R & D of technologies for monitoring the operating condition of guidance devices of internal parts of VVER 440 reactor pressure vessels

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Image Analysis in Nuclear Research workshop
9.-11. 9. 2024, ÚTIA AV ČR Prague, Czech Republic

CVŘ Research Centre Řež

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1. R & D project introduction

- The aim of the R & D project was development and experimental verification of measurement of dimensions and 3D profiles of machine components with accuracy ±40 μm in places with high radiation up to 20 Gy/hr and under water to depth of 12 m. By means of developer these technologies it will be possible to perform an assessment of the current status, during repeated measurements to assess changes and trends of measured parameters (dimensions and profiles), thereby verify the condition of measured machine components and manage their service lifetime.
- The technologies were developed with the aim of their applicability to other locations in the primary circuit of the NPP.
- The R & D was specifically focused on measuring the dimensions and surface profiles of 8 keys of reactor pressure vessel and the corresponding 8 grooves of core support barrel of the VVER 440 type NPP (see figure 1). The key-to-groove clearance determined during measurement will be compared with the clearance at the time of commissioning.
- The duration of the project was 36 months, the project was launched in July 2020.
- The partners of the project were CVŘ, ÚJV Řež, ŠKODA JS, a.s. and ČEZ, a.s.

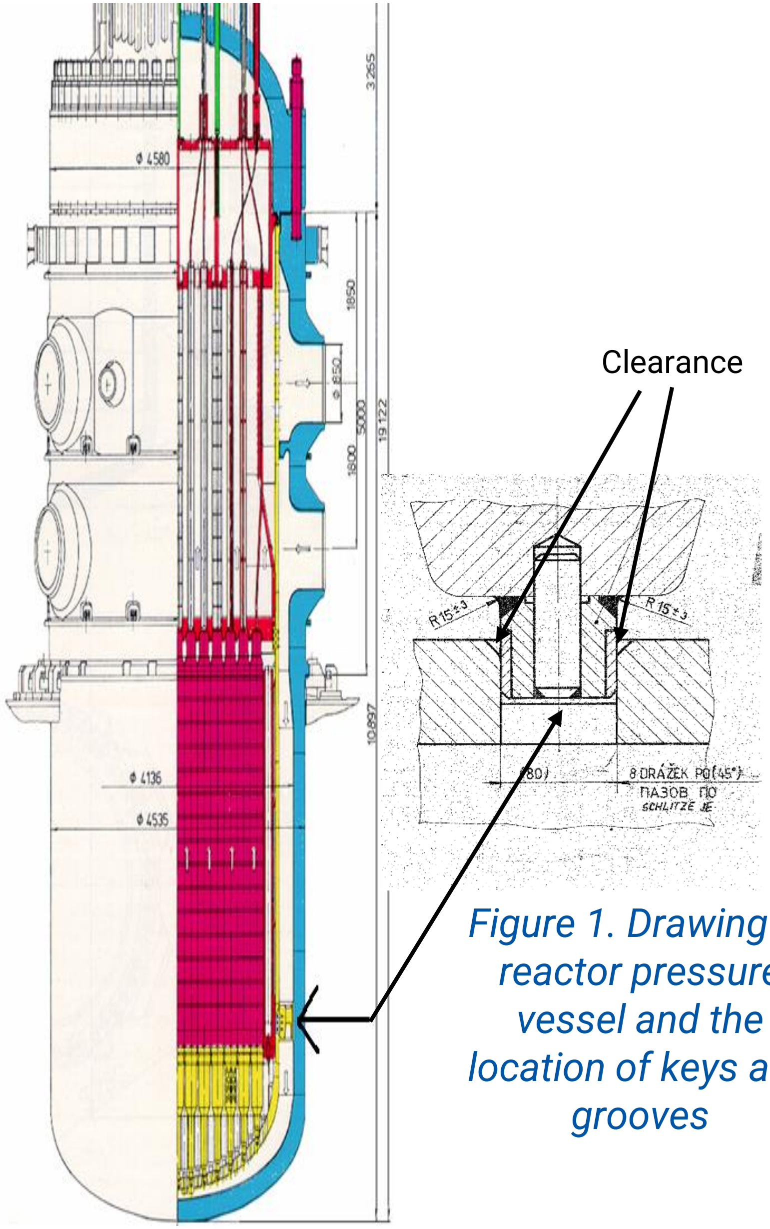


Figure 1. Drawing of reactor pressure vessel and the location of keys and grooves

2. Requirements and Limitations

- The measuring device must be radiation-resistant up to dose of 20 Gy and for measuring on the reactor vessel keys (which are located at a depth of about 8 m) resistant to 12 m water column (= 1.5 times of the expected water column). The expected pressure is approx. 0,22 MPa.
  Example of doses: Dávky z jednotlivých rentgenových vyšetření - Lucie Súkupová (sukupova.cz)

- The measuring methods must be qualified for the declared accuracy ± 40 µm. The requirements for measurement accuracy were based on the requirements for a specific application, where the mounting clearance between the key and groove was determined at 50 to 170 µm in the Dukovany NPP project. Accuracy of measuring methods must be at least 4 times better than the maximum design (assembly) clearance, ie about ±40 µm.

- The side wall distances of the keys and grooves (approximately 80 mm – see figure 2) are measured to determine the clearances. In order to determine the condition of the measured components, there is also a requirement to measure the profiles of the side wall surfaces with an area of 25 x 5 mm.
  During the project, it was agreed with industrial partner that it is sufficient to measure the profile of the key and groove surfaces with an accuracy of better than ± 40 µm.

- The measuring device must meet the requirements of the NPP operator from the FME (Foreign material Exclusion) point of view.

Figure 2. Groove mock-up

2. Requirements and Limitations – cont.

- The measurements would take place at different times of the outage, when the complete removal of the internal parts of the reactors is carried out (nowadays, this would be possible once every 8 years). The measurement of the grooves would take place at the moment the core support barrel is pulled out of the reactor pressure vessel. The measurement of the keys would probably take place after the non-destructive inspections from inside the reactor pressure vessel.

- Since the measurements will take place during the critical path of the outage, another requirement for the measurements is that they take place in the shortest possible time.

- The measurement of the reactor pressure vessel keys would take place in the reactor pressure vessel with the removed internal parts. The measuring system will be placed on the horizontal arm of the manipulator for non-destructive inspections (see Figure 3). This is an MKS manipulator from ŠKODA JS a.s. for NDT inspections of reactor pressure vessels. At the time of inspection, there will be primary circuit water (boric acid solution - up to 16 g/kg) in the reactor pressure vessel. The keys are in a water depth of about 8 m.

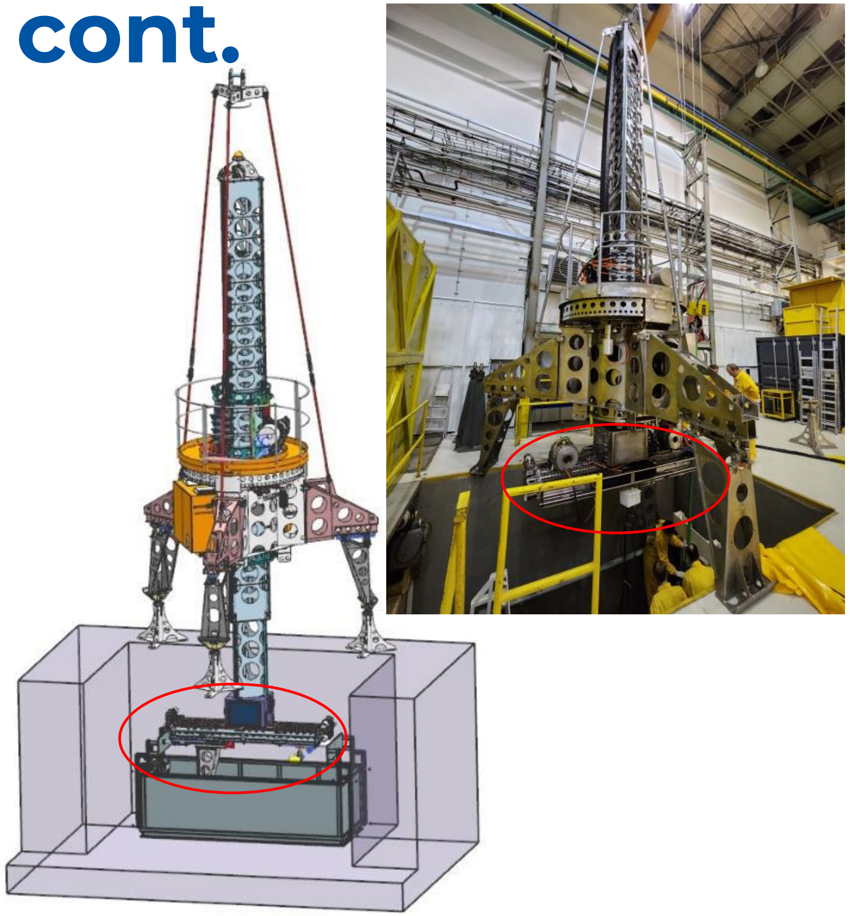


Figure 3. Drawing and photo of MKS manipulator from ŠKODA JS a.s. for inspections of reactor pressure vessels with horizontal frame (red oval)

2. Requirements and Limitations – cont.

- The core support barrel grooves would be measured by a measuring system located on the reactor hall floor in front of the window of the shielding cylinder(see Figure 4). Inside this cylinder would be a core barrel suspended from a crane. By successive rotation, individual grooves would be placed behind the door of the shielding cylinder.

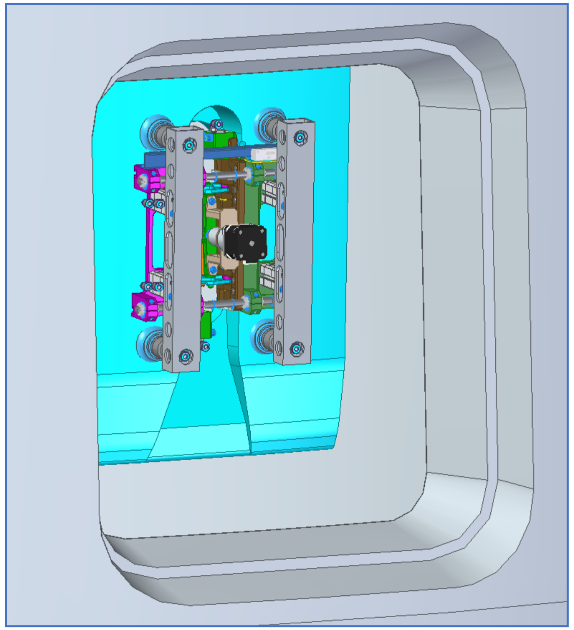


Figure 4. From the left - Photo of Reactor hall, photo of the the shielding cylinder, drawing of the shielding cylinder window

3. R & D focus areas

There were two technologies being developed:

1. 3D camera system that consists of:
    i. A set of video cameras fixed on holder for adjusting the height level of the position of the lenses.
    ii. A vertical laser for horizontal image folding and secondary lasers for projecting a bent line for the scan itself which are also fixed on the holder of the measuring system.
    iii. The cameras provide raw data, which are then processed by software. A system of cameras and lasers is located on a support holder, to ensure continuous scanning of the entire key or groove at a constant speed. Processing the raw data with the software will provide the final 3D point cloud.
2. Replicator system for remote replica sampling of two surfaces of key or groove. After removing the replicas from the sampling area and decontaminating them, the replicas will be scanned using, for example, using a mobile 3D laser scanner.
3. Verification of the developer technologies took place on the mock-ups of the reactor key and the core support barrel groove (see figure 5). The mock-ups contained predefined defects.

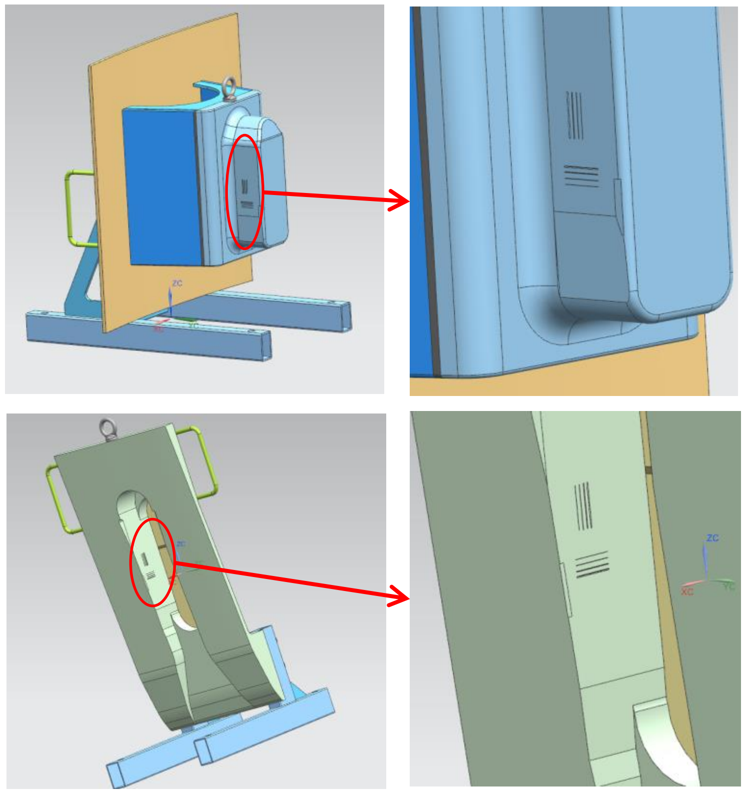


Figure 5. Key (top) and groove (bottom) mock-up models with artificial defects

4. Developed 3D Measuring system for keys

Manipulator

The main purpose of the developer manipulator is the precise positioning (in the Y and Z axes) of the attached 3D camera system to the measured component and ensuring movements along the scanned component – see figure 6.

The manipulator is connected to a horizontal frame of the MKS – see figure 7.

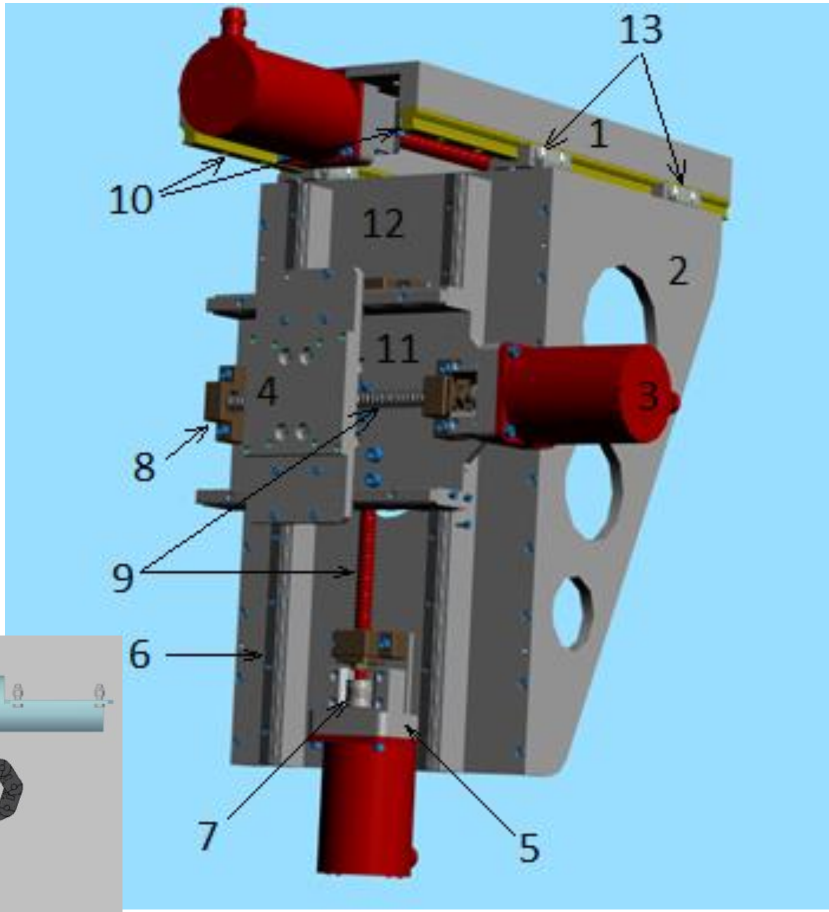


Figure 6. Manipulator parts list:

1. *pen manipulator base plate*
2. *side of the manipulator*
3. *manipulator motors 3 pcs*
4. *platform for fixing the camera system / replicator*
5. *motor holder 3 pieces*
6. *linear drives*
7. *flexible couplings 3 pieces*
8. *ball screw housings 6 pieces*
9. *ball screws*
10. *linear movements of the base plate*
11. *X-axis carriage*
12. *manipulator base plate*
13. *linear carriages*

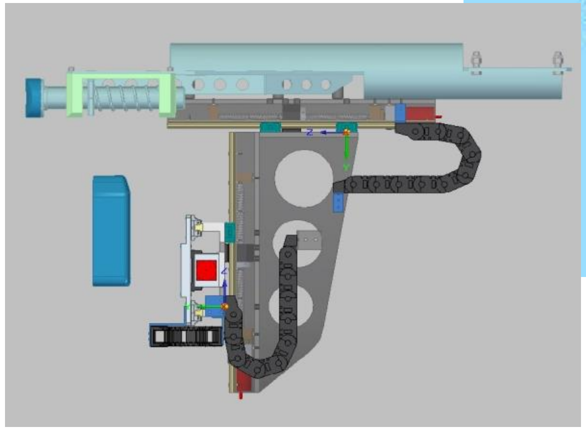


Figure 7. Measuring assembly for the case of the key's measurement

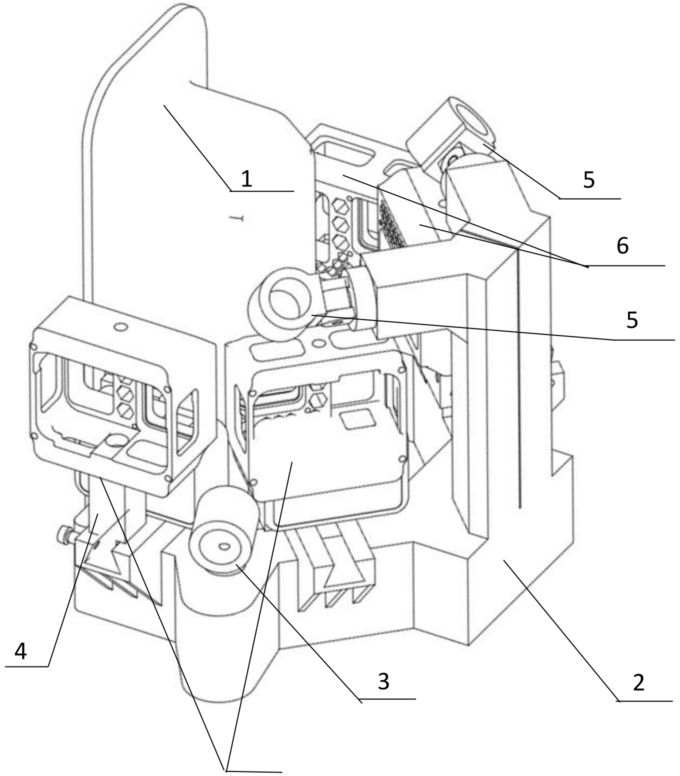
4. Developed 3D Measuring system for keys

3D camera system

The main purpose of the 3D camera system is to provide raw data, which are then processed by software - see figure 7.

Legend

1. *Scanned component – RPV key*
2. *Holder of the measuring system*
3. *Vertical laser for horizontal image stacking*
4. *Camera holder – ensuring 2nd to 3rd degrees of freedom*
5. *Overhead laser – projection of a bent line for the scan itself*
6. *Camera*



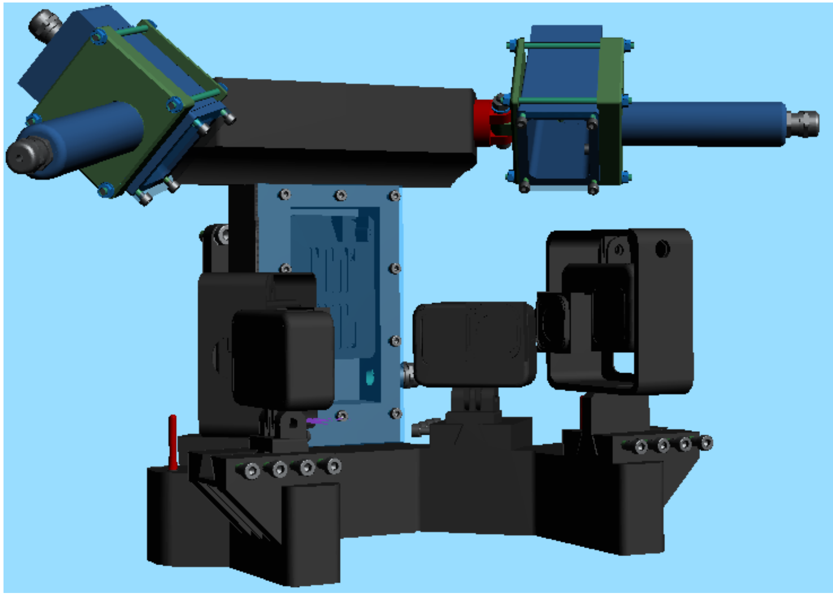


Figure 7. Schematic drawing (left) and drawing (right) of the 3D camera system

4. Developed 3D Measuring system for keys

3D camera system – cont.

The camera system is controlled remotely, from the level of the reactor hall. The main communication element is the raspberry microcomputer located inside the support column of the system connecting the upper frame of the laser and the lower frame of the cameras. The Raspberry, located in a waterproof housing (support structure of the column), is connected to the computer in the reactor hall using a long LAN cable (in the tested case – 50 m).

Raspberry serves as the main element for controlling the camera system - it receives commands from the operator and collects (or sends) recorded data from the cameras. Raspberry has its own, integrated sensor for wireless Bluetooth communication with receivers (in this case with here cameras), which is strong enough to work with cameras at a distance of 12.5 cm in water, assuming the absence of external influences.

4. Developed 3D Measuring system for keys

3D camera system – SW description

The processing of the records taken within the key inspection is carried out with the help of the SW developed for this purpose. The processing procedure is set as:

1. Video editing at the beginning and end of the calibration body, removal of secondary recording tracks (audio from GoPro)
2. Converting images from Yuv/RGB to HSV color space
3. Cropping images to contain only the required footage
4. Perform gamma correction
5. Perform segmentation in the HSV color space according to the shade of the laser used
6. Extracting the position of points
7. Pairing of points (manually) with the reference point cloud of the calibration body
8. Transformation of sets of pairs of points into one transformation matrix using the singular value decomposition method, whereby:
    - a transformation matrix is created, according to the accuracy of the marked points
    - the equation of the laser plane is created
    - manual correction of other scanning deficiencies is being addressed (back transformation, elimination of points that are too close to each other, fitting to a reference pointcloud)

4. Developed 3D Measuring system for keys

3D camera system – SW description – cont.

The first step of processing is the determination of calibration values based on the scan of the calibration body. According to these obtained points, the spatial and image distortion of the scanned object is set for each camera.

In the next step, individual video frames are segmented from the video and calibration constants are applied to them.

After achieving "cleaning" of individual images, de novo calibration points are detected on the calibration body. These are matched and a transformation matrix is assembled to go from the caliber to the scanning object.

In the following step, within each frame, the image is cropped, and the individual laser reflections are segmented, from which individual points are further extracted, to which the previously assembled correction is applied.

After the segmentation of the point, it is possible to finally assemble the pointcloud while maintaining the geometry calibrated according to the calibration body.

It follows from the above that any configuration change (eg camera vs laser position) requires a repeated scan of the caliber and component to resolve the transformation problem.

5. Verification tests - Irradiation test

3D Camera system radiation tests

Radiation resistance criterion was chosen as follows: During the 1-hour radiation exposure corresponding to the dose rate of the R&D project, ie min. 20 Gy / hour, is the loss of a pixel in the image of a random and not permanent nature.

Figure 9 confirms the fact that even at 180 Gy / hour there is no problem of permanent damage to the chip - there are no bad pixels. The current pixel discharge changes intensity and position over time according to gamma shots. The test success criteria were met.

At an exposure of 20 Gy / hour (target exposure according to the R&D project), it has been shown that 3 to 4 pixels of the image will be lost in the area of interest of an individual image. Using a larger number of images to process a single profile during component scanning can eliminate the problem of bad pixels. The influence of gamma effect on the measurement result will be eliminated using SW.

Figure 9. Tracking bad pixels at maximum exposure (180 Gy/hr.) at three different points in time

5. Verification tests - Pressure and boric acid resistance test

Pressure and boric acid resistance tests were performed in the CVR infrastructure used for LOCA tests (see figure 10). The tests were performed with a measuring device placed in a LOCA vessel with boric acid 16 g/kg and a pressure simulating a water column of 12 m.



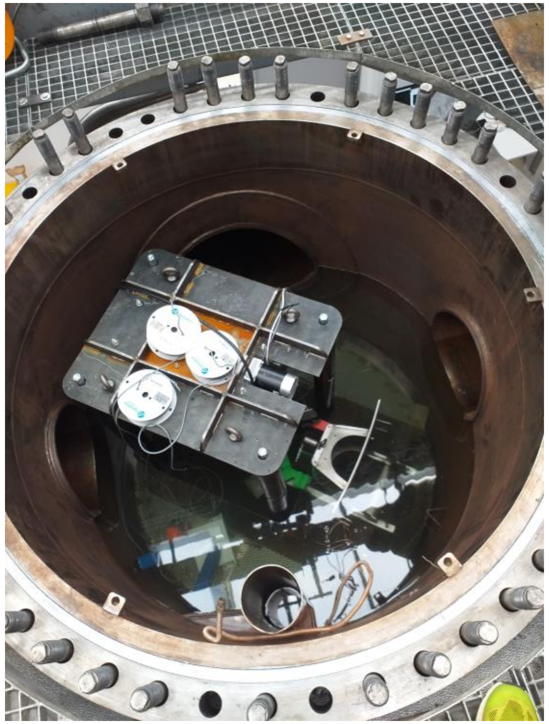
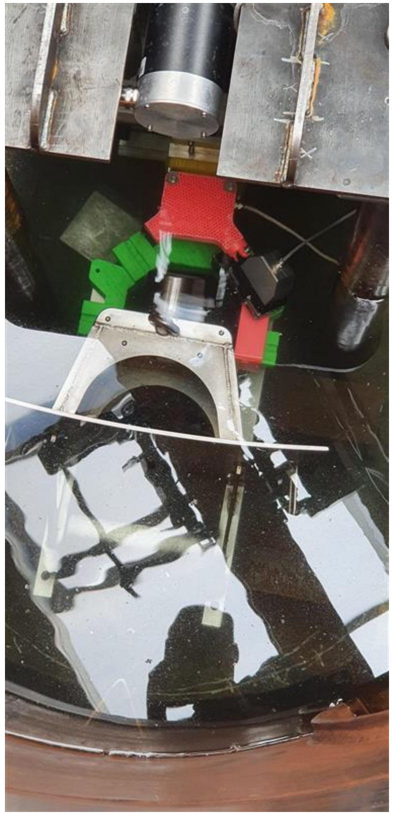



Figure 10. Photos of the CVR infrastructure used for LOCA test

5. Verification tests –
Test of the measuring system and MKS manipulator connection

Tests were performed in the test hall of operational inspections of ŠKODA JS, a.s. Pilsen.

The following tests were performed for both technologies:

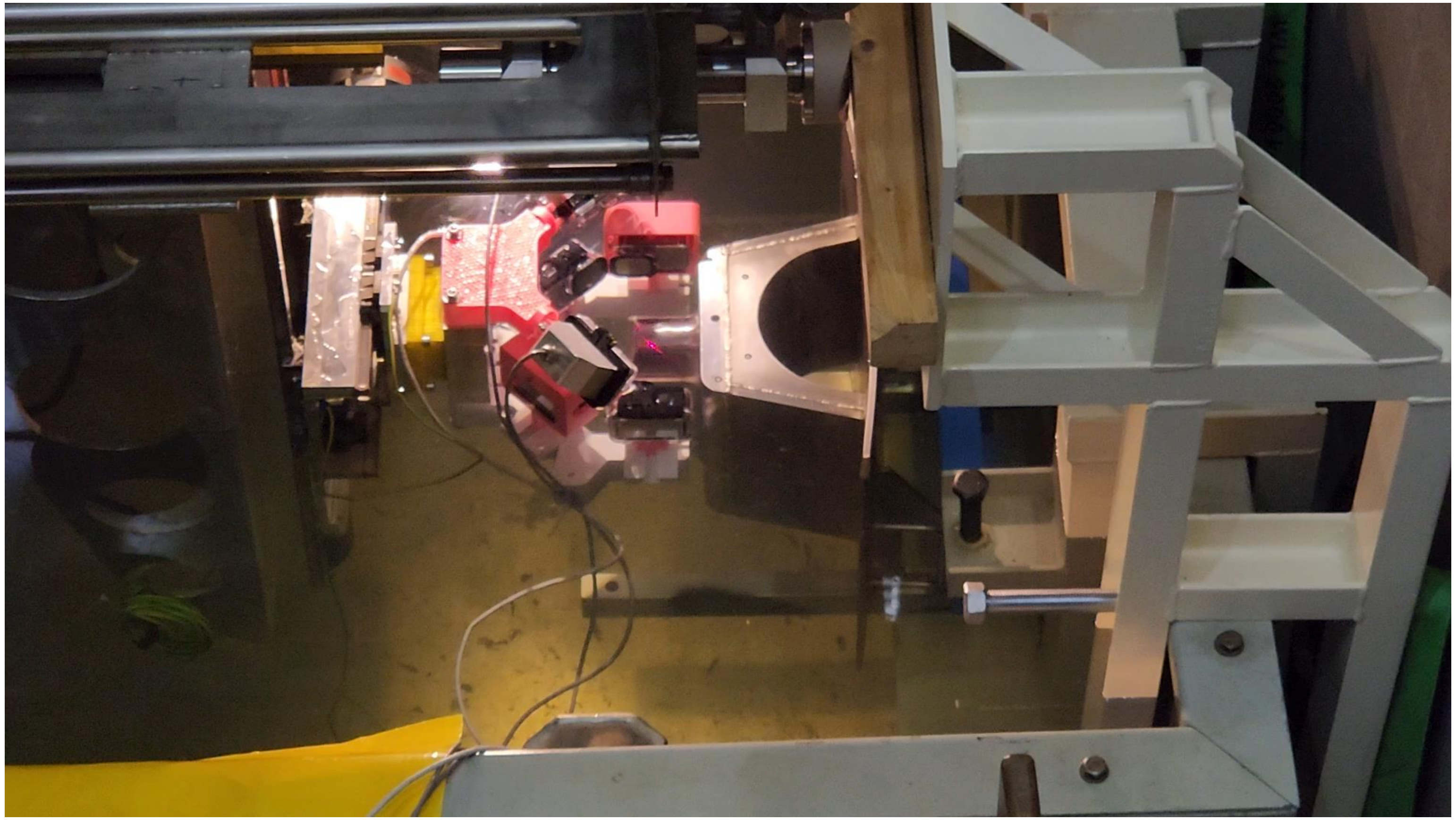
- possibility of remote manipulation by the measuring system to the location of the mock-ups with an accuracy of ± 2 mm
- simulation of measurements with electrical cables resp. pneumatic hoses at 60 m distance.

The device configuration was as follows - see Figure 11:

- The MKS manipulator was standing on stands above the pit
- In the test pit, there was a tub in which a structure carrying key mock-up was placed.
- In certain places of the tub, there was an imitation of the reactor pressure vessel wall against which the MKS support system was pressed.
- There was a transition piece on the horizontal frame, to which the support frame with 3D camera system was attached.

Figure 11. Photos of the device configuration during the tests in ŠKODA JS, a.s. Pilsen test hall

5. Verification tests –
Test of the measuring system and MKS manipulator connection



Video 1. Remote scanning of key mock-up using camera system and manipulator mounted on MKS manipulator of ŠKODA JS, a.s. in ŠKODA JS, a.s. the test hall

5. Verification tests – Measurement accuracy tests

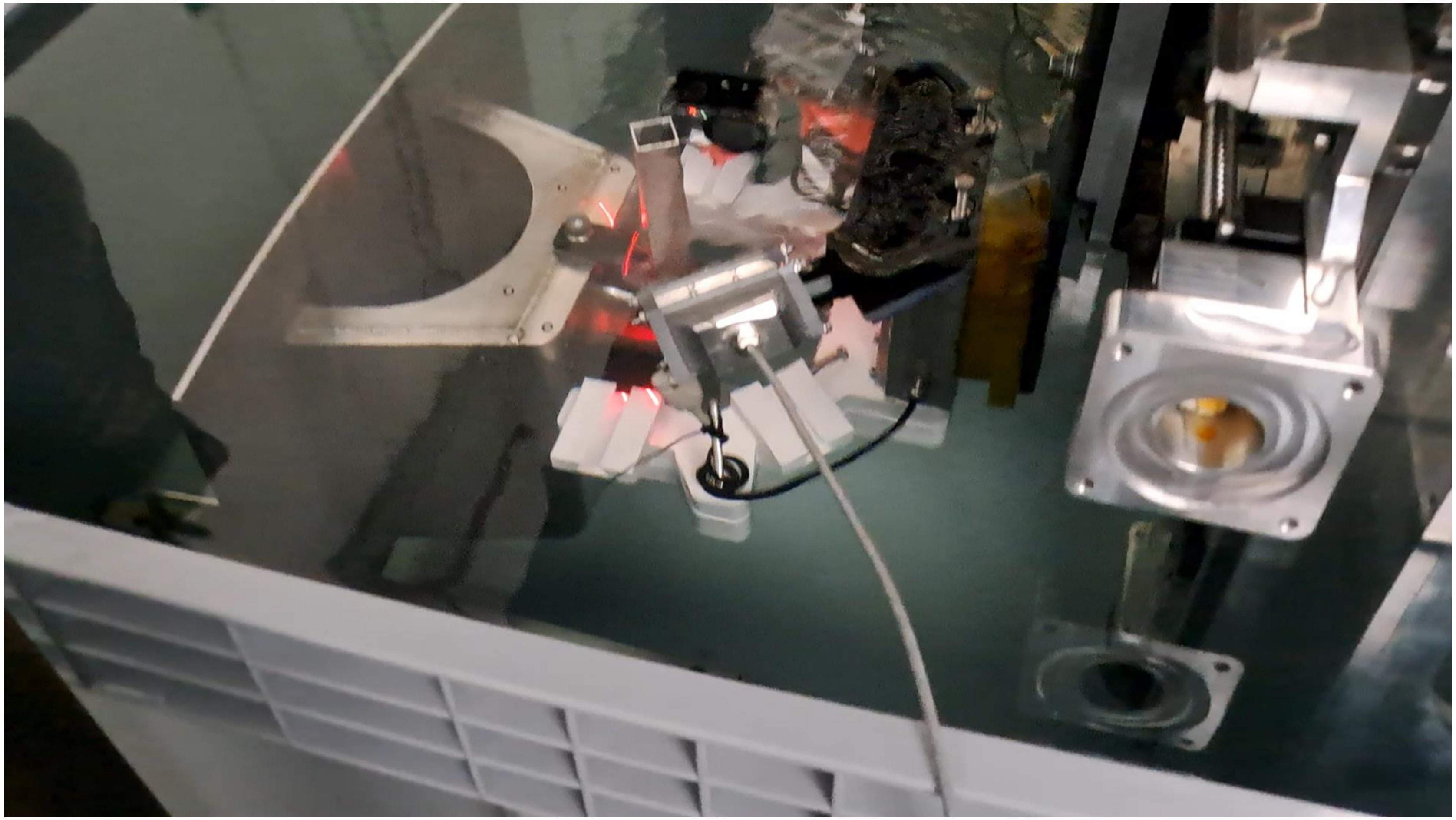
Tests which were performed in the laboratory hall of the CVŘ in Pilsen.

Two scans of the key or groove mock-up were compared:

1. Precise scan measured with an accuracy of ± 4 μm.

2. Scan measured by developed 3D measuring system in two configurations: in air (dry) and underwater.

Achieved accuracy of 130 μm on the entire scanned surface.

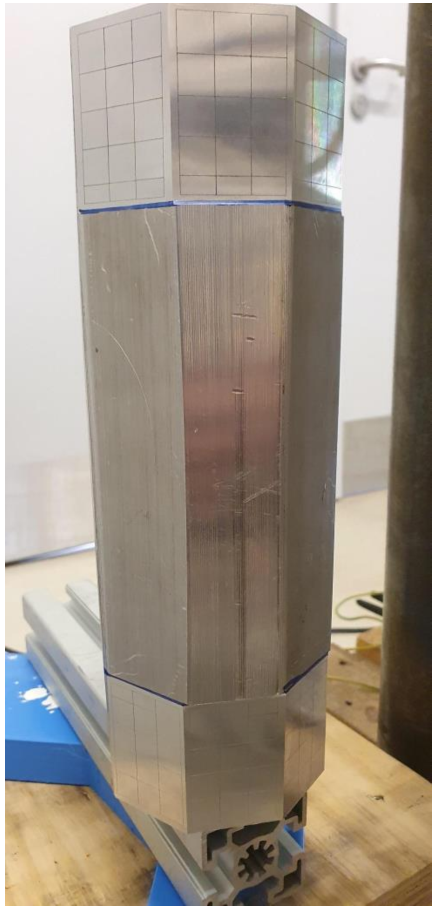


Video 2. Scanning of verification test piece and key mock-up using camera system and manipulator

5. Verification tests – Measurement accuracy tests

Tests which were performed in the CVR laboratory in Řež with the aim of proving a higher accuracy of the camera system, achieving a better than achieved so far accuracy of 130 μm.

- a new calibration body was made
- a new laser system was assembled



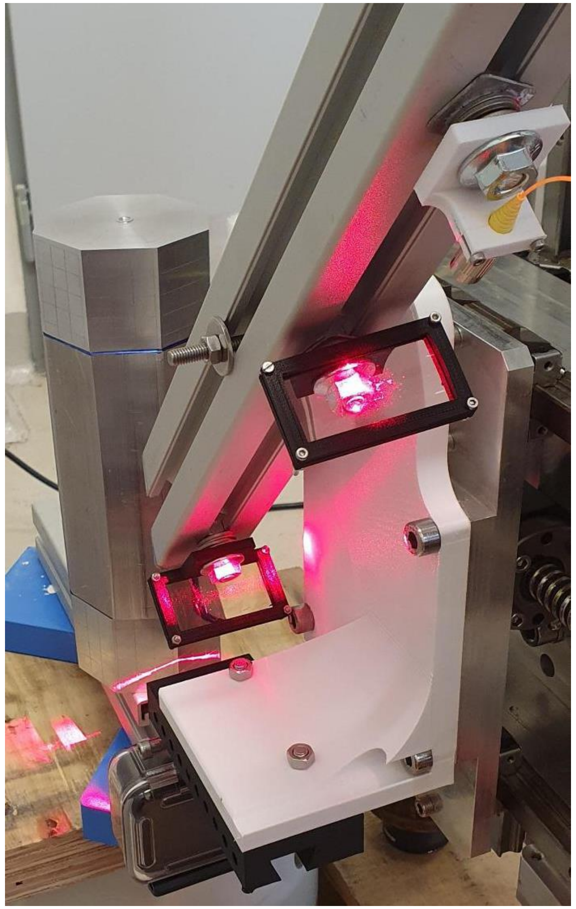


Figure12. Photos of a new calibration body (left side) and new laser system (right side)

5. Verification tests – Measurement accuracy tests

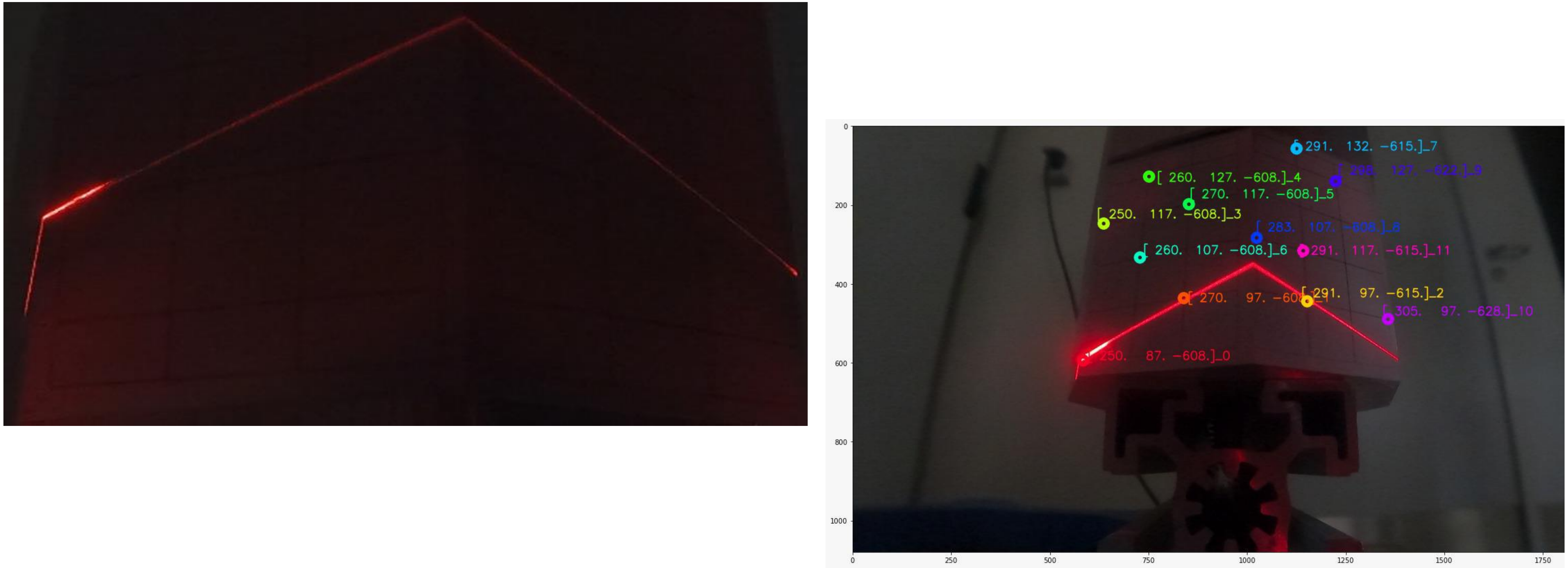


Fig.11. Achieved laser line quality

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5. Verification tests – Measurement accuracy tests

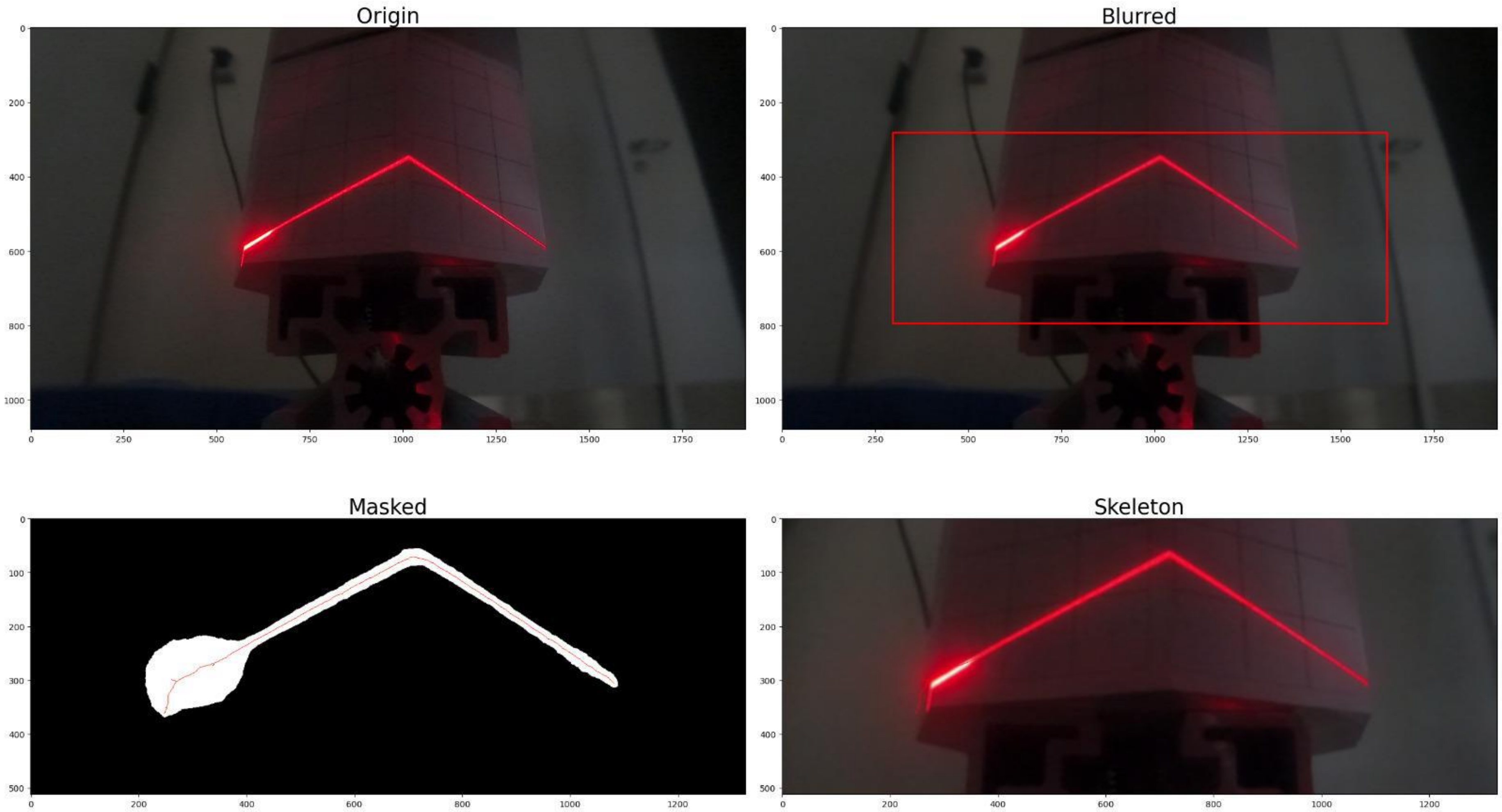


Fig.11. Segmentation process

5. Verification tests – Measurement accuracy tests

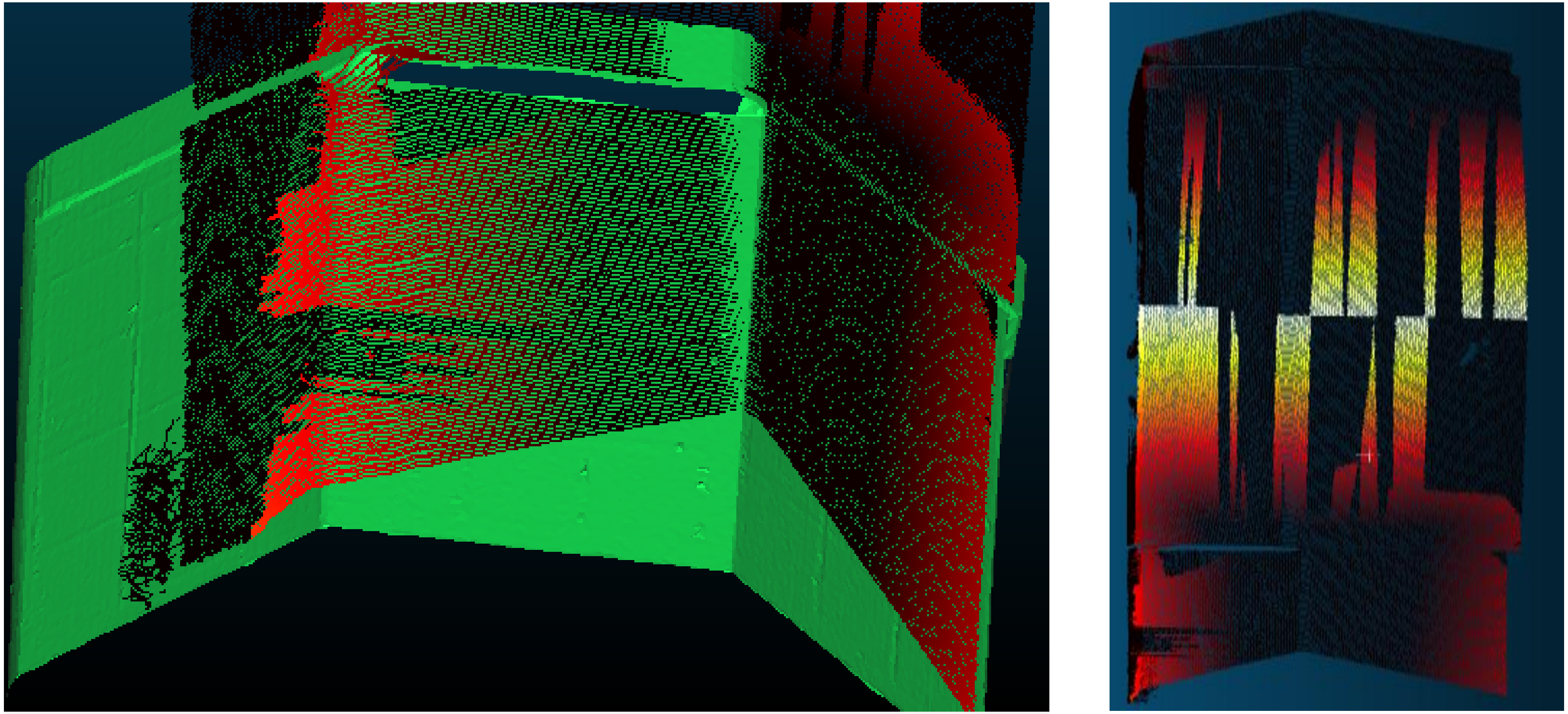
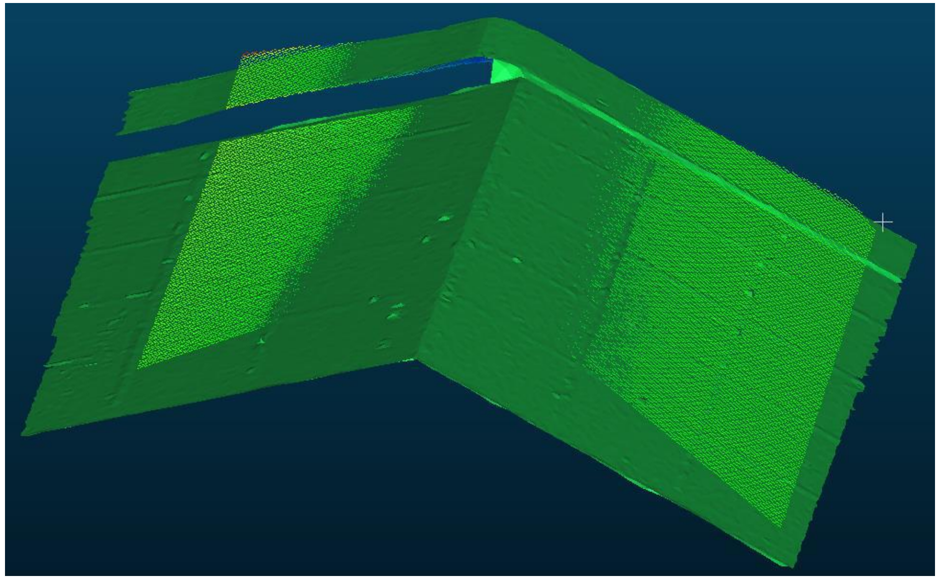
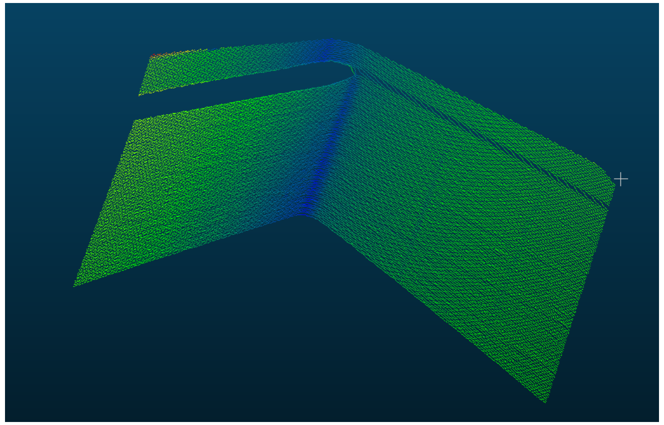


Fig.11. Obtained 3D pointcloud (under the same conditions as for accuracy 130 microns

5. Verification tests – Measurement accuracy tests

Ratio	1 dist. : 0.582 mm
Abs. mean	0.089 mm





C2M absolute distances (64467 values) [252 classes]

Fig.11. The result obtained 3D pointcloud by optimizing the parameters

Achieved scan accuracy

Total detected points within classes (reference locations): 43,775.

Median meshing accuracy: 51.9 µm for 80% of reference points (35,049).

Implementation of rotation optimizations, updated lens parameters and the discrimination of burnt points allowed to achieve a total accuracy of 89 µm on the entire scanned surface.

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6. Conclusions

The R&D project are developing measuring technologies that achieve high dimensional accuracy under very specific measurement conditions such as underwater and in radiation. For this, it was necessary to develop special manipulators and measuring techniques.

The developed techniques of measurement using replicas, with an accuracy of 40 μm, and 3D scanning with an accuracy of 89 μm, will make it possible to evaluate the condition of the reactor pressure vessel keys and the core barrel grooves and to determine the degree of wear due to operation.

The developed technologies are very promising and can be used with modifications on other components of the primary circuit in NPPs as well as in other industrial technologies, where standard measurement methods cannot be used.

This presentation was created with the state support of the Technology Agency of the Czech Republic in the THETA Program within the project No. TK03020085.

Thank you for your attention

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