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ROBBE – Robot-aided processing of assemblies during the dismantling of nuclear power plants

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Abstract. For a successful decommissioning and dismantling of an NPP (Nuclear Power Plant), correct and controlled processing of all components is necessary, whereby a large part of the work relates to coated (mainly painted) steel components, which make up a significant proportion of the total inventory of the power plant to be processed. The contamination of these components is reduced by removing the surface coating using UHP (Ultra-High-Pressure) water jet blasting technology. Thus, the decontaminated material is released to be recycled conventionally after receiving clearance in accordance with Chap. 3 StrlSchV (German Federal Law Gazette 2018 No. 41: StrlSchV, 2018). The manual processing of these individual parts is cost-intensive, so that an autonomous, automated solution is more economical while increasing throughput at repeatable high quality. ROBBE aims at implementing a robot-assisted, automated and autonomous decoating procedure of component groups using UHP water jet blasting technology and implements it ata German NPP in Biblis on an industrial, productive scale.

1 Introduction

RWE Nuclear GmbH has already implemented the processing method based on UHP water jet blasting technology – initially with manual process control. The UHP water jet technology is used in such a way that the coating is completely removed from the entire surface of the components. This enables the complete removal of any contamination that may be bound in the coating itself, on its surface or underneath at the boundary layer to the substate and thus achieving a high level of process reliability. ROBBE builds up on the existing infrastructure for manual UHP waterjet coating removal and expands it to an autonomous processing facility automating the following steps:

- geometry recognition of the coated (steel) components.
- Coating removal with the UHP water jet process.

After dismantling assemblies into manageable components, they fit into Euronorm stackable steel boxes and are ready to be processed. Most of the components can be classified as parts of

- pipelines, fittings, valves, pumps, containers, etc.
- retaining profiles
- machinery
- diverse apparatus
- steel structures.

The component geometries can be of any dimension that fits into an Euronorm box ($1200 \times 8000 \times 600\,\mathrm{mm}^3$). Many components have free-form surfaces, so there typically are not repeating known component geometries. All objects exhibit unique geometric shapes including cavities and occlusions making the autonomous 3D scan of arbitrary objects one of the main challenges to overcome.

1.1 Technical and scientific goals

For component clamping and geometry recognition, the dismantled components are removed from the box and fixed on a zero point clamping plate with clamping tools. The clamping plate with the attached component is then placed on a turntable with a zero point clamping system in the UHP decontamination cabin. An embedded

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autonomous, robot-supported 3D laser scanner captures their individual geometry, the geometry of the used clamping tools and their spatial orientation on the clamping plate. Then a detailed and complete surface geometry model of the component as well as the clamps is calculated and, with knowledge of additional procedural parameters as well as the robot kinematics and taking into account reachability constraints, the best possible trajectories for the decoating process are determined which completely cover the component's whole visible surfaces minus those of the clamping tools.

The decoating process is carried out inside the decontamination cabinet by the robot-assisted UHP water jet blasting technology.

The machining process ensures that the required quality criteria are achieved and that the processed components can therefore be approved according to German Federal Law StrlSchV [1]. The outstanding feature of our technology is the autonomous and complete real-time capture of the 3D geometry of arbitrary components of any shape and size with multiple coatings, as well as the adaptive trajectory planning for the robot-assisted decoating process using UHP water jet blasting technology including repositioning of the component for complete coating removal, if required. In addition, we have implemented a sustainable, energy-saving, innovative filter and water circulation system further reducing radioactive waste and saving resources.

The scanning process chosen by ROBBE (Fig. 1) places high demands on the scan quality (complete and closed 3D models) and the recording and processing speed of the system. We developed a fully automated scanning system with an autonomous view planning that minimizes reflections of the laser on the component surface through a suitable choice of the wavelength range and the corresponding scan trajectories. As shown schematically in (Fig. 1), a control loop for the autonomous 3D detection of the surface geometry is put in place, which is based on dynamic scanning of the component using a real-time laser line scanner.

Each scan line is evaluated in terms of its quality allowing conclusions to be drawn, which area could be accessed poorly and which will be difficult to access later on during the decoating process. In addition, intelligent algorithms analyze the point cloud with the aim of eliminating surface reflections and points that do not belong to the object as well as possibly incorrectly recorded points (background reflections and other artifacts). The subsequent cleanup of the pointcloud is very efficient and leaves a smooth realistic surface model.

The focus of our R&D approach has therefore been on the development of a real-time laser scanner for the autonomous detection of individual and initially unknown component geometries as well as the development of a technology for the subsequent complete, autonomous, robot-assisted coating removal of these components using UHP water jet technology. This includes the calculation of the robot trajectories and complete control of its inverse kinematics, taking into account physical effect parameters and interfering geometries (e.g., from the clamps).

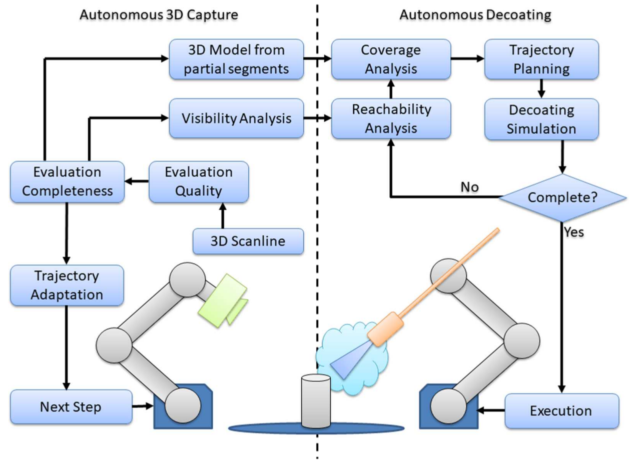

Fig. 1. Autonomous 3D geometry capturing and robot-assisted coating removal – shown here by two robot arms for the sake of clarity.

2 State-of-the-art

In preparation for this project, we evaluated the current state-of-the art, e.g., at the trade association for industrial parts cleaning in Hilden/Germany, at trade fairs and conferences such as the international trade fair Parts2Clean in Stuttgart (October 2018) and the Kontec in Dresden 2017 and 2021. Scientific institutes were also surveyed, such as the Fraunhofer "Cleaning Technology Alliance" (FAR) based in Berlin (Fraunhofer Gesellschaft, 2018). In industry, various process technologies for cleaning and decoating metal components are used in a wide variety of sectors. So-called blasting processes are among the most established techniques in industrial surface cleaning technology. They use the momentum exchange between blasting media and the workpiece surface to increase the removal rate, sometimes with the addition of abrasive substances. Based on a patent application in 1870, the blasting process was successfully and systematically further developed [2]. The result shows that in industrial applications a large part of the process is already automated when high numbers of similar items or large areas are to be processed.

The main difference to the current state of the art is that ROBBE needs to be able to capture the most diverse 3D object geometries, because there are no CAD models that could be used for the trajectory planning of a cleaning robot.

There have already been national funded projects [3], which also aimed at autonomous cleaning and decoating of components, but on a laboratory scale. They were based on the assumption that objects to be decoated can be reduced and approximated by basic primitives (CAD), calculating trajectories on these surfaces through simplified parametric paths.

In ROBBE we developed a more complex process for 3D acquisition working with dynamic view planning which independently selects the optimal scan trajectory during the 3D digitization of the objects. This ensures that the entire surface of the object is measured and ambivalences or unresolved surface areas are excluded.

At Fraunhofer Institute for Computer Graphics Research IGD, CultLab3D [4] funded by the Federal German Ministry for Economic Affairs and Energy (BMWi) laid the foundation for the first, fast, economical and fully automated approach to 3D digitization of cultural heritage objects. The CultLab3D is a 3D scanning pipeline, consisting of two scanning stations, an arc scanner that captures most of the surface of an object and a robotic arm scanner that takes care of all remaining cavities and occlusions that were not detected by the first scanning station. Unique to this autonomous scanning system are intelligent view planning algorithms for the robotic arm scanner, which allow it to capture every region the optical sensor can see on the surface of an object with the smallest number of perspectives and optimal depth of field [5–8]. In ROBBE these algorithms have been adapted to laser-based approaches for the autonomous real-time acquisition of arbitrary 3D surfaces eliminating manual post-processing of the resulting 3D models which are complete and closed.

A study from Hübner et al. [9] provides an up-to-date overview of the procedures mostly used in previous dismantling projects. It also analyzes the outcome of an expert survey on the status of the processes used and their future prospects. Mechanical processes, especially blasting processes, and above all the abrasive blasting processes, have therefore proven to be indispensable. High-pressure water jet processes are being commended for future applications, however pointing out, that the required water treatment might be demanding. However, this is one of the aspects solved in ROBBE already. In addition, in the aforementioned study, the ability to automate decontamination work is viewed rather skeptically. Currently, the automation of dismantling processes is almost impossible to implement, mainly because of arbitrary geometries of the components and the lack of adaptation capability of the processing machines to unknown geometries. Again, this is precisely what ROBBE overcomes.

3 Idea and implementation

The project idea of using a new, innovative and autonomous technology to achieve high throughput at repeatable high quality was developed at an early stage when the decontamination room at RWE was completely renovated and a new UHP water jet technology was installed, leading to a high level of motivation for the exploration team to research potentially suitable solutions and development approaches on the international industrial technology market. As is usually the case with such development projects, this process is lengthy and resource-intensive. An engineering office (TSE Wassmann) specializing in cross-sector technologies was called in to provide support. The project then got to a head start when the basic technical and industrial feasibility was clearly and tangibly demonstrated with the autonomous scanning approaches of the Fraunhofer Institute for Computer Graphics Research IGD.

3.1 The industrial prototype plant – technical implementation

The system design was significantly influenced by the process work flow and the existing physical space for the later implementation of the robot system. During the development process, it turned out that dividing the process into spatially different scan and work areas did not seem suitable for various reasons. A wide variety of design variants with different operating parameters were created and evaluated using CE matrices. Accordingly, the process variant with integrated geometry recognition and processing function with an articulated arm robot – without tool change – directly in the UHP processing box turned out to be the most suitable. The main reasons for this were:

- the work area is easy to control from a safety point of view.
- Saving resources (only one robot).
- Harmonizing well with component logistics.
- Processing time is not significantly longer.
- Sufficient protective measures for the optoelectronic systems are available.

Industrial robots: the existing space influenced the choices of the robotic arm. Due to the nature of the UHP blasting process used, only water and moisture-resistant industrial robots can be considered. In addition, it must be suited for its purpose and match all requirements for certification and integration in an NPP environment. The required gripping length and applied payload of around 60 kg limited the number of suitable robot providers. Also, the programming interfaces of the robots must be open to control each joint individually, as well as performing positional data read outs at high frequency. Using a UHP cleaning system with a robot also calls for appropriate precautions to ensure a stable data connection and UHP water supply to the end effector of the machine. Therefore, utmost importance was given to design all supply lines along and partially inside the robotic arm, so they would enable full integration of all necessary technical components (scanning and UHP waterjet technology) in a closed, watertight unit built on the end effector.

UHP waterjet technology: central to the work-flow is the management of the UHP water jet process. Currently, cleaning is still carried out manually. A manipulator-supported, but hand-guided lance is used for coating removal. The guidance of the jet pipe is based on the experience of the human worker. During operation, a direct view of the processing zone is only possible to a very limited extent due to the extreme formation of fog, despite the strong air circulation. The UHP system works at a nominal pressure of 2500 bar, at 24l/min and a water outlet temperature of 80 °C. The jet leaves the nozzle at about $1000\,\mathrm{m\,s^{-1}}$. This ultimately not only leads to the desired cleaning effect, but also generates large amounts of mist and aerosols. For automation, virtual modeling and simulation is necessary to reproduce this process. Therefore, we determined various physical process parameters needed to establish corresponding virtual 3D models of nozzles and

Fig. 2. Left: component sample from the dismantling. Middle: parts with a newly applied, resistant coating for removal tests. Right: experimental setup for determining the jet parameters of various nozzle tools.

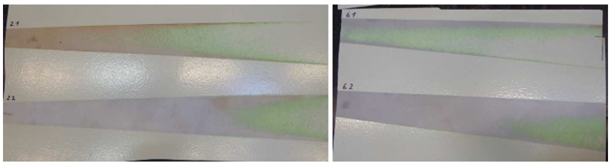

Fig. 3. Experimental results: quite abrupt transition between good and insufficient cleaning. Here, we increased the distance to the plate until colored and therefore still coated areas of the workpiece remained. Other parameters were determined in the same way, such as the angle of attack, etc.

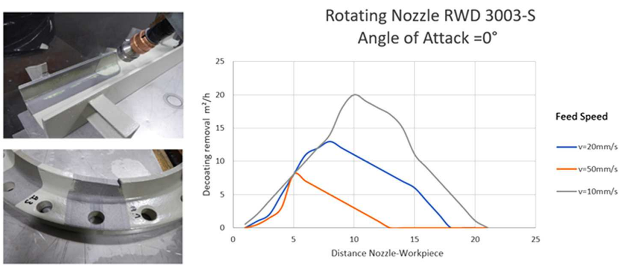

Fig. 4. Experiments on complex objects. It is easy to see that the angle of incidence is a critical parameter. The diagram on the right shows the removal rate on the Y axis and the distance on X at a given speed. One recognizes that a further approach to the workpiece surface of the nozzle does not necessarily produce a better cleaning performance – there are maxima.

optimize their cleaning trajectories in our virtual cleaning simulation.

A whole set of physical parameters had to be considered. In addition to the nature of the tool (nozzle configuration, angle of attack, speed and type of drive), the most important parameters are those describing the relationship between the tool and the surface, depending on the choice of tool. The distance allows to assess the trade-off between speed and cleaning effect. The same applies to the feed rate and the angle of attack on the surface.

To determine these parameters, a series of tests were carried out with the UHP technology on repainted component samples from the demolition process (Fig. 2). The newly painted elements were determined to be a "worst-case or heavy duty" scenario, as the adhesion of the new protective coating is ultra strong but becomes more brittle over time and can thus be removed more easily. Figure 3 shows typical test results by way of example.

Interestingly, the transition between successful and unsuccessful decoating was always quite abrupt in our experiments. Objects with more complex shape geometry have also been examined in order to obtain further key figures when machining curved surfaces, inside and outside corners as well as undercuts and bores (Fig. 4).

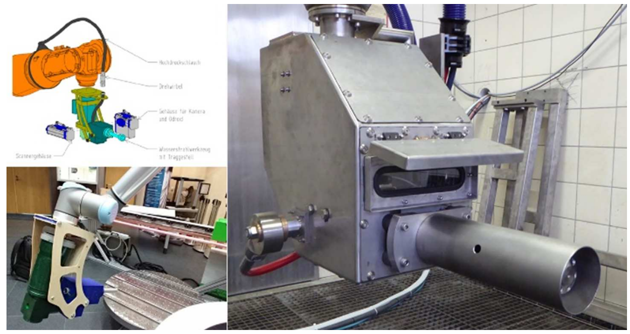

Fig. 5. CAD planning and development of final UHP waterjet nozzle with integrated and water protected laser scanner.

Fig. 6. IGD01 Prototype Setup featuring a Laserscanner and a true-to-scale UHP waterjet mockup.

Based on these tests, we designed and developed a high performance nozzle (Fig. 5). In addition to the scanner, the UHP blasting tool is an essential component of the robot end effector unit and significantly determines its shape geometry and the water supply through a hose guided along the robot arm.

Research prototype: the aim of the research prototype IGD01 was to simulate the industrial prototype in a collaborative environment located at the Fraunhofer laboratory in Darmstadt (Fig. 6). No high forces were to be expected on this prototype, as the focus here was on the development of the scanning technology and the simulation of cleaning. The research prototype works with a compliant, collaborative robot system and a dummy UHP waterjet tool at the end effector, but which already contains the real scan head. This prototype allows a simulation of the entire process, experiments with different end effector configurations and work in the immediate vicinity of the robot.

Autonomous capture and cleaning: in order to carry out an autonomous, robot-assisted cleaning of system parts, various sub-components are necessary (see Fig. 1). In addition to the hardware components such as robots, turntables, scanners and high-pressure cleaners, various software components are also necessary to make it possible. The process can roughly be broken down into three parts: The detection of the object on the turntable filtering out interfering geometry from fasteners and clamping, trajectory planning, simulation and optimization of the

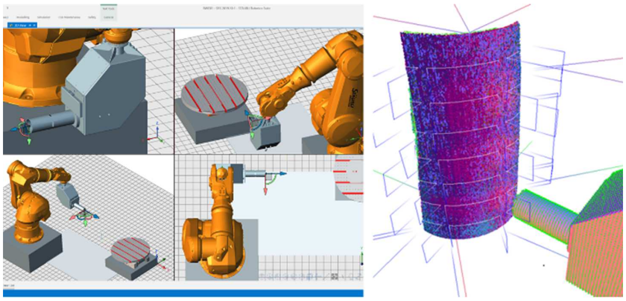

Fig. 7. Simulation of the cleaning process directly on the point cloud allows the cleaning tracks to be optimized with a focus on the areas that have not yet been decoated.

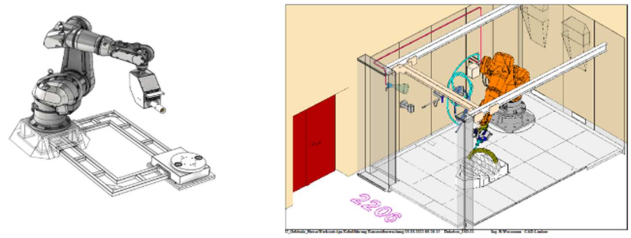

Fig. 8. Virtual planning and simulation of RWE01/RWE02 for the final decont cabin.

cleaning path and finally cleaning with optional repositioning of the object.

Object capture – shape and surface recognition and modeling: the detection of the objects on the turntable takes place performing adaptive scan runs. The scan head consists of a triangulation scanner with a (high speed) camera and laser line. In addition to the depth line, the scan head also provides information on the quality of the data obtained. This allows for direct readjustment/guidance of the scan head if the object gets out of focus or lighting is too bright or too dark. For the adaptive part of the scan, a mechanism is used that estimates the completeness of the 3D model obtained. At the end of the acquisition, the 3D model is cleaned in order to filter out artifacts (e.g., reflections between bare metal parts). In addition, an analysis is carried out to separate the component to be cleaned from interfering geometry from fasteners and clamping devices to limit cleaning to only the visible part of the component.

Planning and optimization of the cleaning path: the path planning algorithm uses the computed 3D model and the measurement data obtained from the UHP waterjet experiments. Various techniques are combined to get to the final cleaning path. The method starts with a group of pre-defined departure strategies and evaluates which one to choose. Based on the starting point, the geometric complexity of the component to be decoated and taking into account the best effective parameters of the UHP waterjet tool, the most efficient path is chosen. The method makes sure adequate spacing between the cleaning paths is observed and complete coverage of the object is achieved. Treated surface parts are marked on the 3D model as to know what has already been cleaned. Ultimately, this creates a complete cleaning program that includes the movements of the robot and the turntable.

The data obtained in the experiments represent the basis for using physical simulation to obtain a plausible virtual image of the nozzle under varying operating parameters. This means that the cleaning process can be reproduced virtually (Fig. 7) and the cleaning paths can be optimized with a view to optimal surface treatment. The optimized movement data are finally transferred to the industrial robot for coating removal and the UHP tool is guided over the assemblies to be processed according to these data, practically executing the generated cleaning program. Additional, non-optical protective functions (including collision and collision protection) monitor any errors in the calculation or operation.

Coating removal process: the optimized cleaning trajectory data are finally transferred to the industrial robot for decoating, the UHP tool is navigated over the components to be processed according to these data, and the cleaning program is executed. The cleaning program may involve repositioning of the object (due to surface regions where clamping was performed in previous positions) to make sure coating of a component is fully removed. Additional non-optical sensors are used to complement vision-based collision protection and monitor any errors during operation.

Multi-stage development and transition to productive operation: ROBBE focussed very much on the research and development of all necessary next generation technologies required to achieve an autonomous coating removal process. This applied above all to the areas of real-time, autonomous laser scanning, path planning and simulation of the decoating process. The theoretical approaches have been transferred in terms of software and technology to microelectronic or mechatronic systems, tested and built as industrial components into first a research prototype built by Fraunhofer and now the final decont cabin (Fig. 8) built by a certified system integrator (manufacturer).

The latter is undergoing the last evaluation round until going into operation at Biblis NPP in a two-stage process named RWE01 and RWE02. RWE01 is first evaluated and tested in a washing bay outside of the controlled area of the reactor buildings at Biblis power station premises to make sure UHP technology and the decoating process with the integration of a mobile UHP pump unit as well as the safety-related functions are working as planned. This is also where all necessary control steps and the later required interconnection to the system control of the decontamination room are tested. A control-related simulator based on an adapted dummy PLC is used for the safety, signal and data technology, capable of exactly mimicking the subsequent installation situation and connection to the existing plant facility.

The whole complex autonomous decoating process involving 3D scanning of an arbitrary object followed by dynamic trajectory planning for the UHP waterjet

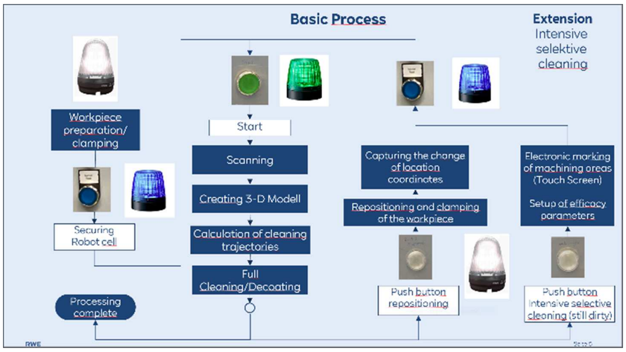

Fig. 9. Elegance lies in Simplicity: Final Process Workflow and User Interface.

Fig. 10. RWE01 prototype evaluation in washing bay prior to operational release into decontamination room as RWE02. The scan head is designed as part of the blasting tool with a humid and watertight protective flap protecting the sensible laser and camera optics during decoating operation.

treatment has been reduced to a simple and easy to use push button interface (Fig. 9).

RWE01 has been delivered and successfully set up in Mid November 2021. It is currently performing a series of operational tests as described above (Fig. 10). After successful conclusion of those tests, the system will be installed as RWE02 in the decontamination cabin inside the controlled area of Biblis NPP Block A. The transfer is being supported by an experienced NPP system manufacturer to ensure efficient and comprehensive trials as well as a short conversion process from RWE01 to RWE02. We expect RWE02 to go operational by the end of 2022.

4 Conclusion

We have presented the results of ROBBE which advances the current state-of-the-art by automating a once manual process in the dismantlement of NPPs increasing efficiency while enhancing workplace safety and health protectioncombined with a sustainable, energy-saving, innovative filter and water circulation system further reducing radioactive waste. ROBBE introduces autonomous digitization of arbitrary object geometries, generating dynamic trajectories for efficient decoating using UHP waterjet technology, based on physical evaluation results. Intelligent path planning algorithms allow robot-assisted laser scanners to capture arbitrary object geometries in repeatable high quality and to calculate a closed 3D surface model immediately after a scan is completed without manual post-processing. Neither CAD models are required for the 3D digitization of the objects, nor is it required to teach the scanning robot manually how to scan the component surface. The real-time laser scanner developed is capable of capturing highly reflective surfaces (stainless steel, chrome). The resulting 3D point cloud is examined for reflections and other faulty 3D measurement points through plausibility analysis. Object recognition distinguishes between clamping tools and object geometry. The machining process starts after an iterative object decoating simulation has been carried out determining the most efficient trajectory for the UHP waterjet nozzle. Among the optimization parameters considered are the accessibility of the object surface by the robotic arm, the achievable distance between jet nozzle and the workpiece surface, the range of adjustable angles of attack and the feed speed to ensure an optimized and complete decoating of the component. This may include the repositioning and re-clamping of the component to make sure all of its surface is thoroughly cleaned. The technical solution can also be transferred to other applications, such as alternative cleaning processes or subsequent processes (radiological measurements, quality assurance, component documentation) in dismantling, or to other industrial applications (surface processing of components with individual shape geometry in small batches).

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Conflict of interests

The authors declare that they have no competing interests to report.

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Data availability statement

Data associated with this article cannot be disclosed due to patents pending.

Author contribution statement

The following authors have contributed to this paper and to the implementationof the ROBBE industrial prototype:
- Dieter Fellner – foundations of computer science for laser-based digitization
- Pedro Santos – autonomous robotic digitization and surface treatment.
- Martin Knuth – autonomous view and trajectory planning.

• Martin Ritz – robot calibration, robotic command interfaces.
• Jörg Recknagel – overall project coordination, requirements UHP waterjet technology, efficiency evaluation, collecting ground truth data, water treatment technology, system integration
• Klaus Steinbacher – workplace safety mechanisms, radiation protection, system integration.
• Burkhard Wassmann – industrial prototype engineering, system integration.

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