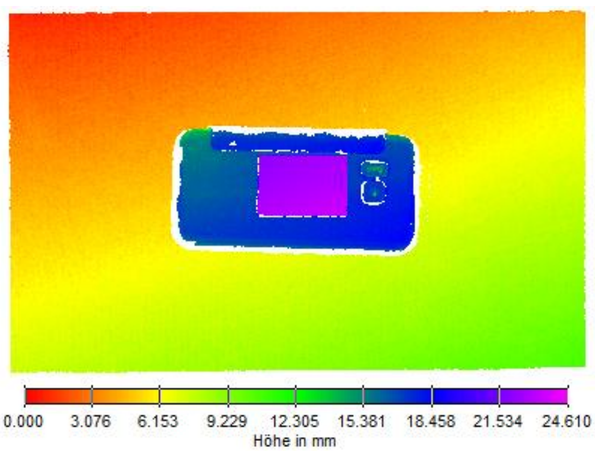
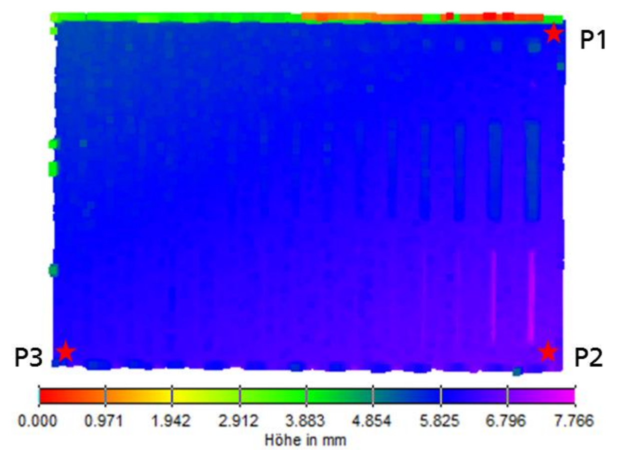
The achievable resolution is determined primarily by two influences: The point pitch distance in the 3D point cloud and the noise in the 3D data. While the first influence is determined by the sensor components, the second component is strongly connected with the reflection characteristics of the surface. Impression at crime scenes can occur in a wide range of underground materials. Three relevant and most difficult underground types were chosen for the resolution test. The underground types were replicated out of workable material with similar reflectance to create specimens with known geometry. The specimens were manufactured with precision milling machines by IOF. The materials represent typical undergrounds for impression traces:

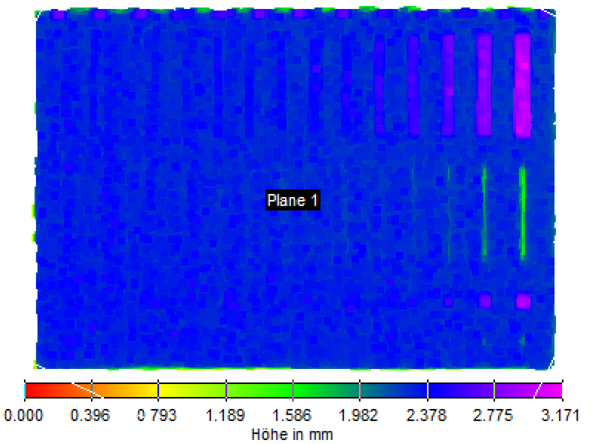
- Dark matt (soil / shoe sole)
- White translucent (snow surface)
- Reflective metallic (wet surface)

The size of the structure is between 0.12 … 1.0 mm. The smallest structures are intentionally smaller than the nominal resolution of the 3D scanner (defined by the point pitch distance) so that the limit of the resolution can be assessed. The evaluation foresees to identify the smallest visible bar / dot size. It is not the task to measure their size.

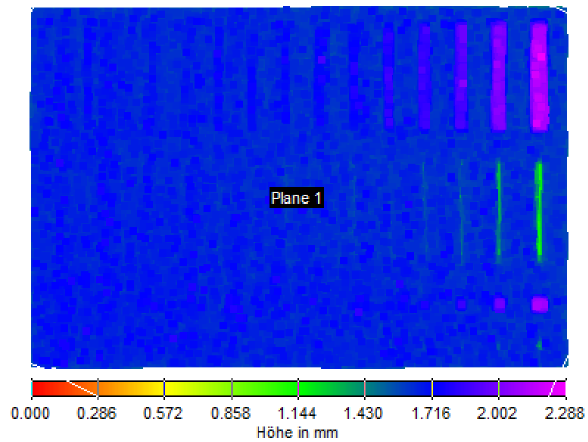
Figure 47: 3D resolution specimens with dark matt (Rescor ceramic), white translucent (Macor ceramic) and reflective metallic (Aluminium) surface

The following guideline is applied to evaluate the resolution in a 3D scan of the specimen:

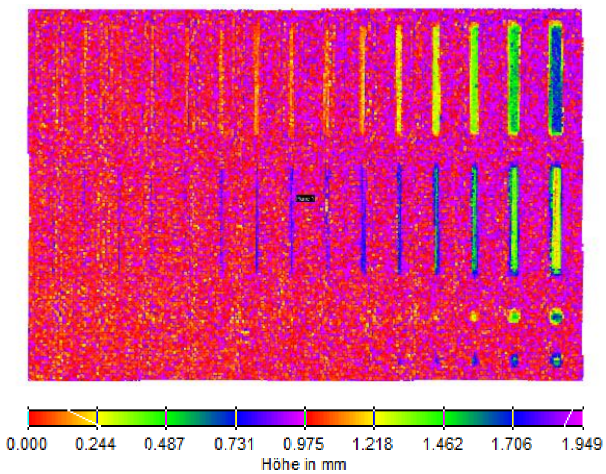
	
(1) Crop the region of the specimen (remove background)	(2) Fit a plane by selecting 3 points in the corners of the specimen



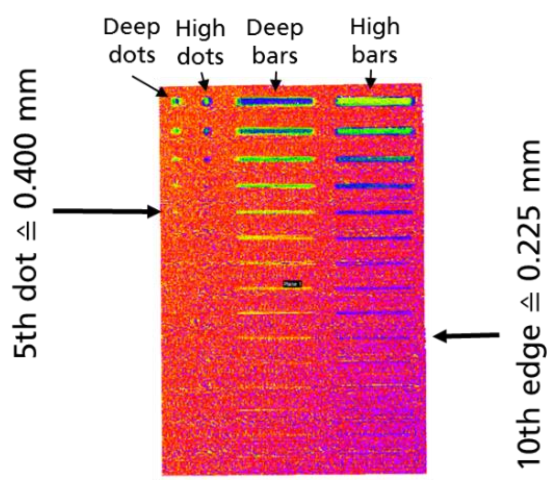
(3) Register the point clouds relative to the plane: The colour-code equals now the points distance to the plane. The plane fit remedies the fact that the scans were not perfectly from above.



(4) Optionally: Fine crop of points not belonging to the top side of the resolution specimen.



(5) Fold the colour palette to emphasize small edges: The person who evaluates the data should select a fold setting which allows the best visualisation of the small edges. A too small setting does not give enough colour contrast. A too high setting also emphasizes the noise in the data.



(6) Look from the largest to the smallest edge / dot which is able to be distinguished as a structure (and not noise). The edges are only identified as "visible“, if they are continuous.

(7) Look up the size of this edge in the layout table.

Tests on robustness of the resolution to variations of the parameters were done exclusively with the dark matt specimen. Effects of those variations would be similar for the other two specimens.

Sphere normal

The sphere normal was used to determine the maximum inclination angle. This test is typically used for industrial 3D sensors [Reference]. A single 3D scan of the sphere is acquired. It is evaluated how much of the sphere is visible (see Figure 48). Often (and also in this report) half opening angle α is taken as result. Typically for stereo camera based 3D sensors are 60…70° (α = 120…140°).

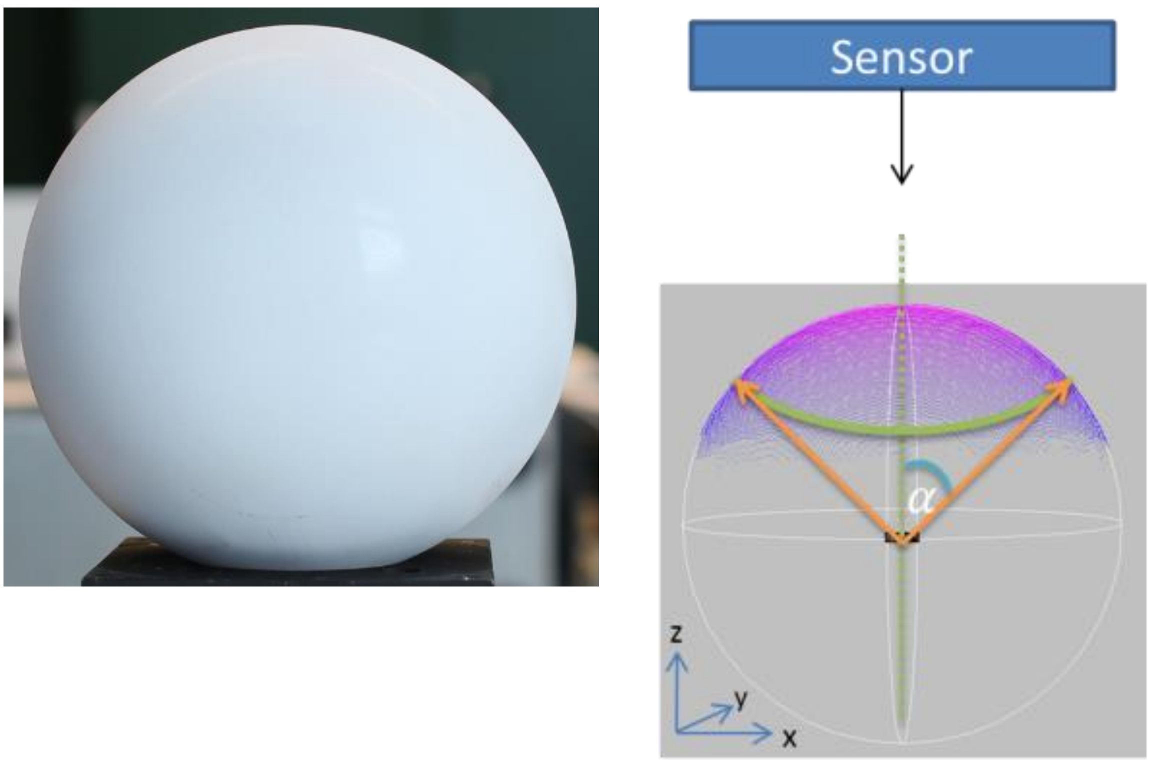


Figure 48: Sphere normal specimen (diameter 80 mm) and the evaluation of the maximum inclination angle.

Calibration board

The calibration board is a fixed component to the 3D-Scanner which is to be used for quality control by the end users. It can be used at the crime scenes to validate the accuracy of the 3D data and to recalibrate the external camera alignment. Basically it provides a pattern of 19 circles printed with high quality (50,000 dpi) on photo paper, which was then laminated on a plane glass plate. The position of each circle was calibrated in sub-micrometre precision. Compared to the other specimens it is quite robust, so that it can be taken outdoor to crime scenes.

In the validation process, the calibration board was used as specimen for the tools 1 and 2. Here it is one way to validate the accuracy of the 3D data (tool 1) and it is the only specimen to evaluate the accuracy of the external colour photo mapping (tool 2). For the evaluation of the colour mapping accuracy no tools or specimens exist beside a visual inspection. The 3D accuracy is evaluated by comparing the distances between the circles to the reference values from the calibration certificate. The colour mapping accuracy is checked by comparing the circle positions in the point cloud and the mapped photo.

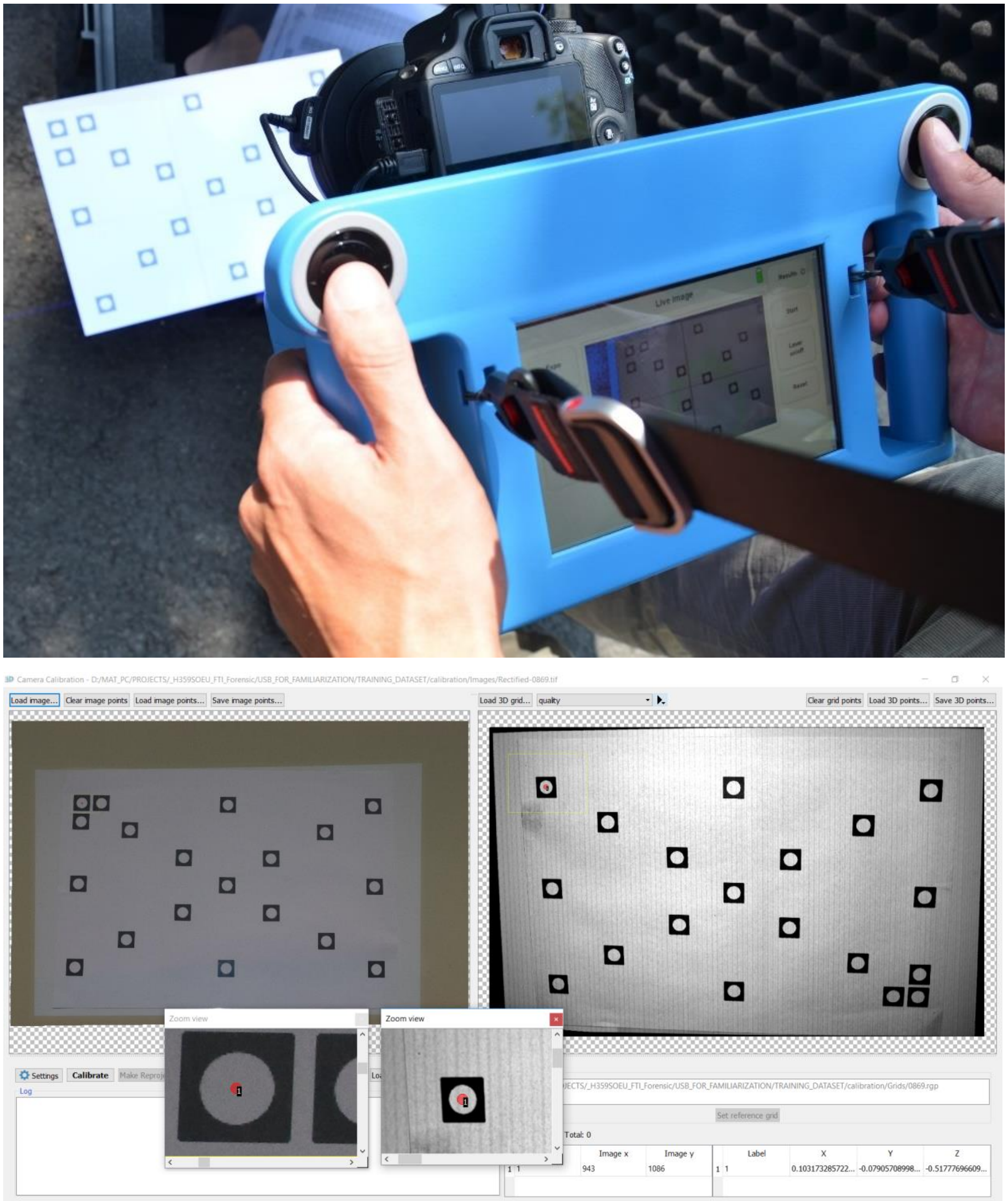


Figure 49: Scan of the calibration board and checking of the colour mapping

Sphere distance normal

The sphere distance normal is the standard specimen for industrial 3D sensor used to evaluate their accuracy. The test approach is described in the industrial guideline VDI2634. Because of its wide usage and its established status it was used in the validation, although the test of accuracy (including robustness and repeatability of accuracy) is already considered by the calibration board specimen.

The VDI guidelines propose the measurement of the sphere distance normal in 7 defined positions in the measurement volume.

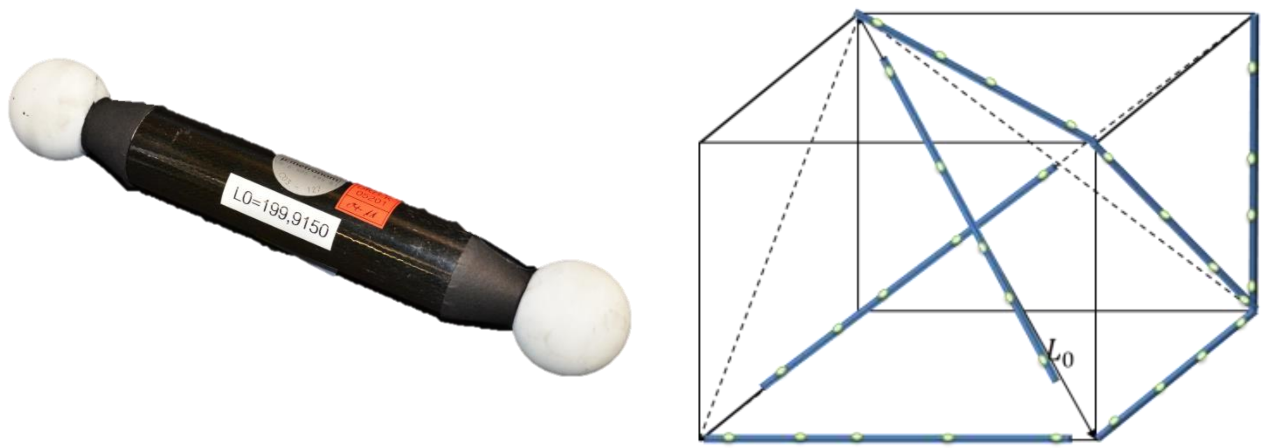


Figure 50: Example of a sphere distance normal (left) and the sketch of the 7 proposed test positions within the measurement volume (right)

Realistic objects: Shoe sole / MikroTrack™ impression

The evaluation of the 3D-Scanner accuracy was already covered by the calibration board and the sphere distance normal. But a recommendation of the end users was that also realistic objects which are typical for the application field should be used in the validation. However some restrictions needed to be considered.

First problem is that the typical underground materials for impression traces have no long term stability (like sand or snow) and are not suitable for a specimen. With some restrictions, shoe soles and MikroTrack™ (impressions) can be taken as specimens with stable shapes. During the test scenarios care needed to be taken that the sole / MikroTrack™ was not deformed.

Another problem is that the real geometrical characteristics are not known (not like the calibrated distances of the calibration board or the sphere distance normal). This means that those test scenarios could not provide a feedback on the absolute accuracy of the 3D-Scanner. But through comparison of the scans between each other the reproducibility and repeatability as well as the robustness on “realistic” objects was evaluated.

To compare the scans between each other, each test scenario foresaw first the acquisition of a reference scan. Then, the point clouds of the following scans were registered to that reference and then a “3D comparison” is performed. Hereby the distances between nearest neighbours between the test and reference point cloud were calculated. As a result of this 3D comparison a colour coded deviation map was output as well as a standard deviation between both scans.

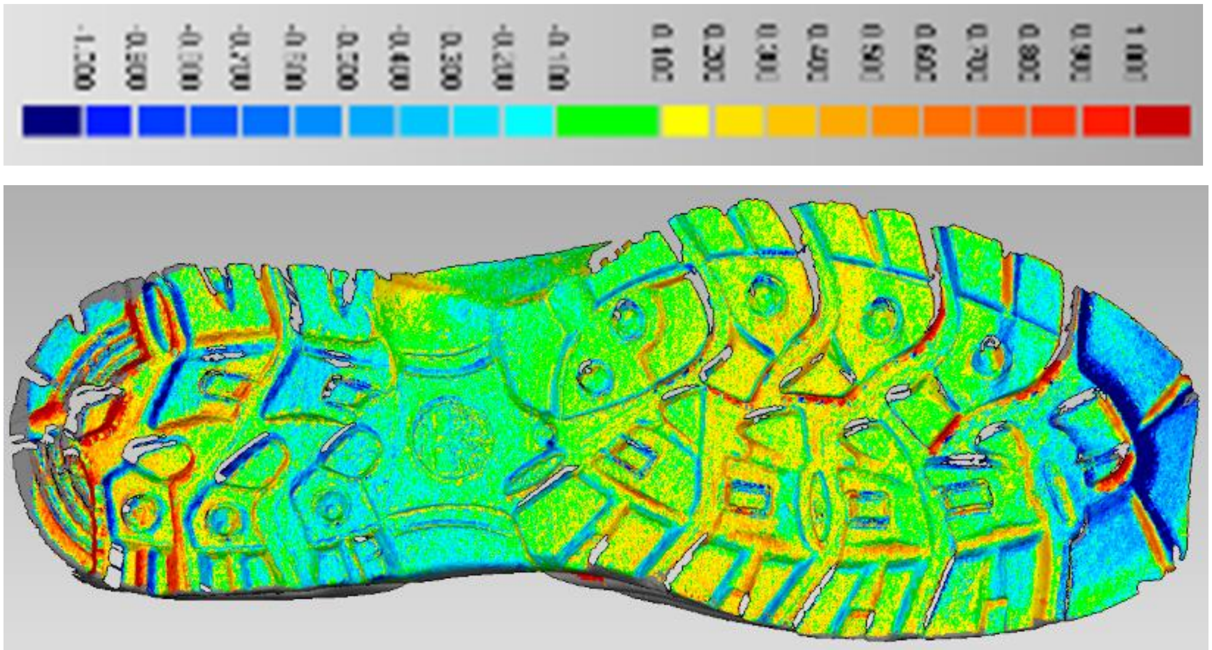


Figure 51: Example of a 3D comparison and the color coded deviation

3D point cloud visualisation specimen

To validate that the 3D analysis software emphasises only those 3D features which are encoded in the point cloud a simulated point cloud without any artefacts or noise was created. As a basis, the design of the 3D resolution specimen was used. The perfectly smooth design model was converted into a perfect point cloud. With this simulated point cloud also the capability of the software to visualise tiny features could be demonstrated.

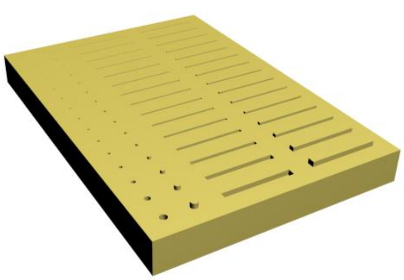


Figure 52: Design model of the 3D resolution specimen

Overlapping 3D scans specimen

A dataset including two overlapping 3D scans of the same impression trace was used to validate the tools 4 and 5 (registration and meshing tools of the analysis software).

The registration phase is subdivided in two steps:

a) Pre-registration: the user must select two overlapping scan and select 3 homologous points

A preliminary error evaluation is provided to the user (Figure 52)

b) After the pre-registration the ICP best fitting can start

In the fine registration tool the residual error between the two point clouds after registration is captured (Figure 53).

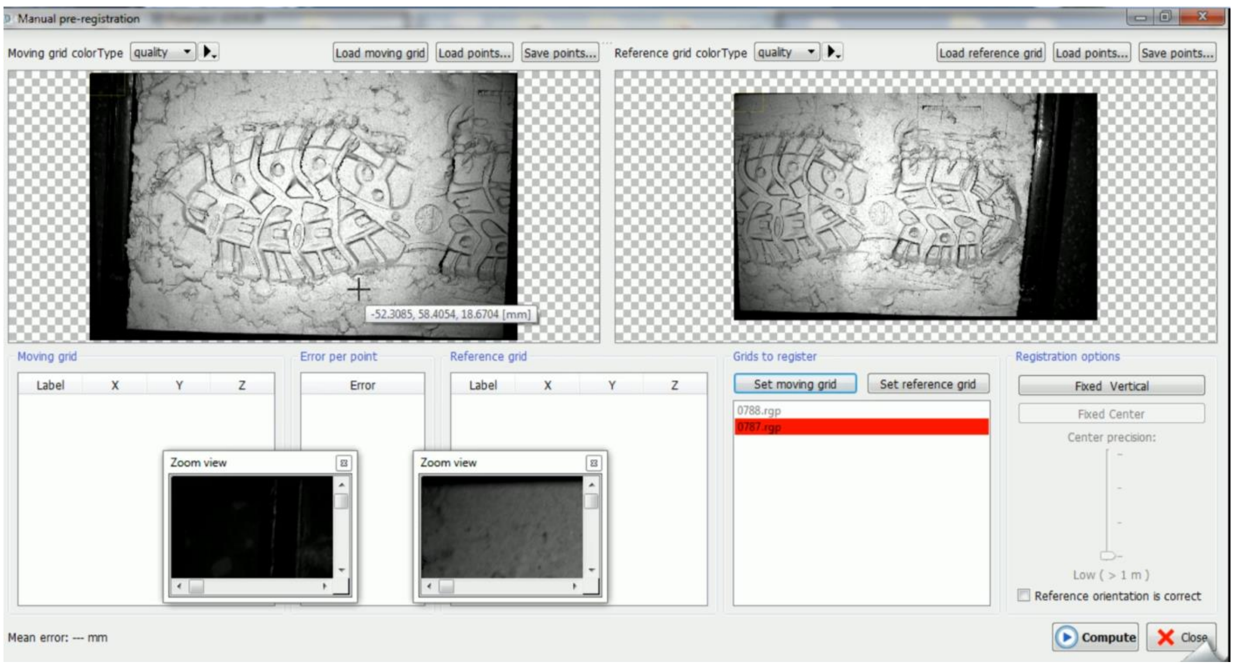


Figure 53: Pre-registration step

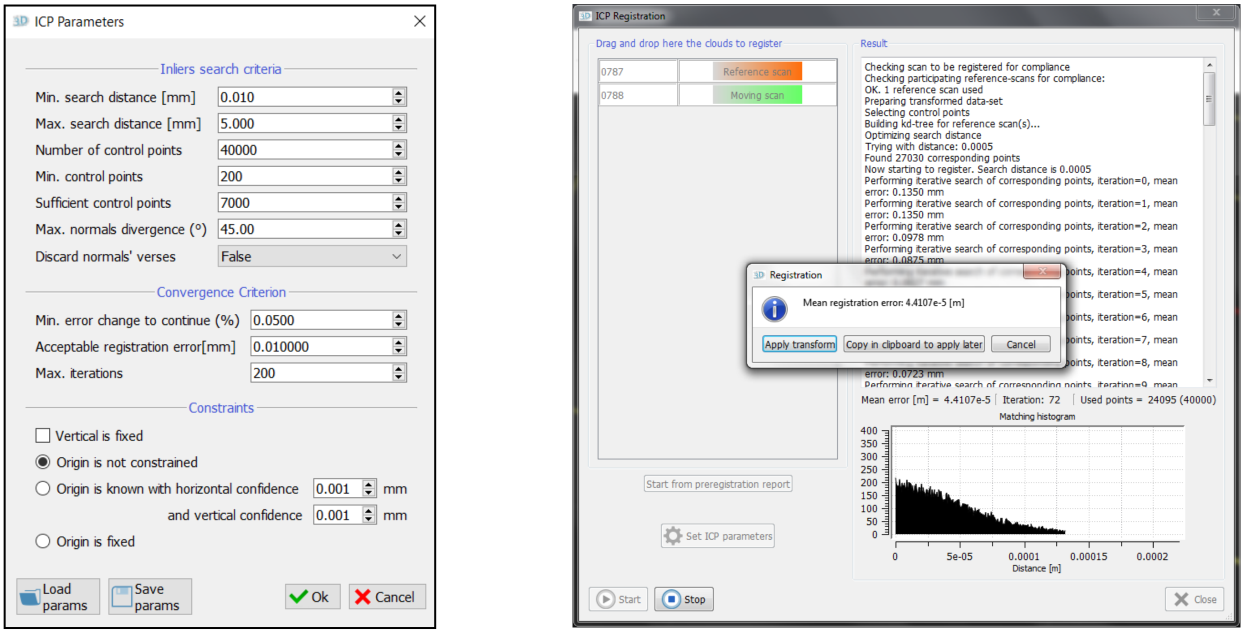


Figure 54: a) default parameters, b) ICP best fitting

After the mesh was created from the registered point clouds (software function "Create impression") it was compared to the original point cloud to determine the accuracy. Meshes could also be compared between each other to evaluate the repeatability and reproducibility using and external tool capable to evaluate the changes (Figure 57).

Notes: The ICP best fitting converges to the noise level of the 3D data. Occasionally, in the case of higher noise levels in the scans, the first ICP iteration can converge to a "mean registration error" higher than 50 µm. In this case it is suggested to run the ICP a second time using the parameters from Figure 55.

For particular noisy scans, the mean error can be larger than 50 µm after the second ICP run. In this case the user should additionally check the scan alignment visually for correctness in the region of interest, e.g. by using the Screen Setting "Color by ID" or by displaying the two aligned scans in slice view (Figure 56). If visually the scans show no mismatch, also a larger mean error is acceptable.

Single scans can still be analyzed independently from the registration process to identify specific characteristics.

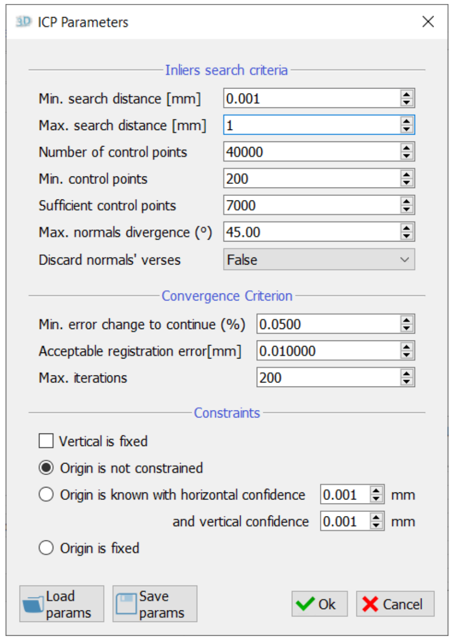


Figure 55: Suggested parameters for the second iteration of ICP

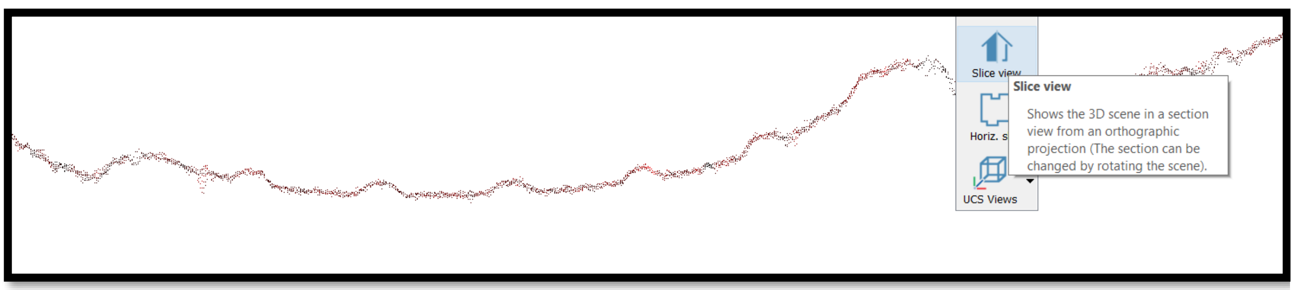


Figure 56: Slice view after ICP registration

Figure 57: Differences analysis between the final mesh model and the point cloud. All the points are coloured cyan indicating they are within the tolerance.

Annex 4: Detailed test scenarios and full and final developmental validation results

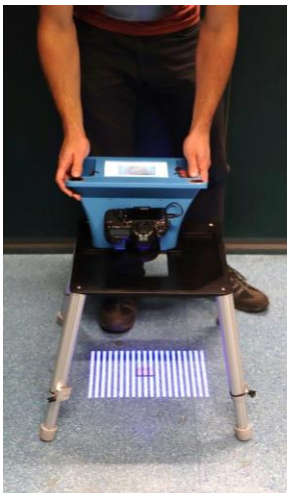
On the following pages content of the test scenarios and the full and final results are explained in detail. Each test scenario is documented on an individual test sheet.

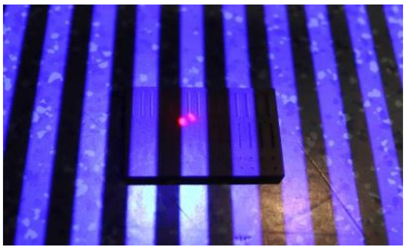
Under the specification “Reproducibility”, the full and final results of the round robin tests are provided.

Test reference:	3DFFTI_TC_1a				
Test name:	3D resolution and repeatability	**Location:**	IOF, Jena	**Date:**	21/02/2019
Tested requirements:	3D resolution for different undergrounds, scan mode Quad Repeatability of 3D resolution for different undergrounds, scan mode Quad				

Test set-up:

- 3D resolution specimens
    - in materials Rescor, Macor, Aluminium
    - in scan mode Quad
- grey matt material Rescor is used to determine the resolution under best conditions of the surface to be scanned
- white translucent Macor is used to determine the resolution under the limitation of a translucent surface (snow)
- metallic shiny Aluminium is used to determine the resolution under the limitation of a shiny / wet surface





Test assumptions, conditions & constraints:

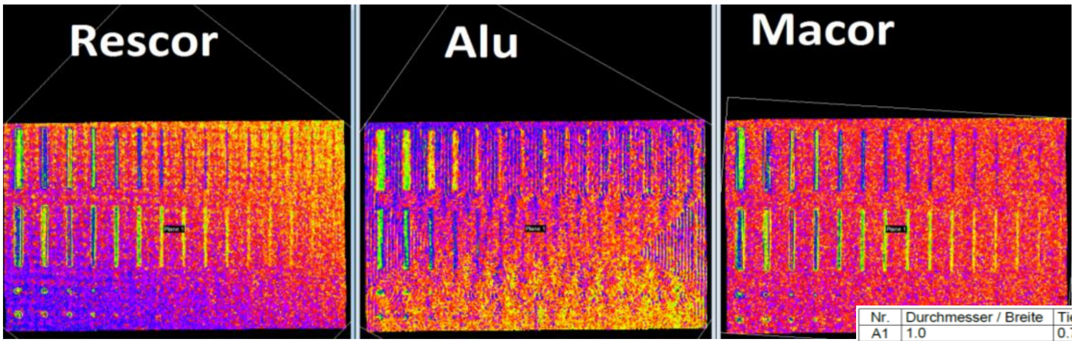
- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Specimen in center of FOV
- Scanner in perpendicular scan orientation
- Bars on specimen rotated vertical relative to baseline of stereocameras
- Exposure step 1
- LED brightness optimal for each specimen material
- External light <10,000 lux (indoor)
- Scans with quadpod can be performed in another stationary scan situation, e.g. with 3D-Scanner standing on table

Test reference: 3DFFTI_TC_1a

Test procedure:

1. 10 quadpod scans for each specimen material by one person in scan mode Quad

Expected results:



Nr.	Durchmesser / Breite	Tiefe / Höhe
A1	1.0	0.75
A2	0.8	0.6
A3	0.6	0.45
A4	0.5	0.38
A5	0.4	0.3
A6	0.35	0.26
A7	0.3	0.23
A8	0.275	0.21
A9	0.25	0.19
A10	0.225	0.17
A11	0.2	0.15
A12	0.18	0.14
A13	0.16	0.12
A14	0.14	0.11
A15	0.12	0.09
T	±0.005	±0.01

- The evaluation of the scans is performed by one independent user
- Colour coded height map after registration on a plane with folded palette
- One (experienced) examiner assesses the smallest visible structures
- The size of the structures is looked up from the technical drawing
- It is not the task to measure the size of the structures!
  - 3D resolution = Mean values of 3D resolution (for each materials and each structural element)
  - Repeatability = Measurement uncertainties of 3D resolution

Measurement uncertainty is given by confidence interval for p = 0.95

$\pm U = \pm t_\alpha * s$ — t_α is the Student-factor for 10 measurements (with p=0.95): 2.228
s is the standard deviation over 10 measurements

Test reference: **3DFFTI_TC_1a**

Results:

2.228 Student-factor for two-sided confidence interval 0.95 with 10 measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

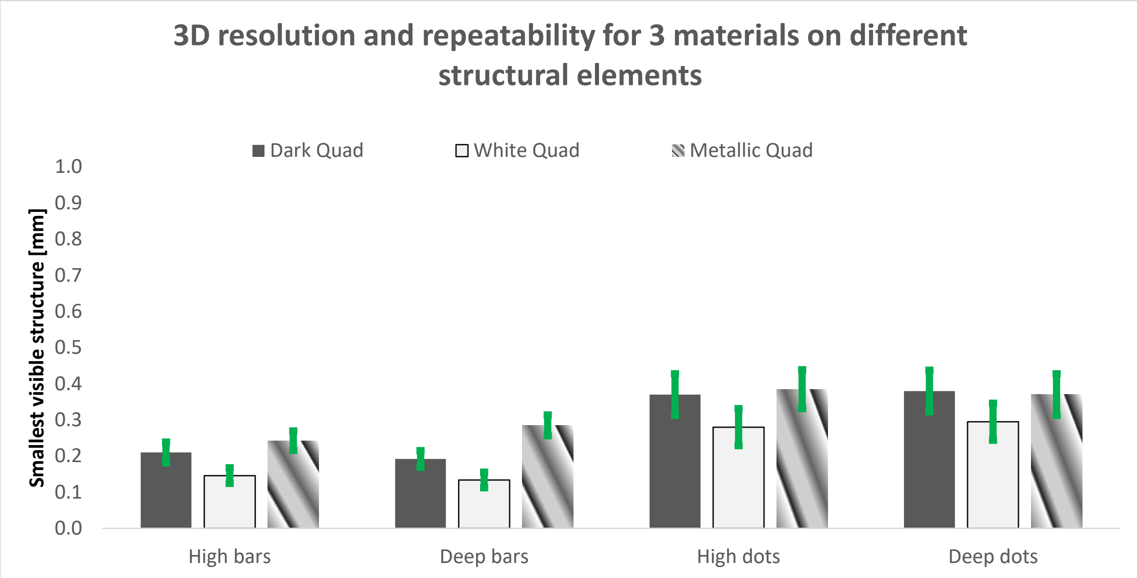
Rescor	*Smallest structure Quad [mm]*			
Scan-ID	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1486	0.200	0.180	0.350	0.400
1487	0.200	0.180	0.400	0.400
1488	0.225	0.200	0.350	0.350
1489	0.200	0.180	0.350	0.350
1490	0.225	0.200	0.350	0.400
1491	0.200	0.200	0.350	0.350
1492	0.225	0.200	0.400	0.350
1493	0.200	0.200	0.400	0.400
1494	0.225	0.200	0.350	0.400
1495	0.200	0.180	0.400	0.400
3D resolution MEAN [mm]	0.210	0.192	0.370	0.380
Repeatability UNC [mm]	0.029	0.023	0.058	0.058
3D resolution BEST [mm]	0.200	0.180	0.350	0.350
3D resolution WORST [mm]	0.225	0.200	0.400	0.400
Repeatability RANGE [mm]	0.025	0.020	0.050	0.050

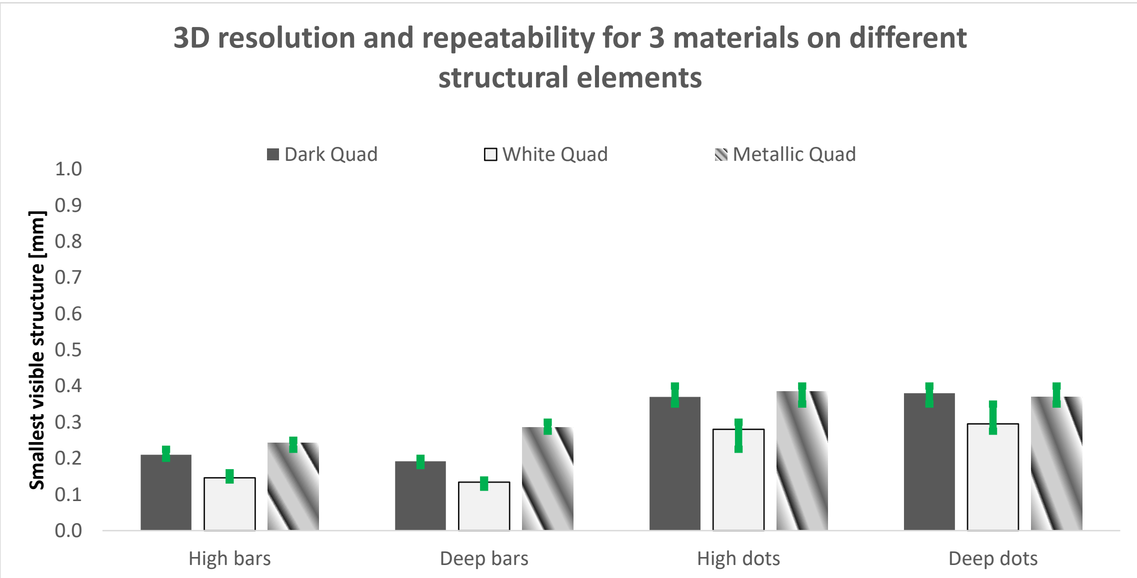
Macor	*Smallest structure Quad [mm]*			
Scan-ID	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1496	0.140	0.120	0.300	0.275
1497	0.160	0.140	0.225	0.275
1498	0.140	0.120	0.275	0.350
1499	0.160	0.140	0.300	0.300
1500	0.140	0.140	0.300	0.300
1501	0.140	0.140	0.275	0.300
1502	0.140	0.140	0.300	0.275
1503	0.160	0.140	0.275	0.300
1504	0.140	0.140	0.275	0.275
1505	0.140	0.120	0.275	0.300
3D resolution MEAN [mm]	0.146	0.134	0.280	0.295
Repeatability UNC [mm]	0.022	0.022	0.051	0.051
3D resolution BEST [mm]	0.140	0.120	0.225	0.275
3D resolution WORST [mm]	0.160	0.140	0.300	0.350
Repeatability RANGE [mm]	0.020	0.020	0.075	0.075

Aluminium	*Smallest structure Quad [mm]*			
Scan-ID	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1506	0.250	0.300	0.350	0.350
1507	0.250	0.275	0.400	0.350
1508	0.225	0.275	0.400	0.400
1509	0.250	0.275	0.400	0.350
1510	0.225	0.300	0.350	0.400
1511	0.250	0.300	0.350	0.400
1512	0.225	0.275	0.400	0.350
1513	0.250	0.275	0.400	0.350
1514	0.250	0.300	0.400	0.350
1515	0.250	0.275	0.400	0.400
3D resolution MEAN [mm]	0.243	0.285	0.385	0.370
Repeatability UNC [mm]	0.027	0.029	0.054	0.058
3D resolution BEST [mm]	0.225	0.275	0.350	0.350
3D resolution WORST [mm]	0.250	0.300	0.400	0.400
Repeatability RANGE [mm]	0.025	0.025	0.050	0.050

Test reference: **3DFFTI_TC_1a**

Conclusion and notes:

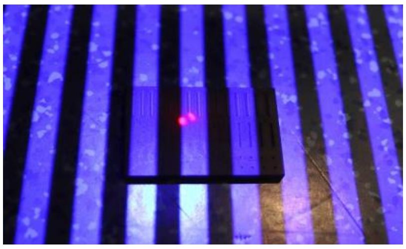




Test reference:	3DFFTI_TC_1aH				
Test name:	3D resolution and repeatability - influence of scan mode	Location:	IOF, Jena	Date:	21/02/2019
Tested requirements:	3D resolution and repeatability for different undergrounds, scan mode Hand				

Test set-up:

- 3D resolution specimens
  - in materials Rescor, Macor, Aluminium
  - in scan mode Hand
- grey matt material Rescor is used to determine the resolution under best conditions of the surface to be scanned
- white translucent Macor is used to determine the resolution under the limitation of a translucent surface (snow)
- metallic shiny Aluminium is used to determine the resolution under the limitation of a shiny / wet surface

Test assumptions, conditions & constraints:

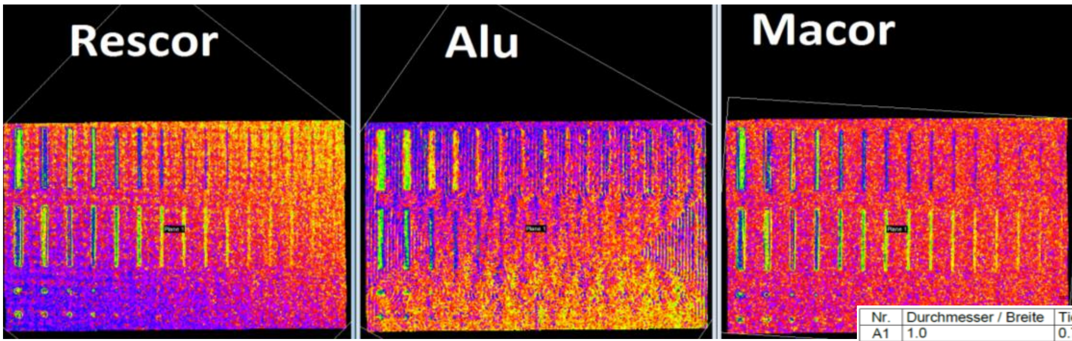
- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Specimen in center of FOV
- Scanner in perpendicular scan orientation
- Bars on specimen rotated vertical relative to baseline of stereocameras
- Exposure step 1
- LED brightness optimal for each specimen material
- External light <10,000 lux (indoor)

Test reference: **3DFFTI_TC_1aH**

Test procedure:

1. 10 handheld scans for each specimen material by one person in scan mode Hand

Expected results:



Nr.	Durchmesser / Breite	Tiefe / Höhe
A1	1.0	0.75
A2	0.8	0.6
A3	0.6	0.45
A4	0.5	0.38
A5	0.4	0.3
A6	0.35	0.26
A7	0.3	0.23
A8	0.275	0.21
A9	0.25	0.19
A10	0.225	0.17
A11	0.2	0.15
A12	0.18	0.14
A13	0.16	0.12
A14	0.14	0.11
A15	0.12	0.09
T	±0.005	±0.01

- The evaluation of the scans is performed by one independent user
- Colour coded height map after registration on a plane with folded palette
- One (experienced) examiner assesses the smallest visible structures
- The size of the structures is looked up from the technical drawing
- It is <u>not</u> the task to measure the size of the structures!
  - 3D resolution = Mean values of 3D resolution (for each materials and each structural element)
  - Repeatability = Measurement uncertainties of 3D resolution

Measurement uncertainty is given by confidence interval for $p = 0.95$

$\pm U = \pm t\alpha * s$ — $t\alpha$ is the Student-factor for 10 measurements (with p=0.95): 2.228
s is the standard deviation over 10 measurements

Test reference: 3DFFTI_TC_1aH

Results:

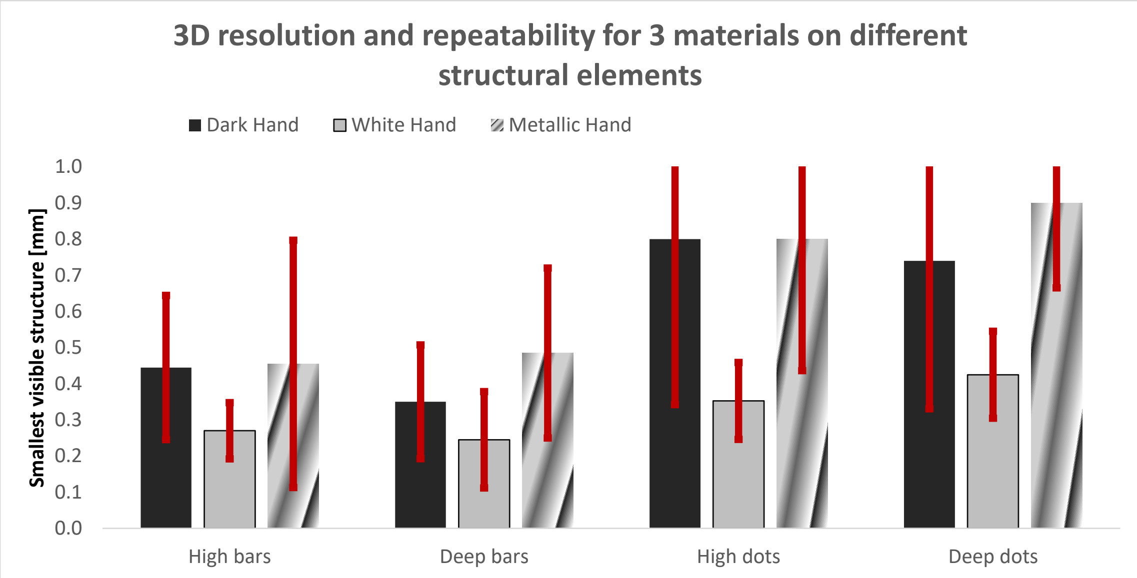
2.228 Student-factor for two-sided confidence interval 0.95 with 10 measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

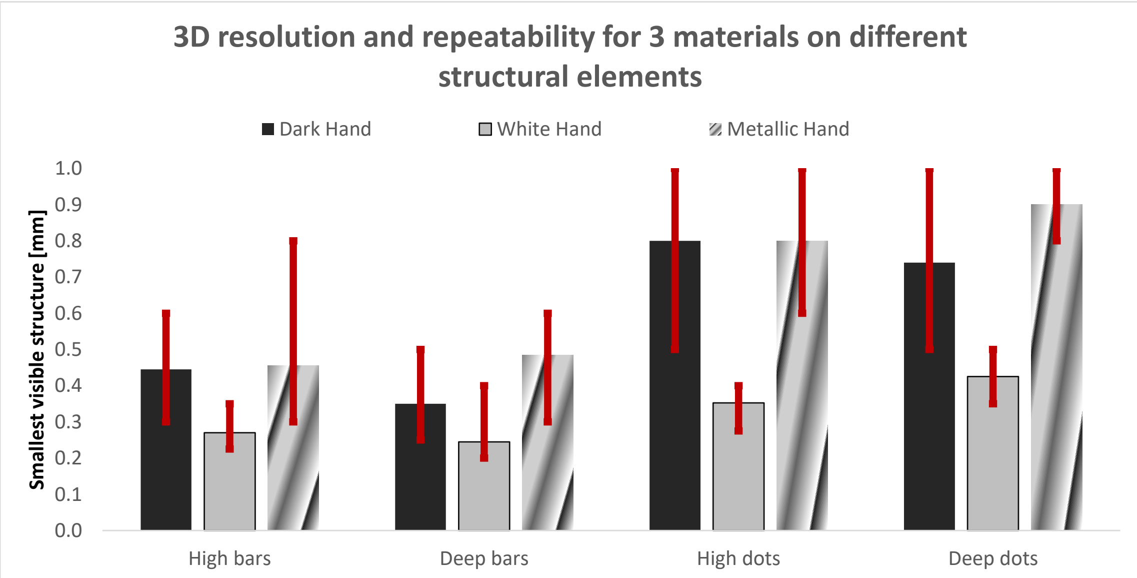
Rescor	*Smallest structure Hand [mm]*			
Scan-ID	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1275	0.500	0.500	1.000	0.800
1276	0.400	0.400	1.000	1.000
1535	0.300	0.300	0.500	0.500
1536	0.400	0.250	0.800	0.800
1537	0.350	0.350	0.800	0.600
1538	0.500	0.350	0.600	0.600
1539	0.500	0.300	0.800	0.800
1540	0.600	0.300	1.000	1.000
1541	0.400	0.350	1.000	0.800
1542	0.500	0.400	0.500	0.500
3D resolution MEAN [mm]	0.445	0.350	0.800	0.740
Repeatability UNC [mm]	0.200	0.158	0.458	0.409
3D resolution BEST [mm]	0.300	0.250	0.500	0.500
3D resolution WORST [mm]	0.600	0.500	1.000	1.000
Repeatability RANGE [mm]	0.300	0.250	0.500	0.500

Macor	*Smallest structure Hand [mm]*			
Scan-ID	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1543	0.225	0.200	0.300	0.400
1544	0.250	0.250	0.275	0.400
1545	0.250	0.200	0.400	0.400
1546	0.300	0.200	0.350	0.400
1547	0.275	0.275	0.350	0.350
1548	0.275	0.225	0.300	0.400
1549	0.250	0.250	0.400	0.500
1550	0.250	0.225	0.400	0.400
1551	0.350	0.400	0.350	0.500
1552	0.275	0.225	0.400	0.500
3D resolution MEAN [mm]	0.270	0.245	0.353	0.425
Repeatability UNC [mm]	0.078	0.133	0.106	0.120
3D resolution BEST [mm]	0.225	0.200	0.275	0.350
3D resolution WORST [mm]	0.350	0.400	0.400	0.500
Repeatability RANGE [mm]	0.125	0.200	0.125	0.150

Aluminium	*Smallest structure Hand [mm]*			
Scan-ID	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1553	0.500	0.600	1.000	1.000
1554	0.300	0.300	0.600	0.800
1555	0.600	0.600	0.800	0.800
1556	0.400	0.500	0.800	1.000
1557	0.300	0.350	0.600	1.000
1558	0.800	0.600	0.800	0.800
1559	0.350	0.400	0.600	1.000
1560	0.500	0.500	1.000	1.000
1561	0.400	0.500	0.800	0.800
1562	0.400	0.500	1.000	0.800
3D resolution MEAN [mm]	0.455	0.485	0.800	0.900
Repeatability UNC [mm]	0.342	0.235	0.364	0.235
3D resolution BEST [mm]	0.300	0.300	0.600	0.800
3D resolution WORST [mm]	0.800	0.600	1.000	1.000
Repeatability RANGE [mm]	0.500	0.300	0.400	0.200

Test reference:	3DFFTI_TC_1aH
Conclusion and notes:	





Test reference:	**3DFFTI_TC_1b**				
Test name:	3D resolution reproducibility	**Location:**	varying	**Date:**	varying
Tested requirements:	3D resolution of different underground materials, scan mode Quad, under influence of varying user and device				

Test set-up:

- 3D resolution specimens
    - in materials Rescor, Macor, Aluminium
    - Variation of users and device

- grey matt material Rescor is used to determine the resolution under best conditions of the surface to be scanned
- white translucent Macor is used to determine the resolution under the limitation of a translucent surface (snow)
- metallic shiny Aluminium is used to determine the resolution under the limitation of a shiny / wet surface

Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad

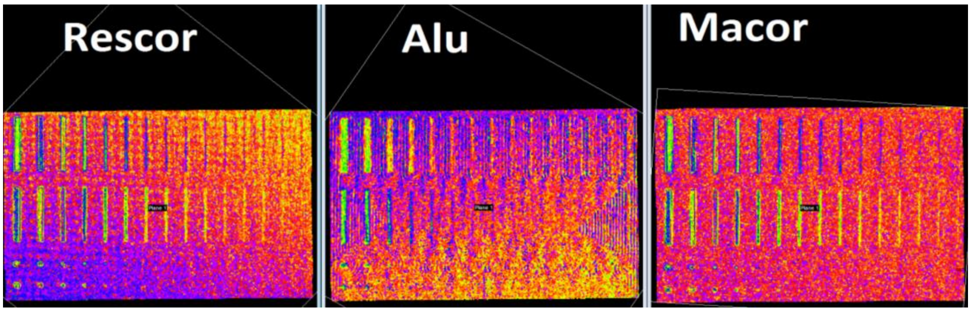
- Standard parameters: center FOV, NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C
- Scans are made in cooperation with EETG at different locations and different devices

Test procedure:

1. 3 scans per user of specimens Rescor, Macor and Aluminium in scan mode Quad

Test reference: 3DFFTI_TC_1b

Expected results:



example

- The evaluation of the scans is performed by one independent user
- Colour coded height map after registration on a plane with folded palette
- One examiner assesses the smallest visible structures of the high bars, deep bars, high dots, deep dots
- The size of the structures ("Durchmesser / Breite") is looked up from the technical drawing
- It is not the task to measure the size of the structures!
- A screenshot of the processed 3D view is saved
    - Reproducibility = Measurement uncertainty between repeated scans

Measurement uncertainty is given by confidence interval for p = 0.95

±U = ±tα * s   tα is the Student-factor for N measurements (with p=0.95)
s is the standard deviation over 10 measurements

Results:

2.228 Student-factor for confidence interval 0.95 with **10** measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

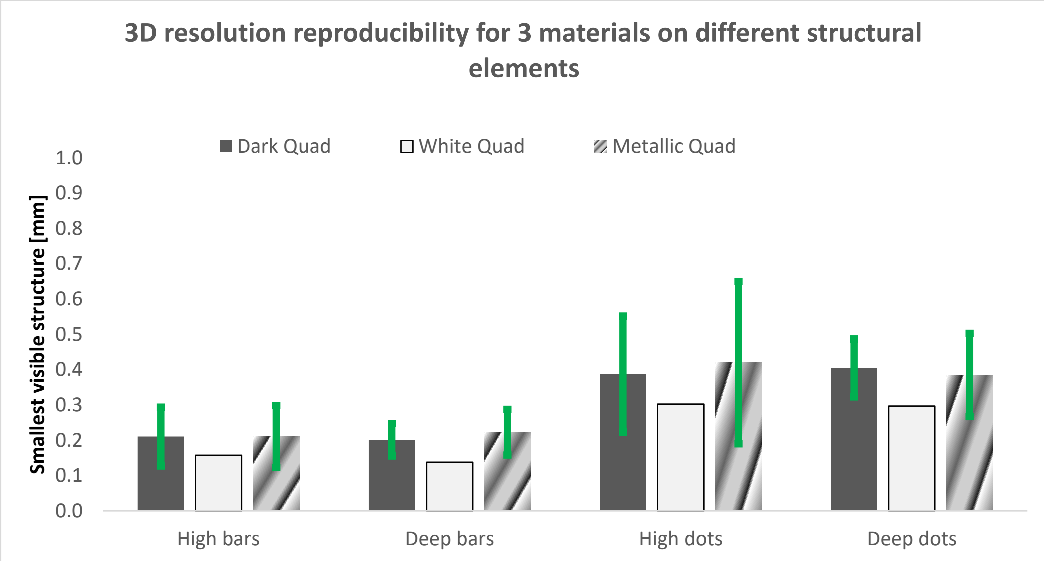
Rescor		*Settings*		*3D resolution Quad [mm]*			
Scan-ID	*User-ID*	*Device*	*Mode*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
742	IOF1	006	Quad	0.180	0.200	0.350	0.400
827	YHP1	006	Quad	0.225	0.225	0.400	0.400
839	YHP2	006	Quad	0.225	0.200	0.400	0.500
852	YHP3	006	Quad	0.225	0.200	0.500	0.400
93	LKASA1	007	Quad	0.225	0.200	0.350	0.400
107	LKASA2	007	Quad	0.140	0.200	0.300	0.350
120	LKASA3	007	Quad	0.160	0.180	0.275	0.400
68	LKAMV1	008	Quad	0.225	0.160	0.400	0.400
84	LKAMV2	008	Quad	0.250	0.225	0.400	0.400
90	LKAMV3	008	Quad	0.250	0.225	0.500	0.400
			3D resolution MEAN [mm]	0.211	0.202	0.388	0.405
			Reproducibilty UNC [mm]	0.083	0.046	0.165	0.082
			3D resolution BEST [mm]	0.140	0.160	0.275	0.350
			3D resolution WORST [mm]	0.250	0.225	0.500	0.500
			Reproducibilty RANGE [mm]	0.110	0.065	0.225	0.150

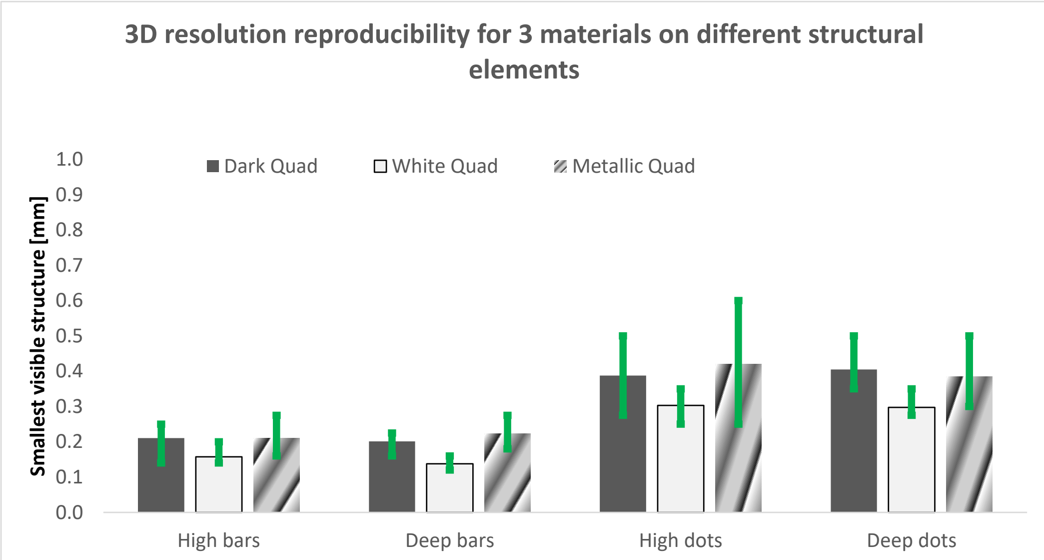
Test reference: 3DFFTI_TC_1b

Macor		*Settings*		*3D resolution Quad [mm]*			
Scan-ID	*User-ID*	*Device*	*Mode*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
743	IOF1	006	Quad	0.140	0.120	0.250	0.350
828	YHP1	006	Quad	0.140	0.120	0.350	0.275
840	YHP2	006	Quad	0.160	0.140	0.350	0.300
853	YHP3	006	Quad	0.180	0.160	0.350	0.300
94	LKASA1	007	Quad	0.140	0.120	0.300	0.275
108	LKASA2	007	Quad	0.140	0.120	0.300	0.275
121	LKASA3	007	Quad	0.140	0.140	0.300	0.275
69	LKAMV1	008	Quad	0.180	0.160	0.250	0.275
85	LKAMV2	008	Quad	0.200	0.160	0.275	0.350
			3D resolution MEAN [mm]	0.158	0.138	0.303	0.297
			Reproducibilty UNC [mm]	0.052	0.041	0.090	0.071
			3D resolution BEST [mm]	0.140	0.120	0.250	0.275
			3D resolution WORST [mm]	0.200	0.160	0.350	0.350
			Reproducibilty RANGE [mm]	0.060	0.040	0.100	0.075

Aluminium		*Settings*		*3D resolution Quad [mm]*			
Scan-ID	*User-ID*	*Device*	*Mode*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
744	IOF1	006	Quad	0.180	0.200	0.400	0.350
829	YHP1	006	Quad	0.275	0.250	0.600	0.500
841	YHP2	006	Quad	0.180	0.225	0.350	0.400
854	YHP3	006	Quad	0.225	0.200	0.500	0.400
95	LKASA1	007	Quad	0.180	0.225	0.350	0.350
109	LKASA2	007	Quad	0.180	0.200	0.350	0.300
122	LKASA3	007	Quad	0.160	0.180	0.250	0.400
70	LKAMV1	008	Quad	0.225	0.225	0.400	0.400
86	LKAMV2	008	Quad	0.250	0.250	0.500	0.350
92	LKAMV3	008	Quad	0.250	0.275	0.500	0.400
			3D resolution MEAN [mm]	0.211	0.223	0.420	0.385
			Reproducibilty UNC [mm]	0.088	0.065	0.230	0.118
			3D resolution BEST [mm]	0.160	0.180	0.250	0.300
			3D resolution WORST [mm]	0.275	0.275	0.600	0.500
			Reproducibilty RANGE [mm]	0.115	0.095	0.350	0.200

Test reference:	3DFFTI_TC_1b
Conclusion and notes:	





Test reference:	**3DFFTI_TC_1bH**				
Test name:	3D resolution reproducibility - influence of scan mode	**Location:**	varying	**Date:**	varying
Tested requirements:	3D resolution of different underground materials, scan mode Hand, under influence of varying user and device				

Test set-up:

- 3D resolution specimens
  - in materials Rescor, Macor, Aluminium
  - Variation of users and device

- grey matt material Rescor is used to determine the resolution under best conditions of the surface to be scanned
- white translucent Macor is used to determine the resolution under the limitation of a translucent surface (snow)
- metallic shiny Aluminium is used to determine the resolution under the limitation of a shiny / wet surface

Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Hand

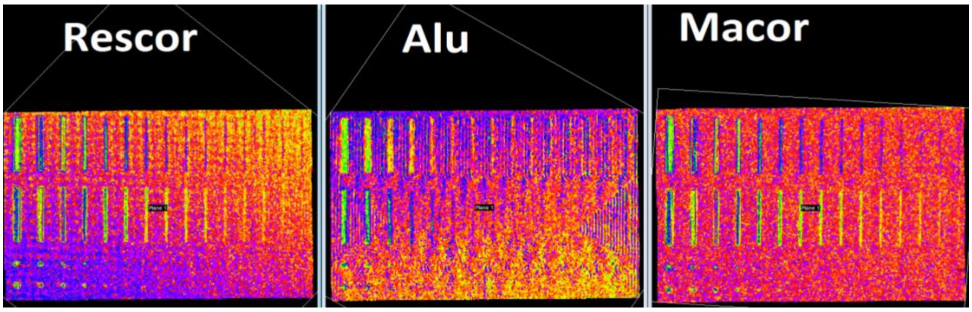
- Standard parameters: center FOV, NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C
- Scans are made in cooperation with EETG at different locations and different devices

Test procedure:

1. 3 scans per user of specimens Rescor, Macor and Aluminium in scan mode Hand

Test reference: **3DFFTI_TC_1bH**

Expected results:



example

- The evaluation of the scans is performed by one independent user
- Colour coded height map after registration on a plane with folded palette
- One examiner assesses the smallest visible structures of the high bars, deep bars, high dots, deep dots
- The size of the structures ("Durchmesser / Breite") is looked up from the technical drawing
- It is not the task to measure the size of the structures!
- A screenshot of the processed 3D view is saved
  - Reproducibility = Measurement uncertainty between repeated scans

Measurement uncertainty is given by confidence interval for p = 0.95

$\pm U = \pm t\alpha * s$ — $t\alpha$ is the Student-factor for N measurements (with p=0.95)
s is the standard deviation over 10 measurements

Results:

2.228 Student-factor for confidence interval 0.95 with **10** measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

Rescor		*Settings*		*3D resolution Hand [mm]*			
Scan-ID	*User-ID*	*Device*	*Mode*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
751	IOF1	006	Hand	0.350	0.350	0.600	0.800
832	YHP1	006	Hand	0.300	0.300	0.600	0.500
844	YHP2	006	Hand	0.400	0.500	0.600	0.600
857	YHP3	006	Hand	0.350	0.300	0.500	0.800
100	LKASA1	007	Hand	0.300	0.350	0.350	0.500
114	LKASA2	007	Hand	0.250	0.250	0.350	0.800
127	LKASA3	007	Hand	0.350	0.350	0.500	1.000
72	LKAMV1	008	Hand	0.300	0.300	0.500	0.600
79	LKAMV2	008	Hand	0.600	0.500	0.800	0.600
94	LKAMV3	008	Hand	0.500	0.600	0.800	0.800
727	CAR1	009	Hand	0.350	0.350	0.500	0.400
			3D resolution MEAN [mm]	0.368	0.377	0.555	0.673
			Reproducibilty UNC [mm]	0.224	0.241	0.332	0.400
			3D resolution BEST [mm]	0.250	0.250	0.350	0.400
			3D resolution WORST [mm]	0.600	0.600	0.800	1.000
			Reproducibilty RANGE [mm]	0.350	0.350	0.450	0.600

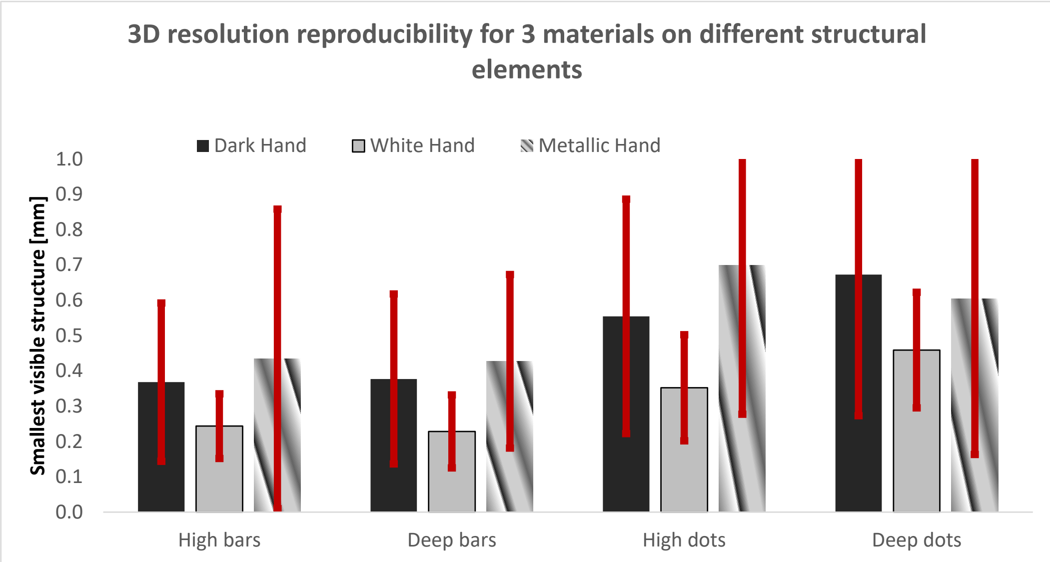
Test reference: 3DFFTI_TC_1bH

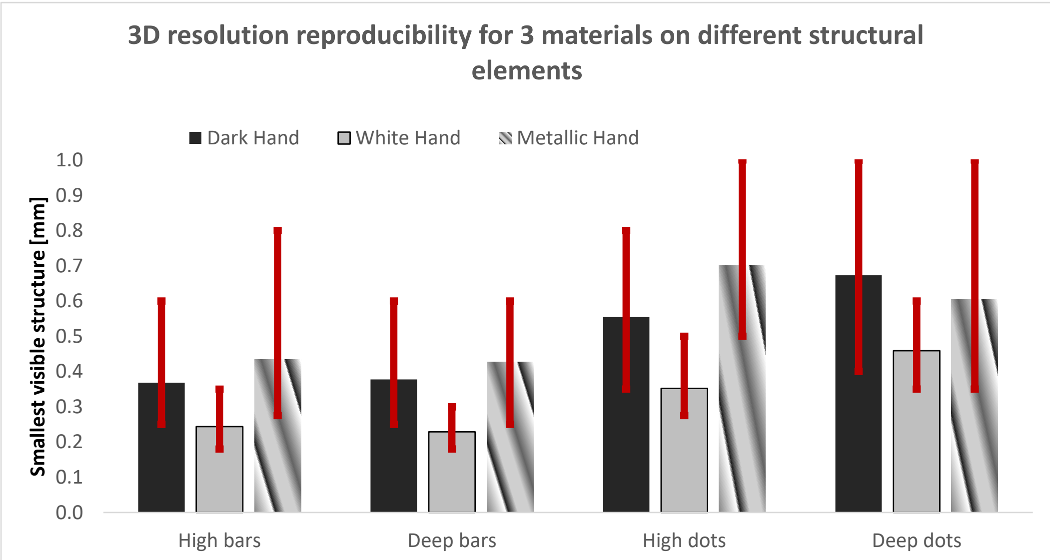
Macor		*Settings*		*3D resolution Hand [mm]*			
Scan-ID	*User-ID*	*Device*	*Mode*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
753	IOF1	006	Hand	0.225	0.250	0.300	0.500
833	YHP1	006	Hand	0.250	0.275	0.275	0.400
845	YHP2	006	Hand	0.250	0.225	0.300	0.500
858	YHP3	006	Hand	0.250	0.225	0.350	0.350
99	LKASA1	007	Hand	0.250	0.200	0.350	0.400
113	LKASA2	007	Hand	0.225	0.180	0.300	0.500
126	LKASA3	007	Hand	0.180	0.180	0.400	0.500
73	LKAMV1	008	Hand	0.250	0.200	0.400	0.500
80	LKAMV2	008	Hand	0.350	0.300	0.500	0.600
95	LKAMV3	008	Hand	0.225	0.300	0.300	0.400
728	CAR1	009	Hand	0.225	0.180	0.400	0.400
			3D resolution MEAN [mm]	0.244	0.229	0.352	0.459
			Reproducibilty UNC [mm]	0.092	0.103	0.150	0.164
			3D resolution MIN [mm]	0.180	0.180	0.275	0.350
			3D resolution MAX [mm]	0.350	0.300	0.500	0.600
			Reproducibilty RANGE [mm]	0.170	0.120	0.225	0.250

Aluminium		*Settings*		*3D resolution Hand [mm]*			
Scan-ID	*User-ID*	*Device*	*Mode*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
755	IOF1	006	Hand	0.300	0.350	0.500	0.400
834	YHP1	006	Hand	0.400	0.500	0.800	0.600
846	YHP2	006	Hand	0.500	0.500	0.500	0.600
859	YHP3	006	Hand	0.350	0.400	0.600	0.800
98	LKASA1	007	Hand	0.275	0.400	0.500	0.350
112	LKASA2	007	Hand	0.350	0.400	0.600	0.600
125	LKASA3	007	Hand	0.350	0.250	0.800	0.500
74	LKAMV1	008	Hand	0.300	0.350	0.600	0.800
81	LKAMV2	008	Hand	0.800	0.600	1.000	0.400
96	LKAMV3	008	Hand	0.800	0.600	1.000	1.000
729	CAR1	009	Hand	0.350	0.350	0.800	0.600
			3D resolution MEAN [mm]	0.434	0.427	0.700	0.605
			Reproducibilty UNC [mm]	0.424	0.246	0.423	0.441
			3D resolution BEST [mm]	0.275	0.250	0.500	0.350
			3D resolution WORST [mm]	0.800	0.600	1.000	1.000
			Reproducibilty RANGE [mm]	0.525	0.350	0.500	0.650

Test reference: 3DFFTI_TC_1bH

Conclusion and notes:





Test reference:	**3DFFTI_TC_1c d e f**				
Test name:	3D resolution robustness	**Location:**	IOF, Jena	**Date:**	21/02/2019
Tested requirements:	3D resolution robustness against small variations in parameters				

Test set-up:

- 3D resolution specimen Rescor material (dark matt) in scan mode Quad
- Variation of certain parameters which can vary between scans are only under limited control by the device or user:

c) Distance to 3D Scanner
d1) Position in field of view
d2) Tilt relative to 3D Scanner
d3) Orientation relative to 3D Scanner
e) Temperature
f) Sunlight

- Robustness is slightly covered also in handheld Repeatability and Reproducibility

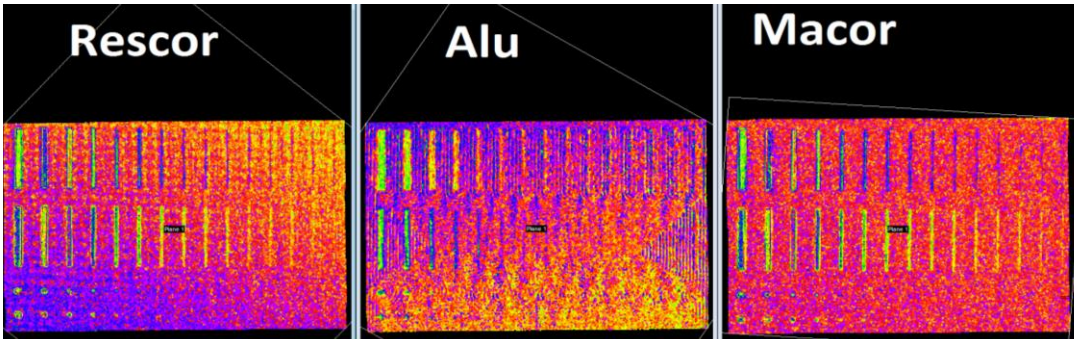
Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad
- Usage of quadpod
- Standard parameters: center FOV, NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C

Test procedure:

1. Scans in Distances (NWD - 50 mm, NWD - 25 mm, NWD, NWD + 25 mm, NWD + 50 mm), others standard parameters
2. Scans in center and corner of FOV, tilted position, horizontal and vertical orientation, other standard parameters
3. Scans under varying temperature (-10…+40°C), others standard parameters
4. Scans under varying sunlight (measure sunlight intensity with Luxmeter), others standard parameters

Expected results:



- The evaluation of the scans is performed by one independent user
- Colour coded height map after registration on a plane with folded palette
- One examiner assesses the smallest visible structures of the high bars, deep bars, high dots, deep dots
- The size of the structures is looked up from the technical drawing
- It is <u>not</u> the task to measure the size of the structures!
- 3D resolution is independent from small variations of position, orientation, rotation, temperature
- 3D resolution decreases with increasing working distance
- 3D resolution is not possible to evaluate over a certain threshold of external sunlight (sun shielding required)

Test reference: **3DFFTI_TC_1c d e f**

Results:

Rescor		*Smallest structure Quad [mm]*			
Scan-ID	*Distance [mm]*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1565	-50	0.160	0.140	0.350	0.350
1566	-25	0.225	0.180	0.400	0.400
1567	0	0.225	0.225	0.400	0.400
1568	25	0.300	0.275	0.500	0.400
1569	50	0.500	0.400	0.600	0.600

Systematic: - Resolution is worse with increasing distance
- But field of view as well

Rescor		*Smallest structure Quad [mm]*			
Scan-ID	*Position*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1567	*Center*	0.225	0.225	0.400	0.400
1571	*Corner LB*	0.225	0.250	0.500	0.400
1570	*Corner RB*	0.300	0.300	0.500	0.500
1572	*Corner LT*	0.250	0.275	0.350	0.400
1573	*Corner RT*	0.350	0.275	0.500	0.400

Systematic: - Slightly reduced resolution in right corners

Rescor		*Smallest structure Quad [mm]*			
Scan-ID	*Tilt*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
1567	*No tilt*	0.225	0.225	0.400	0.400
1574	*horizontal 1*	0.225	0.225	0.400	0.400
1575	*horizontal 2*	0.225	0.225	0.350	0.400
1576	*vertical 1*	0.250	0.275	0.400	0.500
1577	*vertical 2*	0.200	0.250	0.400	0.500

Systematic: - No significant influence

Rescor		*Smallest structure Quad [mm]*			
Scan-ID	*Orientation*	*High bars*	*Deep bars*	*High dots*	*Deep dots*
928	*Vertical*	0.225	0.250	0.500	0.600
929	*Vertical*	0.225	0.225	0.500	0.500
930	*Vertical*	0.225	0.225	0.500	0.500
	Orientation vertical	*0.225*	*0.233*	*0.500*	*0.533*
931	*Horizontal*	0.225	0.275	0.500	0.500
932	*Horizontal*	0.250	0.250	0.500	0.500
933	*Horizontal*	0.250	0.250	0.400	0.500
	Orientation horizontal	*0.242*	*0.258*	*0.467*	*0.500*

Systematic: - No significant influence

Test reference: 3DFFTI_TC_1c d e f

Sunlight intensity was measured with a Luxmeter "digilux 9500" from optronik

Rescor		*Smallest structure Quad [mm]*				
Scan-ID	*Sunlight [lx]*	*High bars*	*Deep bars*	*High dots*	*Deep dots*	
955	*750*	0.180	0.180	0.350	0.400	
956	*750*	0.225	0.200	0.400	0.500	
935	*5400*	0.200	0.200	0.400	0.400	
936	*5400*	0.180	0.180	0.400	0.500	
940	*21000*	0.180	0.200	0.400	0.400	
941	*21000*	0.200	0.200	0.500	0.400	
946	*28000*	0.200	0.200	0.400	0.400	
947	*28000*	0.225	0.225	0.400	0.350	
960	*41000*	0.225	0.225	0.400	0.500	laser pointers not visible
967	*48000*	0.250	0.250	0.500	0.400	
968	*48000*	0.250	0.250	0.500	0.500	
974	*60000*	0.600	0.600	1.000	1.000	very hard to find ap-
975	*60000*	0.400	0.500	0.800	0.600	propriate light settings
983	*73000*					bad light setting
984	*73000*					bad light setting
985	*73000*	0.300	0.300	0.600	0.500	
986	*85000*					bad light setting
987	*85000*	0.800	1.000			

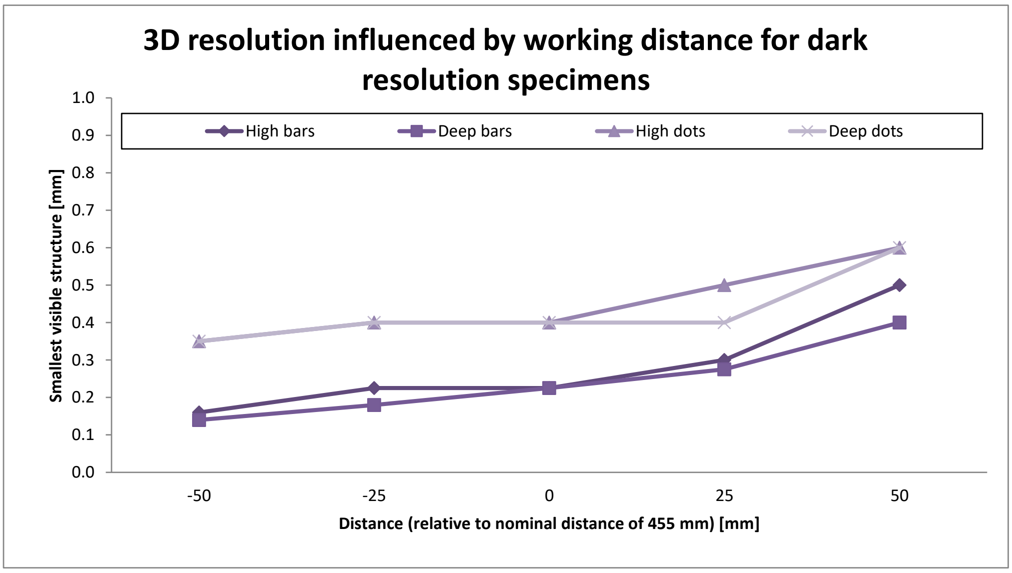
Systematic:

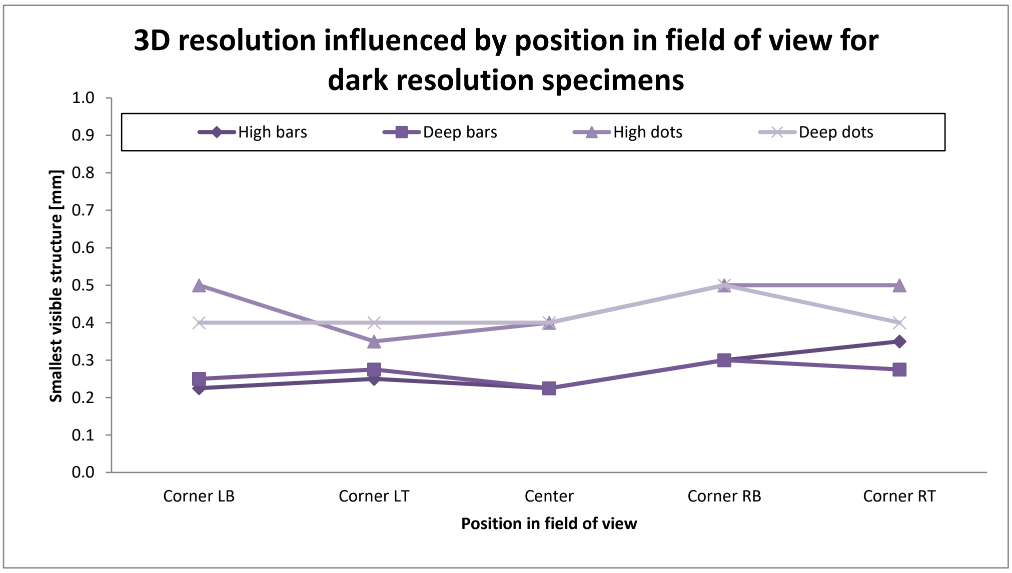
Temperature was measured with a thermometer "tpm-30" from BASEtech

Rescor		*Smallest structure Quad [mm]*					
Scan-ID	*Temperature [°C]*	*High bars*	*Deep bars*	*High dots*	*Deep dots*		
1437	*-2.5*	0.180	0.180	0.350	0.300	ca. 2,500 lx	outdoors
1438	*-2.5*	0.200	0.160	0.350	0.350	ca. 2,500 lx	outdoors
1439	*-2.5*	0.180	0.160	0.300	0.350	ca. 2,500 lx	outdoors
925	*3.3*	0.225	0.225	0.400	0.500	ca. 2,500 lx	outdoors
926	*3.3*	0.250	0.225	0.400	0.500	ca. 2,500 lx	outdoors
992	*6.7*	0.250	0.250	0.500	0.500		
993	*6.7*	0.225	0.225	0.500	0.400		
1046	*13.2*	0.225	0.250	0.400	0.350		
1047	*13.2*	0.200	0.200	0.400	0.400		
1567	*23.0*	0.225	0.225	0.400	0.400		
935	*23.0*	0.200	0.200	0.400	0.400		
936	*23.0*	0.180	0.180	0.400	0.500		
955	*26.5*	0.180	0.180	0.350	0.400		
956	*26.5*	0.225	0.200	0.400	0.500		
978	*31.0*	0.180	0.180	0.350	0.400		
979	*31.0*	0.180	0.180	0.350	0.400		

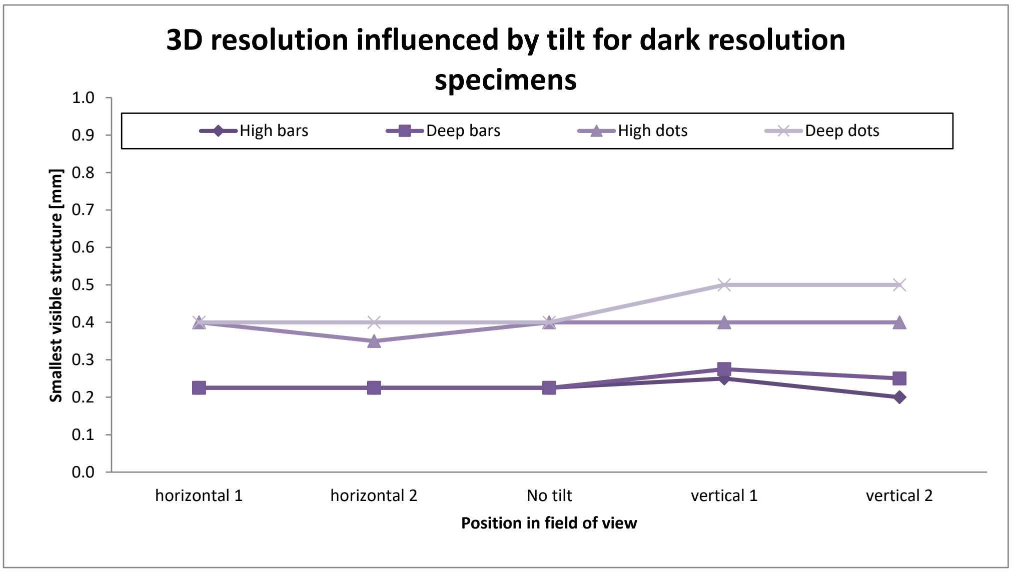
Systematic:

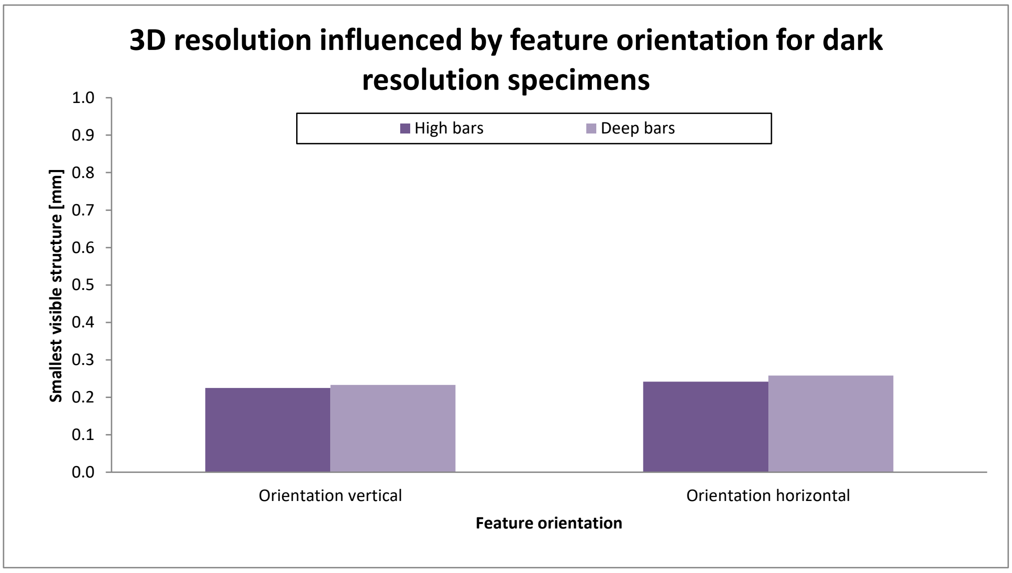
Test reference:	3DFFTI_TC_1c d e f
Conclusion and notes:	



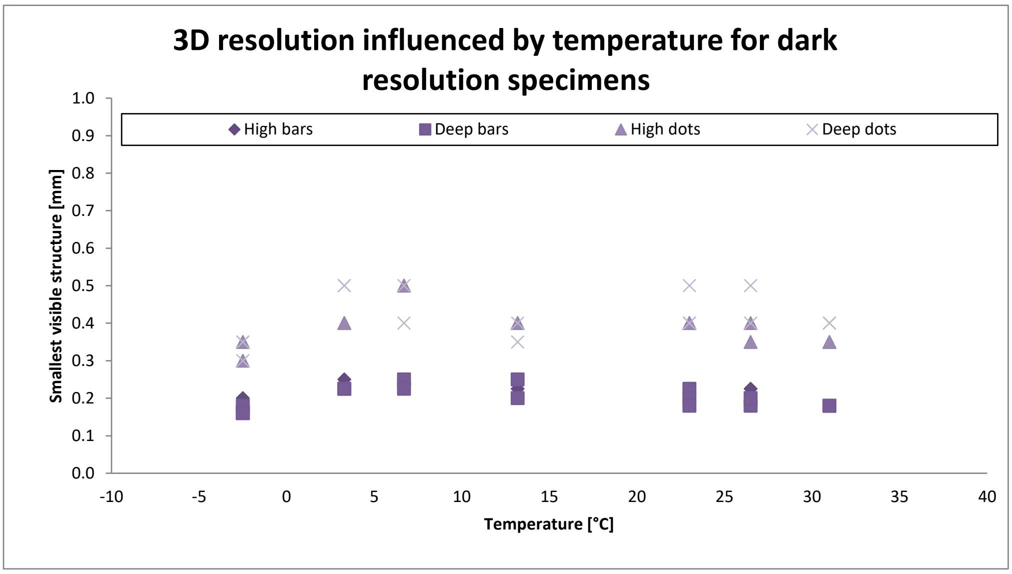


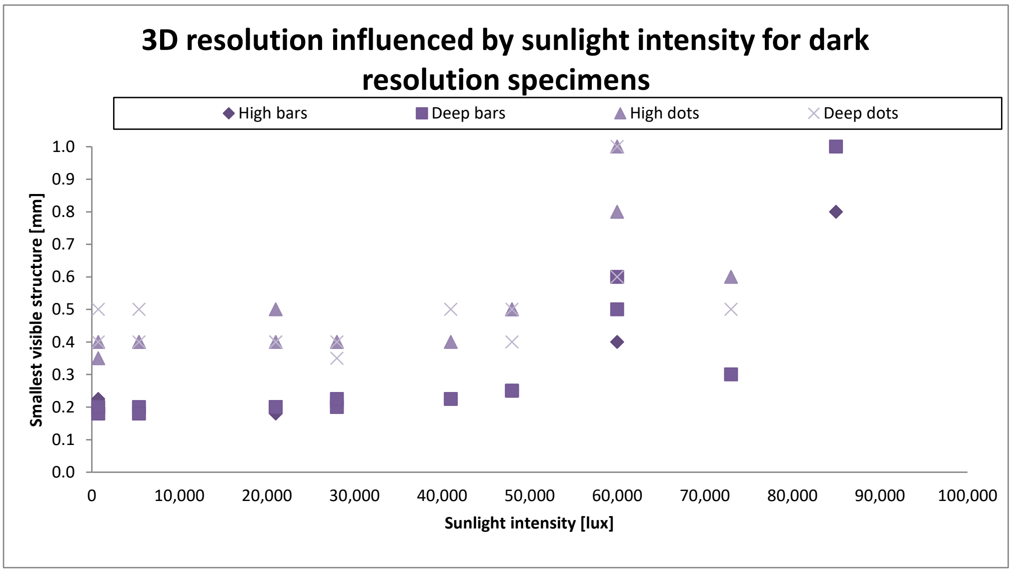
Test reference:	3DFFTI_TC_1c d e f





Test reference: 3DFFTI_TC_1c d e f

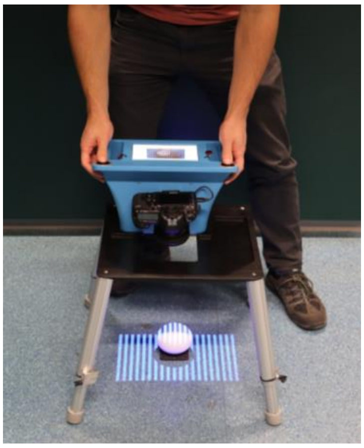


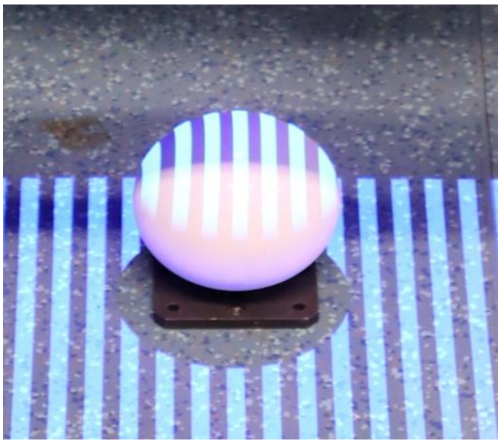


Test reference:	**3DFFTI_TC_2**				
Test name:	Range of inclination angle	**Location:**	IOF, Jena	**Date:**	21/02/2018
Tested requirements:	Range of inclination angle				

Test set-up:

- Sphere normal (Diameter 80mm)





Test assumptions, conditions & constraints:

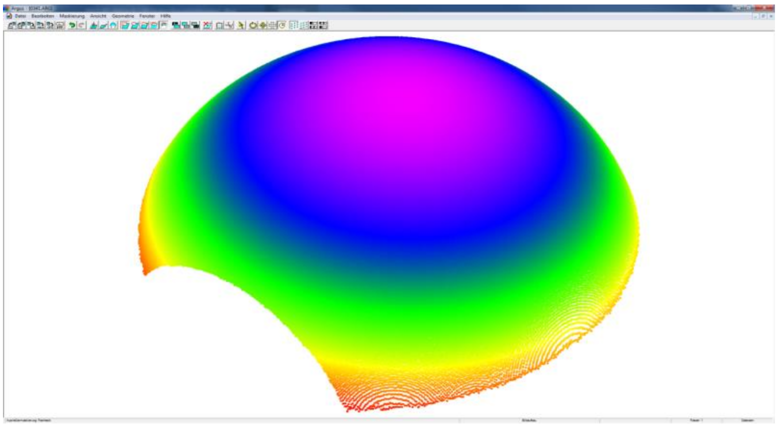
- FOV – Field of view (325 x 200 mm²)
- NWD - Nominal working distance (455 mm)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad
- External light <10,000 lux (indoor)
- Scans with quadpod can be performed in another stationary scan situation, e.g. with 3D-Scanner on table
- Specimen in center of FOW, at NWD, Scanner in perpendicular scan orientation

Test procedure:

1. 1 quadpod scan: Center of FOV, NWD, perpendicular scan orientation in scan mode Quad

Test reference: **3DFFTI_TC_2**

Expected results:



- Range of inclination angle = Maximal inclination angle which can be captured

Results:

Range of inclination angle

Scan-ID	*Angle [°]*
1482	65.440

View of the sphere surface in sphere coordinate system

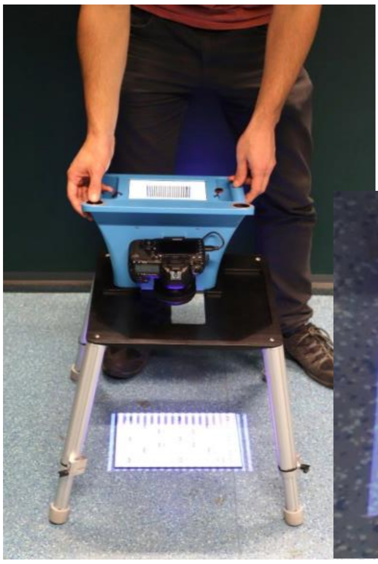
Conclusion and notes:

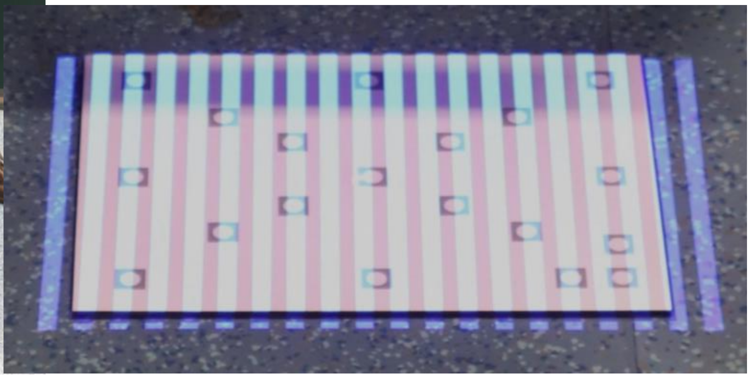
Range of inclination angle ≥ 65.440 °

Test reference:	**3DFFTI_TC_3a**					
Test name:	3D accuracy, colour mapping accuracy and corresponding repeatabilities	**Locatio**	IOF, Jena		**Date:**	20/02/2018
Tested requirements:	3D accuracy, colour mapping accuracy and corresponding repeatabilities, scan mode Quad					

Test set-up:

- Circle board





Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad
- External light <10,000 lux (indoor)
- Scans with quadpod can be performed in another stationary scan situation, e.g. with 3D-Scanner on table
- Specimen in center of FOW, at NWD, Scanner in perpendicular scan orientation

Test procedure:

1. 10 quadpod scans + photo by one person in scan mode Quad

Test reference: **3DFFTI_TC_3a**

Expected results:

- Exported .csv files with deviation between measured and calibrated circles positions
- Exported .csv files with deviations between 3D coordinates of circle positions and their photo position

- The circle no. 11 is taken as reference location, thus its deviation is 0

- 3D accuracy length measurement error = Mean values over all circle position deviations
- Repeatability 3D accuracy length measurement error = Measurement uncertainties circle positions
- 3D accuracy probing error = Standard deviation from plane in an area of ca. 40x40 mm²
- Repeatability 3D accuracy probing error =Stability of standard deviation in an area of ca. 40x40 mm²
- Colour mapping accuracy = Mean values of alignment deviations of cirlce centers
- Repeatability colour mapping accuracy = Measurement uncertainties alignment deviations of circle centers

Results:

1.960 Confidence-factor for two-sided confidence interval 0.95

	Quadpod		
	Scan-ID	*3D accuracy LME [mm]*	*3D accuracy FOV variance [mm]*
	1351	0.026	0.058
	1352	0.026	0.056
	1353	0.028	0.055
	1354	0.025	0.060
	1355	0.028	0.059
	1356	0.028	0.060
	1357	0.026	0.057
	1358	0.027	0.057
	1359	0.026	0.056
	1360	0.029	0.060
3D accuracy LME MEAN [mm]		0.027	
Repeatability LME UNC [mm]		0.008	
Robustness LME FOV MEAN [mm]			0.057
Robustness LME FOV WORST [mm]			0.069

	Quad	
	Scan-ID	*3D accuracy PE [mm]*
	1351	0.035
	1352	0.035
	1353	0.035
	1354	0.035
	1355	0.035
	1356	0.035
	1357	0.035
	1358	0.035
	1359	0.035
	1360	0.035
3D accuracy PE MEAN [mm]		0.035
Repeatability PE UNC [mm]		0.000

Test reference: **3DFFTI_TC_3a**

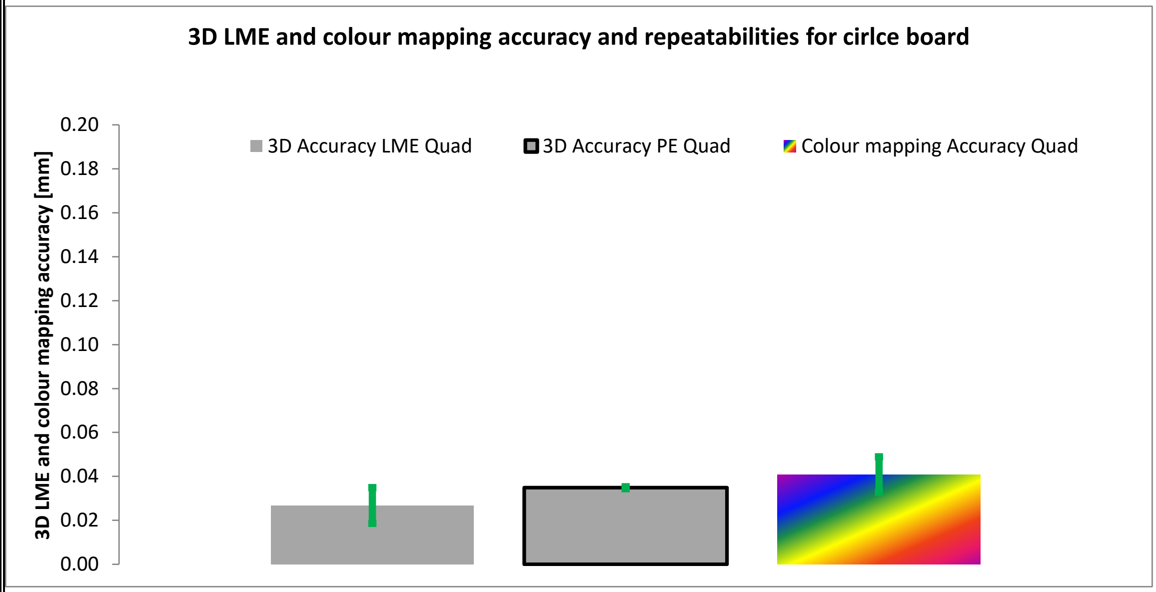
5D Mark IV 50mm **1px=** 0.05 mm

Quad

Scan-ID	*Colour mapping accuracy [px]*	*Colour mapping accuracy [mm]*	*Colour mapping accuracy FOV variance [px]*	*Colour mapping accuracy FOV variance [mm]*
1351	0.795	0.040	0.807	0.040
1352	0.802	0.040	0.832	0.042
1353	0.861	0.043	0.951	0.048
1354	0.802	0.040	0.783	0.039
1355	0.815	0.041	0.857	0.043
1356	0.798	0.040	0.919	0.046
1357	0.826	0.041	0.843	0.042
1358	0.819	0.041	0.894	0.045
1359	0.824	0.041	0.858	0.043
1360	0.822	0.041	0.864	0.043

Colour mapping accuracy MEAN [px,mm]	0.816	0.041		
Repeatability UNC [px,mm]	0.162	0.008		
Robustness Colour Mapping FOV MEAN [px,mm]			0.842	0.042
Robustness Colour Mapping FOV WORST [px,mm]			3.494	0.175

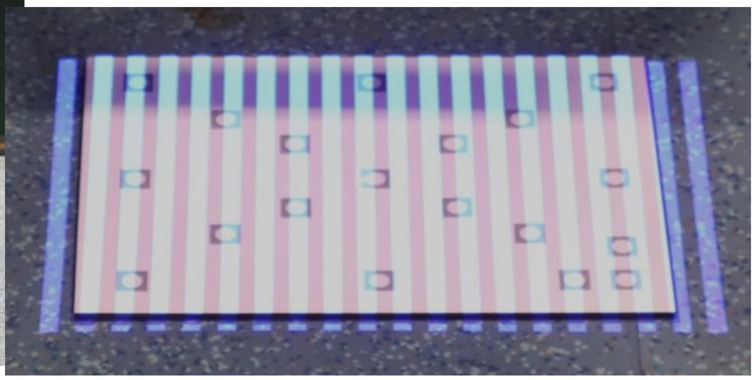
Test reference:	3DFFTI_TC_3a
Conclusion and notes:	



Test reference:	**3DFFTI_TC_3aH**				
Test name:	3D accuracy, colour mapping accuracy and corresponding repeatabilities - influence of scan mode	**Location:**	IOF, Jena	**Date:**	20/02/2018
Tested requirements:	3D accuracy, colour mapping accuracy and corresponding repeatabilities, scan mode Hand				

Test set-up:

- Circle board



Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Hand
- External light <10,000 lux (indoor)
- Specimen in center of FOW, at NWD, Scanner in perpendicular scan orientation

Test procedure:

1. 10 handheld scans + photo by one person in scan mode Hand

Test reference: **3DFFTI_TC_3aH**

Expected results:

- Exported .csv files with deviation between measured and calibrated circles positions
- Exported .csv files with deviations between 3D coordinates of circle positions and their photo position

- The circle no. 11 is taken as reference location, thus its deviation is 0

- 3D accuracy length measurement error = Mean values over all circle position deviations
- Repeatability 3D accuracy length measurement error = Measurement uncertainties circle positions
- 3D accuracy probing error = Standard deviation from plane in an area of ca. 40x40 mm²
- Repeatability 3D accuracy probing error =Stability of standard deviation in an area of ca. 40x40 mm²
- Colour mapping accuracy = Mean values of alignment deviations of cirlce centers
- Repeatability colour mapping accuracy = Measurement uncertainties alignment deviations of circle centers

Results:

1.960 Confidence-factor for two-sided confidence interval 0.95

	Hand		
	Scan-ID	*3D accuracy LME [mm]*	*3D accuracy FOV variance [mm]*
	1361	0.040	0.097
	1362	0.040	0.099
	1364	0.042	0.105
	1365	0.040	0.109
	1368	0.042	0.106
	1369	0.040	0.099
	1370	0.043	0.110
	1371	0.039	0.097
	1372	0.044	0.110
	1373	0.044	0.109
3D accuracy LME MEAN [mm]		0.041	
Repeatability LME UNC [mm]		0.015	
Robustness LME FOV MEAN [mm]			0.102
Robustness LME FOV WORST [mm]			0.158

	Hand	
	Scan-ID	*3D accuracy PE [mm]*
	1361	0.066
	1362	0.067
	1364	0.065
	1365	0.073
	1368	0.064
	1369	0.068
	1370	0.066
	1371	0.066
	1372	0.067
	1373	0.069
3D accuracy PE MEAN [mm]		0.067
Repeatability PE UNC [mm]		0.005

Test reference: 3DFFTI_TC_3aH

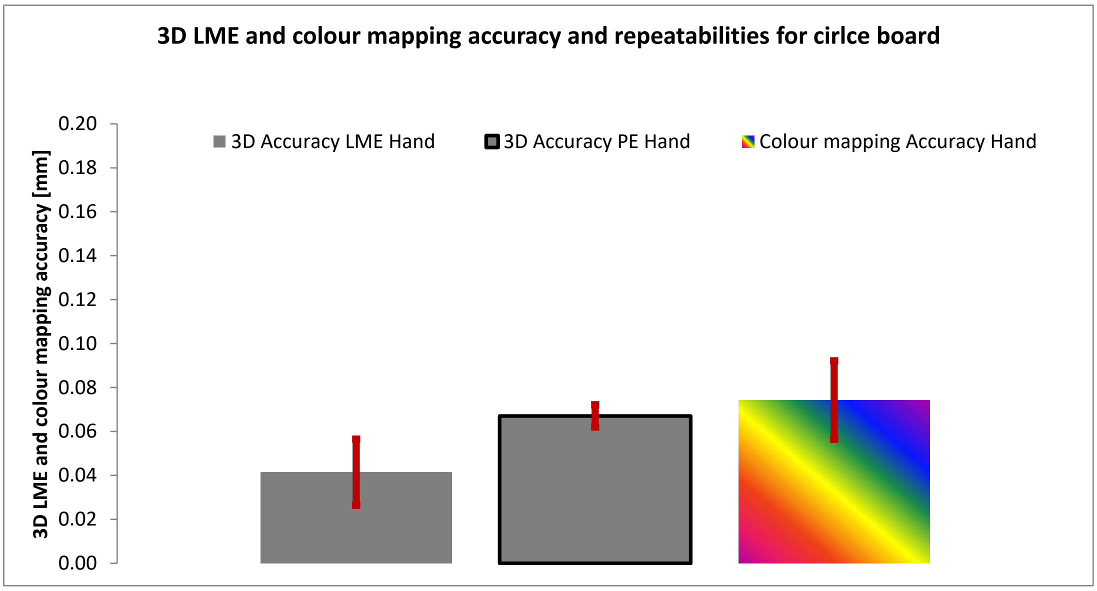
5D Mark IV 50mm **1px=** 0.05 mm

Hand

Scan-ID	*Colour mapping accuracy [px]*	*Colour mapping accuracy [mm]*	*Colour mapping accuracy FOV variance [px]*	*Colour mapping accuracy FOV variance [mm]*
1361	1.436	0.072	1.531	0.077
1362	1.372	0.069	1.495	0.075
1364	1.619	0.081	1.413	0.071
1365	1.228	0.061	1.348	0.067
1368	1.342	0.067	1.192	0.060
1369	1.464	0.073	1.432	0.072
1370	1.437	0.072	1.351	0.068
1371	1.590	0.079	1.732	0.087
1372	1.530	0.076	1.543	0.077
1373	1.842	0.092	1.909	0.095

Colour mapping accuracy MEAN [px,mm]	1.486	0.074		
Repeatability UNC [px,mm]	0.357	0.018		
Robustness Colour Mapping FOV MEAN [px,mm]			1.505	0.075
Robustness Colour Mapping FOV WORST [px,mm]			6.558	0.328

Test reference:	3DFFTI_TC_3aH
Conclusion and notes:	



Test reference:	**3DFFTI_TC_3b**				
Test name:	Reproducibilty of 3D accuracy and colour mapping accuracy	**Location:**	varying	**Date:**	varying
Tested requirements:	Reproducibilty of 3D accuracy and colour mapping accuracy, scan mode Quad				

Test set-up:

- Circle board

Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad
- External light <10,000 lux (indoor)
- Standard parameters: center FOV, NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C
- Scans are made in cooperation with EETG at different locations and each EETG member with different device

Test procedure:

1. 1 scan + photo per user wiht others standard parameters in scan mode Quad

Expected results:

- Exported .csv files with deviation between measured and calibrated circles positions
- Exported .csv files with deviations between 3D coordinates of circle positions and their photo position

- The circle no. 11 is taken as reference location, thus its deviation is 0

- Reproducibility 3D accuracy length measurment error = Standard deviation between repeated scans
- Reproducibility 3D accuracy probing error = Standard deviation between repeated scans
- Reproducibility colour mapping accuracy = Standard deviation between repeated scans

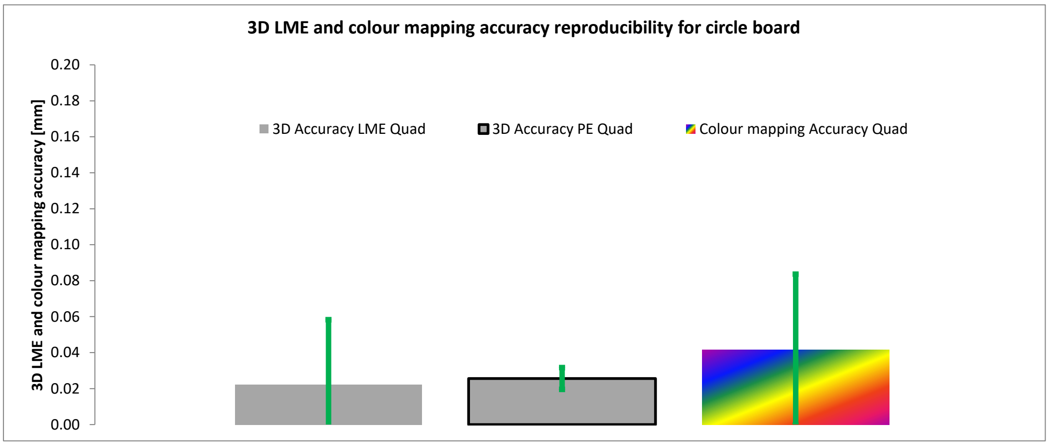
Test reference: **3DFFTI_TC_3b**

Results:

1.960 Confidence-factor for two-sided confidence interval 0.95

Settings				*Accuracy Quad*					
Scan-ID	*User-ID*	*Device*	*Mode*	*3D accuracy LME [mm]*	*3D accuracy LME variance FOV [mm]*	*3D accuracy PE [mm]*	*Colour mapping accuracy [px]*	*Colour mapping accuracy [mm]*	
761	IOF1	006	Quad	0.020	0.051	0.020	0.422	0.032	EOS100D 28mm
825	YHP1	006	Quad	0.014	0.038	0.027	0.415	0.031	1px = 0.075mm
837	YHP2	006	Quad	0.016	0.039	0.024	0.370	0.028	EOS100D 28mm
850	YHP3	006	Quad	0.015	0.040	0.028	0.387	0.029	1px = 0.075mm
92	LKASA1	007	Quad	0.021	0.049	0.023	1.368	0.068	5D Mark IV 50mm
106	LKASA2	007	Quad	0.019	0.049	0.026	1.321	0.066	1px = 0.05mm
119	LKASA3	007	Quad	0.021	0.048	0.027	1.294	0.065	
67	LKAMV1	008	Quad	0.021	0.048	0.026	0.495	0.035	EOS200D 28mm
83	LKAMV2	008	Quad	0.037	0.078	0.025	0.440	0.031	1px = 0.07mm
89	LKAMV3	008	Quad	0.038	0.085	0.031	0.460	0.032	
									5D Mark IV 50mm
									1px = 0.05mm
3D accuracy LME MEAN | Colour mapping accuracy MEAN [mm]				0.022		0.026		0.042	
Reproducibility UNC [mm]				0.036		0.006		0.042	

Test reference:	3DFFTI_TC_3b
Conclusion and notes:	



Test reference:	3DFFTI_TC_3bH				
Test name:	Reproducibilty of 3D accuracy and colour mapping accuracy - influence of scan mode	Location:	varying	Date:	varying
Tested requirements:	Reproducibilty of 3D accuracy and colour mapping accuracy, scan mode Hand				

Test set-up:

- Circle board

Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Hand
- External light <10,000 lux (indoor)
- Standard parameters: center FOV, NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C
- Scans are made in cooperation with EETG at different locations and each EETG member with different device

Test procedure:

1. 1 scan + photo per user wiht others standard parameters in scan mode Hand

Expected results:

- Exported .csv files with deviation between measured and calibrated circles positions
- Exported .csv files with deviations between 3D coordinates of circle positions and their photo position

- The circle no. 11 is taken as reference location, thus its deviation is 0

- Reproducibility 3D accuracy length measurment error = Standard deviation between repeated scans
- Reproducibility 3D accuracy probing error = Standard deviation between repeated scans
- Reproducibility colour mapping accuracy = Standard deviation between repeated scans

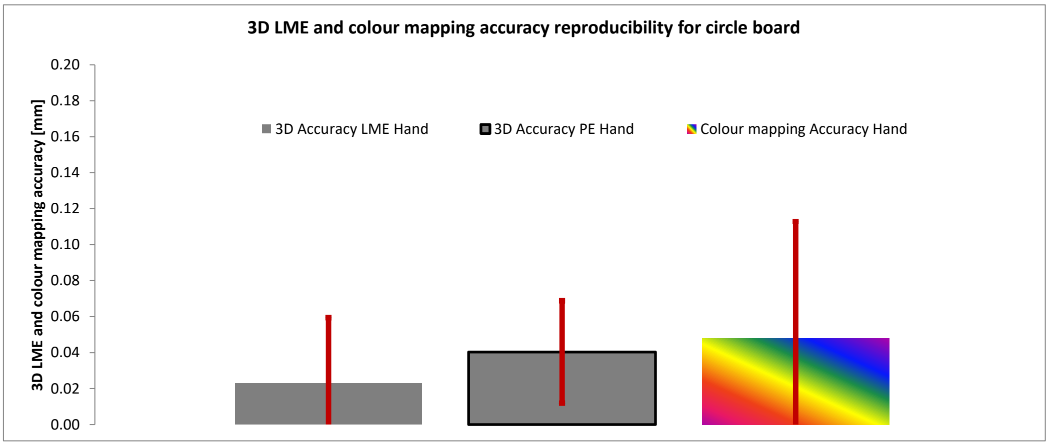
Test reference: **3DFFTI_TC_3bH**

Results:

1.960 Confidence-factor for two-sided confidence interval 0.95

Settings				*Accuracy Hand*					
Scan-ID	*User-ID*	*Device*	*Mode*	*3D accuracy LME [mm]*	*3D accuracy LME variance FOV [mm]*	*3D accuracy PE [mm]*	*Colour mapping accuracy [px]*	*Colour mapping accuracy [mm]*	
772	IOF1	006	Hand	0.020	0.042	0.021	0.350	0.026	
830	YHP1	006	Hand	0.014	0.037	0.032	0.444	0.033	EOS100D 28mm
842	YHP2	006	Hand	0.013	0.034	0.031	0.357	0.027	1px = 0.075mm
855	YHP3	006	Hand	0.017	0.039	0.028	0.357	0.027	
101	LKASA1	007	Hand	0.017	0.036	0.063	2.012	0.101	5D Mark IV 50mm
117	LKASA2	007	Hand	0.019	0.050	0.048	1.322	0.066	1px = 0.05mm
128	LKASA3	007	Hand	0.027	0.075	0.026	1.449	0.072	
71	LKAMV1	008	Hand	0.033	0.074	0.048	0.597	0.042	EOS200D 28mm
78	LKAMV2	008	Hand	0.032	0.070	0.049	0.496	0.035	1px = 0.07mm
93	LKAMV3	008	Hand	0.037	0.084	0.058	0.706	0.049	
									5D Mark IV 50mm
									1px = 0.05mm
3D accuracy LME MEAN | Colour mapping accuracy MEAN [mm]				0.023		0.040		0.048	
Reproducibility UNC [mm]				0.037		0.028		0.065	5D Mark IV 50mm
									1px = 0.05mm

Test reference:	3DFFTI_TC_3bH
Conclusion and notes:	



Test reference:	3DFFTI_TC_3c d e				
Test name:	Robustness of 3D accuracy and colour mapping accuracy	Location:	IOF, Jena	Date:	20/02/2019
Tested requirements:	Robustness of 3D accuracy and colour mapping accuracy against small variations in parameters "Authentication" and "Checking correct operation of equipment"				

Test set-up:

- Circle board
c1) Distance to 3D Scanner
c2) Tilt relative to 3D Scanner
c3) Position in field of view
d) Temperature
e) Sunlight

Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad
- External light <10,000 lux (indoor)
- Scans with quadpod can be performed in another stationary scan situation, e.g. with 3D-Scanner on table
- Standard parameters: NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C
- Due to the size of the specimen this test does already cover robustness against position within FOV

Test procedure:

1. Scans under changing distance and changing tilt
2. Scans under varying temperature
3. Scans under varying sunlight

Expected results:

- Exported .csv files with deviation between measured and calibrated circles positions
- Exported .csv files with deviations between 3D coordinates of circle positions and their photo position

- The circle no. 11 is taken as reference location, thus its deviation is 0

- Robustness 3D accuracy length measurement error = Systematic influences / variation of 3D accuracy
- Robustness 3D accuracy probing error = Systematic influences / variation of 3D accuracy
- Robustness colour mapping accuracy = Systematic influences / variation of colour mapping accuracy

Test reference: **3DFFTI_TC_3c d e**

Results:

EOS 100D 28mm	**1px=**	0.075	mm
5D Mark IV 50mm	**1px=**	0.05	mm

3D accuracy

Distance	*Scan-ID*	*3D accuracy LME [mm]*	*3D accuracy PE [mm]*
-50	1374	0.029	0.027
-25	1375	0.025	0.034
0	1376	0.023	0.044
25	1377	0.025	0.057
50	1378	0.031	0.074

Systematic: - Probing error is increasing with distance

Colour mapping accuracy

Distance	*Scan-ID*	*Colour mapping accuracy [px]*	*Colour mapping accuracy [mm]*
-50	1374	0.819	0.041
-25	1375	0.901	0.045
0	1376	0.836	0.042
25	1377	0.802	0.040
50	1378	0.835	0.042

Systematic: - None

3D accuracy

Tilt	*Scan-ID*	*3D accuracy LME [mm]*	*3D accuracy PE [mm]*
Horizonal 1	1379	0.024	0.046
Horizontal 2	1380	0.033	0.042
Vertical 1	1382	0.033	0.048
Vertical 2	1384	0.025	0.051
normal	1376	0.023	0.044

Systematic: - None

Colour mapping accuracy

Tilt	*Scan-ID*	*Colour mapping accuracy [px]*	*Colour mapping accuracy [mm]*
Horizonal 1	1379	0.999	0.050
Horizontal 2	1380	0.376	0.019
Vertical 1	1382	0.789	0.039
Vertical 2	1384	0.468	0.023
normal	1376	0.836	0.042

Systematic: - None

Temperature was measured with a thermometer "tpm-30" from BASEtech

3D accuracy

Temperature	*Scan-ID*	*3D accuracy LME [mm]*	*3D accuracy PE [mm]*
-2.5	1434	0.024	0.027
-2.5	1435	0.026	0.027
-2.5	1436	0.024	0.027
3.3	924	0.030	0.047
6.7	991	0.027	0.050
13.2	1045	0.034	0.049
23	1376	0.023	0.044
23	937	0.021	0.032
26.5	954	0.019	0.022
31	977	0.016	0.046

Systematic: - None

Colour mapping accuracy

Tilt	*Scan-ID*	*Colour mapping accuracy [px]*	*Colour mapping accuracy [mm]*
-2.5	1434	1.129	0.056
-2.5	1435	1.104	0.055
-2.5	1436	1.086	0.054
3.3	924	0.578	0.043
6.7	991	0.774	0.058
13.2	1045	0.410	0.031
23	1376	0.836	0.042
23	937	0.472	0.035
26.5	954	0.460	0.035
31	977	0.425	0.032

Systematic: - Sligthly reduced colour mapping accuracy at low temperature

Sunlight intensity was measured with a Luxmeter "digilux 9500" from optronik

3D accuracy

Sunlight [lx]	*Scan-ID*	*3D accuracy LME [mm]*	*3D accuracy PE [mm]*
750	954	0.019	0.022
5,400	937	0.021	0.032
21,000	943	0.019	0.046
28,000	945	0.020	0.045
41,000	958	0.018	0.091
48,000	966	0.022	0.070
60,000	973	0.019	0.063
73,000	982	0.017	0.115
85,000	989	0.020	0.271

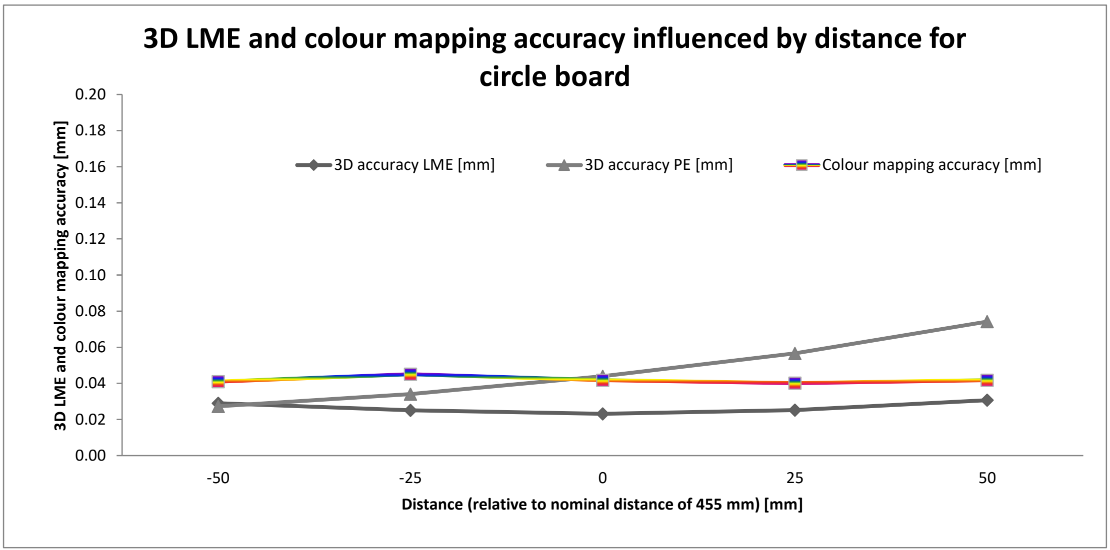
Systematic: - PE is increasing at values larger than ca. 40,000 lux
- LME not influenced

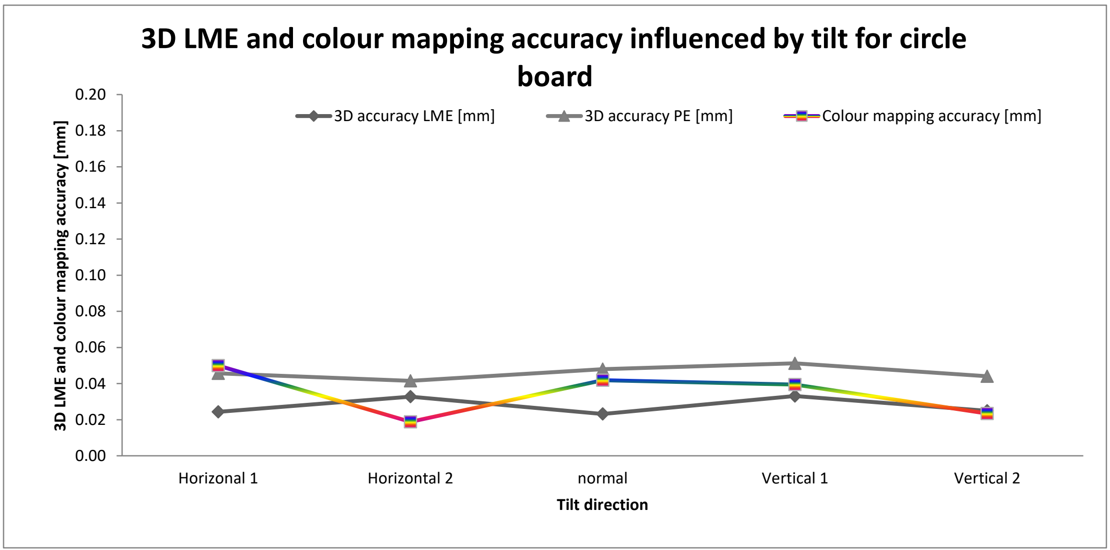
Colour mapping accuracy

Sunlight [lx]	*Scan-ID*	*Colour mapping accuracy [px]*	*Colour mapping accuracy [mm]*
750	954	0.460	0.035
5,400	937	0.472	0.035
21,000	943	0.486	0.036
28,000	945	0.418	0.031
41,000	958	0.479	0.036
48,000	966	0.530	0.040
60,000	973	0.554	0.042
73,000	982	0.450	0.034
85,000	989	0.774	0.058

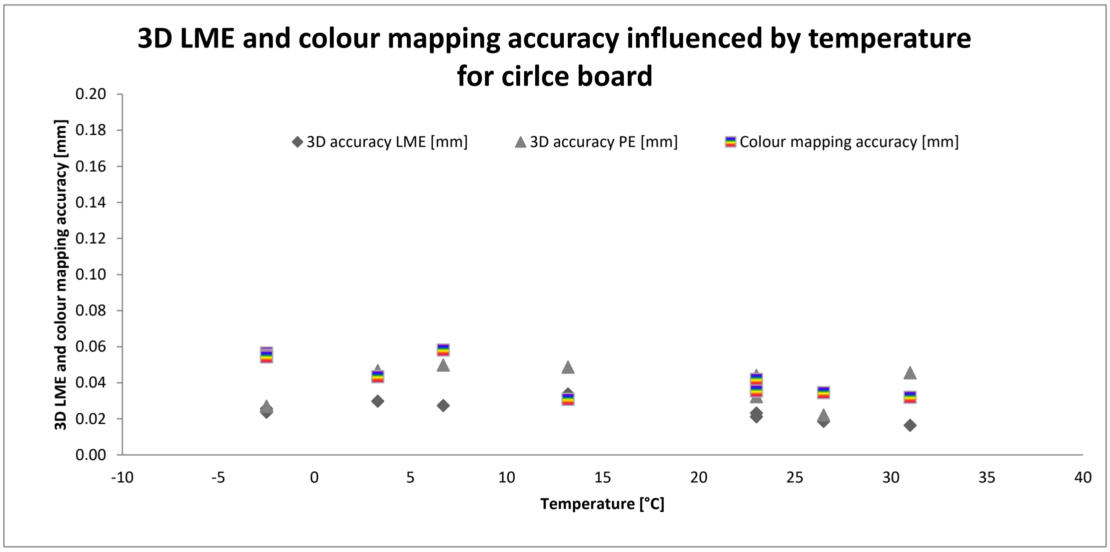
Systematic: - None

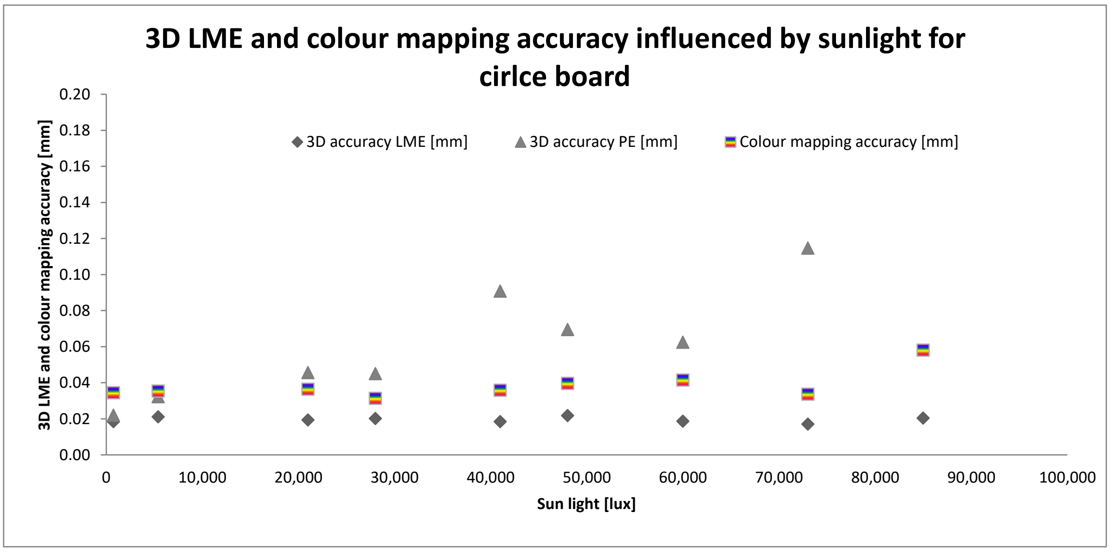
Test reference:	3DFFTI_TC_3c d e
Conclusion and notes:	





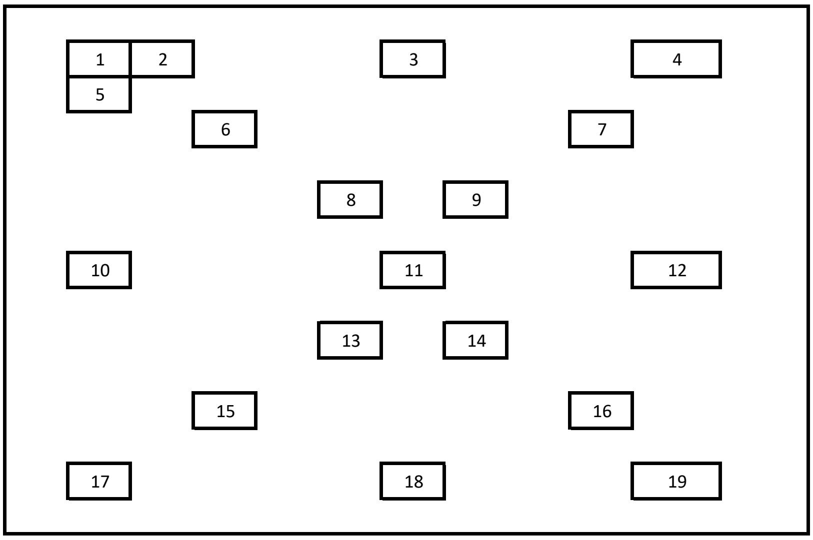
Test reference: 3DFFTI_TC_3c d e





Influence of position in field of view on 3D accuracy LME and colour mapping accuracy

Scheme of circle board

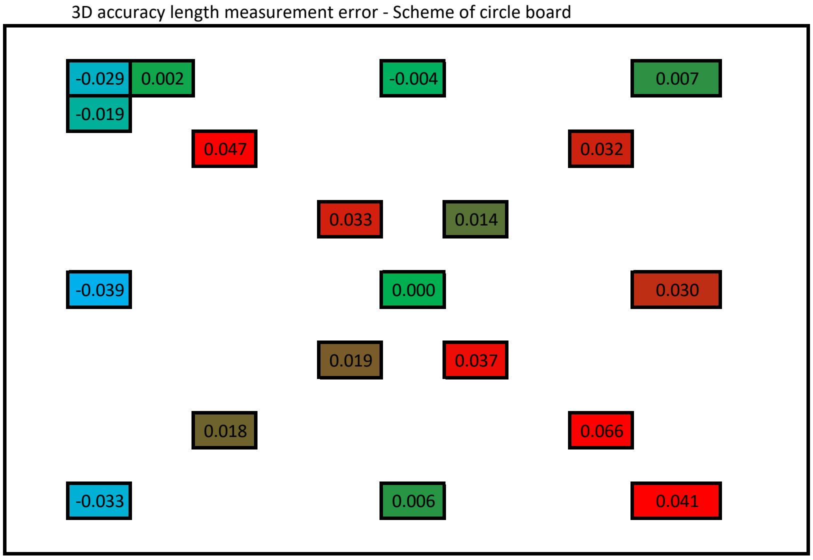


3D accuracy - Length measurement error

circle is more than 0.04 mm too far away from center

circle is more than -0.04 mm too far away from center

3D accuracy length measurement error - Scheme of circle board



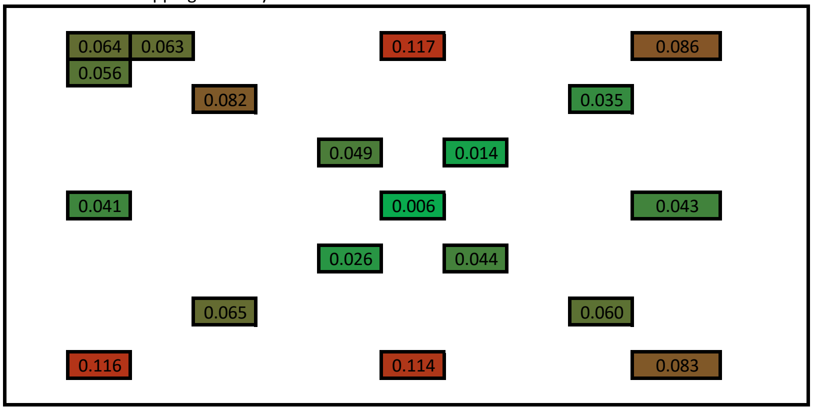
Systematic: - on left side, distances slightly too small
- on right side, distances slightly too big

Colour mapping accuracy

circle is more than 0.165 mm too far away from center

circle is more than -0.165 mm too far away from center

Colour mapping accuracy - scheme of circle board

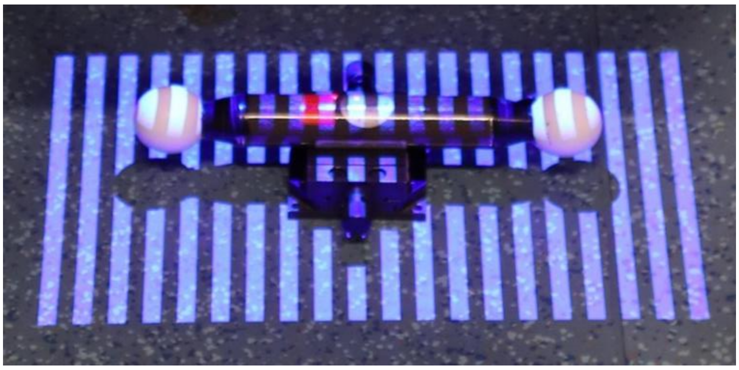


Systematic: - on top and bottom side the deviations are increased (but below the point pitch distance of 0,165mm

Test reference:	**3DFFTI_TC_4a**				
Test name:	3D accuracy in terms of length measurement and probing error and repeatability	**Location:**	IOF, Jena	**Date:**	varying
Tested requirements:	3D accuracy in terms of length measurement and probing error and repeatability, scan mode Quad				

Test set-up:

- Sphere distance normal (Distance ca. 200 mm)



Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad
- External light <10,000 lux (indoor)
- Scans with quadpod can be performed in another stationary scan situation, e.g. with 3D-Scanner on table
- Specimen in center of FOW, at NWD, Scanner in perpendicular scan orientation

Test reference: 3DFFTI_TC_4a

Test procedure:

1. 10 quadpod scans by one person in scan mode Quad

Expected results:

- Distances between sphere centers
- 3D accuracy length measurement error = Mean of sphere distance deviations
- Repeatability 3D accuracy length measurement error = Measurement uncertainty of 3D accuracy length measurement error

- Standard deviation of fitted spheres
- 3D accuracy probing error form = Mean of sphere deviations
- Repeatability 3D accuracy probing error form = Measurement uncertainty of 3D accuracy probing error

Results:

2.228 Student-factor for two-sided confidence interval 0.95 with 10 measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

Reference 199.926

	Quad	
Scan-ID	*Distances [mm]*	*Deviation [mm]*
329	199.886	0.040
330	199.882	0.044
331	199.880	0.046
332	199.883	0.042
333	199.886	0.040
334	199.884	0.042
335	199.883	0.042
336	199.881	0.045
337	199.882	0.044
338	199.882	0.044
	3D accuracy LME MEAN [mm]	0.043
	Repeatability LME UNC [mm]	0.004
	3D accuracy LME BEST [mm]	0.040
	3D accuracy LME WORST [mm]	0.046
	Repeatability LME RANGE [mm]	0.006

Test reference: 3DFFTI_TC_4a

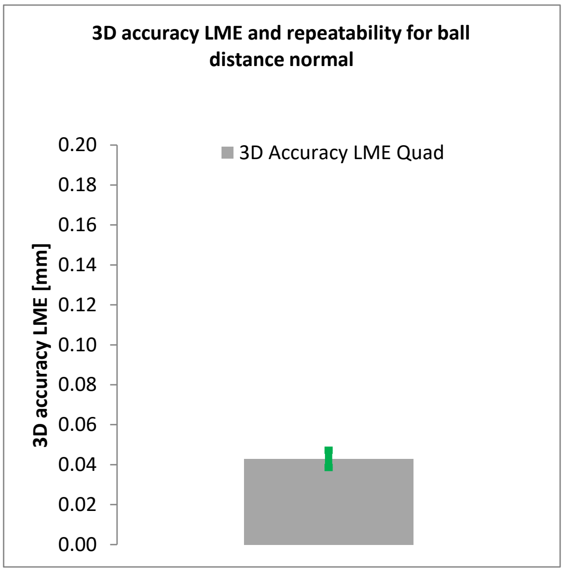
Reference	19.050	19.050
	Quad	
Scan-ID	*Radius [mm]*	*Deviation [mm]*
329	19.060	19.060
	19.066	19.066
330	19.061	19.061
	19.064	19.064
331	19.062	19.062
	19.063	19.063
332	19.062	19.062
	19.064	19.064
333	19.061	19.061
	19.064	19.064
334	19.061	19.061
	19.063	19.063
335	19.061	19.061
	19.063	19.063
336	19.073	19.073
	19.064	19.064
337	19.060	19.060
	19.063	19.063
338	19.062	19.062
	19.064	19.064

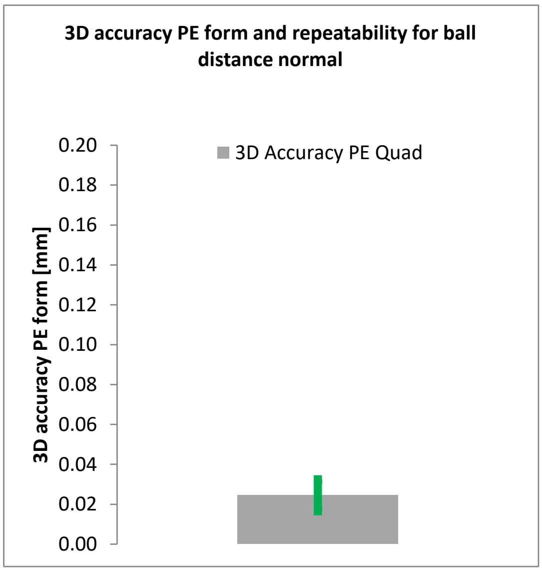
3D accuracy PE dimension MEAN [mm]	19.063
Repeatability PE dimension UNC [mm]	0.006
3D accuracy PE dimension BEST [mm]	19.060
3D accuracy PE dimension WORST [mm]	19.073
Repeatability PE dimension RANGE [mm]	0.013

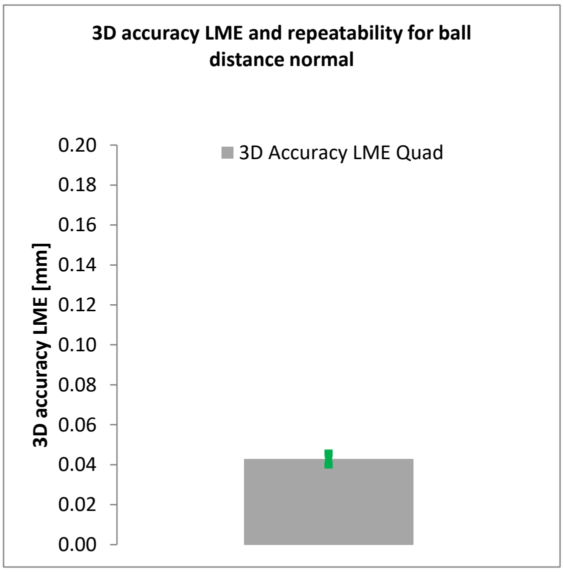
	Quad
Scan-ID	*Sphere standard deviation [mm]*
329	0.028
	0.021
330	0.028
	0.021
331	0.028
	0.021
332	0.028
	0.021
333	0.028
	0.021
334	0.028
	0.021
335	0.028
	0.021
336	0.028
	0.021
337	0.028
	0.021
338	0.028
	0.021

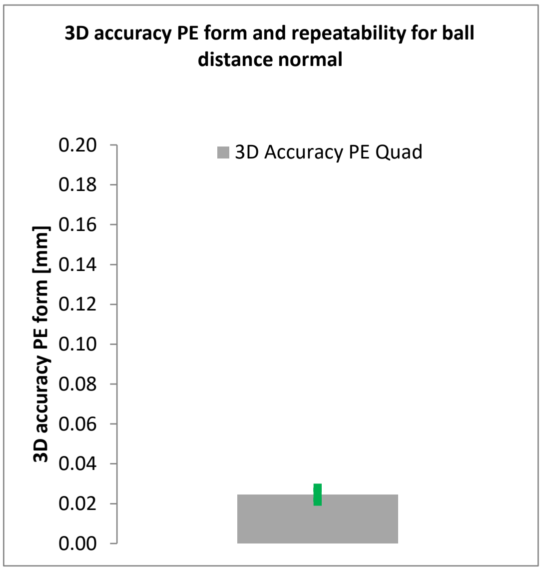
3D accuracy PE form MEAN [mm]	0.025
Repeatability PE form UNC [mm]	0.008
3D accuracy PE form BEST [mm]	0.021
3D accuracy PE form WORST [mm]	0.028
Repeatability PE form RANGE [mm]	0.007

Test reference:	3DFFTI_TC_4a
Conclusion and notes:	





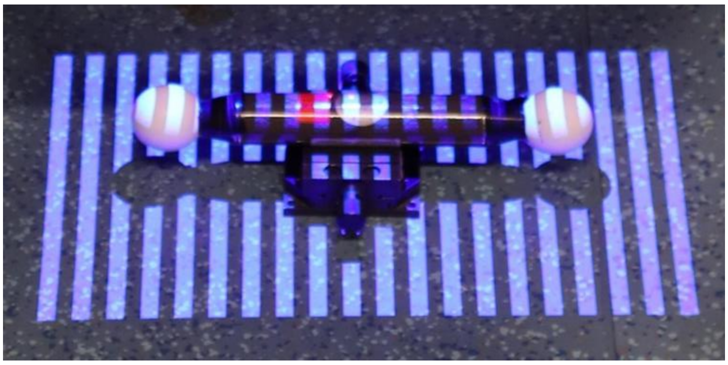




Test reference:	**3DFFTI_TC_4aH**				
Test name:	3D accuracy in terms of length measurement and probing error and repeatability - influence of scan mode	**Location:**	IOF, Jena	**Date:**	varying
Tested requirements:	3D accuracy in terms of length measurement and probing error and repeatability, scan mode Hand				

Test set-up:

- Sphere distance normal (Distance ca. 200 mm)



Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Hand
- External light <10,000 lux (indoor)
- Specimen in center of FOW, at NWD, Scanner in perpendicular scan orientation

Test reference: **3DFFTI_TC_4aH**

Test procedure:

1. 10 handheld scans by one person in scan mode Hand

Expected results:

- Distances between sphere centers
- 3D accuracy length measurement error = Mean of sphere distance deviations
- Repeatability 3D accuracy length measurement error = Measurement uncertainty of 3D accuracy length measurement error

- Standard deviation of fitted spheres
- 3D accuracy probing error form = Mean of sphere deviations
- Repeatability 3D accuracy probing error form = Measurement uncertainty of 3D accuracy probing error

Results:

2.228 Student-factor for two-sided confidence interval 0.95 with 10 measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

Reference 199.926

Handheld scans were done at a different time

Hand		
Scan-ID	*Distances [mm]*	*Deviation [mm]*
1450	199.960	0.034
1451	199.962	0.036
1452	199.957	0.031
1453	199.957	0.031
1454	199.943	0.018
1455	199.955	0.029
1456	199.957	0.031
1457	199.950	0.024
1458	199.951	0.025
1459	199.970	0.044

3D accuracy LME MEAN [mm]	0.031
Repeatability LME UNC [mm]	0.016
3D accuracy LME BEST [mm]	0.018
3D accuracy LME WORST [mm]	0.044
Repeatability LME RANGE [mm]	0.027

Test reference: **3DFFTI_TC_4aH**

Reference	19.050	19.050

Handheld scans were done at a different time

	Hand	
Scan-ID	*Radius [mm]*	*Deviation [mm]*
1450	19.084	0.034
	19.136	0.086
1451	19.084	0.034
	19.114	0.064
1452	19.082	0.032
	19.128	0.078
1453	19.077	0.028
	19.093	0.043
1454	19.025	0.025
	19.067	0.017
1455	19.051	0.001
	19.066	0.016
1456	19.080	0.030
	19.103	0.053
1457	19.071	0.021
	19.092	0.042
1458	19.076	0.026
	19.138	0.088
1459	19.103	0.053
	19.074	0.024

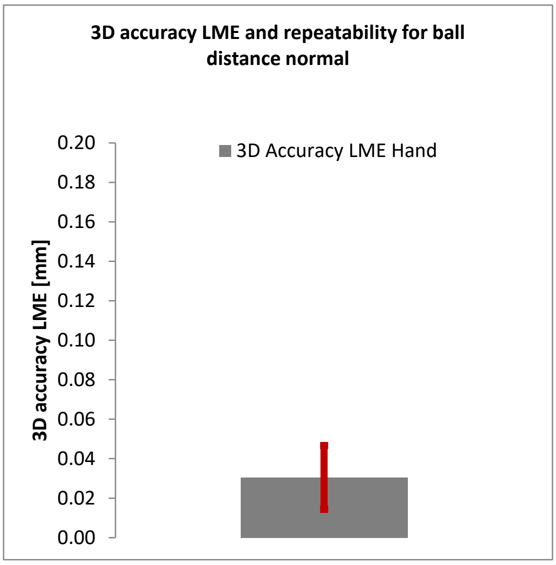
3D accuracy PE dimension MEAN [mm]	0.040
Repeatability PE dimension UNC [mm]	0.053
3D accuracy PE dimension BEST [mm]	0.001
3D accuracy PE dimension WORST [mm]	0.088
Repeatability PE dimension RANGE [mm]	0.087

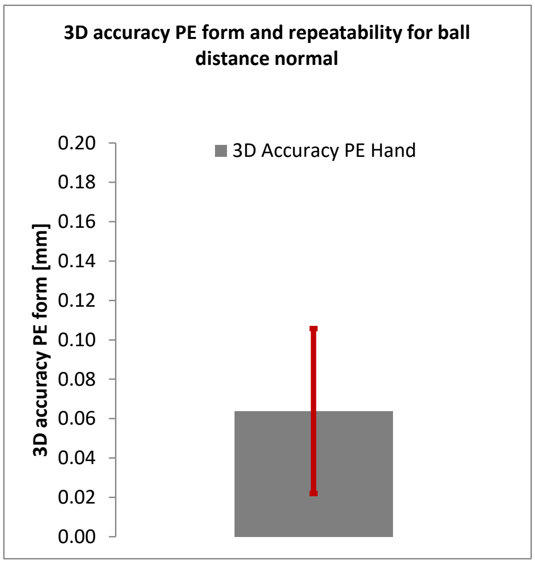
Handheld scans were done at a different time

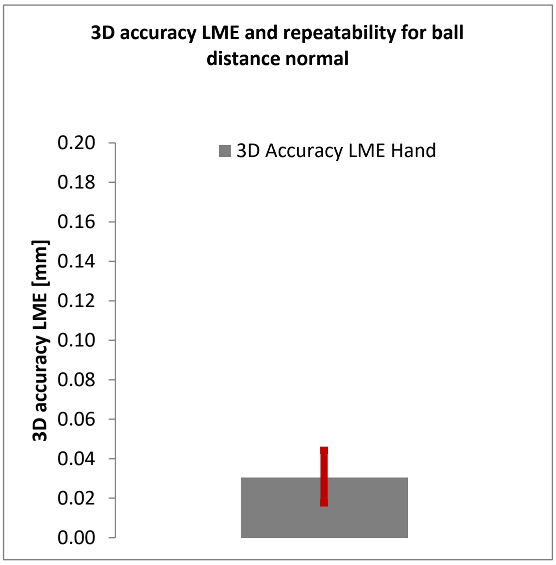
	Hand
Scan-ID	*Sphere standard deviation [mm]*
1450	0.072
	0.061
1451	0.061
	0.056
1452	0.065
	0.064
1453	0.052
	0.039
1454	0.103
	0.085
1455	0.100
	0.086
1456	0.058
	0.048
1457	0.039
	0.038
1458	0.066
	0.078
1459	0.058
	0.048

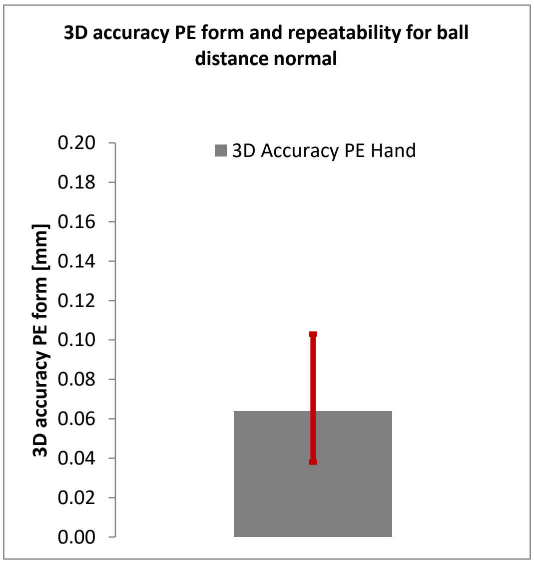
3D accuracy PE form MEAN [mm]	0.064
Repeatability PE form UNC [mm]	0.042
3D accuracy PE form BEST [mm]	0.038
3D accuracy PE form WORST [mm]	0.103
Repeatability PE form RANGE [mm]	0.065

Test reference:	3DFFTI_TC_4aH
Conclusion and notes:	





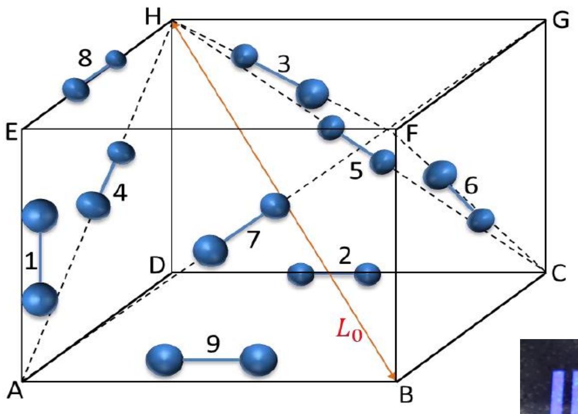


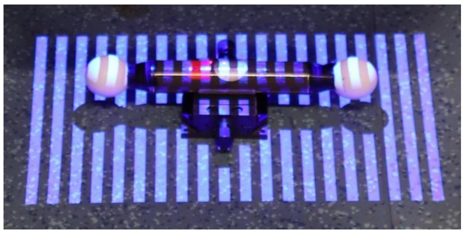


Test reference:	3DFFTI_TC_4b				
Test name:	Robustness of 3D accuracy in terms of length measurement and probing error	Location:	IOF, Jena	Date:	######
Tested requirements:	Robustness of 3D accuracy in terms of length measurement and probing error against small variantions in parameters				

Test set-up:

- Sphere distance normal (Distance ca. 200 mm)





Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quadpod
- External light <10,000 lux (indoor)
- Scans with quadpod can be performed in another stationary scan situation, e.g. with 3D-Scanner on table
- Standard parameters: NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C

Test procedure:

1. 7 (9) scans by one person in position / orientiation according to VDI2634 in scan mode Quad

Test reference: 3DFFTI_TC_4b

Expected results:

- Distances between sphere centers
- Robustness 3D accuracy length measurement error = Maximum deviation of sphere distance (according to VDI)
- Robustness 3D accuracy length measurement error = Systematic influences / variation of distance deviation

- Standard deviation of fitted spheres
- Robustness 3D accuracy probing error = Maximum sphere deviation (according to VDI)
- Robustness 3D accuracy probing error = Systematic influences / variation of sphere deviations

Results:

2.262 Student-factor for two-sided confidence interval 0.95 with 9 measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

Reference 199.926

VDI2634 Length measurement error

Scan-ID	*Distances [mm]*	*Deviation [mm]*
308	199.930	0.004
315	199.882	0.044
311	199.956	0.030
309	199.959	0.033
324	199.885	0.041
326	199.954	0.029
313	199.884	0.041
310	199.945	0.019
312	199.874	0.052
	Robustness LME [mm]	0.052
		0.032

Systematic: - No systematic effects

Reference 19.050 19.050

VDI2634 Probing error dimension

Scan-ID	*Radius [mm]*	*Deviation [mm]*
308	19.057	0.007
	19.062	0.012
315	19.071	0.021
	19.072	0.022
311	19.061	0.011
	19.111	0.061
309	19.067	0.017
	19.108	0.058
324	19.068	0.018
	19.071	0.021
326	19.072	0.022
	19.048	0.002
313	19.068	0.018
	19.063	0.013
310	19.099	0.049
	19.072	0.022
312	19.067	0.017
	19.056	0.006
	Robustness PE dimension [mm]	0.061
		0.038

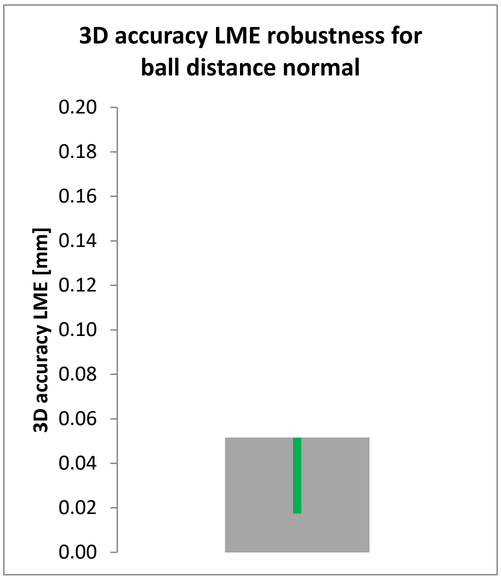
Systematic: - No systematic effects

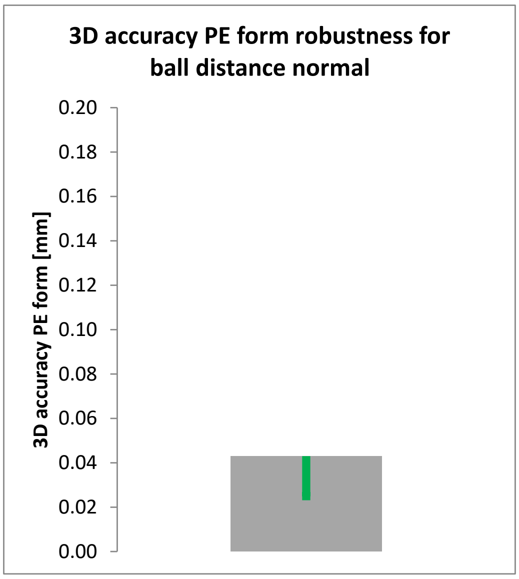
VDI2634 Probing error form

Scan-ID	*Sphere standard deviation [mm]*
308	0.020
	0.028
315	0.027
	0.026
311	0.016
	0.032
309	0.018
	0.041
324	0.025
	0.023
326	0.029
	0.018
313	0.016
	0.033
310	0.043
	0.024
312	0.019
	0.019
Robustness PE form [mm]	0.043
	0.018

Systematic: - No systematic effects

Test reference:	3DFFTI_TC_4b
Conclusion and notes:	

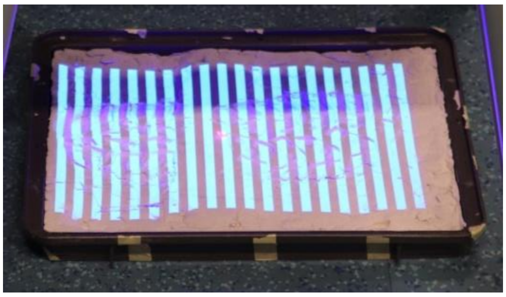


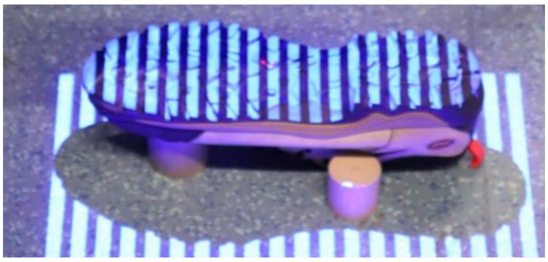


Test reference:	3DFFTI_TC_5a				
Test name:	3D accuracy in terms of probing error and repeatability	**Location:**	IOF, Jena	**Date:**	06/02/2019
Tested requirements:	3D accuracy in terms of probing error and repeatability, scan mode Quad				

Test set-up:

- Reference shoe sole / Mikrotrack impression





Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad
- External light <10,000 lux (indoor)
- Scans with quadpod can be performed in another stationary scan situation, e.g. with 3D-Scanner on table
- Specimen in center of FOW, at NWD, Scanner in perpendicular scan orientation
- Not move object during procedure

Test reference: 3DFFTI_TC_5a

Test procedure:

1. Reference scans: Quadpod, center of FOV, NWD, perpendicular scan orientation
1. 10 quadpod scans by one person in scan mode Quad
- Repeat for shoe sole and Mikrotrack impression

Geomagic Quality 12 evaluation chain:
- Manual pre-registration with 3 points
- BestFit Registration
- 3D comparison (max. error 0.5 mm, critical angle 180°, 3D deviation) -> export deviation table (only deviation values)

Expected results:

- Be aware that no deformations of the object itself are evaluated
- For Mikrotrack be aware that the specimen is not (too much) damaged
- Removel of outlier is necessary, especially for the handheld scans, because depending on the user the scans may contain slightly different parts of the specimen

- 3D accuracy probing error = Mean value of average distances
- Repeatability 3D accuracy probing error = Measurement uncertainties / standard deviation of average distances

Results:

2.228 Student-factor for two-sided confidence interval 0.95 with 10 measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

Quad	*Shoe sole*	
Scan-ID	*Deviation [mm]*	*Reference ID*
1941	0.076	1951
1942	0.078	1951
1943	0.078	1951
1944	0.075	1951
1945	0.078	1951
1946	0.080	1951
1947	0.077	1951
1948	0.080	1951
1949	0.081	1951
1950	0.077	1951

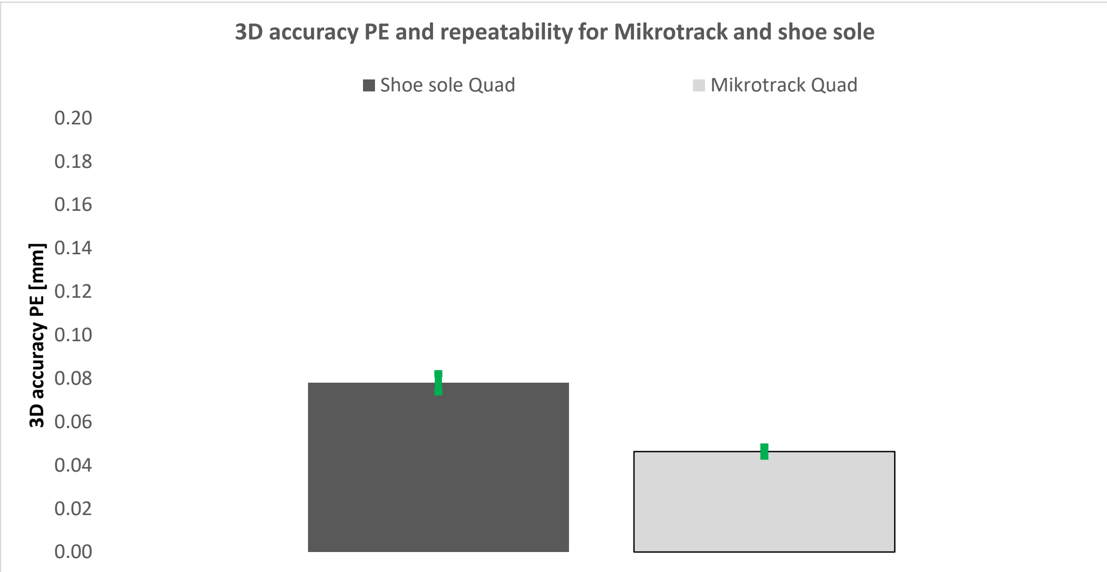
Accuracy PE form MEAN [mm]	0.078
Repeatability PE form UNC [mm]	0.004
Accuracy PE form BEST [mm]	0.075
Accuracy PE form WORST [mm]	0.081
Repeatability PE form RANGE [mm]	0.006

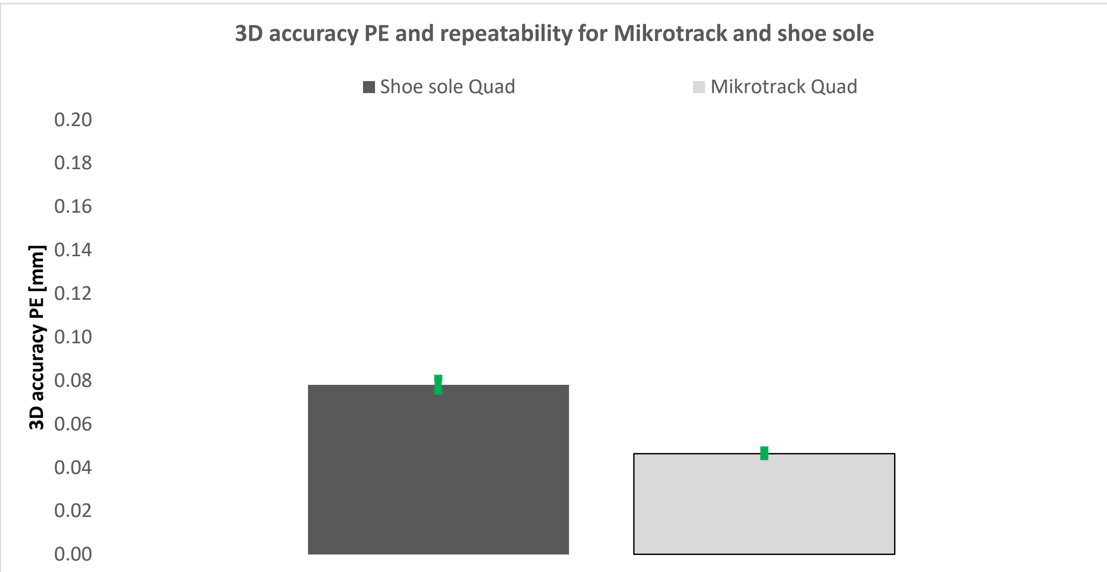
Quad	*Mikrotrack*	
Scan-ID	*Deviation [mm]*	*Reference ID*
1412	0.045	1411
1413	0.047	1411
1414	0.046	1411
1415	0.045	1411
1416	0.047	1411
1417	0.046	1411
1418	0.046	1411
1419	0.046	1411
1420	0.047	1411
1421	0.048	1411

Accuracy PE form MEAN [mm]	0.046
Repeatability PE form UNC [mm]	0.002
Accuracy PE form BEST [mm]	0.045
Accuracy PE form WORST [mm]	0.048
Repeatability PE form RANGE [mm]	0.003

Test reference: **3DFFTI_TC_5a**

Conclusion and notes:

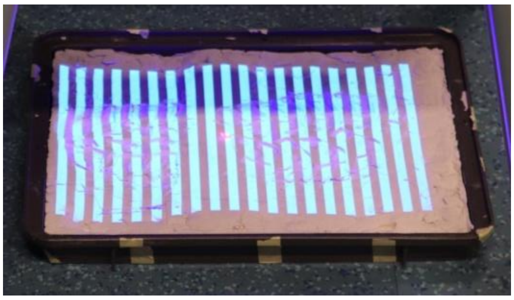


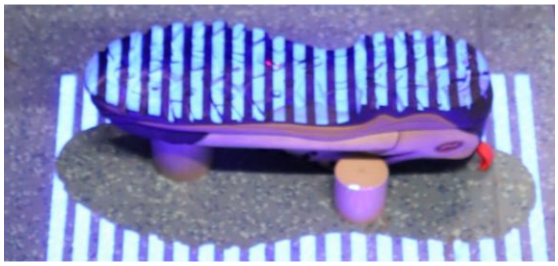


Test reference:	3DFFTI_TC_5aH				
Test name:	3D accuracy in terms of probing error and repeatability - influence of scan mode	**Location:**	IOF, Jena	**Date:**	06/02/2019
Tested requirements:	3D accuracy in terms of probing error and repeatability, scan mode Hand				

Test set-up:

- Reference shoe sole / Mikrotrack impression





Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Hand
- External light <10,000 lux (indoor)
- Scans with quadpod can be performed in another stationary scan situation, e.g. with 3D-Scanner on table
- Specimen in center of FOW, at NWD, Scanner in perpendicular scan orientation
- Not move object during procedure

Test reference: 3DFFTI_TC_5aH

Test procedure:

1. Reference scans: Quadpod, center of FOV, NWD, perpendicular scan orientation
2. 10 handheld scans by one person in scan mode Hand

- Repeat for shoe sole and Mikrotrack impression

Geomagic Quality 12 evaluation chain:
- Manual pre-registration with 3 points
- BestFit Registration
- 3D comparison (max. error 0.5 mm, critical angle 180°, 3D deviation) -> export deviation table (only deviation values)

Expected results:

- Be aware that no deformations of the object itself are evaluated
- For Mikrotrack be aware that the specimen is not (too much) damaged
- Removel of outlier is necessary, especially for the handheld scans, because depending on the user the scans may contain slightly different parts of the specimen

- 3D accuracy probing error = Mean value of average distances
- Repeatability 3D accuracy probing error = Measurement uncertainties / standard deviation of average distances

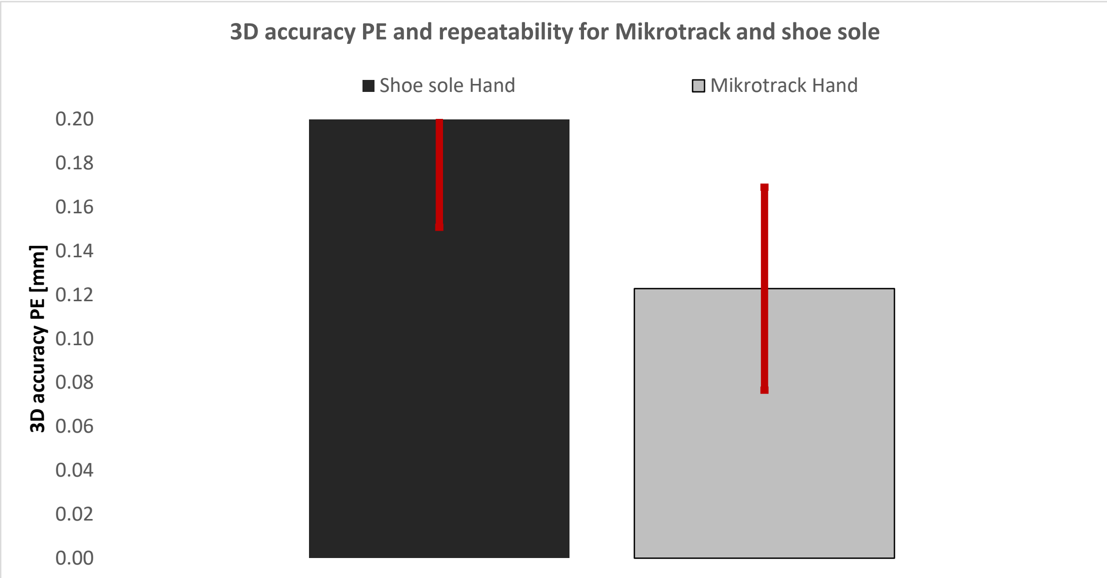
Results:

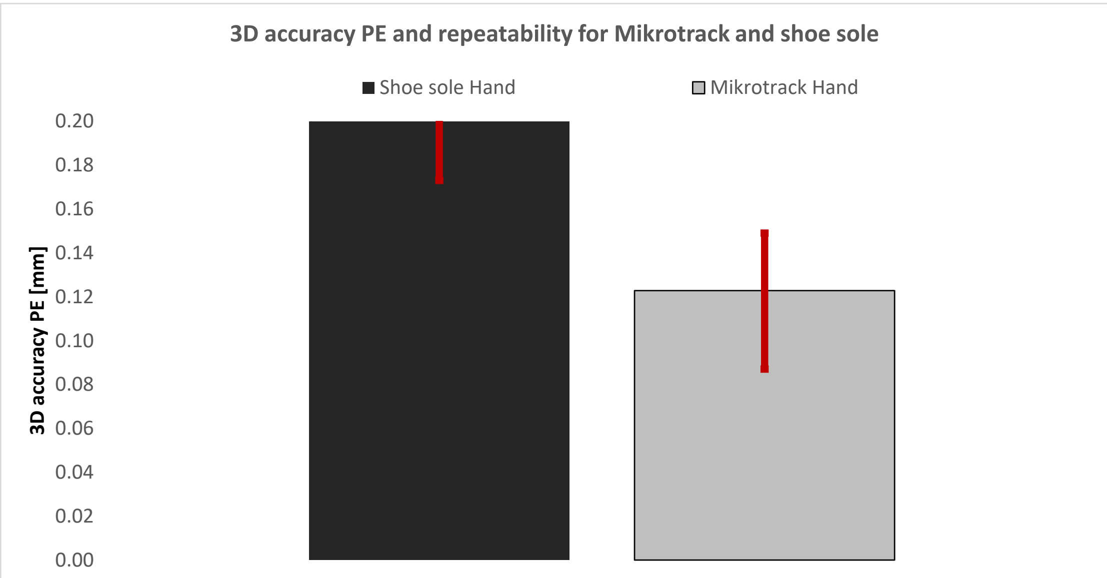
2.228 Student-factor for two-sided confidence interval 0.95 with 10 measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

Hand	*Shoe sole*		*Hand*	*Mikrotrack*	
Scan-ID	*Deviation [mm]*	*Reference ID*	*Scan-ID*	*Deviation [mm]*	*Reference ID*
1400	0.204	1398	1422	0.137	1411
1401	0.190	1398	1423	0.149	1411
1402	0.173	1398	1424	0.097	1411
1403	0.230	1398	1425	0.117	1411
1404	0.228	1398	1426	0.139	1411
1405	0.198	1398	1427	0.112	1411
1406	0.178	1398	1428	0.134	1411
1407	0.194	1398	1429	0.143	1411
1408	0.176	1398	1430	0.087	1411
1409	0.227	1398	1431	0.113	1411

	Shoe sole	Mikrotrack
Accuracy PE form MEAN [mm]	0.200	0.123
Repeatability PE form UNC [mm]	0.049	0.046
Accuracy PE form BEST [mm]	0.173	0.087
Accuracy PE form WORST [mm]	0.230	0.149
Repeatability PE form RANGE [mm]	0.057	0.062

Test reference:	3DFFTI_TC_5aH
Conclusion and notes:	





Test reference:	3DFFTI_TC_5b				
Test name:	Reproducibility of 3D accuracy in terms of probing error	**Location:**	varying	**Date:**	varying
Tested requirements:	Reproducibility of 3D accuracy in terms of probing error, scan mode Quad				

Test set-up:

- Reference shoe sole / MikroTrack impression

Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Quad
- External light <10,000 lux (indoor)
- Standard parameters: center FOV, NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C
- Scans are made in cooperation with EETG at different locations and each EETG member with different device
- Not move object during procedure

Test procedure:

1. Reference scan: Quadpod, center of FOV, NWD, perpendicular scan orientation
2. 1 scan per user in scan mode Quad of shoe sole (sole are typically scanned calmly in the office)
3. 1 scan per user in scan mode Quad of Mikrotrack

Geomagic evaluation chain:

- Manual pre-registration with 3 points
- BestFit Registration
- 3D comparison (max. error 0.5 mm, critical angle 180°, 3D deviation) -> export deviation table (only deviation values)
- Remove 0,3% of largest outliers (VDI conform) -> average deviation

Expected results:

- Be aware that no deformations of the object itself are evaluated
- For MikroTrack be aware that the specimen is not (too much) damaged
- Removel of outlier is necessary, especially for the handheld scans, because depending on the user the scans may contain slightly different parts of the specimen (in Geomagic limit max. deviation to 0.5 mm)

- Reproducibility 3D accuracy probing error = Standard deviation between repeated scans

Test reference: **3DFFTI_TC_5b**

Results:

2.228 Student-factor for confidence interval 0.95 with **10** measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

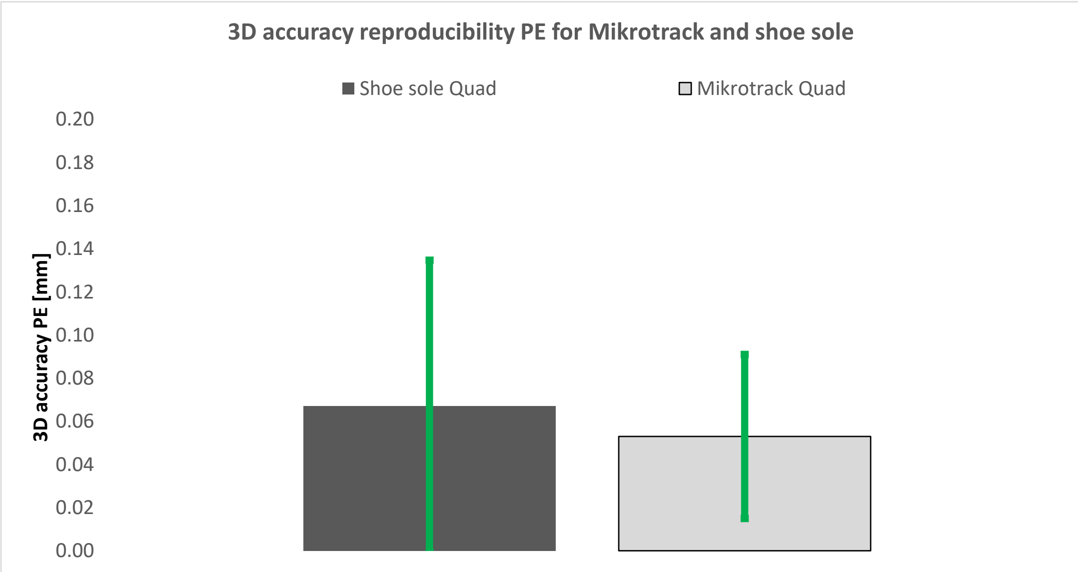
Mikrotrack	*Settings*			*Accuracy Quad [mm]*	
Scan-ID	*User-ID*	*Device*	*Mode*	*Deviation [mm]*	*Reference-ID*
746	IOF1	006	Quad	0.035	745
826	YHP1	006	Quad	0.048	822
838	YHP2	006	Quad	0.049	826
851	YHP3	006	Quad	0.057	838
96	LKASA1	007	Quad	0.039	129
110	LKASA2	007	Quad	0.037	129
123	LKASA3	007	Quad	0.039	129
66	LKAMV1	008	Quad	0.084	64
87	LKAMV2	008	Quad	0.082	66
88	LKAMV3	008	Quad	0.051	66
731	CAR1	009	Quad	0.062	732

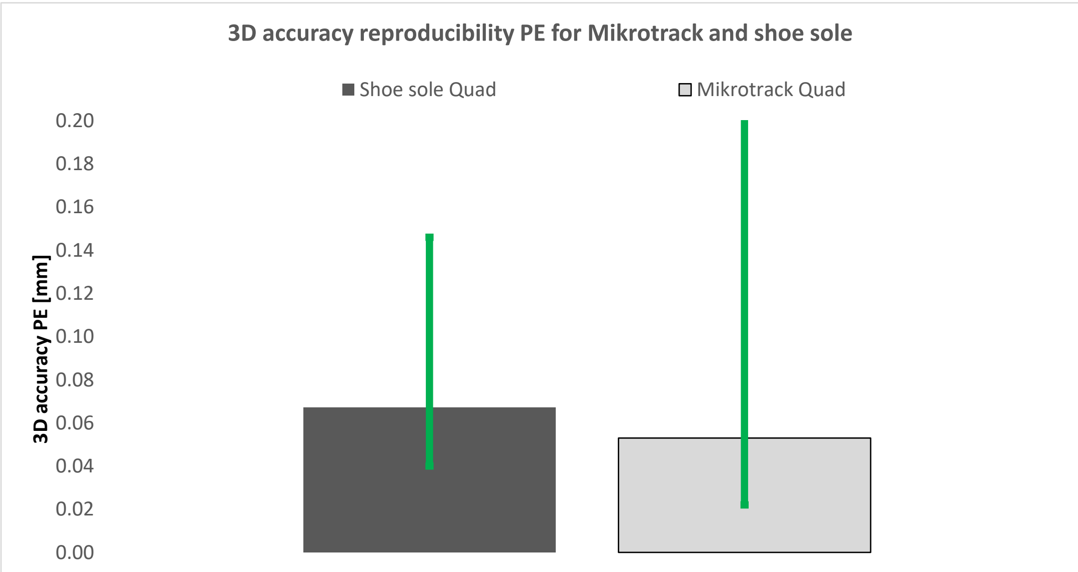
Accuracy PE form MEAN [mm]	0.053
Reproducibility PE form UNC [mm]	0.038
Accuracy PE form BEST [mm]	0.035
Accuracy PE form WORST [mm]	0.084
Reproducibility PE form RANGE [mm]	0.049

Shoe sole	*Settings*			*Accuracy Quad [mm]*	
Scan-ID	*User-ID*	*Device*	*Mode*	*Deviation [mm]*	*Reference-ID*
748	IOF1	006	Quad	0.040	747
836	YHP1	006	Quad	0.048	824
849	YHP2	006	Quad	0.146	824
861	YHP3	006	Quad	0.048	862
131	LKASA1	007	Quad	0.050	130
134	LKASA2	007	Quad	0.096	130
135	LKASA3	007	Quad	0.050	130
102	LKAMV1	008	Quad	0.070	99
101	LKAMV2	008	Quad	0.061	99
100	LKAMV3	008	Quad	0.058	99
723	CAR1	009	Quad	0.070	722

Accuracy PE form [mm]	0.067
Reproducibility PE form [mm]	0.068
Accuracy PE form BEST [mm]	0.040
Accuracy PE form WORST [mm]	0.146
Reproducibility PE form RANGE [mm]	0.106

Test reference:	3DFFTI_TC_5b
Conclusion and notes:	





Test reference:	3DFFTI_TC_5bH				
Test name:	Reproducibility of 3D accuracy in terms of probing error - influence of scan mode	Location:	varying	Date:	varying
Tested requirements:	Reproducibility of 3D accuracy in terms of probing error, scan mode Hand				

Test set-up:

- Reference shoe sole / MikroTrack impression

Test assumptions, conditions & constraints:

- NWD - Nominal working distance = 455 mm
- FOV - Field of view (325 x 200 mm²)
- Exposure step 1
- LED brightness optimal for specimen material
- Scan mode Hand
- External light <10,000 lux (indoor)
- Standard parameters: center FOV, NWD, perpendicular orientation, vertical rotation, <10.000 lx external light, 20-25°C
- Scans are made in cooperation with EETG at different locations and each EETG member with different device
- Not move object during procedure

Test procedure:

1. Reference scan: Quadpod, center of FOV, NWD, perpendicular scan orientation
2. 1 scan per user in scan mode Hand of Mikrotrack (traces are typically scanned quick under pressure at crime scenes)

Geomagic evaluation chain:
- Manual pre-registration with 3 points
- BestFit Registration
- 3D comparison (max. error 0.5 mm, critical angle 180°, 3D deviation) -> export deviation table (only deviation values)
- Remove 0,3% of largest outliers (VDI conform) -> average deviation

Expected results:

- Be aware that no deformations of the object itself are evaluated
- For MikroTrack be aware that the specimen is not (too much) damaged
- Removel of outlier is necessary, especially for the handheld scans, because depending on the user the scans may contain slightly different parts of the specimen (in Geomagic limit max. deviation to 0.5 mm)

- Reproducibility 3D accuracy probing error = Standard deviation between repeated scans

Test reference: **3DFFTI_TC_5bH**

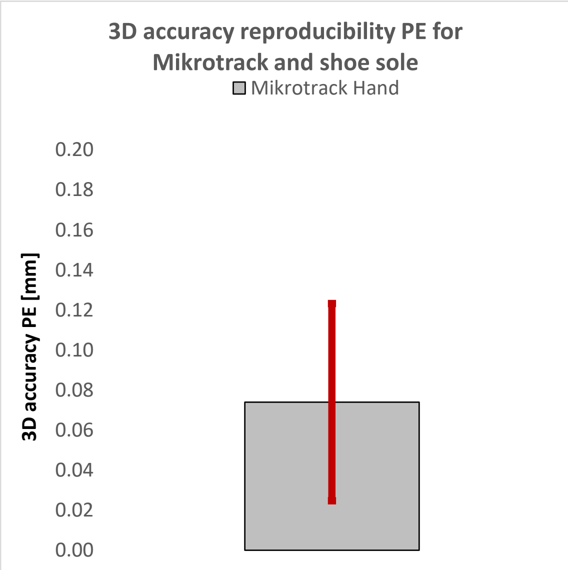
Results:

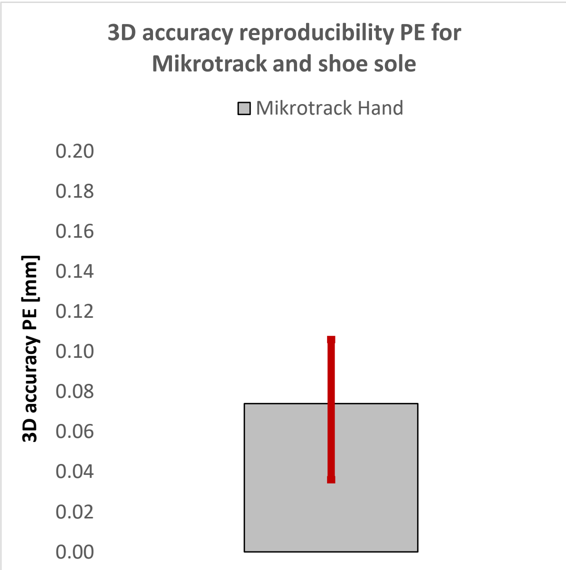
2.228 Student-factor for confidence interval 0.95 with **10** measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

Mikrotrack	*Settings*			*Accuracy Hand [mm]*	
Scan-ID	*User-ID*	*Device*	*Mode*	*Deviation [mm]*	*Reference-ID*
757	IOF1	006	Hand	0.052	745
831	YHP1	006	Hand	0.063	826
843	YHP2	006	Hand	0.070	838
856	YHP3	006	Hand	0.102	851
97	LKASA1	007	Hand	0.063	129
111	LKASA2	007	Hand	0.061	129
124	LKASA3	007	Hand	0.036	129
75	LKAMV1	008	Hand	0.098	66
76	LKAMV2	008	Hand	0.106	66
98	LKAMV3	008	Hand	0.086	88
725	CAR1	009	Hand	0.077	732

Accuracy PE form [mm]	0.074
Reproducibility PE form [mm]	0.049
Accuracy PE form BEST [mm]	0.036
Accuracy PE form WORST [mm]	0.106
Reproducibility PE form RANGE [mm]	0.070

Test reference:	3DFFTI_TC_5bH
Conclusion and notes:	





Test reference:	**3DFFTI_TC_6_1400_neigh100**				
Test name:	Visualization PC 1	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Visualization test of simulated 3D point clouds of the resolution specimen with different point pitch distances				

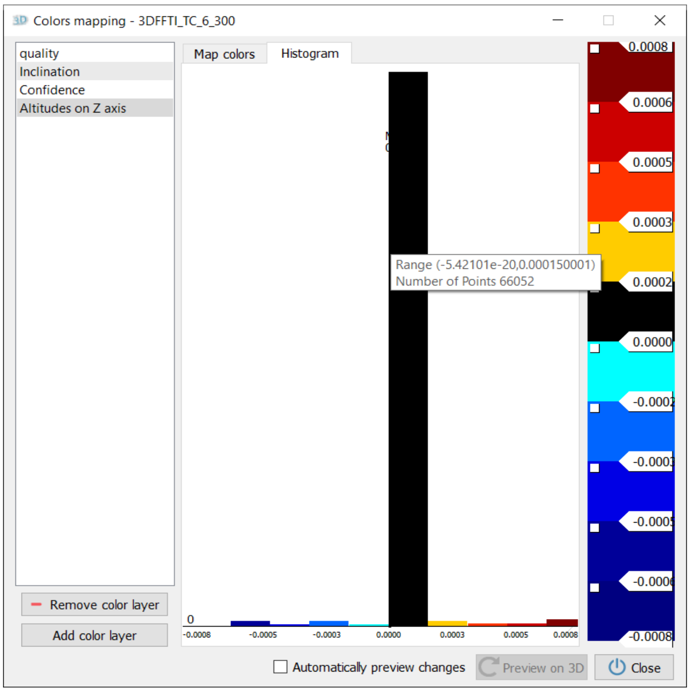
Test set-up:

- The project contains following point clouds:

1400 37.5 µm
700 75 µm
350 150 µm
300 175 µm
250 200 µm
200 260 µm

Test procedure

- the 6 simulates scans has been displayed in 3 different PC with different graphic characteristics
- the 6 simulates scans are rendered with height colour layer that is independent from material reflectivity



- the 6 simulates scans are rendered removing any light effects

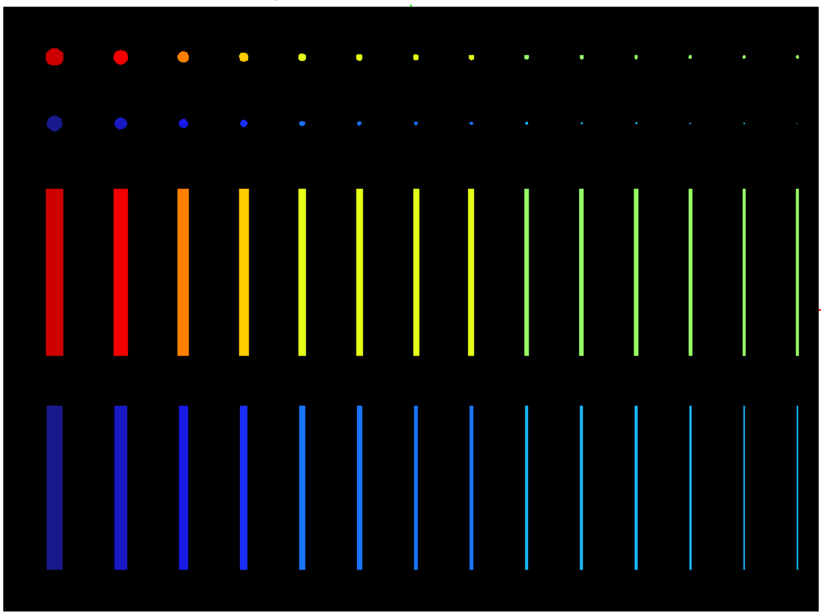
Test reference:	3DFFTI_TC_6_1400_neigh100

Results:

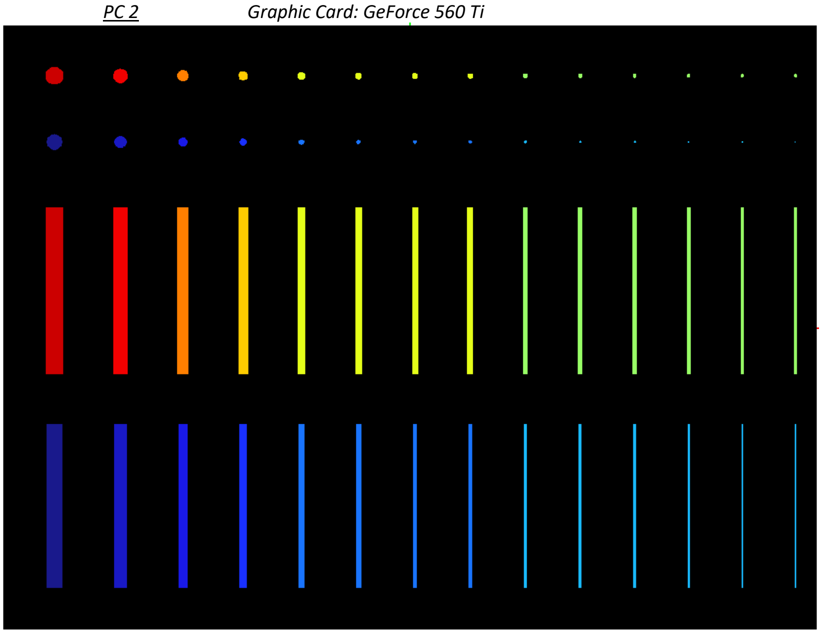
- the 6 simulated scans are visually compared in 3 different PCs

3DFFTI_TC_6_1400

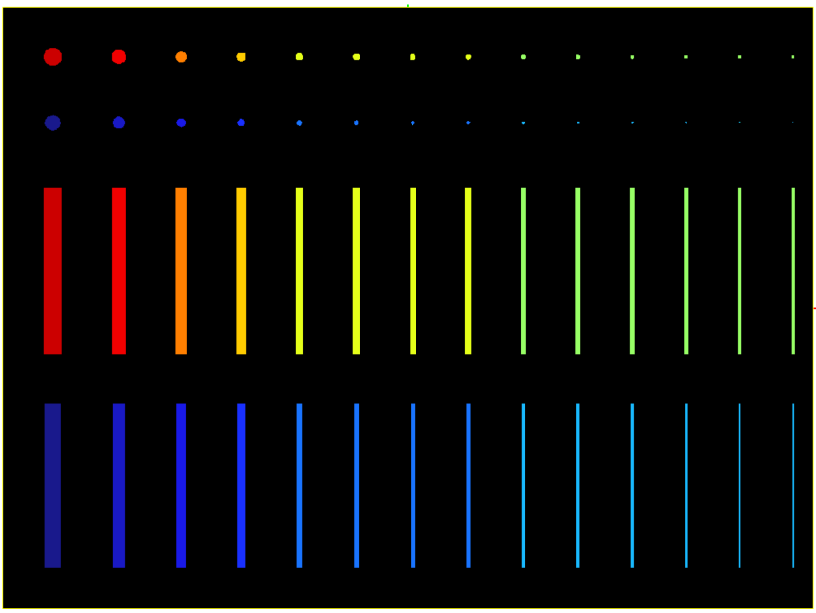
<u>PC 1</u> *Graphic Card: NVIDIA PRO 2000*



<u>PC 2</u> *Graphic Card: GeForce 560 Ti*



Test reference:	3DFFTI_TC_6_1400_neigh100
PC 3	*Graphic Card: NVIDIA Quadro M2000M*



Conclusion and notes:

- no significant differences between different PC in the display of the same 3D clouds

Test reference:	3DFFTI_TC_6_700				
Test name:	Visualization PC 1	Location:	GEX, Brescia	Date:	05/06/2019
Tested requirements:	Visualization test of simulated 3D point clouds of the resolution specimen with different point pitch distances				

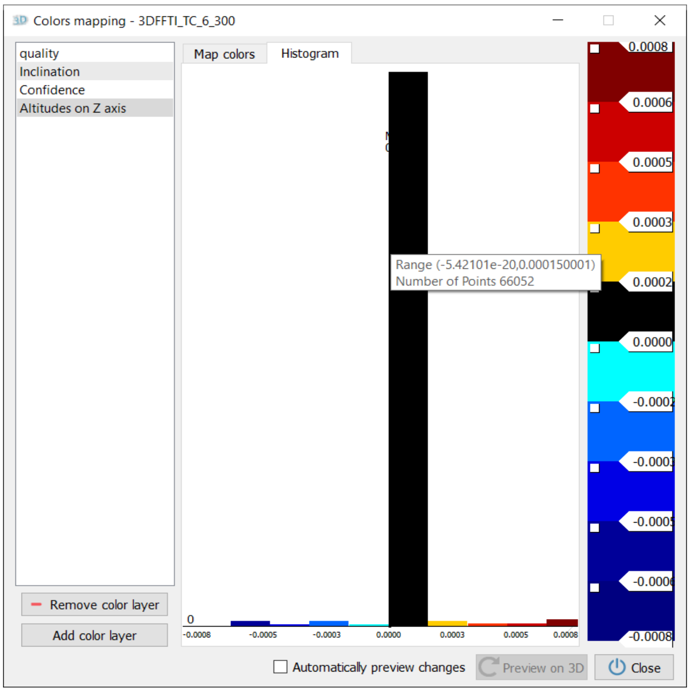
Test set-up:

- The project contains following point clouds:

1400 37.5 µm
700 75 µm
350 150 µm
300 175 µm
250 200 µm
200 260 µm

Test procedure

- the 6 simulates scans has been displayed in 3 different PC with different graphic characteristics
- the 6 simulates scans are rendered with height colour layer that is independent from material reflectivity



- the 6 simulates scans are rendered removing any light effects

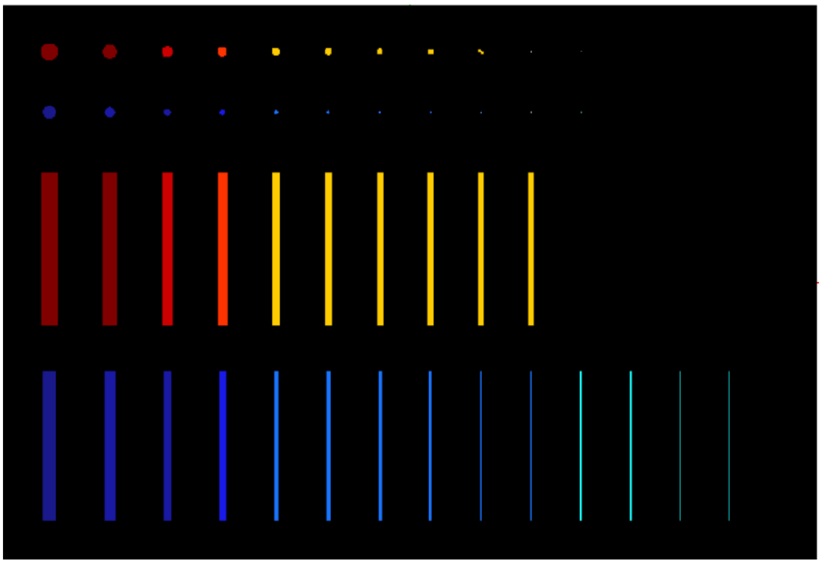
Test reference:	3DFFTI_TC_6_700

Results:

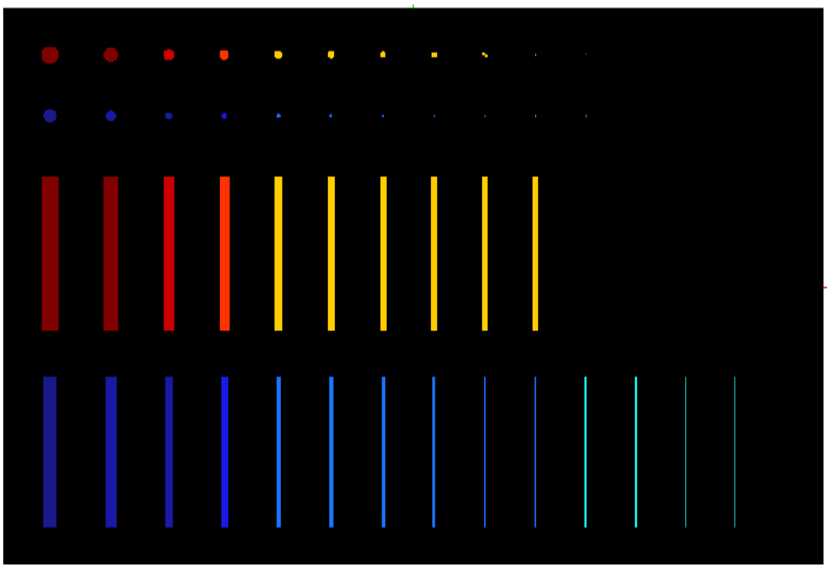
- the 6 simulated scans are visually compared in 3 different PCs

3DFFTI_TC_6_700

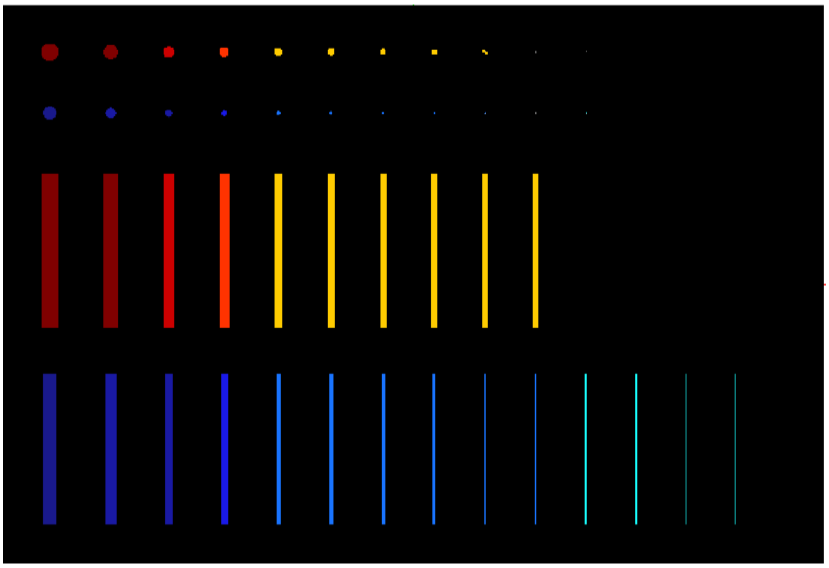
<u>*PC 1*</u> *Graphic Card: NVIDIA PRO 2000*



<u>*PC 2*</u> *Graphic Card: GeForce 560 Ti*



Test reference:	3DFFTI_TC_6_700
<u>*PC 3*</u>	*Graphic Card: Quadro M2000M*



Conclusion and notes:

- no significant differences between different PC in the display of the same 3D clouds

Test reference:	3DFFTI_TC_6_350				
Test name:	Visualization PC 1	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Visualization test of simulated 3D point clouds of the resolution specimen with different point pitch distances				

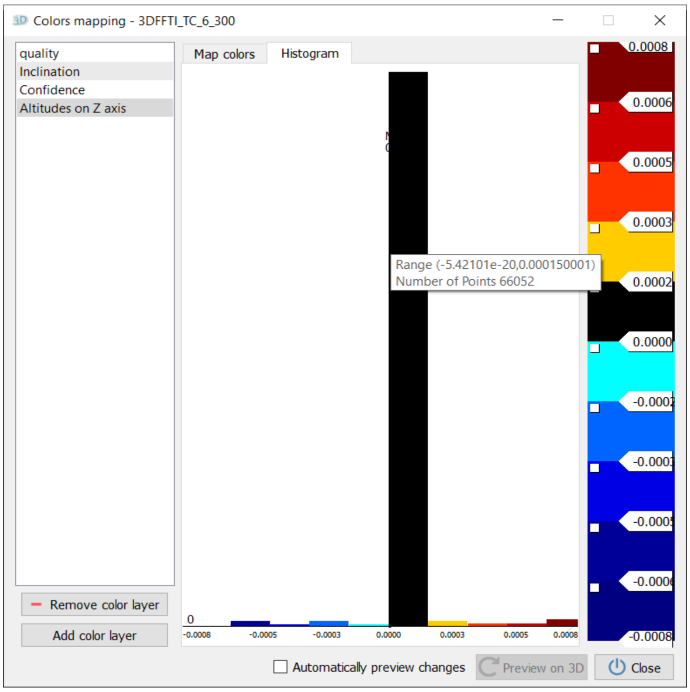
Test set-up:

- The project contains following point clouds:

1400 37.5 µm
700 75 µm
350 150 µm
300 175 µm
250 200 µm
200 260 µm

Test procedure

- the 6 simulates scans has been displayed in 3 different PC with differend graphic characteristics
- the 6 simulates scans are rendered with height colour layer that is independent from material reflectivity



- the 6 simulates scans are rendered removing any light effects

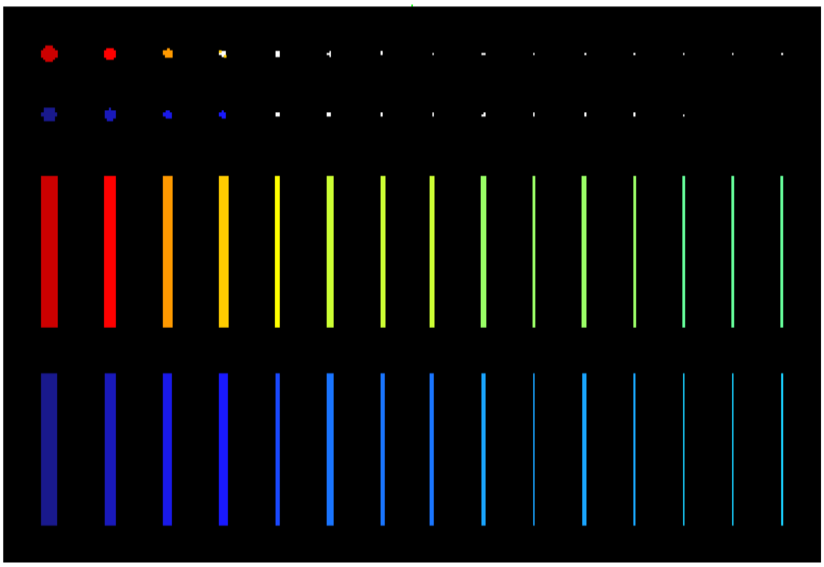
Test reference:	3DFFTI_TC_6_350

Results:

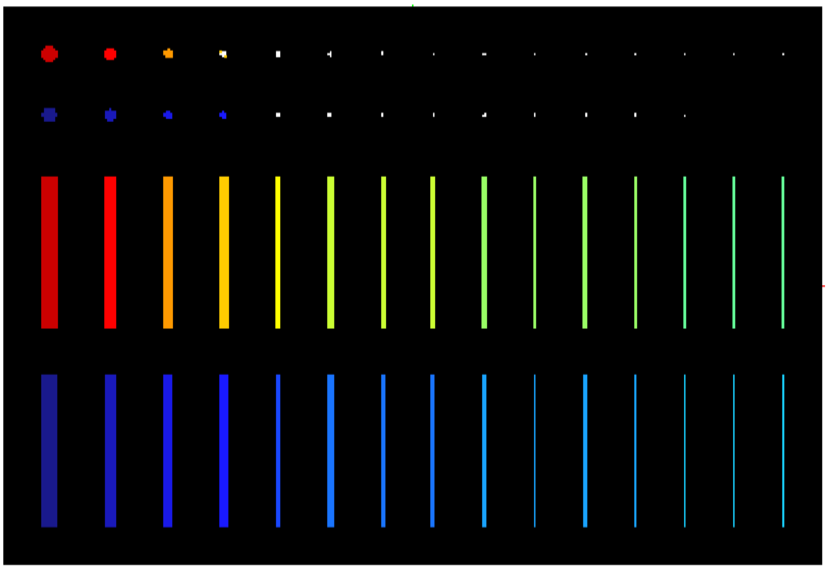
- the 6 simulated scans are visually compared in 3 differents PCs

3DFFTI_TC_6_350

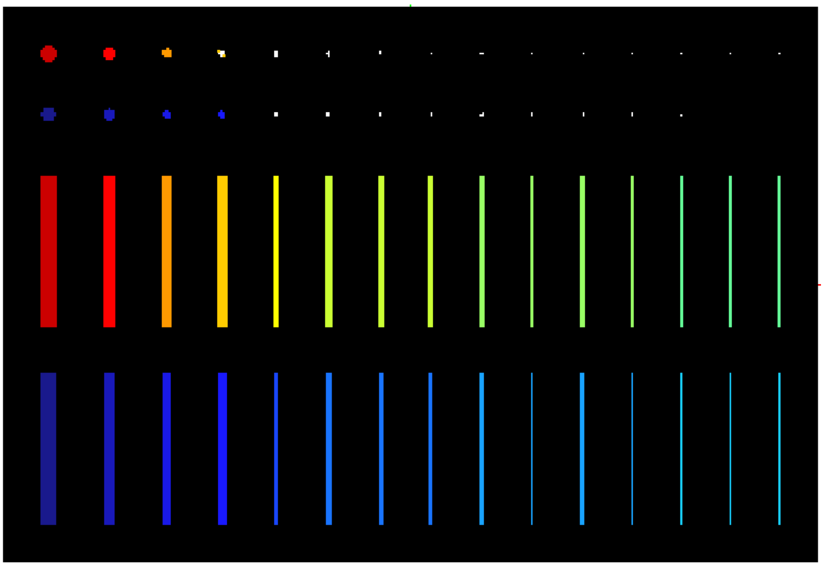
PC 1 *Graphic Card: NVIDIA PRO 2000*



PC 2 *Graphic Card: GeForce 560 Ti*



Test reference:	**3DFFTI_TC_6_350**
PC 3	*Graphic Card: Quadro M2000M*



Conclusion and notes:

- no significant differences between different PC in the display of the same 3D clouds

Test reference:	**3DFFTI_TC_6_300**				
Test name:	Visualization PC 1	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Visualization test of simulated 3D point clouds of the resolution specimen with different point pitch distances				

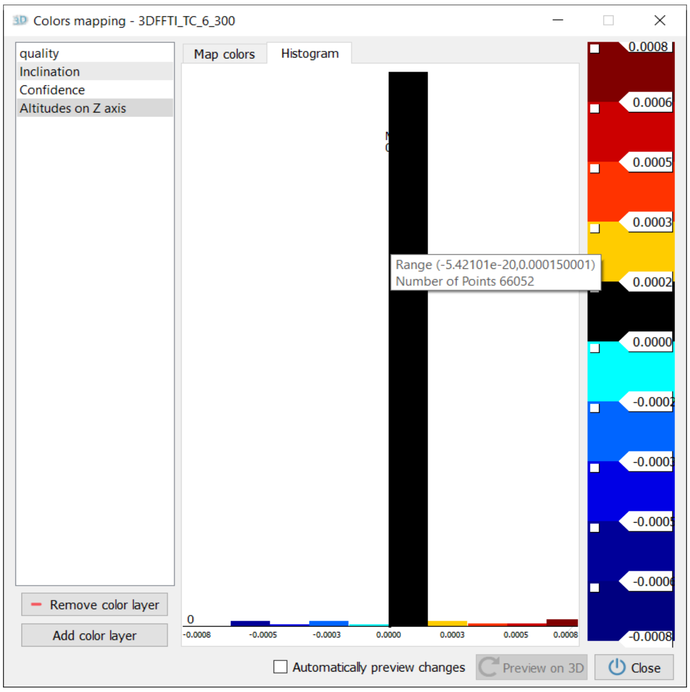
Test set-up:

- The project contains following point clouds:

1400 37.5 µm
700 75 µm
350 150 µm
300 175 µm
250 200 µm
200 260 µm

Test procedure

- the 6 simulates scans has been displayed in 3 different PC with different graphic characteristics
- the 6 simulates scans are rendered with height colour layer that is independent from material reflectivity



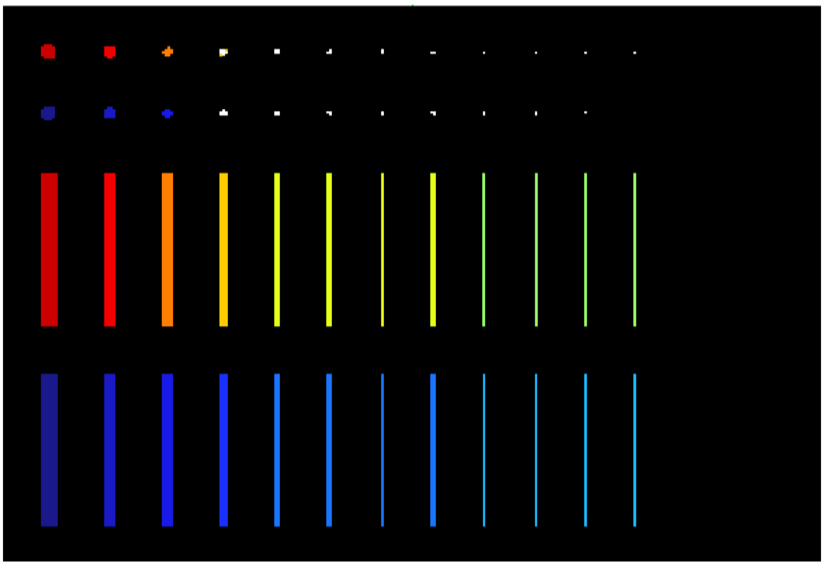
- the 6 simulates scans are rendered removing any light effects

Test reference:	3DFFTI_TC_6_300
Results:	

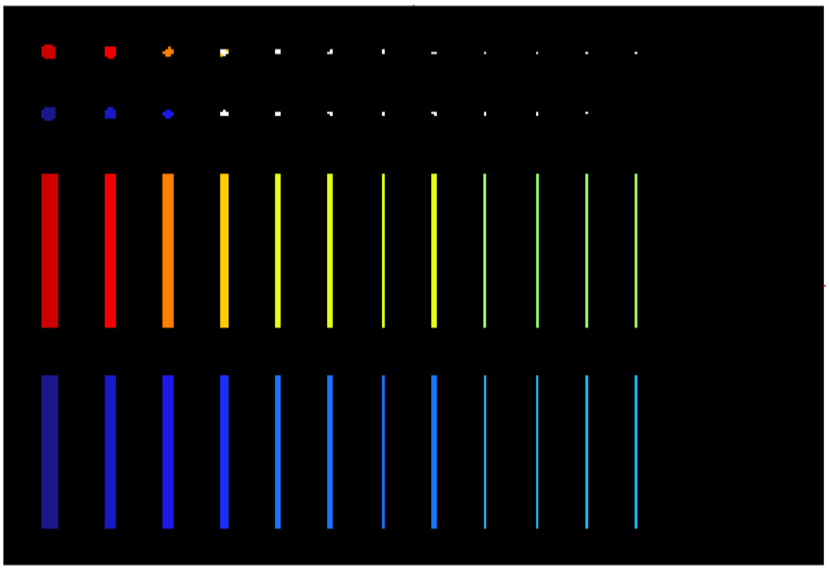
- the 6 simulated scans are visually compared in 3 different PCs

3DFFTI_TC_6_300

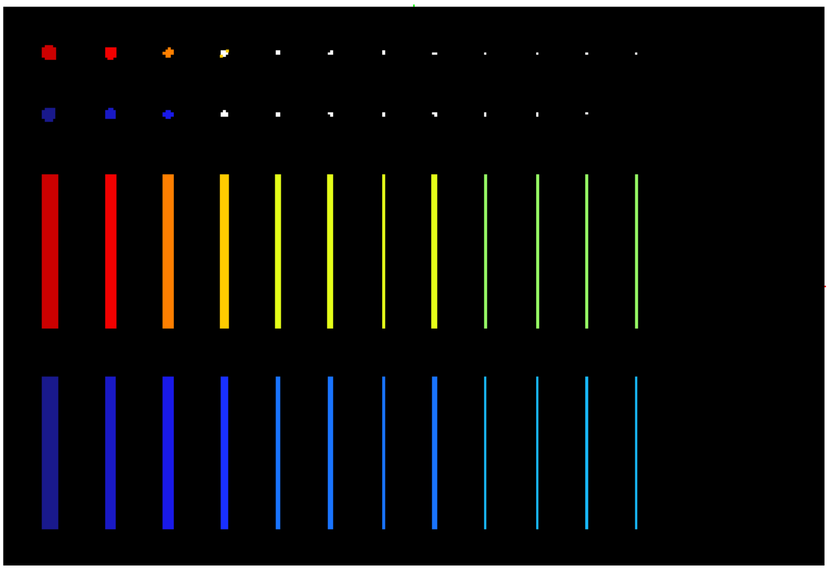
PC 1 *Graphic Card: NVIDIA PRO 2000*



PC 2 *Graphic Card: GeForce 560 Ti*



Test reference:	3DFFTI_TC_6_300
PC 3	*Graphic Card: Quadro M2000M*



Conclusion and notes:

- no significant differences between different PC in the display of the same 3D clouds

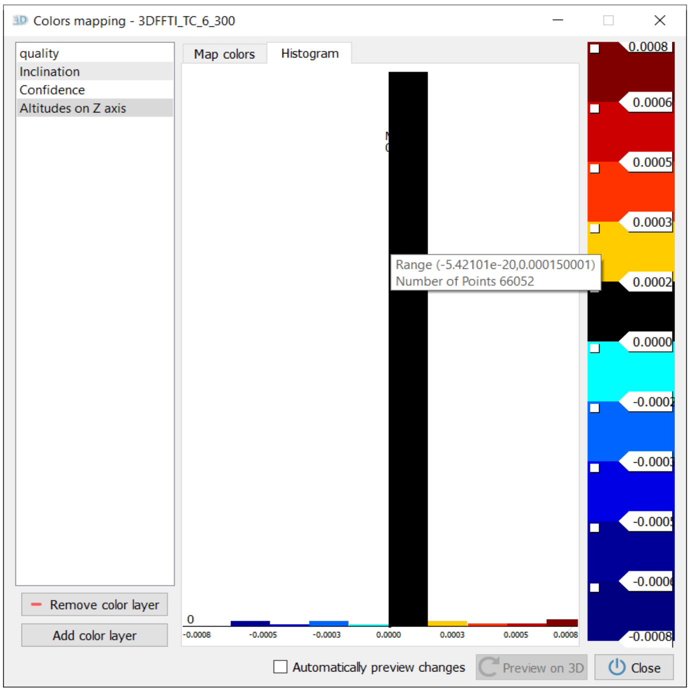
Test reference:	**3DFFTI_TC_6_250**				
Test name:	Visualization PC 1	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Visualization test of simulated 3D point clouds of the resolution specimen with different point pitch distances				

Test set-up:

- The project contains
following point clouds:
1400 37.5 µm
700 75 µm
350 150 µm
300 175 µm
250 200 µm
200 260 µm

Test procedure

- the 6 simulates scans has been displayed in 3 different PC with differend graphic characteristics
- the 6 simulates scans are rendered with height colour layer that is independent from material reflectivity



- the 6 simulates scans are rendered removing any light effects

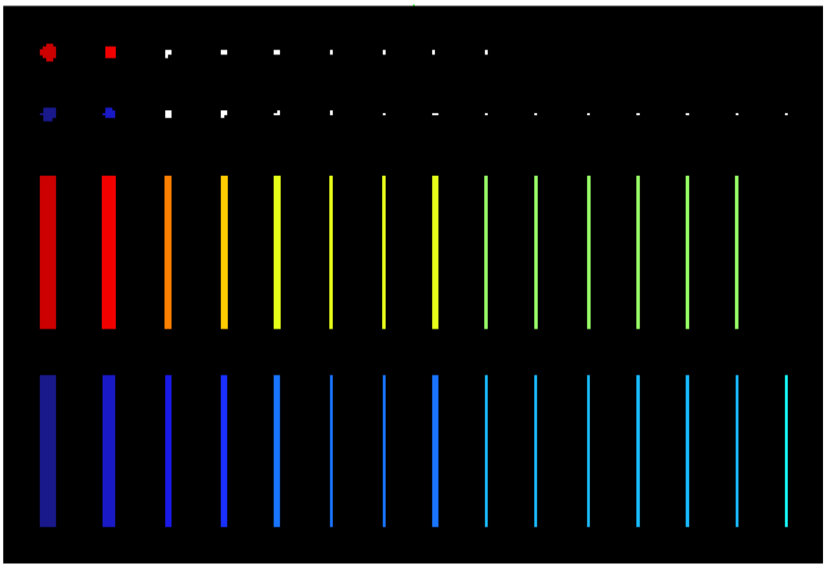
Test reference:	3DFFTI_TC_6_250

Results:

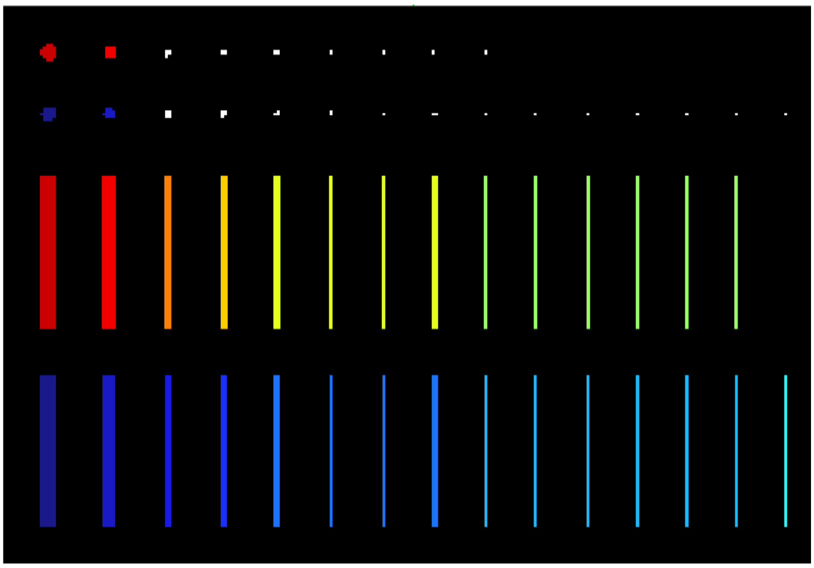
- the 6 simulated scans are visually compared in 3 different PCs

3DFFTI_TC_6_250

PC 1 *Graphic Card: NVIDIA PRO 2000*

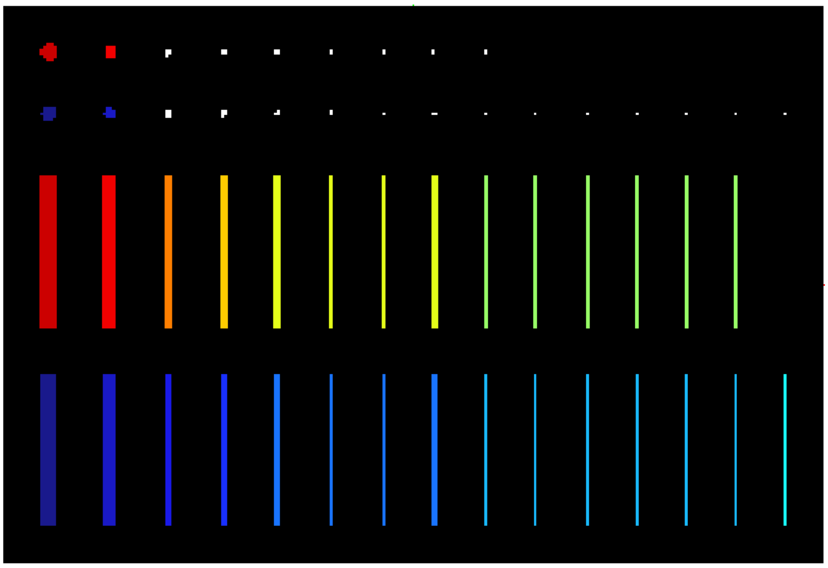


PC 2 *Graphic Card: GeForce 560 Ti*



Test reference: **3DFFTI_TC_6_250**

PC 3 *Graphic Card: Quadro M2000M*



Conclusion and notes:

- no significant differences between different PC in the display of the same 3D clouds

Test reference:	3DFFTI_TC_6_200				
Test name:	Visualization PC 1	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Visualization test of simulated 3D point clouds of the resolution specimen with different point pitch distances				

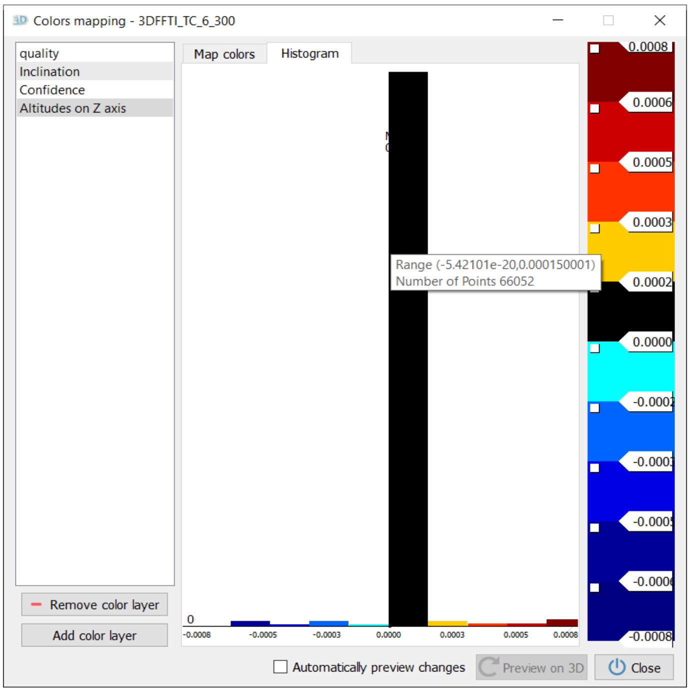
Test set-up:

- The project contains following point clouds:

1400 37.5 µm
700 75 µm
350 150 µm
300 175 µm
250 200 µm
200 260 µm

Test procedure

- the 6 simulates scans has been displayed in 3 different PC with different graphic characteristics
- the 6 simulates scans are rendered with height colour layer that is independent from material reflectivity



- the 6 simulates scans are rendered removing any light effects

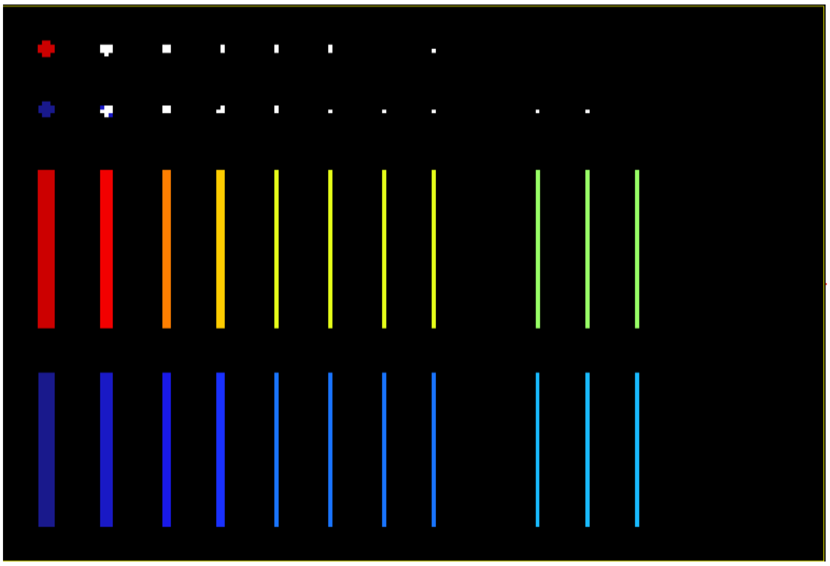
Test reference:	**3DFFTI_TC_6_200**

Results:

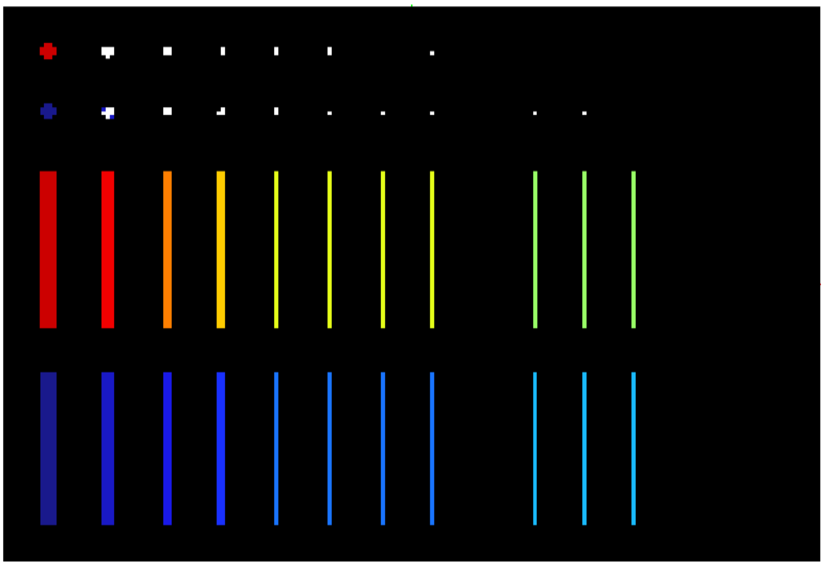
- the 6 simulated scans are visually compared in 3 different PCs

3DFFTI_TC_6_200

PC 1 *Graphic Card: NVIDIA PRO 2000*

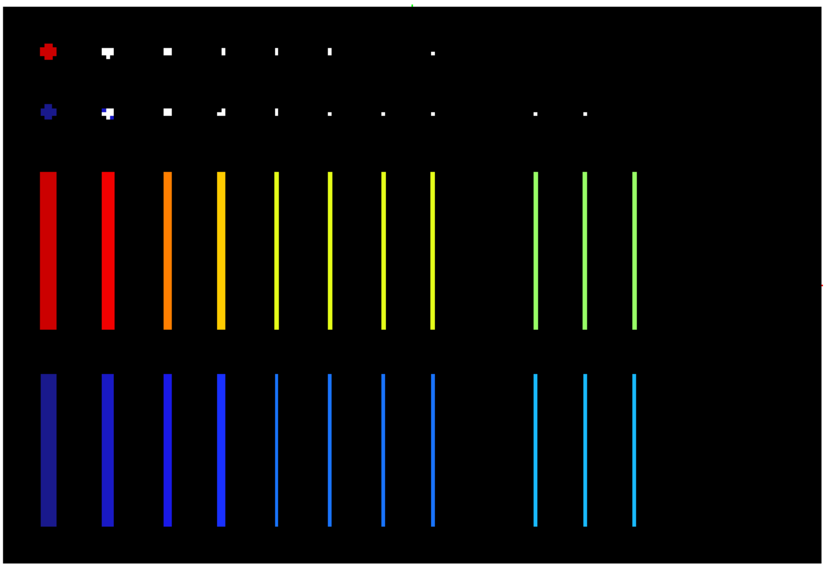


PC 2 *Graphic Card: GeForce 560 Ti*



Test reference: **3DFFTI_TC_6_200**

PC 3 *Graphic Card: Quadro M2000M*



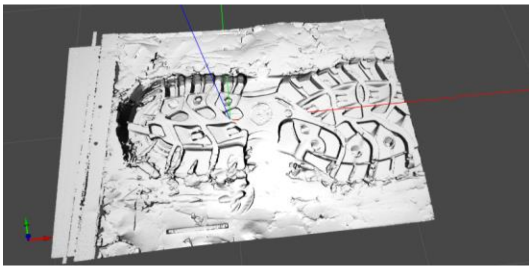
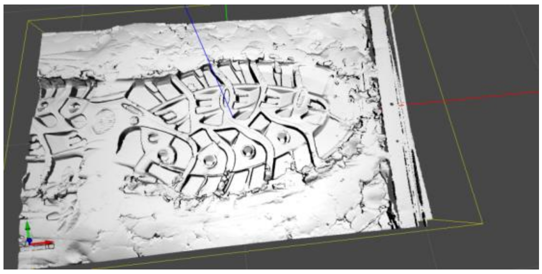
Conclusion and notes:

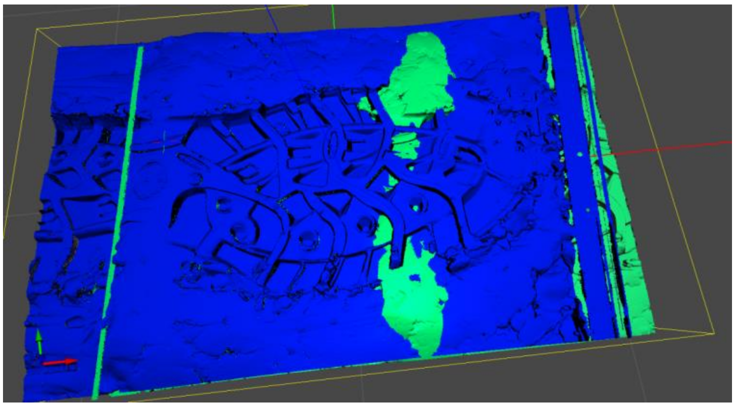
- no significant differences between different PC in the display of the same 3D clouds

Test reference:	**3DFFTI_TC_7_Registration_1**				
Test name:	Alignment of 2 scan in one impression	**Location:**	EETG YHP	**Date:**	Dec 2018
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that "affect the result"				

Test set-up:

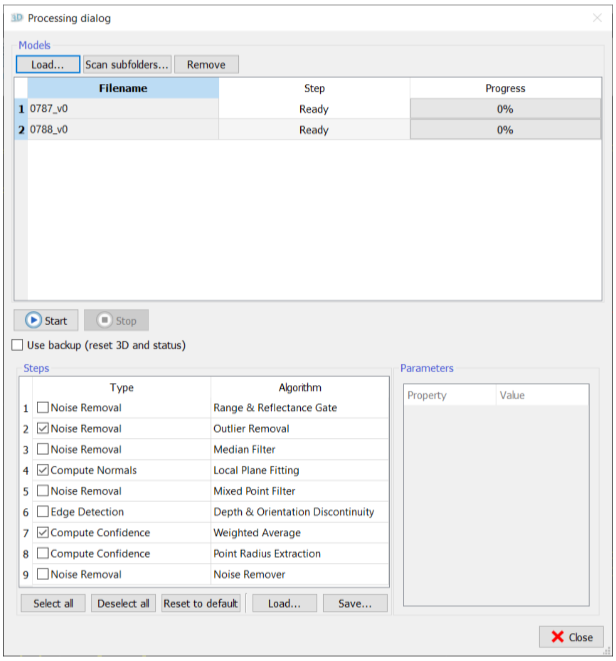
- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)



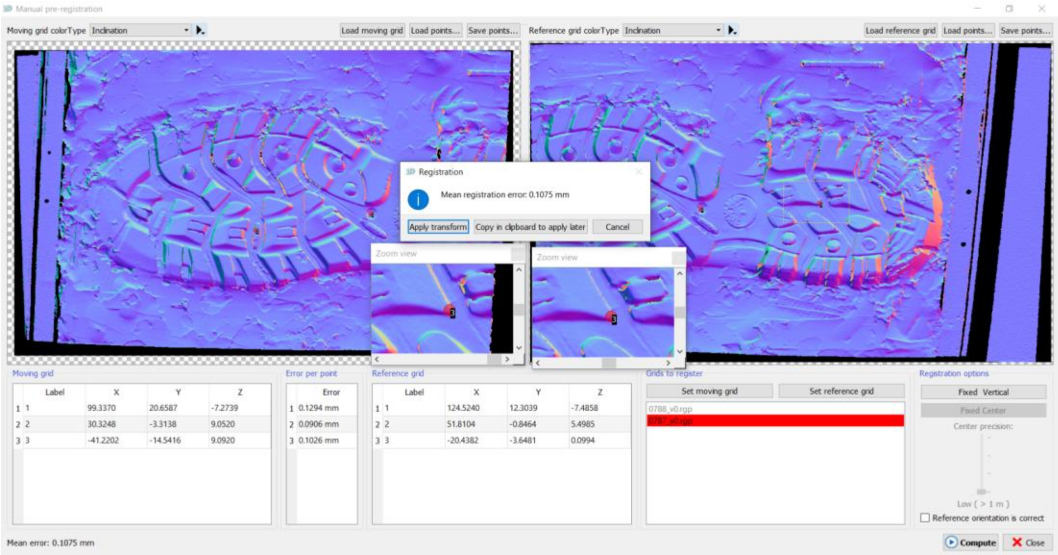
Test procedure

- preprocess the 2 scans with default parameters

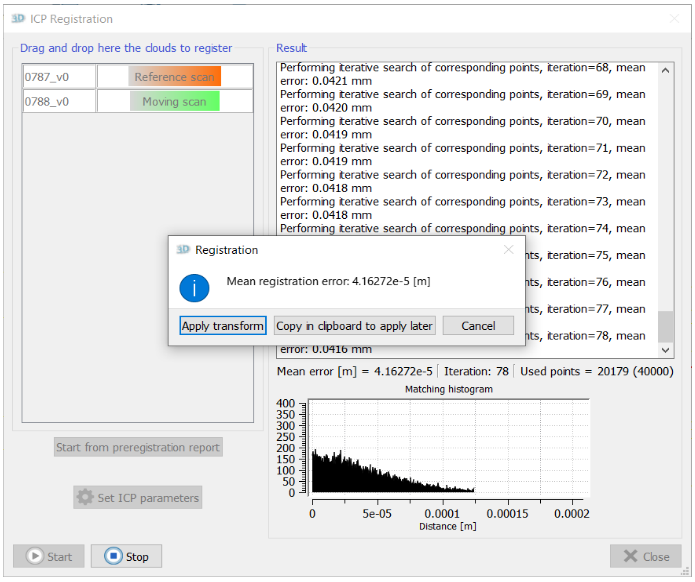


Test reference: **3DFFTI_TC_7_Registration_1**

- manual preregistration by selecting 3 common points



- ICP automatic registration



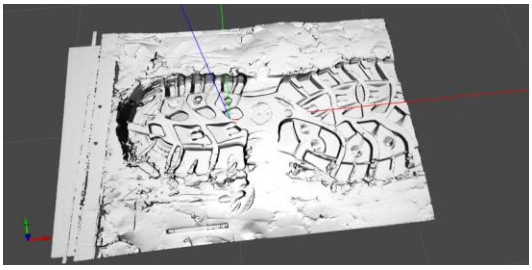
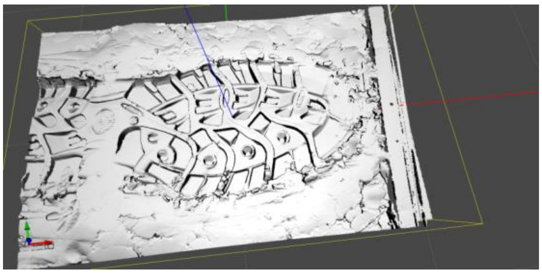
Test reference:	3DFFTI_TC_7_Registration_1	
Results:		
- Starting preregistration error (user interaction)	0.1075	mm
- final registration error after ICP automatic fine registration	$4{,}16 \times 10^{-2}$	mm
Conclusion and notes:		

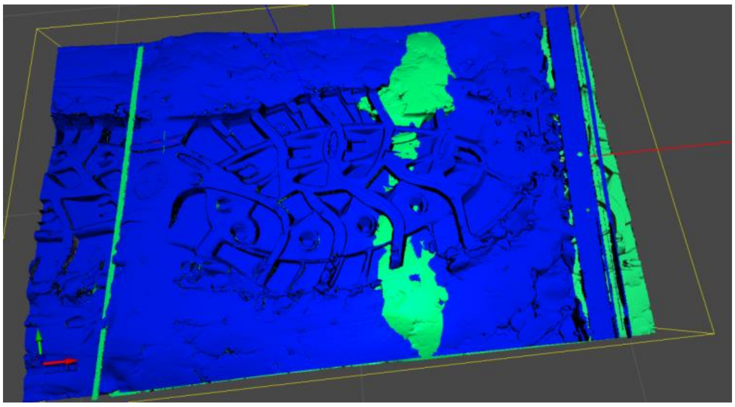
-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

Test reference:	3DFFTI_TC_7_Registration_2				
Test name:	Alignment of 2 scan in one impression	**Location:**	EETG RIS	**Date:**	May 2019
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that "affect the result"				

Test set-up:

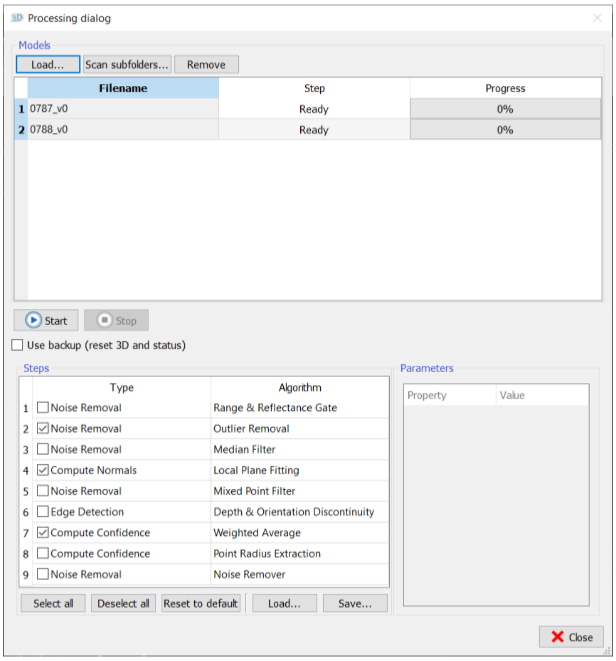
- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)



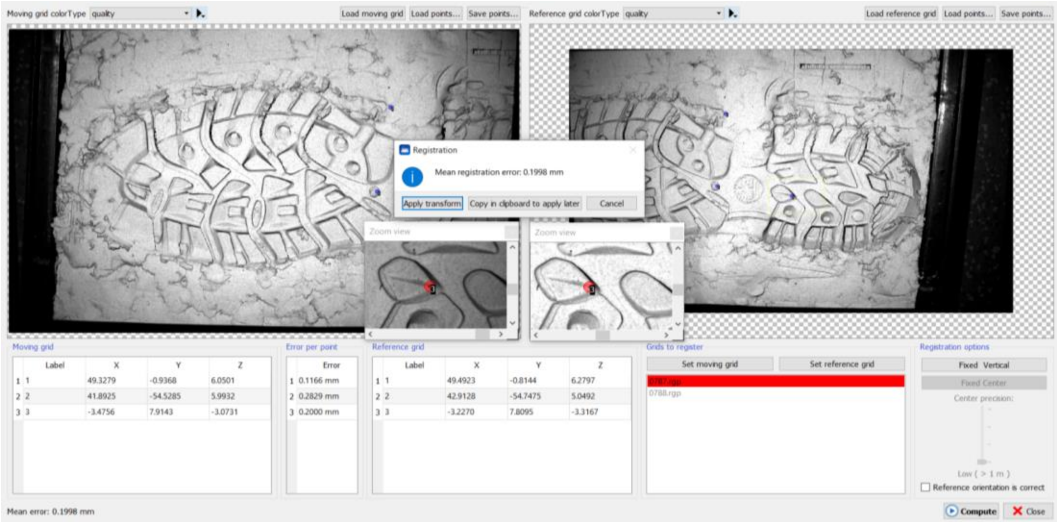
Test procedure

- preprocess the 2 scans with default parameters

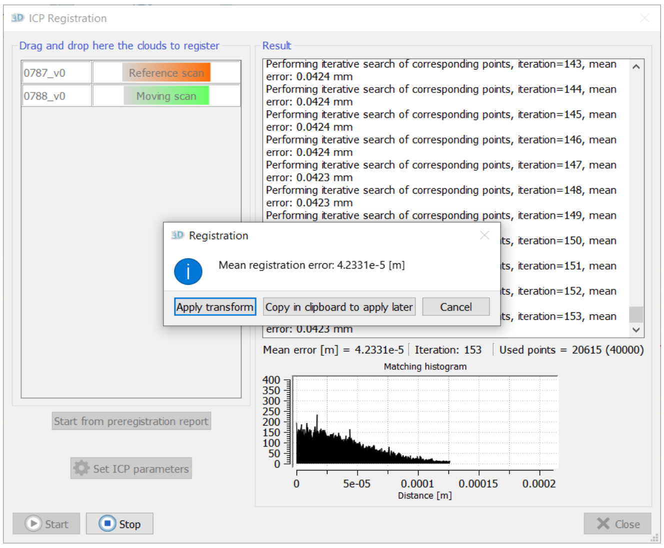


Test reference:	3DFFTI_TC_7_Registration_2

- manual preregistration by selecting 3 common points



- ICP automatic registration

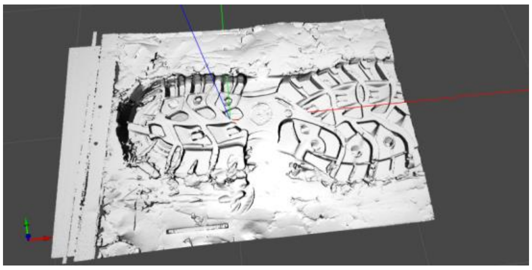


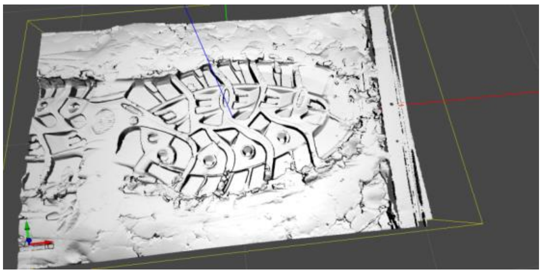
Test reference:	3DFFTI_TC_7_Registration_2	
Results:		
- Starting preregistration error (user interaction)	0.1998	mm
- final registration error after ICP automatic fine registration	$4{,}23 \times 10^{-2}$	mm
Conclusion and notes:		
-The alignment of point clouds results in no visible transition border. -The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment). -Alignment is stable. -Alignment is independent from user. -The point clouds require low overlapping area. -The resulting deviation of the alignment is logged. / Error resistance		

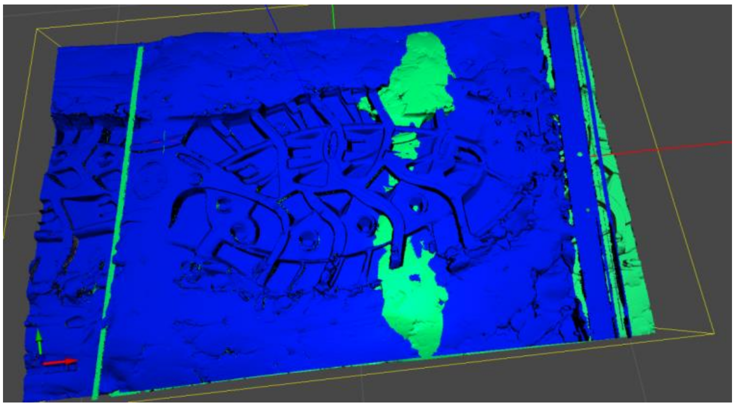
Test reference:	3DFFTI_TC_7_Registration_3				
Test name:	Alignment of 2 scan in one impression	**Location:**	GEX, Brescia	**Date:**	May 2019
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that “affect the result”				

Test set-up:

- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)

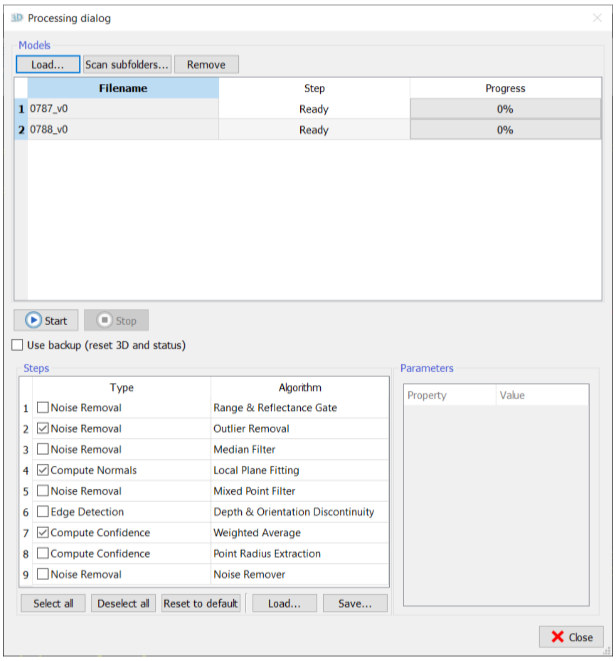






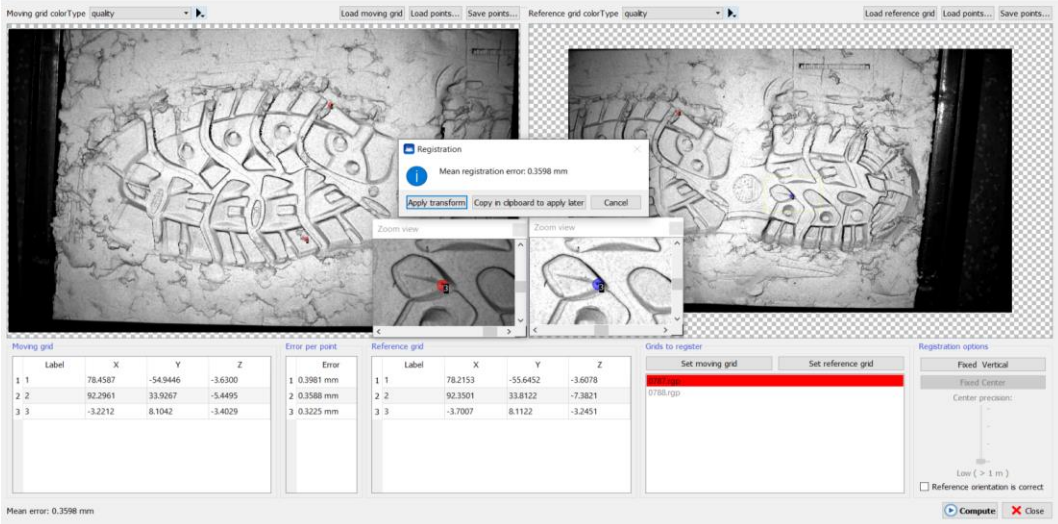
Test procedure

- preprocess the 2 scans with default parameters

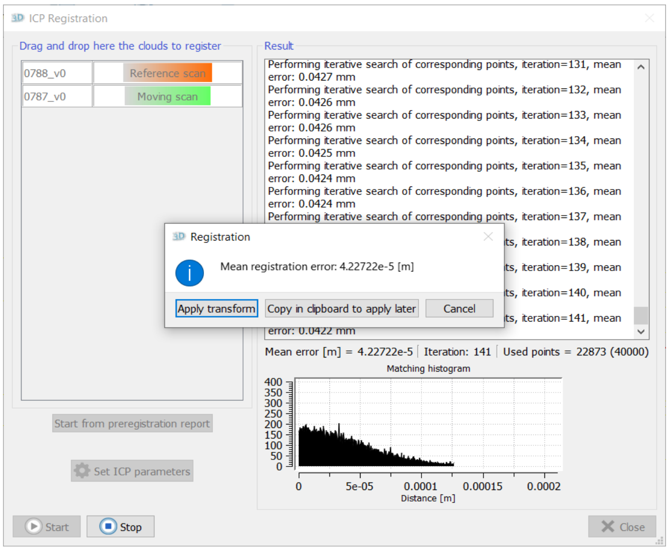


Test reference:	3DFFTI_TC_7_Registration_3

- manual preregistration by selecting 3 common points



- ICP automatic registration



Test reference: **3DFFTI_TC_7_Registration_3**

Results:

- Starting preregistration error (user interaction)	0.3598	mm
- final registration error after ICP automatic fine registration	$4,22 \times 10^{-2}$	mm

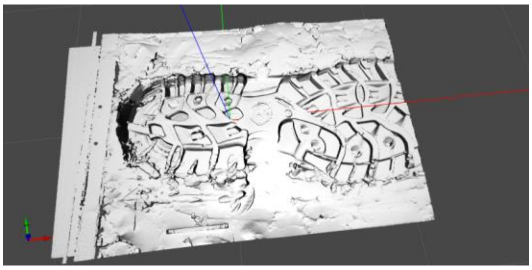
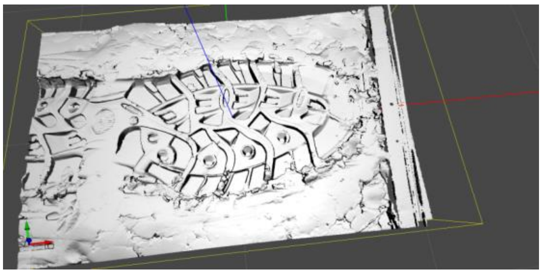
Conclusion and notes:

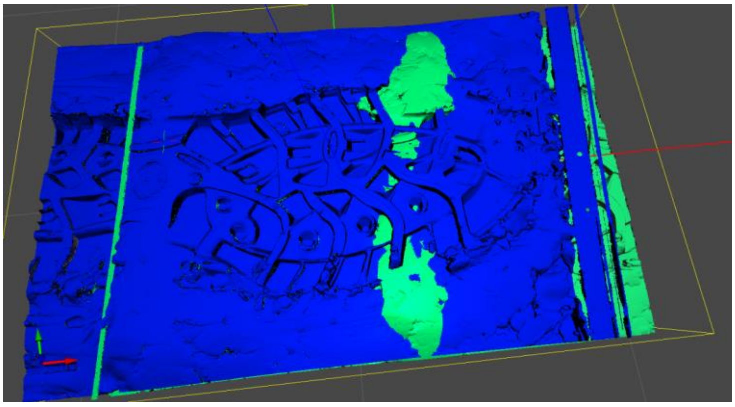
-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

Test reference:	**3DFFTI_TC_7_Registration_4**				
Test name:	Alignment of 2 scan in one impression	**Location:**	EETG YHP	**Date:**	Dec 2018
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that “affect the result”				

Test set-up:

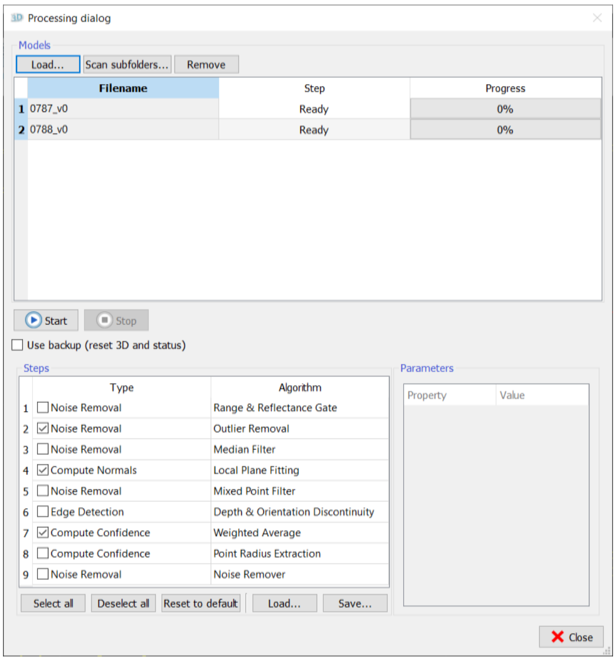
- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)



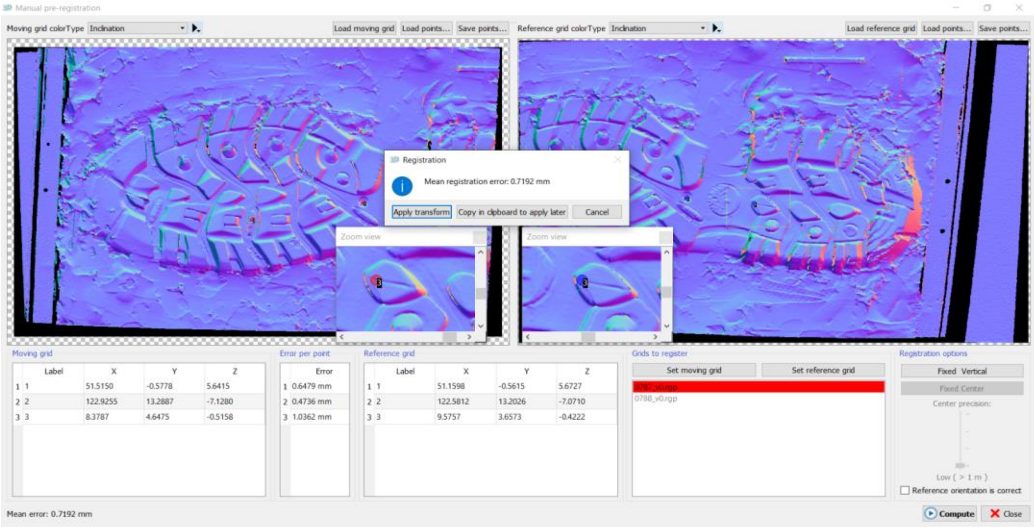
Test procedure

- preprocess the 2 scans with default parameters

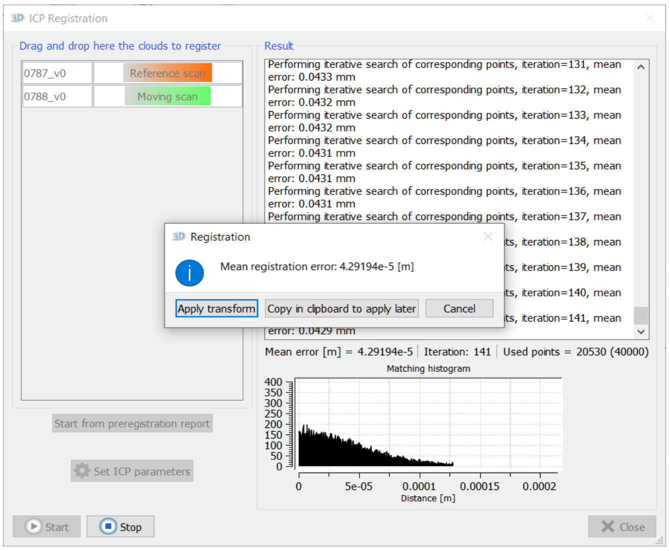


Test reference: 3DFFTI_TC_7_Registration_4

- manual preregistration by selecting 3 common points



- ICP automatic registration



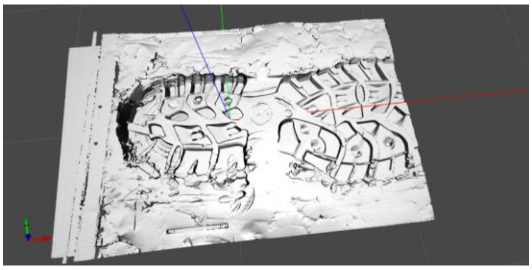
Test reference:	3DFFTI_TC_7_Registration_4	
Results:		
- Starting preregistration error (user interaction)	0.7192	mm
- final registration error after ICP automatic fine registration	4,29 x 10^{-2}	mm
Conclusion and notes:		

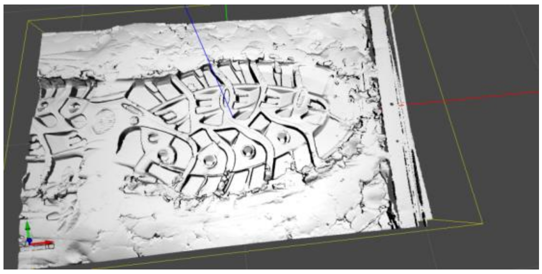
-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

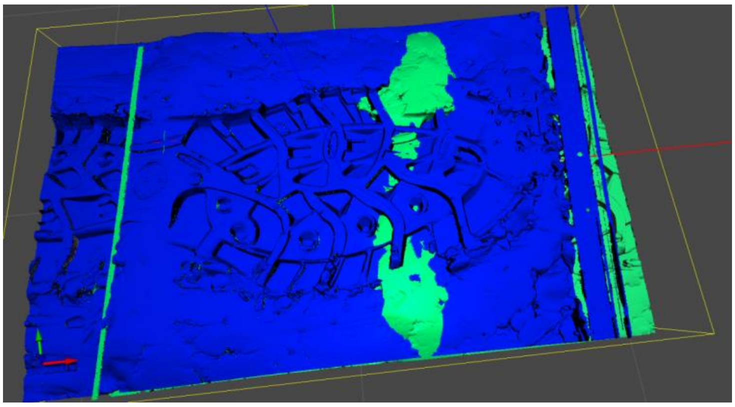
Test reference:	**3DFFTI_TC_7_Registration_5**				
Test name:	Alignment of 2 scan in one impression	**Location:**	GEX, Brescia	**Date:**	May 2019
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that “affect the result”				

Test set-up:

- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)

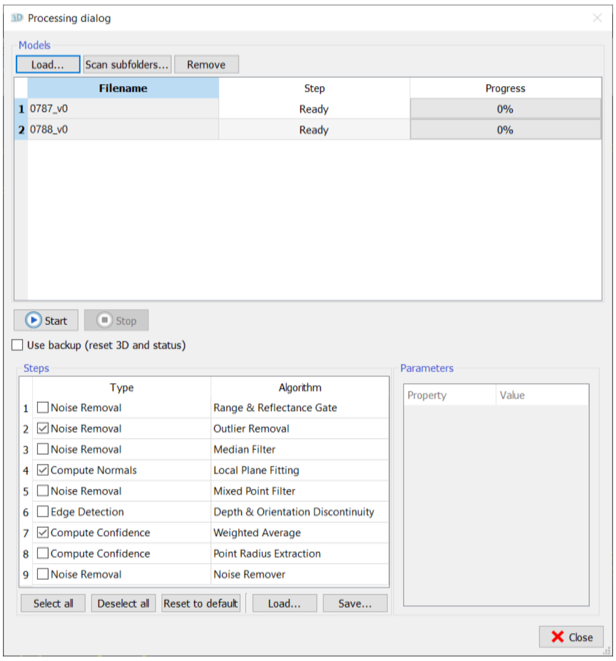






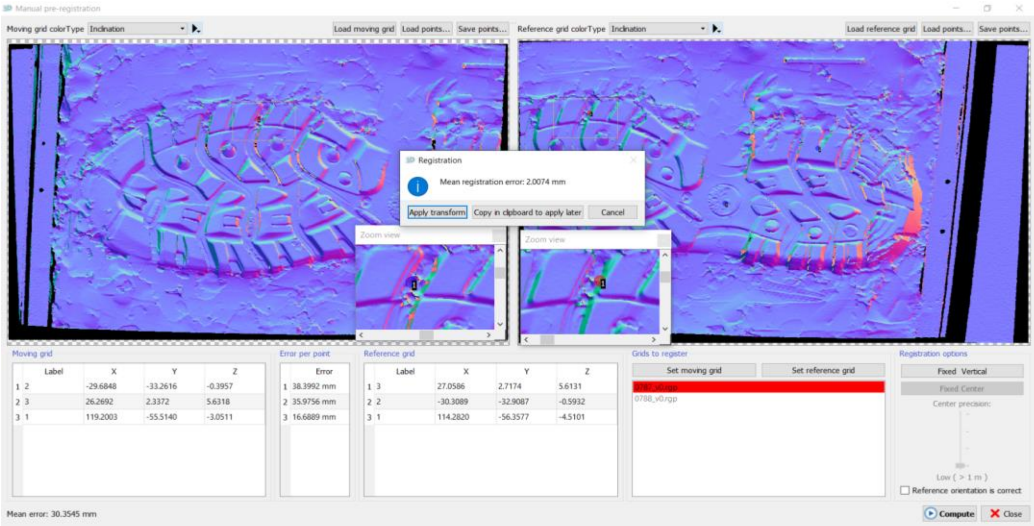
Test procedure

- preprocess the 2 scans with default parameters

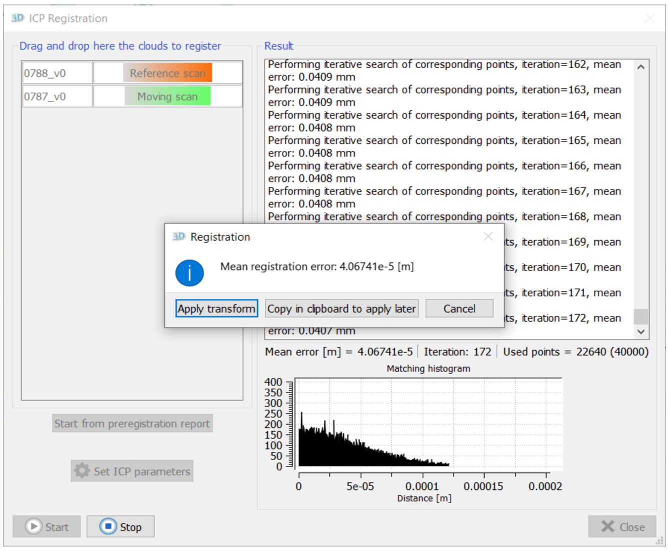


Test reference: 3DFFTI_TC_7_Registration_5

- manual preregistration by selecting 3 common points



- ICP automatic registration



Test reference:	**3DFFTI_TC_7_Registration_5**	
Results:		
- Starting preregistration error (user interaction)	2.074	mm
- final registration error after ICP automatic fine registration	$4{,}06 \times 10^{-2}$	mm

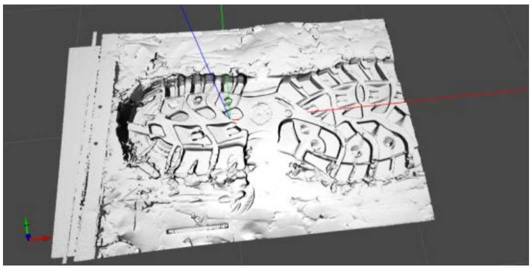
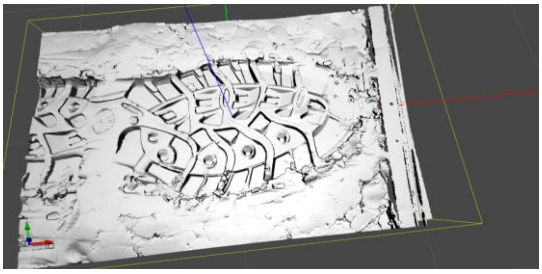
Conclusion and notes:

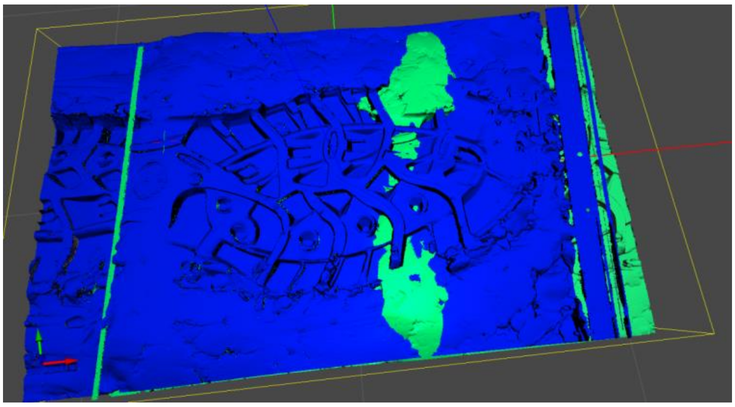
-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

Test reference:	**3DFFTI_TC_7_Registration_6**				
Test name:	Alignment of 2 scan in one impression	**Location:**	GEX, Brescia	**Date:**	May 2019
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that "affect the result"				

Test set-up:

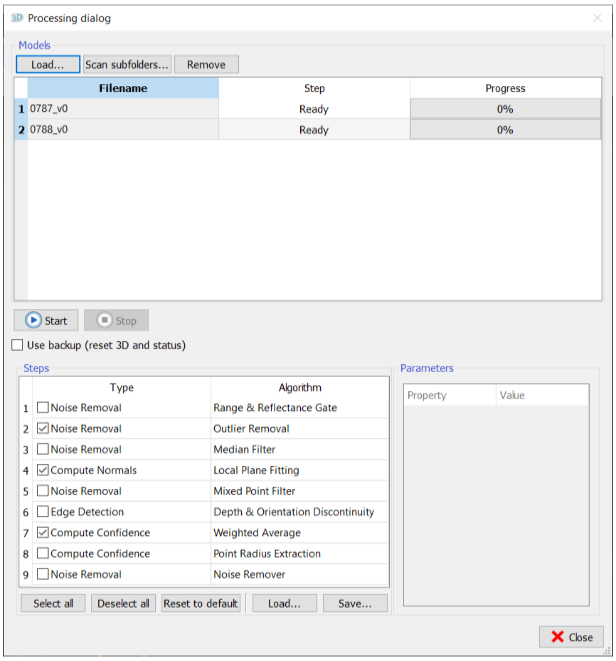
- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)



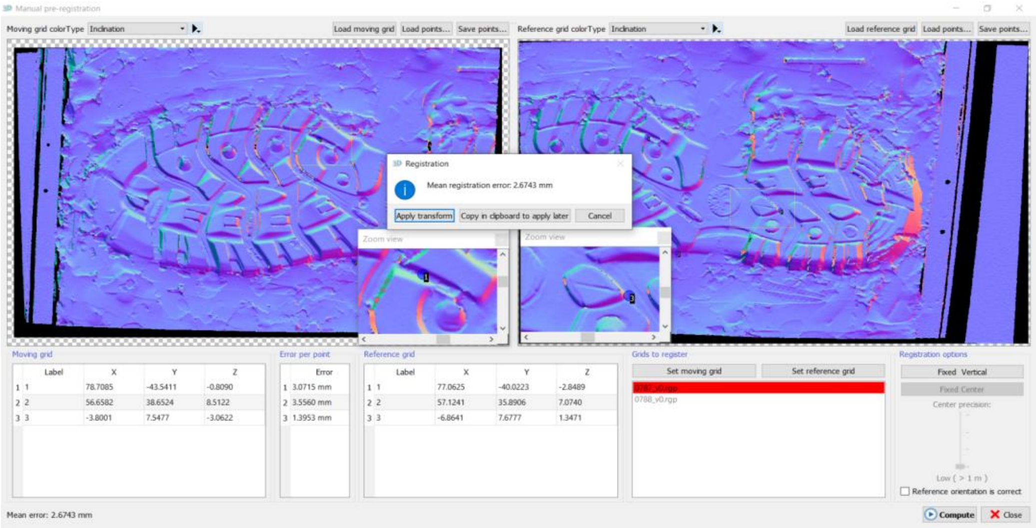
Test procedure

- preprocess the 2 scans with default parameters

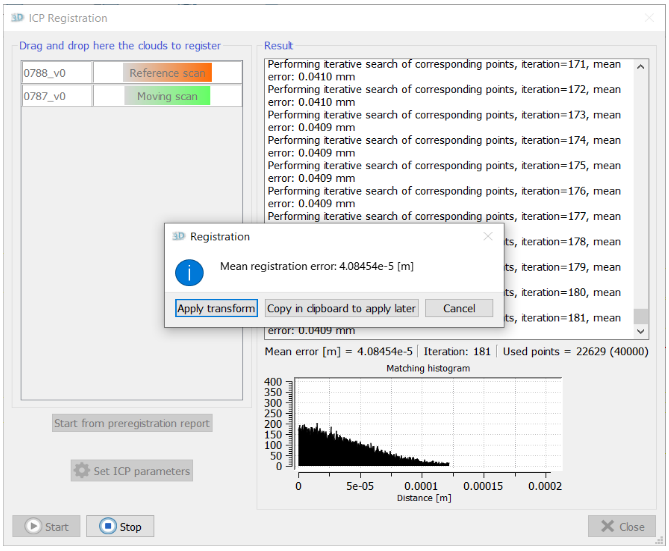


Test reference: **3DFFTI_TC_7_Registration_6**

- manual preregistration by selecting 3 common points



- ICP automatic registration



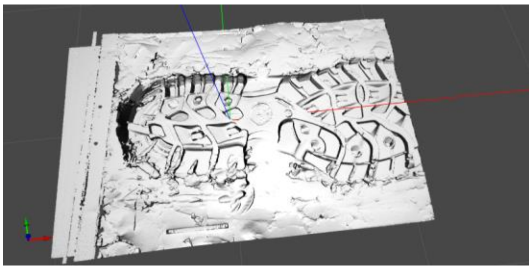
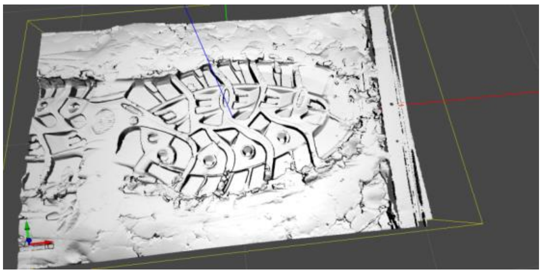
Test reference:	3DFFTI_TC_7_Registration_6	
Results:		
- Starting preregistration error (user interaction)	2.674	mm
- final registration error after ICP automatic fine registration	$4{,}08 \times 10^{-2}$	mm
Conclusion and notes:		

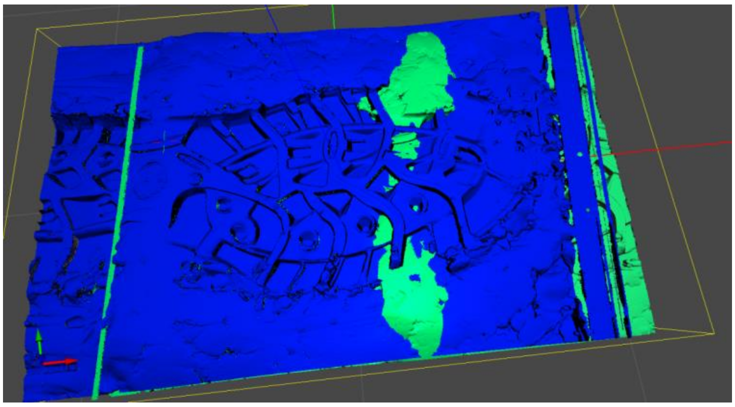
-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

Test reference:	3DFFTI_TC_7_Registration_7				
Test name:	Alignment of 2 scan in one impression	**Location:**	GEX, Brescia	**Date:**	May 2019
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that “affect the result”				

Test set-up:

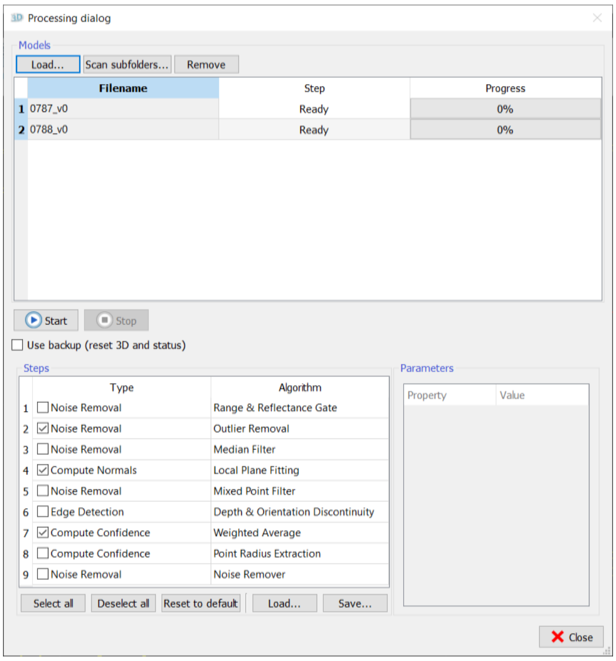
- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)



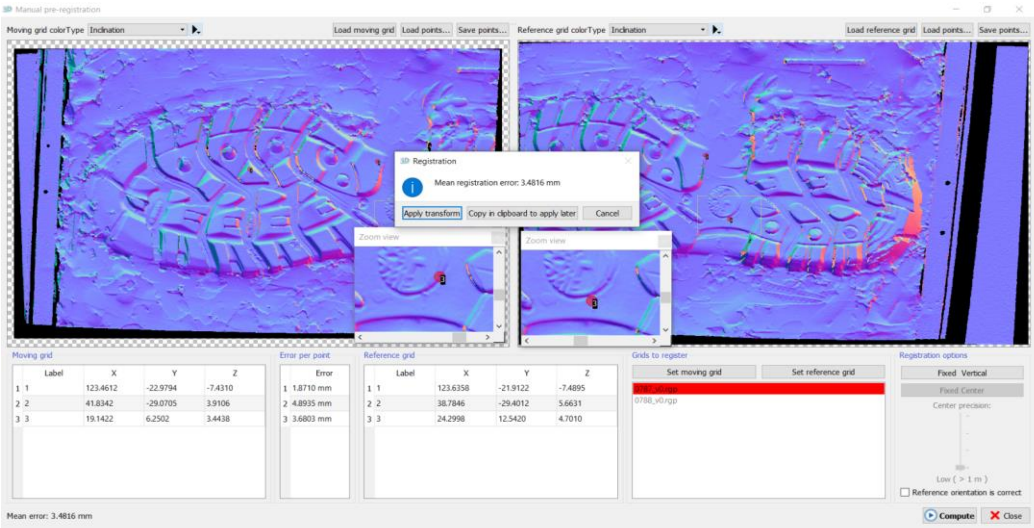
Test procedure

- preprocess the 2 scans with default parameters

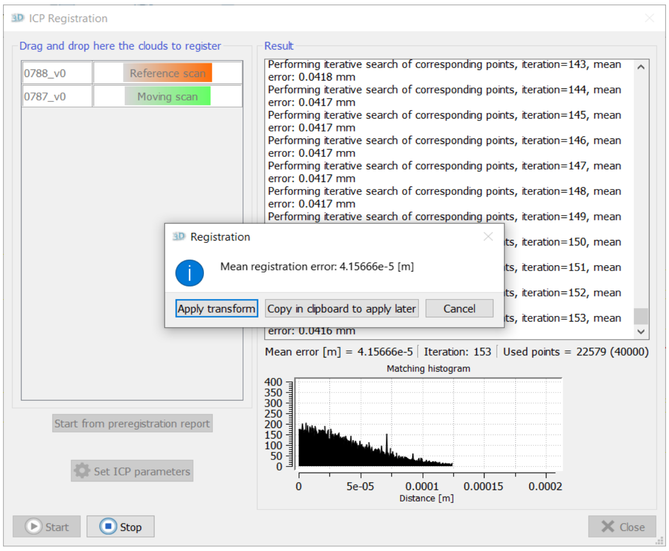


Test reference:	3DFFTI_TC_7_Registration_7

- manual preregistration by selecting 3 common points



- ICP automatic registration



Test reference: **3DFFTI_TC_7_Registration_7**

Results:

- Starting preregistration error (user interaction)	3.481	mm
- final registration error after ICP automatic fine registration	$4,15 \times 10^{-2}$	mm

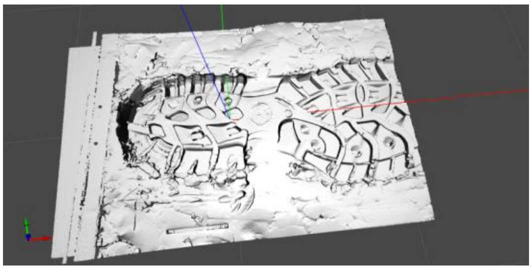
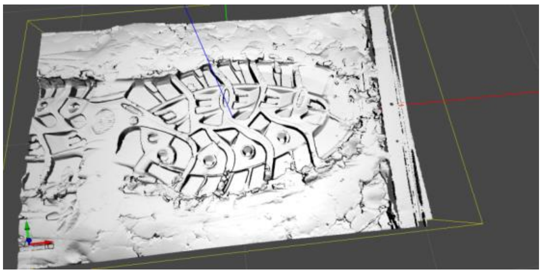
Conclusion and notes:

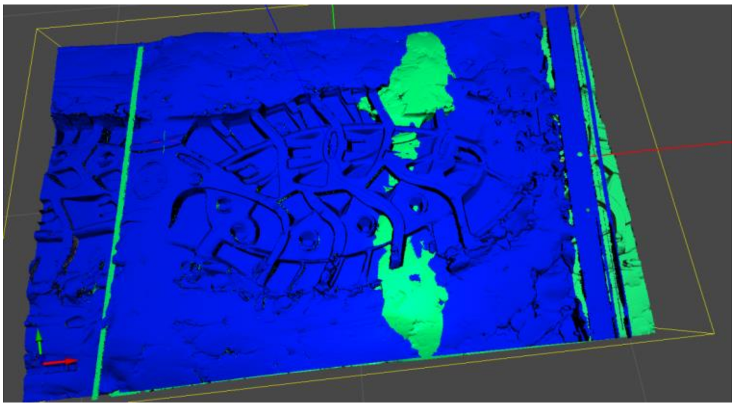
-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

Test reference:	**3DFFTI_TC_7_Registration_8**				
Test name:	Alignment of 2 scan in one impression	**Location:**	GEX, Brescia	**Date:**	May 2019
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that “affect the result”				

Test set-up:

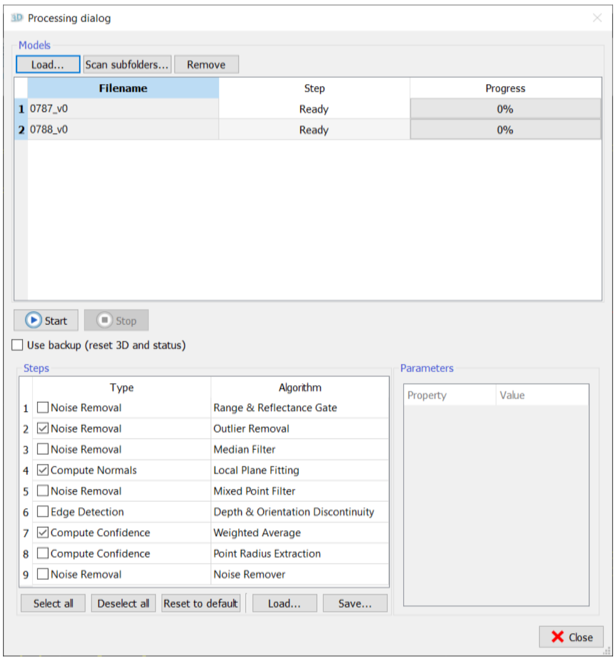
- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)



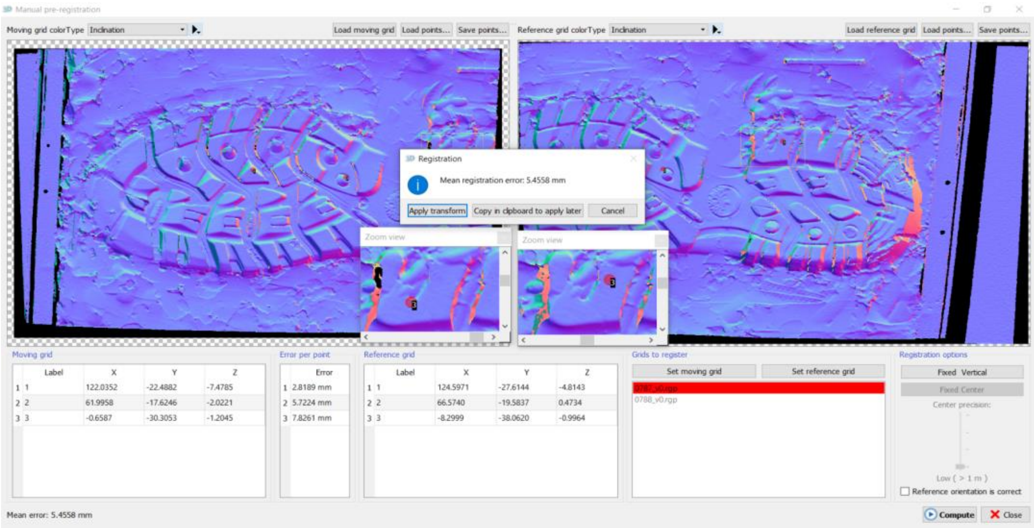
Test procedure

- preprocess the 2 scans with default parameters

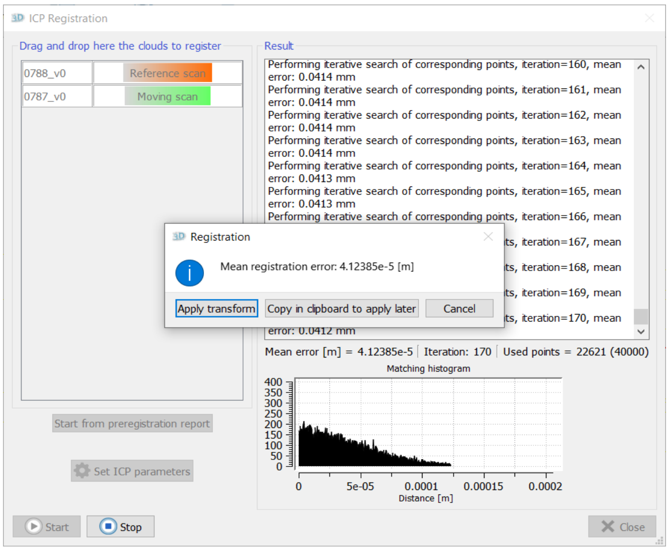


Test reference: 3DFFTI_TC_7_Registration_8

- manual preregistration by selecting 3 common points



- ICP automatic registration



Test reference:	**3DFFTI_TC_7_Registration_8**	
Results:		
- Starting preregistration error (user interaction)	5.455	mm
- final registration error after ICP automatic fine registration	$4{,}12 \times 10^{-2}$	mm

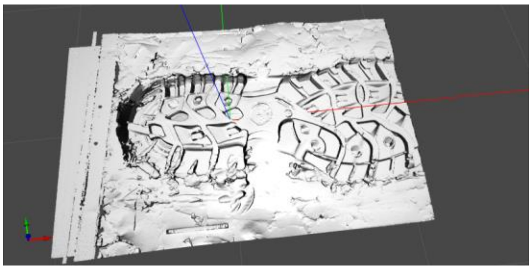
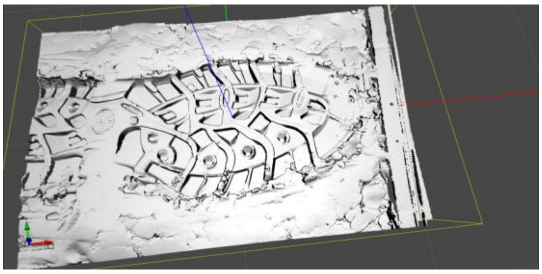
Conclusion and notes:

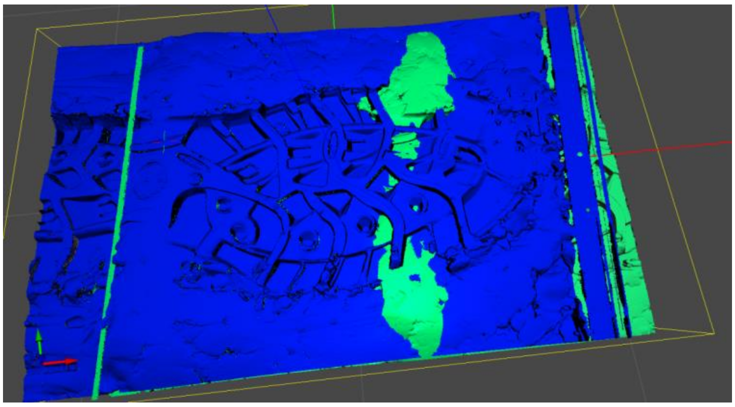
-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

Test reference:	**3DFFTI_TC_7_Registration_9**				
Test name:	Alignment of 2 scan in one impression	**Location:**	GEX, Brescia	**Date:**	May 2019
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that “affect the result”				

Test set-up:

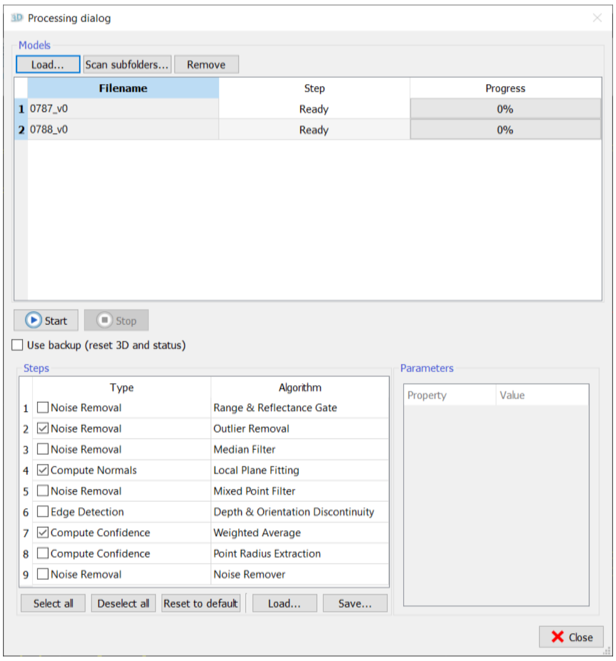
- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)



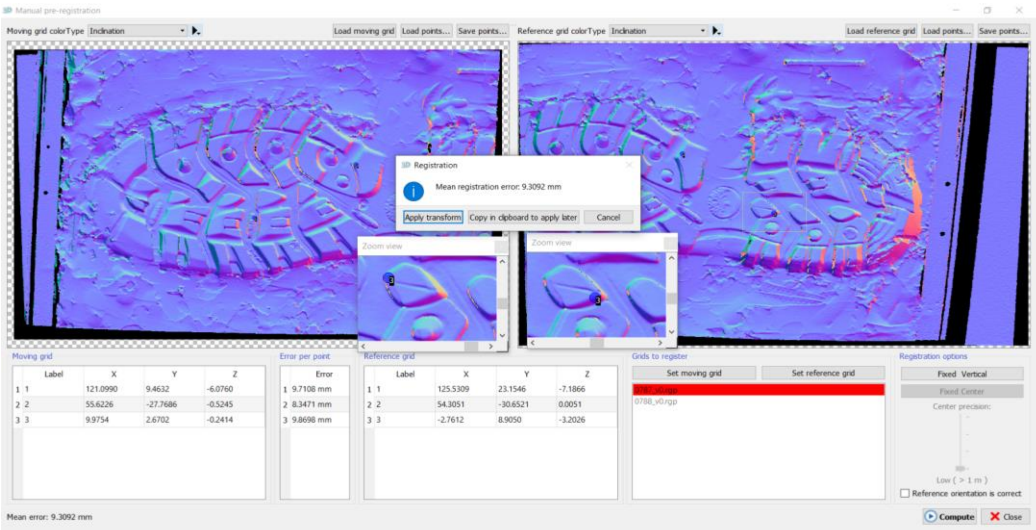
Test procedure

- preprocess the 2 scans with default parameters

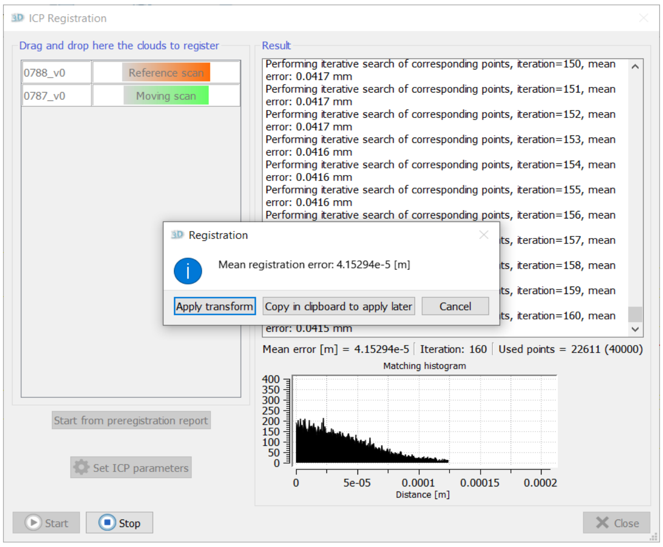


Test reference: 3DFFTI_TC_7_Registration_9

- manual preregistration by selecting 3 common points



- ICP automatic registration



Test reference: **3DFFTI_TC_7_Registration_9**

Results:

- Starting preregistration error (user interaction)	9.309	mm
- final registration error after ICP automatic fine registration	$4{,}15 \times 10^{-2}$	mm

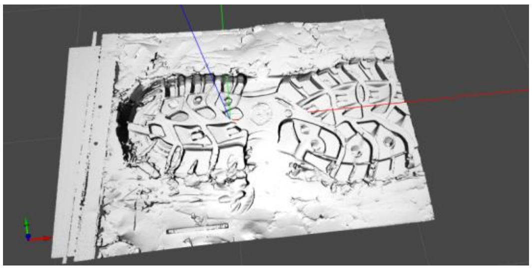
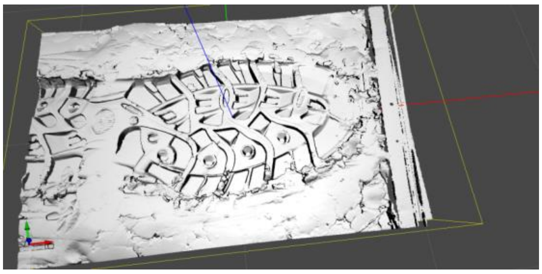
Conclusion and notes:

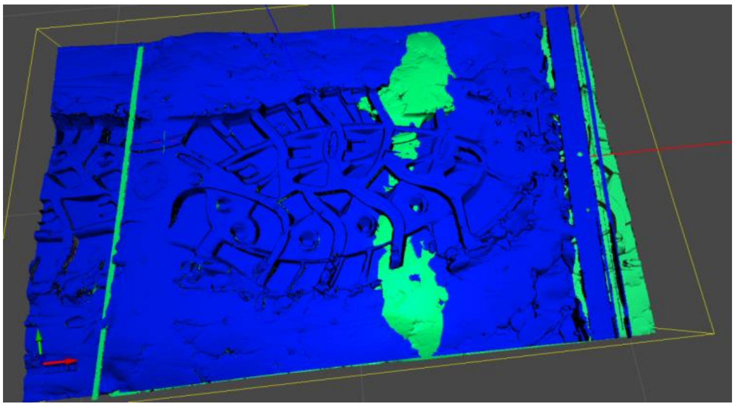
-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

Test reference:	3DFFTI_TC_7_Registration_10				
Test name:	Alignment of 2 scan in one impression	Location:	GEX, Brescia	Date:	May 2019
Tested requirements:	Registration tool: end user requirements were determined for the registration tool, with focus on those that “affect the result”				

Test set-up:

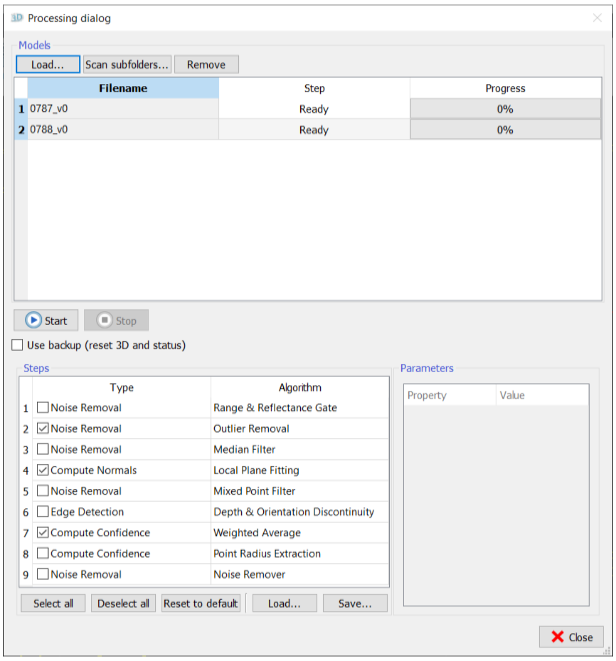
- 2 scans of a shoe impressions (2 portions)
- import the 2 scans in the 3D Forensic analysis software (not aligned)



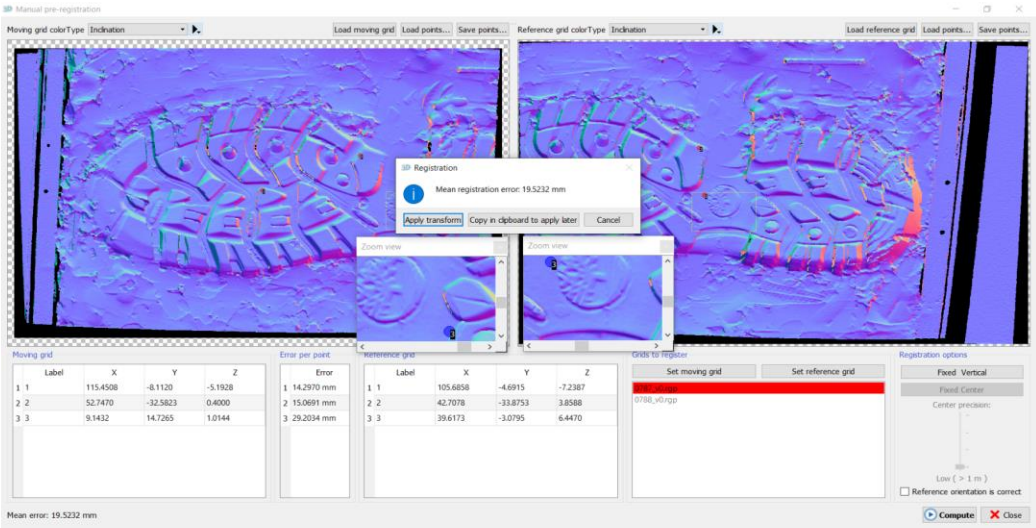
Test procedure

- preprocess the 2 scans with default parameters

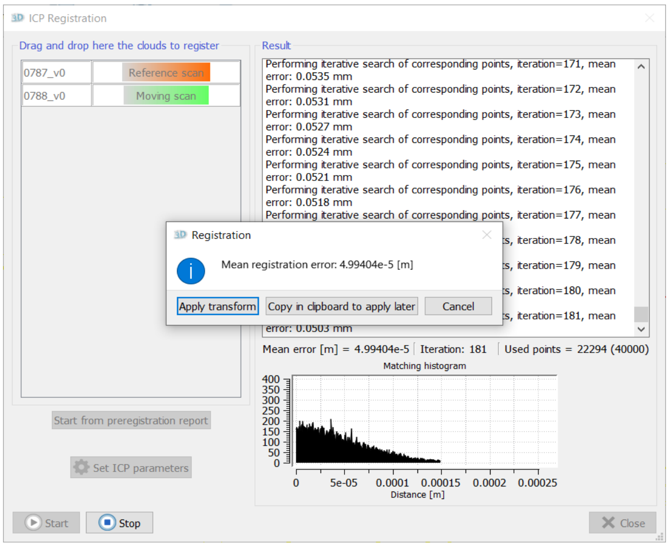


Test reference:	3DFFTI_TC_7_Registration_10

- manual preregistration by selecting 3 common points



- ICP automatic registration



Test reference: **3DFFTI_TC_7_Registration_10**

Results:

- Starting preregistration error (user interaction)	19.523	mm
- final registration error after ICP automatic fine registration	$4{,}99 \times 10^{-2}$	mm

Conclusion and notes:

-The alignment of point clouds results in no visible transition border.
-The resistance to small variations in method parameters and environmental conditions (e.g. manual pre-alignment).
-Alignment is stable.
-Alignment is independent from user.
-The point clouds require low overlapping area.
-The resulting deviation of the alignment is logged. / Error resistance

Results (3DFFTI_TC7_Registration_Results):

	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5	TEST 6	TEST 7	TEST 8	TEST 9	TEST 10
- Starting preregistration error (user interaction) - mm	0.1075	0.1998	0.3598	0.7192	2.074	2.674	3.481	5.455	9.309	19.523
- final registration error after ICP automatic fine registration - mm	4,16 x 10-2	4,23 x 10-2	4,22 x 10-2	4,29 x 10-2	4,06x 10-2	4,08 x 10-2	4,15 x 10-2	4,12 x 10-2	4,15 x 10-2	4,99 x 10-2

- reproducibility [TEST 1 … TEST 4] mean registration error	4.23 $\times 10^{-2}$	mm
- reproducibility [TEST 1 … TEST 4] standard deviation of registration errors	0.05 $\times 10^{-2}$	mm
- reproducibility [TEST 1 … TEST 4] minimum deviation of registration errors	4.16 $\times 10^{-2}$	mm
- reproducibility [TEST 1 … TEST 4] maximum deviation of registration errors	4.29 $\times 10^{-2}$	mm
- robustness [TEST 1 … TEST 10] mean registration error	4.25 $\times 10^{-2}$	mm
- robustness [TEST 1 … TEST 10] standard deviation of registration errors	0.27 $\times 10^{-2}$	mm
- robustness [TEST 1 … TEST 10] minimum deviation of registration errors	4.06 $\times 10^{-2}$	mm
- robustness [TEST 1 … TEST 10] maximum deviation of registration errors	4.99 $\times 10^{-2}$	mm

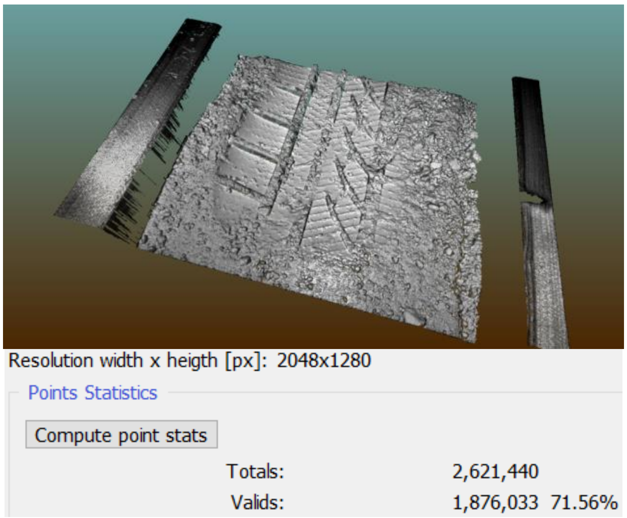
Conclusion and notes:

- 10 registration process are listed according to increased pre-registration error
-the ICP registration is robust to the manual pre-registration error
-for TEST 10 the pre-registration error is largely visible (see picture below) but nevertheless the fine ICP registration converges

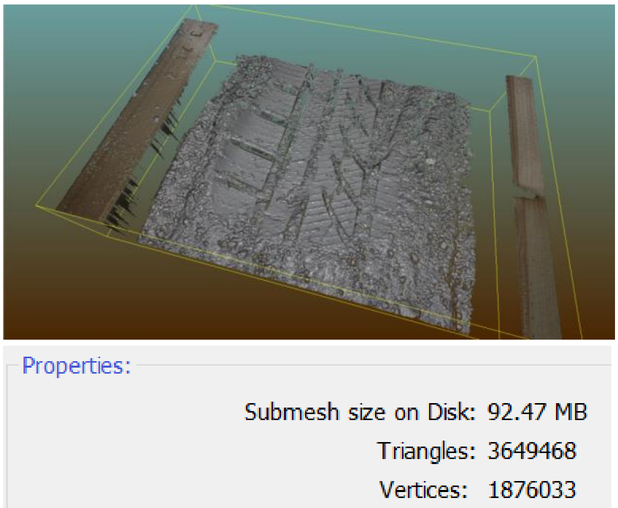
Test reference:	**3DFFTI_TC_8_Meshing_1**				
Test name:	Meshing of 3D points	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Meshing accuracy: the meshing of point clouds results does not change the measurement data. No deviation between mesh and point cloud				

Test set-up:

- 3D scan of a tire impression (portion)
- impression on sand material



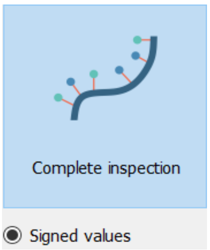
- Uniform mesh generation



Test reference: **3DFFTI_TC_8_Meshing_1**

Test procedure

- comparison between the uniform mesh and the original point cloud
- max research distance= 2 mm
- comparison type



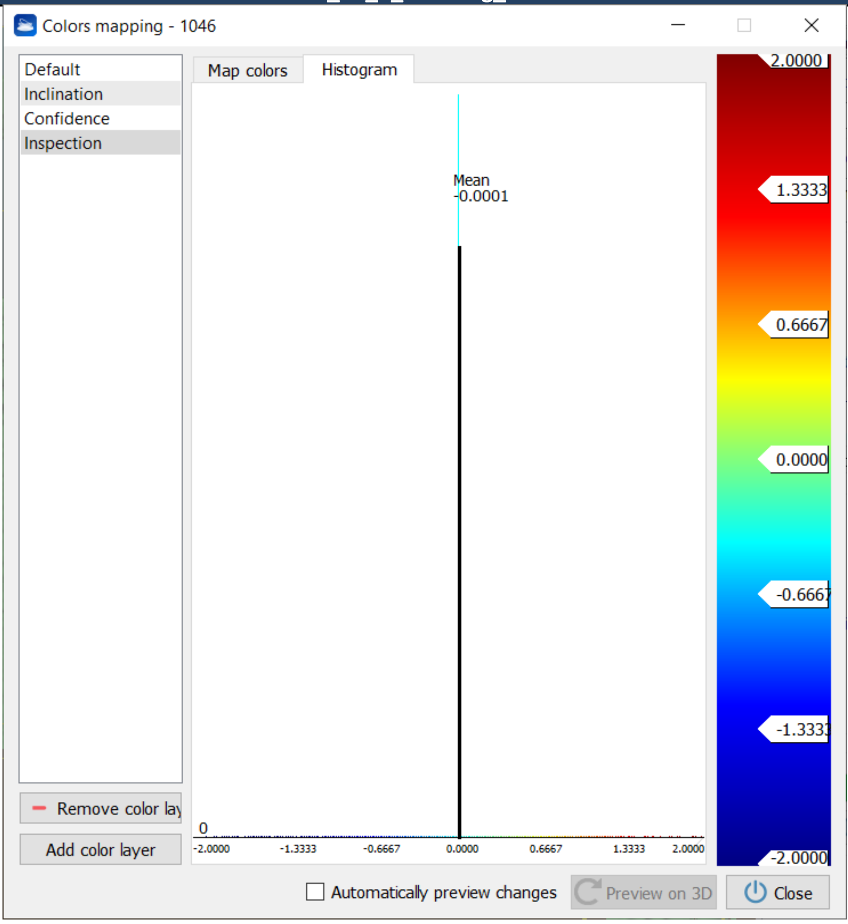
Results:

Inspection mode:
Distance in accordance with mesh normals
Model :
1046
Reference model:
1046_impression
Max Distance:
2.0000 mm
Subsampling:
1

Statistics information

Minimum value:
-2.0000 mm
Maximum value:
2.0000 mm
Mean value:
-0.0001 mm
Standard deviation value:
0.0194 mm
Number of points:
2621440
Number of points used to evaluate the mean:
1875875 (71.559 %)
Number of points out of range:
745565 (28.441 %)

Test reference:	3DFFTI_TC_8_Meshing_1



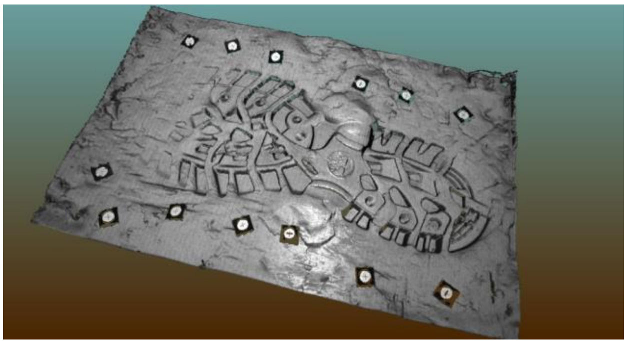
Conclusion and notes:

- no significant differences between the original scan data and the generated uniform mesh

Test reference:	**3DFFTI_TC_8_Meshing_2**				
Test name:	Meshing of 3D points	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Meshing accuracy: the meshing of point clouds results does not change the measurement data. No deviation between mesh and point cloud				

Test set-up:

- 3D scan of a shoe impression
- impression on plaster



Resolution width x heigth [px]: 2048x1280

Points Statistics

Compute point stats

Totals:	2,621,440
Valids:	1,586,423 60.52%

- Uniform mesh generation

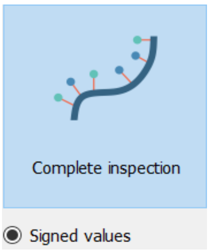
Properties:

Submesh size on Disk:	138.96 MB
Triangles:	4897002
Vertices:	2466904

Test reference:	3DFFTI_TC_8_Meshing_2

Test procedure

- comparison between the uniform mesh and the original point cloud
- max research distance= 2 mm
- comparison type



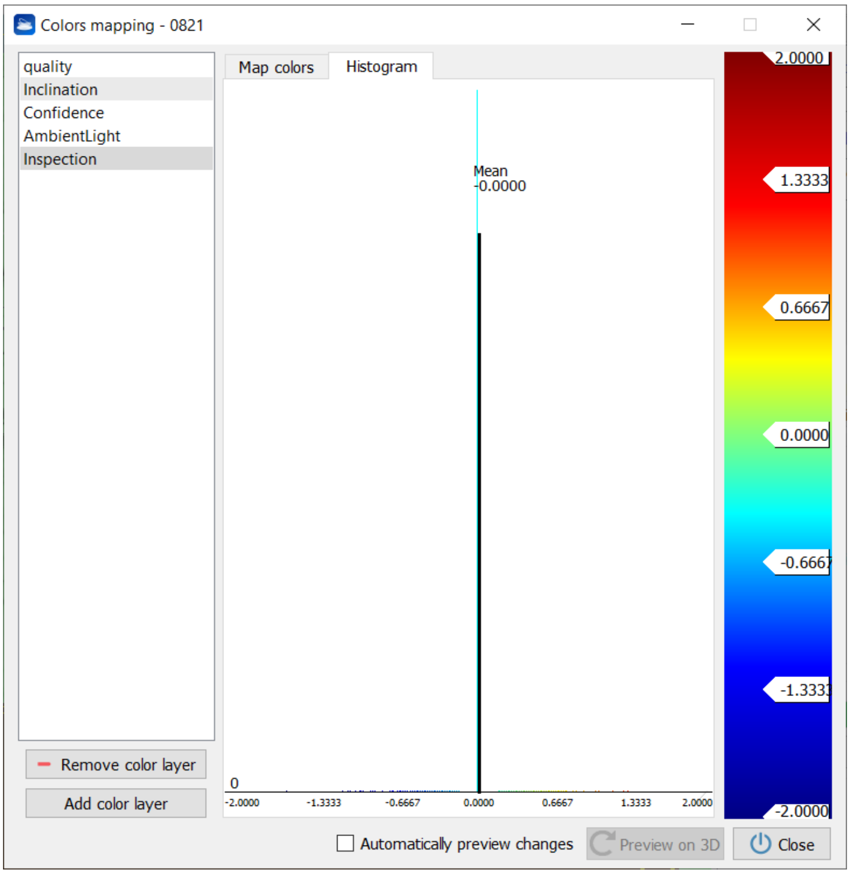
Results:

Inspection mode:
Distance in accordance with mesh normals
Model :
0821
Reference model:
0821_impression
Max Distance:
2.0000 mm
Subsampling:
1

Statistics information

Minimum value:
-2.0000 mm
Maximum value:
2.0000 mm
Mean value:
-0.0000 mm
Standard deviation value:
0.0056 mm
Number of points:
2621440
Number of points used to evaluate the mean:
2466904 (94.105 %)
Number of points out of range:
154536 (5.895 %)

Test reference: **3DFFTI_TC_8_Meshing_2**



Conclusion and notes:

- no significant differences between the original scan data and the generated uniform mesh

Test reference:	**3DFFTI_TC_8_Meshing_3**				
Test name:	Meshing of 3D points	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Meshing accuracy: the meshing of point clouds results does not change the measurement data. No deviation between mesh and point cloud				

Test set-up:

- 3D scan of a shoe

Resolution width x heigth [px]: 2048x1280

Points Statistics

Compute point stats

Totals: 2,621,440

Valids: 974,088 37.16%

- Uniform mesh generation

Properties:

Submesh size on Disk: 10.67 MB

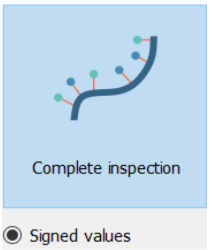
Triangles: 1926289

Vertices: 974088

Test reference: **3DFFTI_TC_8_Meshing_3**

Test procedure

- comparison between the uniform mesh and the original point cloud
- max research distance= 2 mm
- comparison type



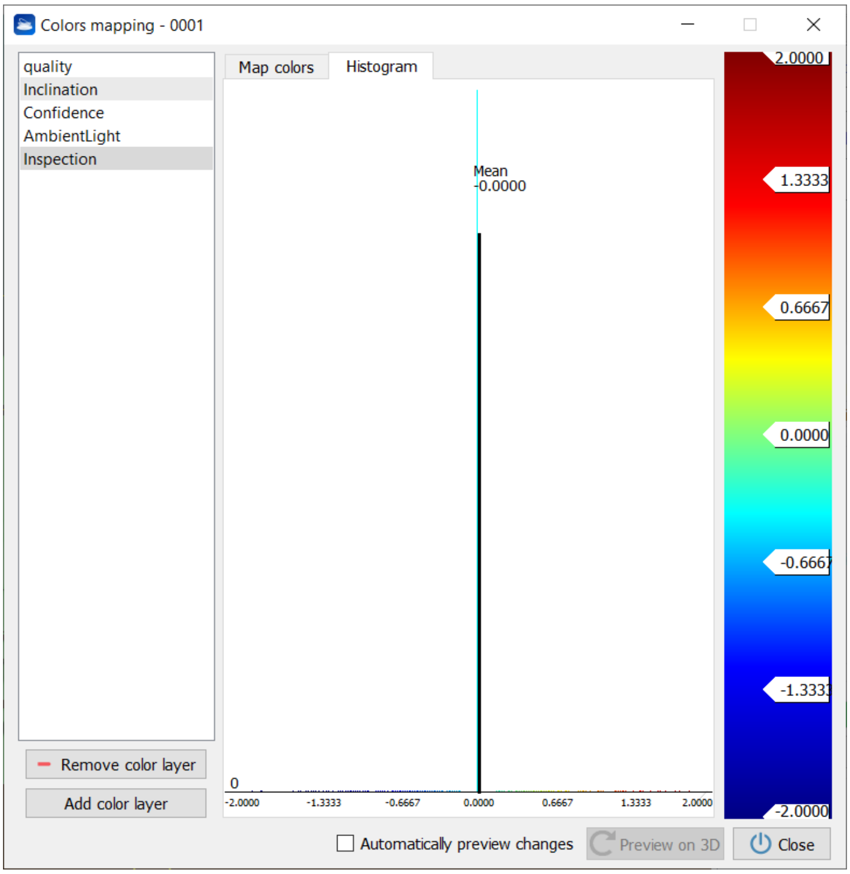
Results:

Inspection mode:
Distance in accordance with mesh normals
Model :
0001
Reference model:
0001
Max Distance:
2.0000 mm
Subsampling:
1

Statistics information

Minimum value:
-2.0000 mm
Maximum value:
2.0000 mm
Mean value:
-0.0000 mm
Standard deviation value:
0.0147 mm
Number of points:
2621440
Number of points used to evaluate the mean:
974081 (37.158 %)
Number of points out of range:
1647359 (62.842 %)

Test reference:	3DFFTI_TC_8_Meshing_3



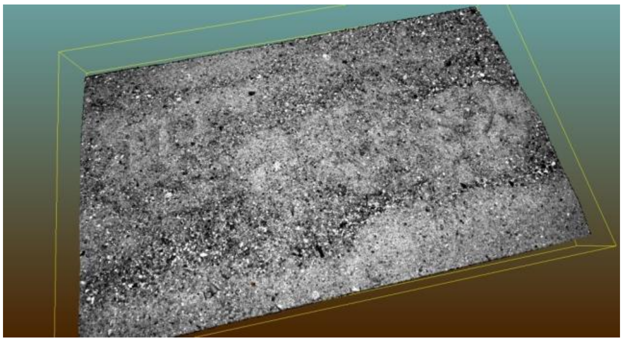
Conclusion and notes:

- no significant differences between the original scan data and the generated uniform mesh

Test reference:	**3DFFTI_TC_8_Meshing_4**				
Test name:	Meshing of 3D points	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Meshing accuracy: the meshing of point clouds results does not change the measurement data. No deviation between mesh and point cloud				

Test set-up:

- 3D scan of a shoe impression
- impression on granulated terrain



Resolution width x heigth [px]: 2048x1280

Points Statistics

Compute point stats

Totals:	2,621,440
Valids:	2,472,659 94.32%

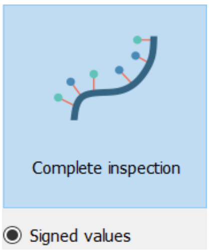
- Uniform mesh generation

Properties:

Submesh size on Disk:	124.63 MB
Triangles:	4937686
Vertices:	2472659

Test reference:	3DFFTI_TC_8_Meshing_4
Test procedure	

- comparison between the uniform mesh and the original point cloud
- max research distance= 2 mm
- comparison type



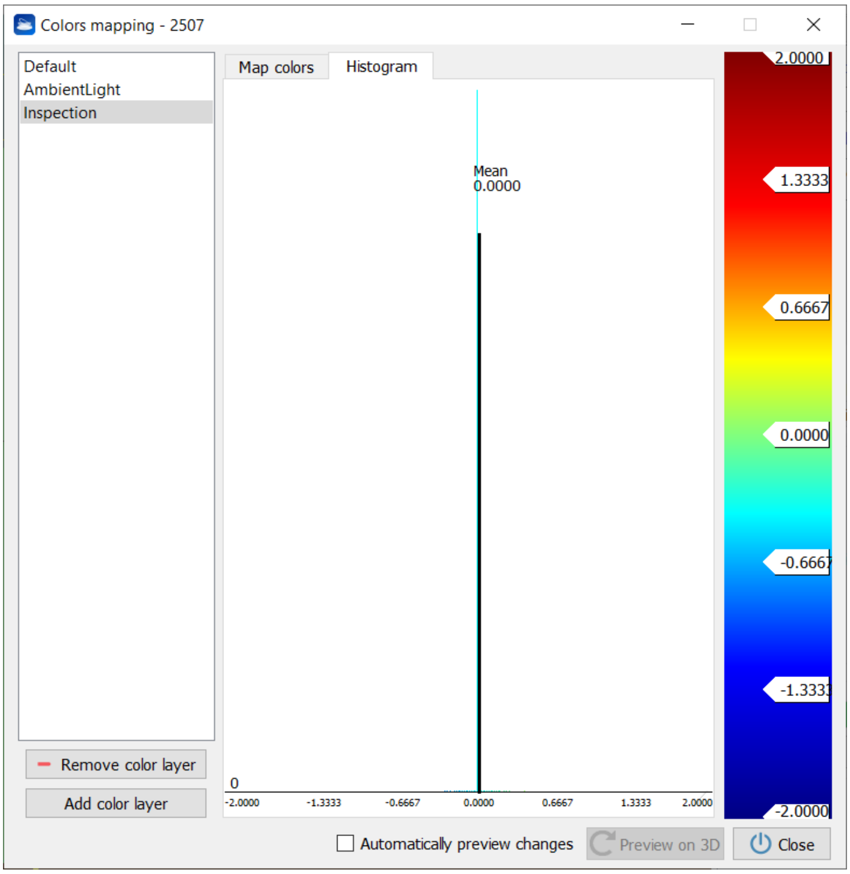
Results:

Inspection mode:
Distance in accordance with mesh normals
Model :
2507
Reference model:
2507_impression
Max Distance:
2.0000 mm
Subsampling:
1

Statistics information

Minimum value:
-2.0000 mm
Maximum value:
2.0000 mm
Mean value:
0.0000 mm
Standard deviation value:
0.0018 mm
Number of points:
2621440
Number of points used to evaluate the mean:
2472659 (94.324 %)
Number of points out of range:
148781 (5.676 %)

Test reference:	3DFFTI_TC_8_Meshing_4



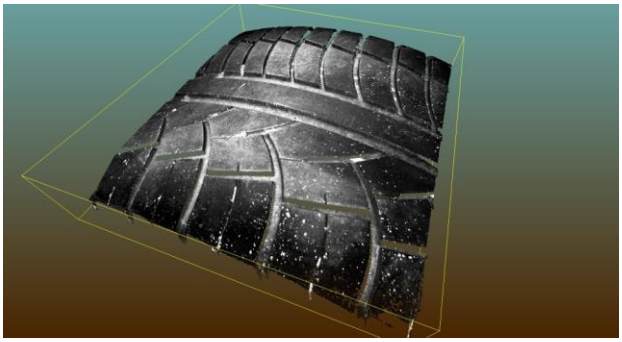
Conclusion and notes:

- no significant differences between the original scan data and the generated uniform mesh

Test reference:	**3DFFTI_TC_8_Meshing_5**				
Test name:	Meshing of 3D points	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Meshing accuracy: the meshing of point clouds results does not change the measurement data. No deviation between mesh and point cloud				

Test set-up:

- 3D scan of a tire portion



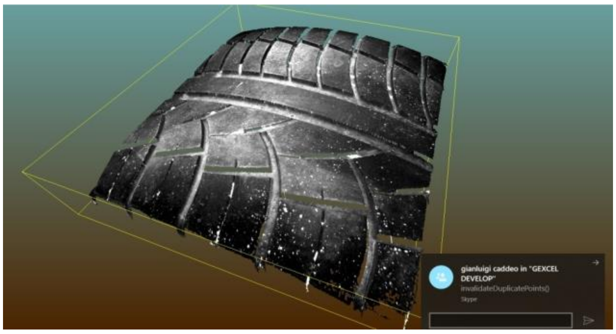
Resolution width x heigth [px]: 2048x1280

Points Statistics

Compute point stats

Totals:	2,621,440
Valids:	1,615,238 61.62%

- Uniform mesh generation



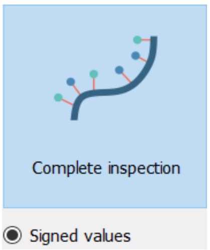
Properties:

Submesh size on Disk:	14.55 MB
Triangles:	3208381
Vertices:	1615350

Test reference:	3DFFTI_TC_8_Meshing_5

Test procedure

- comparison between the uniform mesh and the original point cloud
- max research distance= 2 mm
- comparison type



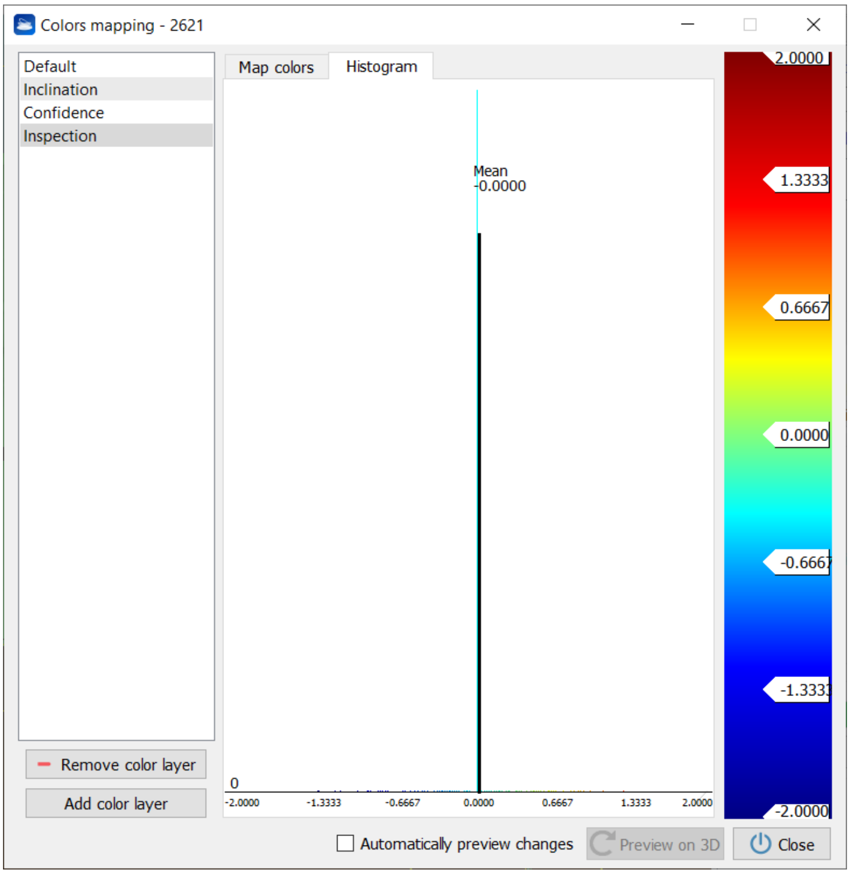
Results:

Inspection mode:
Distance in accordance with mesh normals
Model :
2507
Reference model:
2507_impression
Max Distance:
2.0000 mm
Subsampling:
1

Statistics information

Minimum value:
-2.0000 mm
Maximum value:
2.0000 mm
Mean value:
0.0000 mm
Standard deviation value:
0.0018 mm
Number of points:
2621440
Number of points used to evaluate the mean:
2472659 (94.324 %)
Number of points out of range:
148781 (5.676 %)

Test reference:	3DFFTI_TC_8_Meshing_5



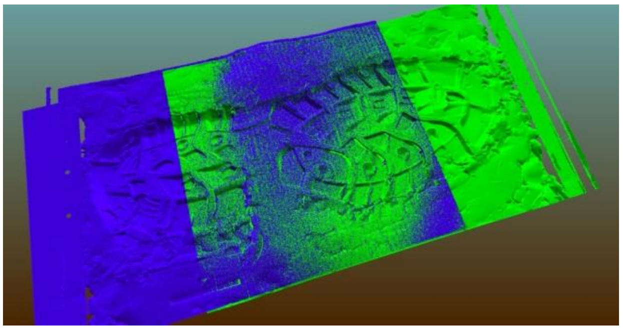
Conclusion and notes:

- no significant differences between the original scan data and the generated uniform mesh

Test reference:	**3DFFTI_TC_8_Meshing_6**				
Test name:	Meshing of 3D points	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Meshing accuracy: the meshing of point clouds results does not change the measurement data. No deviation between mesh and point cloud				

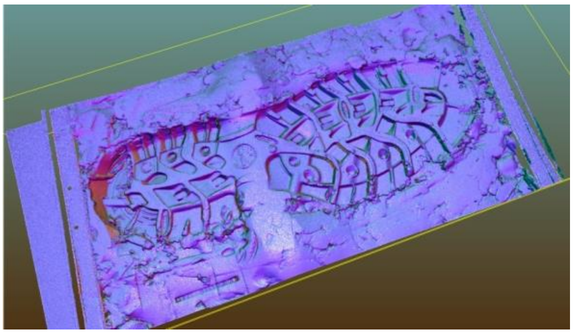
Test set-up:

- 2 3D scans of 2 registered scans



Resolution width x heigth [px]: 2048x1280		Resolution width x heigth [px]: 2048x1280	
Points Statistics		Points Statistics	
Compute point stats		Compute point stats	
Totals:	2,621,440	Totals:	2,621,440
Valids:	2,192,933 83.65%	Valids:	2,393,898 91.32%

- Uniform mesh generation



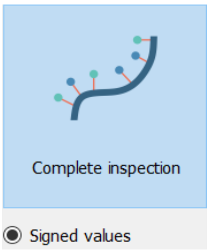
Properties:

Submesh size on Disk: 14.55 MB
Triangles: 3208381
Vertices: 1615350

Test reference: **3DFFTI_TC_8_Meshing_6**

Test procedure

- comparison between the uniform mesh and the original point cloud
- max research distance= 2 mm
- comparison type



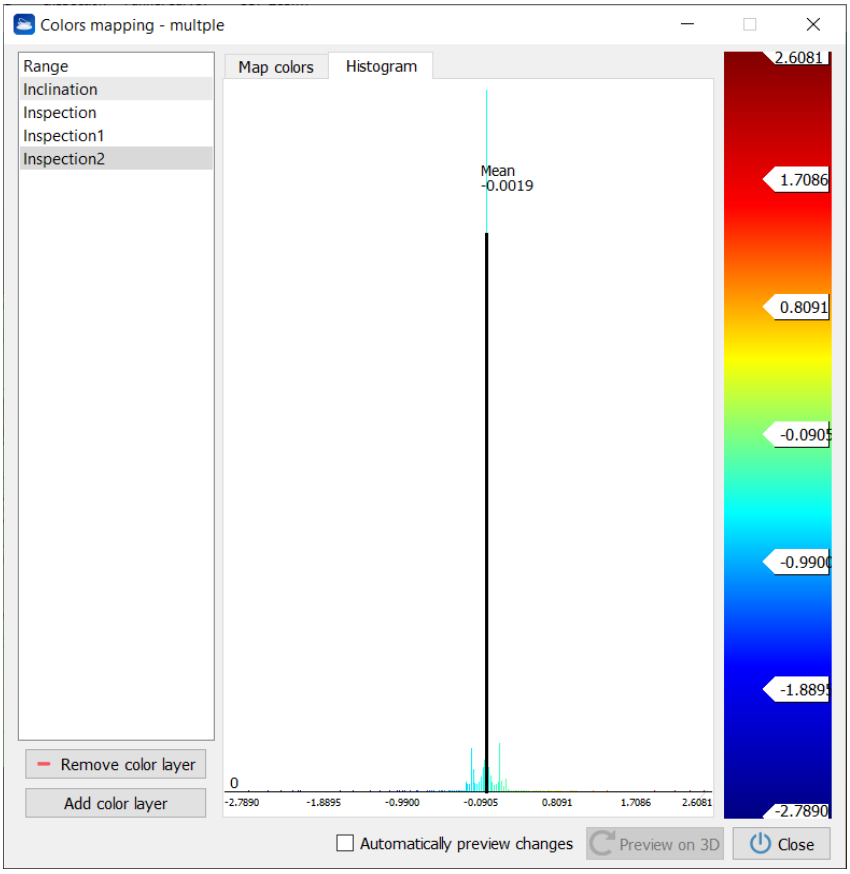
Results:

Reference model:
Multiple
Max Distance:
5.0000 mm
Subsampling:
1

Statistics information

Minimum value:
-2.7890 mm
Maximum value:
2.6081 mm
Mean value:
-0.0019 mm
Standard deviation value:
0.0728 mm
Number of points:
4842587
Number of points used to evaluate the mean:
4842586 (100.000 %)
Number of points out of range:
1 (0.000 %)

Test reference: **3DFFTI_TC_8_Meshing_6**



Conclusion and notes:

- very small differences between the original scan data and the generated uniform mesh combination of 2 meshes

Test reference:	**3DFFTI_TC_9_measure acc**				
Test name:	Visualization PC 1	**Location:**	GEX, Brescia	**Date:**	05/06/2019
Tested requirements:	Verification of the measuring tool accuracy				

Test set-up:

The calibration board adopted for the external camera recalibration was scanned.

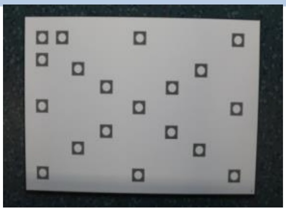
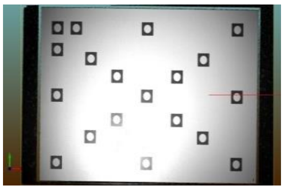


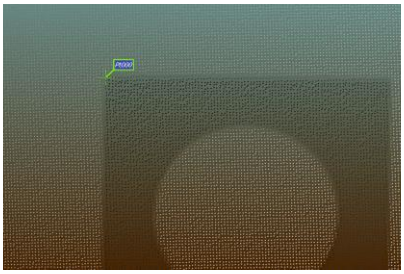
Photo of the the calibration board

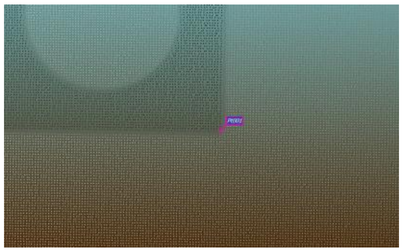
The acquired scan was imported in the 3DForensic analysis software



3D scan of the calibration board

- The measure start/end point has been univocally indentified in the point cloud

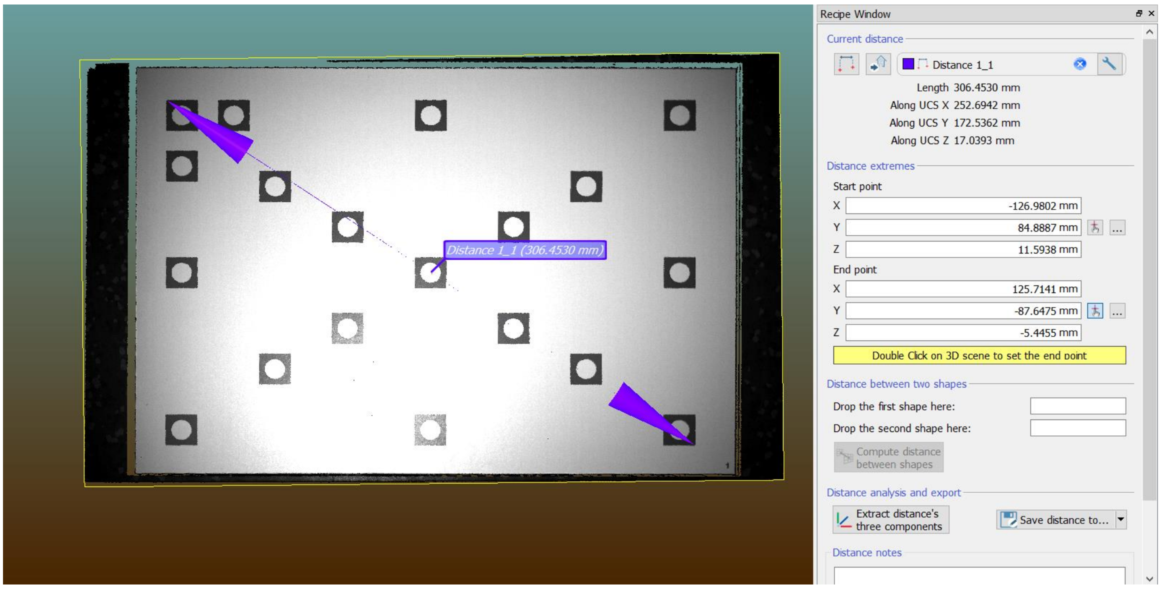




Test reference: 3DFFTI_TC_9_measure acc

Test procedure

- the same start and end point has been used to extract the distance value fo 10 independents measures



Results:

- 10 users repeated the same measure independently with te following results

	distance mm	Start point coordinates:			End point coordinates:		
user 1	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 2	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 3	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 4	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 5	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 6	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 7	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 8	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 9	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455
user 10	306.453	-126.9802	84.8887	11.5938	125.7141	-87.6475	-5.4455

mean	306.453	mm
standar deviation	0	mm

Conclusion and notes:

- the measuring tool provides the same distance value for all the 10 measures

Test reference:	3DFFT_TC_9_measure repr				
Test name:	Measuring test	Location:	GEX, Brescia	Date:	12/06/2019
Tested requirements:	Capability to measure in data accurately and reproducible				

Test set-up:

The calibration board adopted for the external camera recalibration was scanned.

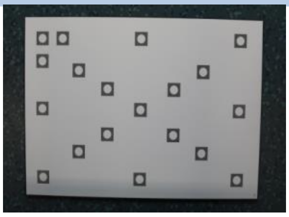
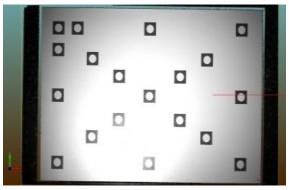


Photo of the the calibration board

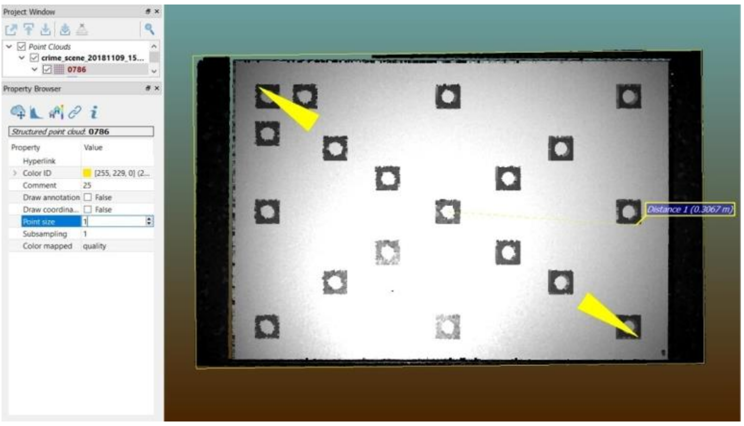
The acquired scan was imported in the 3DForensic analysis software



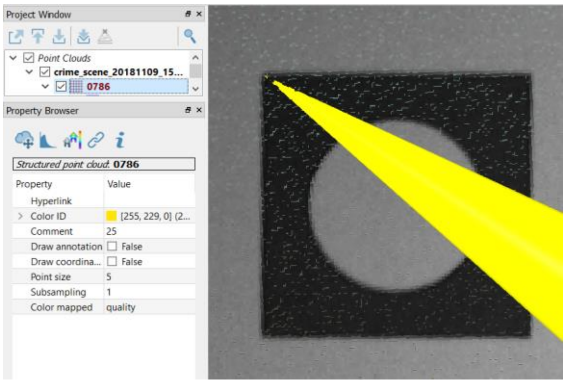
3D scan of the calibration board

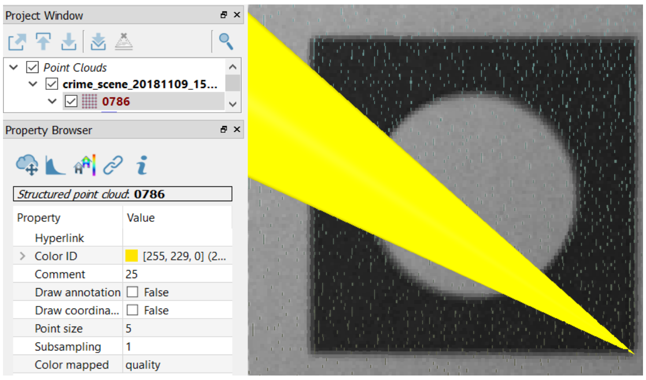
Test procedure

- the 3D scan is rendered in 3D in the 3D Forensic software with a looked orthographic view
- each user can pan and zoom in the 3D scan to identify the measure starting and ending point



- the zoom level and point cloud setting is fixed for all the user at the values reported in picture below





The measure in the original pointcloud (before the import in the analysis software) is **306.575 mm**

Test reference: 3DFFT_TC_9_measure repr

Results:

- 10 users repeated the same measure independently with te following results

- measured value before the data import in the 3D analesys software **306.575 mm**

2.228 Student-factor for two-sided confidence interval 0.95 with 10 measurements
https://en.wikipedia.org/wiki/Student%27s_t-distribution

	distance mm	max error in mm	Start point coordinates:			End point coordinates:		
user 1	306.6709	-0.0959	-126.9802	84.8887	11.5938	125.8679	-87.8136	-5.4003
user 2	306.3039	0.2711	-126.8159	84.7315	11.5576	125.6981	-87.8111	-5.407
user 3	306.7932	-0.2182	-127.1349	84.8748	11.6404	125.8679	-87.8136	-5.4003
user 4	306.7932	-0.2182	-127.1349	84.8748	11.6404	125.8679	-87.8136	-5.4003
user 5	306.7714	-0.1964	-126.9863	85.0575	11.6005	125.8679	-87.8136	-5.4003
user 6	306.7932	-0.2182	-127.1349	84.8748	11.6404	125.8679	-87.8136	-5.4003
user 7	306.8917	-0.3167	-127.1398	85.0413	11.6532	125.8679	-87.8136	-5.4003
user 8	306.8917	-0.3167	-127.1398	85.0413	11.6532	125.8679	-87.8136	-5.4003
user 9	306.8917	-0.3167	-127.1398	85.0413	11.6532	125.8679	-87.8136	-5.4003
user 10	306.6709	-0.0959	-126.9802	84.8887	11.5938	125.8679	-87.8136	-5.4003

			deviaton from the mean value	
mean	306.747	mm	-0.172	mm
standard deviation	0.176	mm		
Reproducibilty UNC	0.391	mm		

Conclusion and notes:

- measured value before the data import in the 3D analesys software	**306.575**	**mm**
- max displacement in 10 measures from the value before data import	-0.317	mm
- mean value in 10 measures	306.747	mm
- max displacement of the mean value for 10 measures from the value before data import	-0.172	mm
- standard deviation of 10 measures	0.176	mm
- measurement uncertainty of 10 measures	0.391	mm