Mediated Reality in Dental Technology

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MEDIATED REALITY IN DENTAL TECHNOLOGY

Christian Steinmetz,
Alexander Christ, Reinhard Heister, Marco Grimm
and Reiner Anderl
Department of Computer Integrated Design
Technische Universität Darmstadt
Otto-Berndt-Str. 2,
D-64287 Darmstadt, Germany
steinmetz@dik.tu-darmstadt.de

Oliver Sandig
and
Christof Ellerbrock

C3System GmbH
Elisabethenstr. 20-22,
D-64283 Darmstadt, Germany

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ABSTRACT

Cost pressure, increasing quality requirements of dental products and the effects on the development and manufacturing of dental products demand efficient computer-aided methods and tools. The utilization of mediated reality solutions in dental technology opens up huge potentials for cost savings, automation of dental workflows and improvement of interoperability. The structural integration of electronics, sensors and actuators in the dental work area, digitalization of dental workflows and virtualization of dental products pave the way for a paradigm shift in dental technology and how dental technicians interact with dental products.
In this paper, a concept for the integration of mediated reality in dental technology is introduced. Based on the digital dental workflow, improvements for the context of use of dental technicians are proposed. The concept focuses on the utilization of visual and haptic feedback in the dental product design and manufacturing process. Elements of dental technicians' future work places are analyzed and validated, resulting in a 3D dental Computer-Aided Vision and Design (CAVD) system with haptic feedback and visual motion tracking.

INTRODUCTION

In today's process chain of denture creation, an indirect, plaster model-based procedure is applied. This procedure is characterized by media discontinuities and a low grade of individuality in denture design. This leads to high costs, long processing time, and unpredictable process uncertainties. Due to uncertainties in the dental design and manufacturing process, a consistent quality level can often not be ensured, resulting in dentures with low durability.

Improvements in dental technology and the integration of approved virtual methods enable the optimization of dental products and corresponding processes. Thereby it is essential, that the familiar work environment of dental technicians remains unchanged. Computer-aided approaches enable the fusion of real and virtual environment, resulting in a mediated reality for dental technicians (Barfield and Mann 2003).

In this paper, the concept for a CAVD system is introduced, which allows dental technicians to receive haptic and visual feedback while working on virtual 3D dental models. The CAVD system is characterized by sensomotoric movement patterns based on dental technicians handcraft skills. It enables the fully digital design of dentures with a high grade of individuality and avoids the shortcomings of conventional denture design and manufacturing. The underlying digital dental process chain is described hereafter.

DIGITAL DENTAL PROCESS CHAIN

Three main classes of dental process chains exist to develop patient individual dentures (Heister and Anderl 2013):

- ChairSide
- LabSide
- CenterSide

The *ChairSide* process chain is characterized by inserting the individual denture in just one session. So the patient is not required to leave the dental chair during the treatment. This is achieved by using an intra-oral 3D scanner and an integrated development framework in order to reduce media discontinuities. With this technology only small scaled, low-complex dentures are producible, e.g. crowns, inlays and veneers (Mörmann 2006).

The most common process chain is the *LabSide*, as shown in Figure 1. By using this approach, almost every type of indication, every available material and every complexity grade is producible. The first step is the preparation of the damaged tooth. Afterwards, a dental cast is taken by the dentist and the plaster model is made by the dental technician. In the next step a media discontinuity occurs by the use of a 3D scanner for digitalization of the model. Thereby, the working method changes from physical into virtual. Based on the digitalized patients' jaw, the denture can be designed by a specialized dental CAD (Computer Aided Design) system. As output a CAD file in tessellated form (stored in the Standard Tessellation Language, STL format) of the reconstruction is generated. This file is processed by the use of a Computer Aided Manufacturing (CAM) system for production in a subtractive (e.g. milling) or additive (Selective Laser Melting, SLM) manufacturing process. Subsequently, a further media discontinuity back from digital into physical working methods appears. To finish the denture, a veneering is manufactured by coating the metal with ceramic. This is manually done by using a brush, ceramic substance and furnace. To ensure functionality and accuracy of fit, the denture is validated with an articulator. Finally, the denture is sent back to the dentist. In a dental treatment, the denture can be finalized and inserted (Beuer et al. 2008; Strietzel and Lahl 2007).

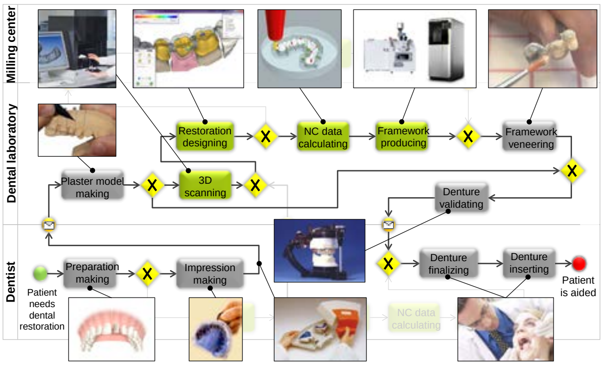

Figure 1: LabSide Process Chain (Heister and Anderl 2013)

The last possibility to walk through the dental process chain is the *CenterSide* method. All steps are equal to the LabSide method, but only CAM processing and manufacturing process are outsourced to a specialized milling center. This paper focuses on the LabSide process chain.

USE CONTEXT OF THE DENTAL TECHNICIAN

Historically, the work of dental technicians is characterized by manual work. The first time digital technologies came up was in the 1970s. In the 1990s, digital dental technology had experienced a breakthrough due to the invention of the CEREC I system. Ever since, the adoption of digital dental work methods has been increased continuously. The advantages of these digital technologies are enhanced productivity, high accuracy as well as improved reliability (Strietzel and Lahl 2007).

Despite all the advances, that have been developed, there are still some disadvantages in the use context of dental technicians:

- No 3D visual experience
- No 3D input interaction
- Lack of physical feedback during interaction
- Lack of digital working methods in education
- Reduced acceptance of non-intuitive digital systems by dental technicians

Today's CAD systems provide the development of 3D parts in a virtual 3D environment. However, the presentation of the 3D representation is rendered on a 2D output device, e.g. a display. Common displays are not able to display virtual 3D parts in an autostereoscopic manner. Therefore, it is challenging to anticipate actual position and orientation of the shape manipulation features during work. Furthermore, accurate assessment of the dental design regarding functional and esthetical requirements is often insufficient (Jobst and Ellerbrock 2013). The human-machine-interface (HMI) of a dental CAD system is shown in Figure 2.

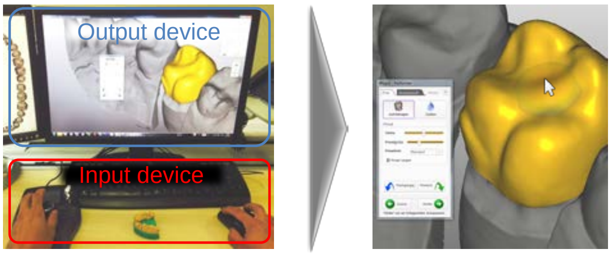

Figure 2: HMI of Dental CAD Systems

Besides the shortcomings in presentation of the virtual model, there is a lack in usability related to the user input. In contrast to intuitive manual movements in the physical denture shaping process, CAD-based denture design is most commonly performed by the use of a 2D computer mouse. The 2D position of the mouse cursor has to be mapped into 3D coordinates. Here, it is difficult to identify the precise 3D position through the 2D cursor, too.

In traditional manual work dental product designers receive direct and immediate feedback. By using digital design technology, designers only receive visual or acoustic feedback. Haptic feedback, comparable to the manual work, is completely missing. Especially for the design of high-accuracy freeform shapes, an immediate and intuitive feedback would contribute to an improved digital design process (Ellerbrock and Kordass 2011).

The German dental technician education is mainly characterized by traditional manual development methods. Digital work methods still play a minor role. As a result, newly qualified dental technicians have to be educated in digital CAD/CAM applications at the dental laboratory. Additionally, sensomotoric movement, which is well-trained during education, is not utilized when using state-of-the-art digital development methods.

CONCEPT FOR THE INTEGRATION OF MEDIATED REALITY IN DENTAL TECHNOLOGY

The integration of approved computer-aided methods and tools offer huge potentials for dental technology. The digitalization and automation of manual processes improve efficiency for the development of dental products and ensure a defined quality level (Christ et al.

2014). A key enabler is the suitable integration of virtual 3D dental models in the digital dental design workflow. 3D dental models allow dental technicians to interact with the virtual representation of real dental products in a virtual 3D environment and pave the way for the further integration of virtual solutions.

For dental technicians the visual and haptic feedback from dental products is very important during the dental manufacturing process. Virtual 3D dental models enable the integration of established solutions like virtual reality applications and haptic devices. The combination of those approaches leads to a mediated reality for dental technicians. There are several approaches for the integration of mediated reality into dental technology. They range from haptic feedback devices to the utilization of camera systems as digital stereomicroscopes and the structural integration of sensors, actuators and electronics in dental input devices.

The innovation of the approach introduced in this paper is the user experience of virtual 3D dental models through the entire development and manufacturing process of dental products. A direct und fully digital procedure is applied to avoid media discontinuities and to increase individuality in denture design. The main objective is the deployment of a Computer-Aided Vison and Design (CAVD) system. Sensomotoric movement patterns based on the dental technicians handcraft skills are used for the interaction between dental technician and CAVD system and for the processing of the 3D dental model.

Architecture of the CAVD System

The proposed concept enables the interaction with 3D dental models and the superposition of virtual and real environments. The concept consists of three modules:

- Haptic feedback system,
- head-mounted display and camera, and
- dental input device.

The *haptic feedback system* enables dental technicians to receive a realistic tactile behavior during the interaction with the 3D dental model. In order to achieve a realistic functioning in the manufacturing of dentures, a pen-based haptic feedback system is used. The pen of the haptic feedback system represents the tools of the dental technician. The pen tip is represented in the CAVD system as cursor position. If the cursor touches the surface of the 3D dental model, a force is applied by the haptic feedback system. Haptic devices are usually intended to interact with 3D models without modification. In this concept, the modification of 3D dental models is one of the main functions of the CAVD system. The modification of the model geometry can be distinguished into operations that add material and remove material.

The *head-mounted display and camera* enables the application of virtual reality and augmented reality methods in the CAVD system. On one hand, scaling of 3D dental models is achieved in the form of a digital stereomicroscope. On the other hand, the display allows a superposition of additional information on 3D dental models by using see-through functionality. Additional information is assigned to the 3D dental model and aligned with the current view. The deployment of the head-mounted display and camera enables dental technicians to interact with dental models in a visual manner. The processing of 3D dental models in a pure virtual environment as well as in an environment that combines virtual and real objects is possible. The system can be used for education and training as well as in daily work for manufacturing and quality control of real dentures.

The *dental input device* is used by dental technicians for modeling of dentures. Usually dental input devices are tongue-shaped plastic plates without further functionality. In the denture manufacturing process, material is added to and removed from these plates. Current dental input devices do not fulfill the requirements of the CAVD system. Therefore, a structure integrated digital dental input device has been developed. Structure integrated sensors enable the continuous determination of position and orientation of the dental input device. For dental technicians the dental input device can be seen as black box: the outer shape remains unchanged, while the digital functionality is achieved with integrated electronics. Thus, the way how dental technicians work stays the same, but is efficiently supported by the virtual modeling system.

Integration of the CAVD System in Dental Workflows

The CAVD system includes the integration of electronic devices, particularly sensors and actuators, into the daily work of dental technicians. In order to integrate the electronic devices to the virtual modeling process, a computer-internal representation of the patient's oral situation is required. Therefore, the oral situation has to be digitalized, as described above in the LabSide process chain. The digitalization is realized by using a 3D scanner, e.g. an intraoral scanner. From the 3D scan a 3D dental model is derived.

The dental technician uses this 3D dental model as basis for the denture modeling process. Standardized 3D teeth models can be loaded from teeth libraries. These teeth models represent relatively coarse geometries that have to be adapted to the individual patient's oral situation by the dental technician. The current procedure is characterized by a variety of manual working tasks on physical objects, time-consuming error corrections and many media discontinuities (Heister and Anderl 2014). This can result in dentures that do not fit correctly and that have a low durability due to overstressing.

The CAVD system enables the digitalization of working procedures of dental technicians, which supports the concept of "cyberizing the physical" (Lee 2010) of Industrie 4.0 (Anderl 2014). Thus, the dental manufacturing process is based mainly on virtual methods. Starting from the 3D dental model, the precise design of dentures can be performed in a pure virtual 3D environment. Scaling of 3D models and overlaying of additional information without interruption of the working process are deployed by the head-mounted display and camera. Besides the visualization, a haptic feedback can be retained by the haptic feedback system. The digitalized dental input device completes the CAVD system as enriched platform for the virtual projection of the 3D dental models, resulting in a mediated reality in form of a smart environment for dental technicians.

Media discontinuities are minimized, while error corrections can be performed more efficiently. Functionality is improved by the individualized design and configuration of the dental technician's tools in the virtual environment. The digitalization leads to time savings in the manufacturing process and to a cost reduction due to material savings compared to the physical dental design process.

Mediated Reality via Multi-sensual Interaction

To bring virtual dental models to a physical user experience, the partial systems

- haptic feedback system,
- head mounted display and camera,
- dental input device, and
- an additional computer with dental modeling software

are integrated to a CAVD system. Therefore, interfaces between these modules have to be harmonized.

The dental input device as well as the haptic feedback input device need to provide high sensor sampling rates for seamless and direct movements of the dental modeling tools. Input delay or lag lead to unnatural movements and modeling errors. To enable fluent and accurate motion, it is important to guarantee low latency transmission with high data rates. To cover the whole 60 full frames per second display output, at least 120 Hz input and output sample rate is recommended.

The modeling core of the CAVD system works with triangulated meshes for virtual constructions. For high accuracy in the dental industry high model resolutions are required. Common virtual dental models contain over 15.000 vertices and 30.000 faces per indication, e.g. a single crown model has a binary file size of about 2 MB (see Figure 3). To prepare the denture model, a 3D scan, stored in the STL file format, is loaded in a conventional dental CAD software and based on the individual situation, a standard denture is generated. Common dental CAD solutions provide a set of denture templates for each required indication and tooth. For modeling of a crown, the specific tooth is selected and the crown is generated by the difference of the existing tooth stump and the tooth template. From the predefined standard denture, the fine modeling is done in the CAVD system. To do so, the pre-designed denture is exported in triangulated form (STL) and loaded in the CAVD software. The data transfer between the systems is done without media discontinuities.

To perfectly fit the patient's dental situation, the pre-designed denture has to be detailed manually. The goal is to fit the occlusion and preparation borders between denture and tooth stump for best functional, hygienic and esthetical results.

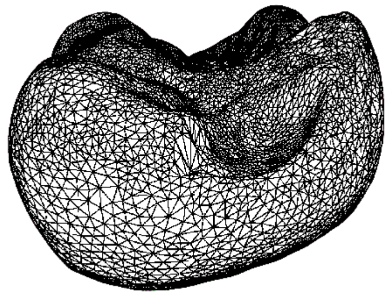

Figure 3: Triangulated Dental CAD Model

The CAVD integrates the linkage-based and pen-type haptic feedback device for both user input and tactile feedback. The input for 3D tool positioning with six degrees of freedom (DOF) is achieved by reading the encoders in the device joints and recalculating the input pen's angular and linear positions. The robotic arm's own weight and introduced momentum is compensated via a closed-loop control integrated in the device to minimize the actual tool weight for the dental technician and make modeling work less straining. The feedback is provided by putting linear force on the end joint of the pen when the virtual modeling tool is touching a surface of the denture model. If the tool is pushed further into the restraining surface, the force of the pen is linearly increased until a maximum value is exceeded. The increase of perceived force is achieved by applying torques to the motors at each joint. With this, forces in all 3D directions can be represented. In practice, a professional haptic feedback device is used for the proposed concept, and its high-level application programming interface (API) is used to cover both input and output streams. See the following section for details on the prototypical implementation.

In accordance to the common manual work the CAVD system is used with both hands. While the haptic feedback system is used with one hand, the dental input device is used with the other hand. The dental input device controls the virtual denture model by acquiring a live spatial position and orientation of the device and maps it to the virtual model in real time. On the model, the virtual presentation of the denture model is projected in a 3D environment. When the input device is moved or tilted, the model is moved and reprojected accordingly. The shape of the device is designed to match the shape of the dental modeling plate that dental technicians are used to. This traditional jaw-like shape provides the best functionality while being ergonomic for the particular dental modeling task. The dental input device does not provide a tactile feedback as the haptic feedback device. The tip of the haptic feedback system modeling pen is not intended to touch the dental input device as the virtual model is projected in between both devices.

The head mounted display and camera is the main module to achieve the mediated reality experience of the overall CAVD system. It is directly connected to the modeling computer, where the CAVD software is running on. The device is held on the head by a head mounting strap, so that the user is looking into the two displays. As displays, high-resolution near-to-eye micro displays are used for vision. The real workplace view is captured by wide angle cameras that are mounted in front of the display. The visual input of the cameras is then projected to the displays and overlaid with the virtual models. In order to detect the dental input device orientation, machine vision algorithms are used to complete the augmentation and gain accurate distance coordinates between viewer and dental input device. The scheme of the overall CAVD system is shown in Figure 4.

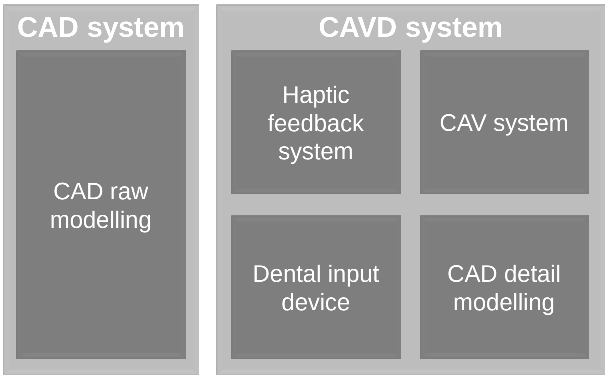

Figure 4: Scheme of the CAVD System

The mediated reality experience is then provided by the combination of the input and output devices to deliver a multi-sensual interaction with the user. The near-to-eye displays provide a natural, first-person visual perspective to the technician on the workplace. The virtual workplace is projected on the real workplace in a way that the augmentation provides a visual feedback to the user about the working process. This visual experience is supported and enriched by the tactile response provided by the haptic feedback system. The dental input device allows natural movements of the model in the virtual environment so that the overall CAVD system provides an immersive and intuitive way of dental work.

PROOF OF CONCEPT

In the proposed operating concept (see Figure 5), the dental technician uses the pen of the haptic feedback device and the dental input device as tools to modify the virtual data that overlay the real scene in the CAVD system (see Figure 6). The real scene is therefore captured by two similar cameras and projected on two similar displays. Both cameras of the CAVD system are connected to the computer via USB 3.0 interfaces and are able to capture images in 1920x1080 pixels (Full HD) resolution at a frame rate of 30 frames per second. The displays are able to show images in 1280x720 pixels (HD) resolution and are connected to the computer via DisplayPort interfaces. The dental input device communicates with the computer via a wireless interface and sends its position and orientation about 120 times per second over this connection. Further, the haptic feedback system with a sampling rate of 1000 Hz is connected over a FireWire (IEEE 1394) interface.

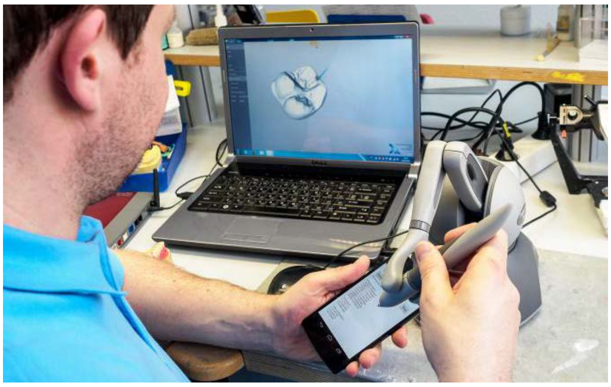

Figure 5: Proposed Operating Concept

The whole optical and mechanical system is optimized for a working distance (distance between the dental technicians head and the working scene) of 300 mm. The computer is thereby the main processing unit of the whole system. While the user or technician can see the live-view of the real scene, a 3D file in STL format is loaded into a 3D viewer based on the Open Graphics Library (OpenGL) and overlays the real scene. Most CAD systems only show the rendered virtual scene in a parallel projection. For a real time manipulation of 3D data, it is advantageous to render a scene with perspective projection. Therefore, a simple and transparent 3D viewer based on OpenGL has been developed in order to overlay the camera images from different points of view, see Figure 6. In addition to these 3D renderings, 3D annotations or other relevant information can be overlaid with the camera images.

The haptic feedback device has six degrees of freedom, a translational resolution of 0.055 mm and a maximum force feedback force of 3.3 N (SensAble 2008). The force feedback is computed and applied by the main processing unit. Therefore the actual position and orientation of the haptic feedback device is compared with the bounding box, nearest point distance and geometry of the loaded CAD model.

Figure 6: Overlay of Digital 3D Scan Data

For various tools of dental technicians different surface properties are applied by calculating a special and individual force feedback. Thereby, it is possible to simulate the haptic behavior of actual und future real and virtual tools. By a basic magnification and almost lossless digital zoom technicians have a huge scope and many possibilities to modify the virtual data. Figure 7 demonstrates the interaction of a dental technician with an early prototype of the CAVD system.

Figure 7: Early Prototype of the CAVD System

In first tests, the cameras have shown a latency/delay of approximately 200 milliseconds between capturing and displaying images which has to be optimized in future studies. The system has also a very good depth of field. The whole jaw model appears sharp in a wide focus range. Further practical tests and developments will show, whether the proposed operating concept is close to traditional manual development methods and can help dental technicians design and manufacture individual dentures.

CONCLUSION AND OUTLOOK

In this paper, the benefits and the necessity of digital dental technology are described. The technology allows vast improvements in quality and development time based on current physical dental modeling techniques. This provides a substantial business potential as well as increased health-care value for patients. However, the complex use context of dental technicians requires comprehensive digital integration to match the flexibility and physical experience of dental technicians work.

As a first step to achieve an integrated virtual environment for dental technicians and to leverage the digital modeling possibilities, a concept for a CAVD system is proposed. This system is based on a mediated reality setup with intuitive input devices and a tactile feedback through the haptic feedback system. The different system elements in combination with the CAVD software provide an immersive modeling experience. Due to the first-person point-of-view, the dental technician's natural work context remains unchanged. To demonstrate and prove the usability and functionality of the proposed concept, a prototypical implementation that combines all modules of the CAVD system has been developed and discussed.

Future research will focus on the extension of the CAVD system as well as on the optimization of the current virtual environment. For example, actuators to provide tactile feedback should be integrated into the dental input device. Furthermore, additional information over the modeling process can be integrated into the user's view through augmentation.

ACKNOWLEDGMENTS

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BIOGRAPHY

CHRISTIAN STEINMETZ studied Computational Engineering at Technische Universität Darmstadt from 2008 to 2011. In September 2013, he completed the master program Computational Engineering at Technische Universität Darmstadt. Since October 2013 he works as research assistant at the Department of Computer Integrated Design of Technische Universität Darmstadt. His research activities focus on web services and Industrie 4.0.

ALEXANDER CHRIST earned his diploma in mechanical engineering at University of Applied Science Giessen-Friedberg in 2009. As student he worked at GM/Opel in the area vehicle simulation. From 2009 to 2011 Mr. Christ studied mechanical and process engineering at Technische Universität Darmstadt and achieved the Master of Science degree. In June 2011 he joined the Department of Computer Integrated Design of Technische Universität Darmstadt as a research assistant. His research activities focus on the development of methods and tools for CAD and PLM in automotive, aerospace and dental technology.

REINHARD HEISTER studied from 2003 until 2006 Reinhard Heister Mechanical Engineering at the Duale Hochschule Baden-Württemberg in association with the company KARL MAYER Textilmaschinenfabrik GmbH. Subsequently he worked for three years as a project manager in machine development and was responsible for the development of several serial machines. From 2009 until 2011 he studied Mechanical and Process Engineering at TU Darmstadt. His master thesis dealt with the optimization of human-machine interface between the air traffic controller and the air traffic control system at the Deutsche Flugsicherung GmbH. Since October 2011 he is a research assistant at the Department of Computer Integrated Design (DiK).

MARCO GRIMM earned his master's degree in mechanical and process engineering at Technische Universität Darmstadt in 2012. In March 2012, he joined the Department of Computer Integrated Design at Technische Universität Darmstadt. Ever since, he is also engaged at the excellence center CASED (Center of Advanced Security Research Darmstadt). His fields of interest are production systems security, knowledge protection in engineering and connected systems for virtual product development.

OLIVER SANDIG studied mechanical and process engineering at Technische Universität Darmstadt from 2008 to 2014. In September 2014, he completed the master program mechanical and process engineering at Technische Universität Darmstadt. Since September 2014 he works as research assistant at C3System GmbH.

REINER ANDERL earned his diploma in mechanical engineering in 1979 and his Dr.-Ing. in mechanical engineering in 1984, both at Universität Karlsruhe. From 1984 to 1985 he served as technical manager of a medium-sized company. Dr. Anderl received his academic habilitation in 1991 and the venia legendi in 1992, and accepted the call for professorship for Computer Integrated Design at the faculty of mechanical engineering at Technische Universität Darmstadt. Dr. Anderl was dean of the faculty of mechanical engineering from 1999 until 2001, when the bachelor and master programs were implemented. He is member of the Zentrale Evaluierungs- und Akkreditierungsagentur (ZEvA), a national accreditation agency, the PACE manager of Technische Universität Darmstadt (Partners for the Advancement of Collaborative Engineering Education), an adjunct professor at Virginia Tech, and a full member of the Academy of Sciences and Literature, Mainz. Dr. Anderl has authored and co-authored more than 230 publications.

CHRISTOF ELLERBROCK earned his diploma as a dentist in 1999 and the doctorate (Dr. med. dent.) in dentistry at the University of Jena in 2000. Before studying dentistry he studied mechanical engineering at the University of Braunschweig from 1990 -1992. 2001 he became a partner in a dental office in Idar-Oberstein where he specialized in treatment of "craniomadibular diorders". 2007 he started the master course "Treatment of craniomadibular diorders" at the University of Greifswald, where he got his master degree in 2010. 2009 he started another master course at the Danube University of Krems in the field of "Interceptive orthodontics". Here he achieved the master degree in 2012. Since 2012 he owns a dental clinic Darmstadt, where he also founded the dental laboratory "Form for Function GmbH". In 2014 he founded "C3System GmbH". He is holder of several patents, international lecturer and international publications.