

PAPER • OPEN ACCESS

Production environment of tomorrow (ProMo): Partially automated repair process of small tool moulds, forming tools, injection moulding tools and sand casting tools

To cite this article: Jan Kuschan *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1140** 012036

View the [article online](#) for updates and enhancements.

You may also like

- [Structural relaxation probed by resistance drift in amorphous germanium](#)
Ning-Ning Dong, Jian-Gen Xu, Jin-Jiang Cui *et al.*
- [The Research of MRO System for NC Equipment Life Cycle](#)
Tao Zhang, Weixi Ji and Yongtao Qiu
- [Persistent homology and many-body atomic structure for medium-range order in the glass](#)
Takenobu Nakamura, Yasuaki Hiraoka, Akihiko Hirata *et al.*



The Electrochemical Society
Advancing solid state & electrochemical science & technology

241st ECS Meeting

May 29 – June 2, 2022 Vancouver • BC • Canada

Extended abstract submission deadline: Dec 17, 2021

Connect. Engage. Champion. Empower. Accelerate.
Move science forward



Submit your abstract



Production environment of toMorrow (ProMo): Partially automated repair process of small tool moulds, forming tools, injection moulding tools and sand casting tools

Jan Kuschan, Vinzenz Müller, Stephan Mönchinger, Oliver Heimann,
Carsten Niebuhr, Oday Kabha

Fraunhofer Institute for Production Systems and Design Technology IPK, Germany

E-mail: jan.kuschan@ipk.fraunhofer.de

Abstract. Small defects in the grain or major damage to a moulded part or tool can bring production to a standstill. SMEs in particular have neither the personnel nor the equipment to repair such damage on their own, so they send it to specialised contractors. The repair process is carried out manually, depending on the accuracy requirements, and is usually completed by a finishing process. This work requires qualified personnel and, at the same time, requires a lot of time in case of larger damages. In this paper we present a way to map the Maintenance, Repair and Operations (MRO) process chain in a partially automated manner.

The symbiosis of individual technologies results in a significantly increased efficiency of the MRO process chain, which continues to focus on people and their process knowledge.

While Directed Energy Deposition (DED) for the MRO of moulded parts is used widely, usually a high manual effort in measuring the component geometries and teaching of the machine tool paths is necessary. However, there are clear advantages compared to the manufacture of new parts or manual laser welding repair. At the same time, the resource and energy requirements can often be significantly reduced compared to new part production. ProMo focuses on automating the time-consuming machine programming by reducing the number of necessary work steps in CAD/CAM-based program creation.

Based on a subsequent robot-guided scan, a digital actual 3D model is generated. Due to intelligent path planning algorithms, no manual programming of the robot is necessary and at the same time it is possible to detect components of different sizes, shapes and covers in this system with a minimum of effort. In addition, the operator passes on elementary information, such as the approach path of the milling head, to the subsequent processes by means of finger gestures and can thus significantly reduce tedious CAM programming steps. Now, the scanned component is transferred to a 3D-CAD model and a target/actual comparison is created for the damaged areas. Those are milled out in a defined manner and then restored using DED.



1. Introduction

Turbine blades, like in stationary gas turbines or aircraft engines are exposed to extreme conditions. High temperature, pressure and depending on the use case also foreign objects reduces the life time of the blades. Since, a broken blade leads to a reduced turbine efficiency or even to a destruction of other parts, the Maintenance, Repair and Operations (MRO) has a major impact on the operator of turbines. The main defects are related to blade tip erosion or cracking defects, but in most cases, damaged parts are discarded and replaced by new parts, resulting in the loss of resources and high costs. [1]

To reduce industrial greenhouse gas emissions with its approximately 30% of the total greenhouse gas emissions, is one of the major challenges of our time [2]. One of the main reason for industrial greenhouse gas originate manly from material processing, i.e. from the conversion of natural resources into materials to convert into manufacturing and construction goods to produce the final product [3]. The use of additive manufacturing (AM) could improve both, an efficient material/resource and energy management. An important technology in AM for the MRO of metal components is laser-based DED which allows a material and cost efficient repair process with high deposition rates. It is widely used in the industry to repair complex gas turbine or moulding parts. [4]

If nowadays, blades are repaired this results in high engineering and machine time. One main disadvantage is the reconstruction and CAD programming of the free-form object. For the engineer this results in a very complex and detailed tool path planning of the DED machine and also the CNC milling machine. This is time consuming not only for the engineer but also in case of machine time.

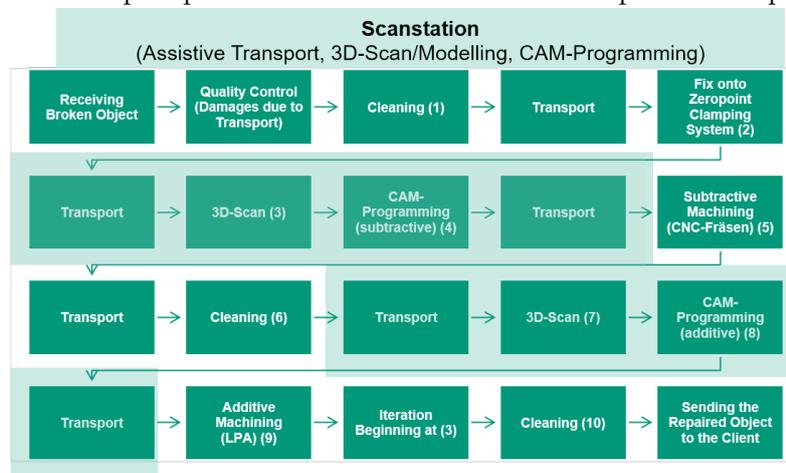
2. Contribution

Within this paper we present a novel approach for a semi-automated damage detection and repair process, that we verified on a turbine blade. Therefore, we present an intuitive human robot interaction specifically designed for manufacturing in workshop environments. For the local workshop employee, the system provides a task oriented programming interface through a projection based augmented reality. The system generates most of the program automatically based on sensor input. This reduces the user input to the critical information required to solve ambiguities.

For maintenance personal or an off-side process engineer, the system offers a virtual reality interface. This allows to immediately bring in a remote expert when a critical problem arises. The system not only monitors the machines state but also reconstruct any object, such as the work piece or a human arm, within the working area. This gives the remote user a unique insight into the current problem and helps him provide the necessary support without an expensive and time-consuming trip to the facility. Within this paper we present and tested a holistic process chain for the MRO of a gas-turbine blade.

3. Related Work

Generally, automated Reverse Engineering, based on optical 3D-data is characterized by six stages in succession. First of all, we need to capture geometrical data of the virtualized object. These are then being post-processed and segmented. Then the generated data can be classified and used as input for model creation. The result is a 3D CAD model [5]. Reverse engineering, as a non-automated process, involves numerous of manual, repetitive and highly know-how-dependent activities. Automated data acquisition systems often require high investments, are not yet available in an industrial context, or are currently only being developed for specific applications [6, 7]. Post-processing of the scan data is often manually been done. By tessellating the scan data, a representation of the surface is created. For further use of the data, we have to transfer it into mathematically described models. This is commonly done by manual

Figure 1. Repair process chain of the defective component compare [13]

reconstruction of a CAD model based on the tessellated surface model. Cycle time and quality varies depending on the level of knowledge of the executor. Therefore, we work on the automation of these process steps.

Having an automated reconstruction process is highly depending on a well performed digitization of the blade or form. The scanning process itself is combined with a robot. Therefore, Heimann and Guhl [8] classifies robot programming methods into three sections: online, offline and hybrid, each with different advantages and disadvantages. Online programming methods like lead through, walk through or by demonstration need direct interaction with the robot, while offline programming methods like text based, graphic interfaces or simulations are done through comprehensive software tools without the physical hardware. Using a hybrid approach, it is possible to define the robots work space and routing offline and adapt the path to the specific problem.

Current work about human robot interaction splits in two topics. One is focusing the recognition of human action while the other focus point is the interface design. Due to current restriction in recognition of human by the computer the design of the interfaces is still narrowed. [9] gives an overview on the diverse ways to detect hand gestures, starting from traditional computer vision up to today's machine learning based methods. [10] describes a current system using traditional computer vision for accurate hand pointing in a robot environment. To bring the user interface to the robot working place augmented reality is a common way. Projectors and AR glasses are used to display UI elements and state information directly in the working area. In [11] a augmented reality system is introduced, where the robot shows its planned action. Touch interaction on a projective interface is shown in [12].

4. Experimental Setup

In our use case, we project a whole repair chain from receiving the broken part via repairing and finally the transfer back to the customer (Fig. 1). Therefore, we designed a scanstation (Fig. 2) equipped with a zero-point clamping system mounted on a workstation table and a 3D-hand-scanner attached to a collaborative robot looking upside down. To control the process directly at the station, a stereo-camera for finger tracking and hand-gesture detection and a projector to visualize a GUI was mounted to the scanstation. An a wearable sensor vest giving a haptic real-time feedback in ergonomic critical movements.

Figure 2. Scanstation with overhead mounted robot, scanner and turbine blade.



5. Process Model

The repair process is described with a specific process model, which includes all processing steps that should be done in sequence from the beginning until the end of the process. The process model represents the interface between the user, and the industrial machine used in this project. The connection between the process model, and the machine is established using a REST-Interface. The process model provides several GUI objects, each one has a specific color, and represents a specific functionalities. Each GUI Object has several subclasses, in order to classify the functions in separate groups. Each group is dealing with the same subject. The most important GUI object is the resource, which is the real function that will be performed in a processing step. The resource has subclasses, which represents REST functions, OPC-UA functions, GUI functions, and others.

In this project the process model will be loaded into the AR-Application. Using a C# script the process model will be processed step by step starting with the START node and ending by the END node.

6. Augmented Reality

Augmented reality (AR) provides several options, in order to make the use of industrial machines easier for new employees. Due to the industrial machines complexity, and multiple functionalities; a training course should be given to the employees, in order to enable them to deal with the machine without making mistakes. These trainings are too expensive, and take a long time, while during the training time the machine will be out of work. Augmented reality helps to make training time shorter, and provides more options to explain the functionalities of the machine. One of the most important benefits of integrating augmented reality (AR) in industrial machines is that we need no additional hardware in the machine itself like screens, and computers for showing texts, and communicating with external servers. In this project the AR-Glass HoloLens 2 from Microsoft is used as an info visualization tool to display the processing state of the machine during the repair process. The HoloLens 2 also provides a GUI, which enables the user to change some settings, and to intervene during the processing, when it is necessary. To complement the HMD HoloLens 2 interface, a projective AR interface was implemented with a DLP projector. This interface augments the key 3D working area and components (plate with the objects) and simple 2D buttons from above onto the scanstation table. Users interact with this interface via finger gestures, e.g. activate virtual buttons by pointing at them. These buttons are the means by which the user controls and triggers the

process flow. Additionally users can define 3D positions with their fingers and by that mark the identified damages on the workpiece. To provide this functionality and correctly project user feedback, the workpiece and its pose are detected via cameras and a CAD model of the object.

7. Realtime Ergonomics Feedback

Since workers often handles heavy objects, we are also presenting a solution to reduce the risks of injuries. Therefore, we designed a textile sensor vest for haptic ergonomic assessment feedback called ErgoJack, containing of three separable different layers, an outer, middle and inner layer. The outer layer is a robust textile that prevents the electronics from physical impacts. The middle layer contains all electronic components, a computing unit, five Inertial Measurement Units (IMUs), a vibration unit and a textile on/off button all connected trough textile wires. The inner layer, which has body contact, contains of breathable spacer fiber material which is comparable to the contact surfaces of backpacks. All layers are connectable through buttons and zippers. With this strategy it is possible to wash the material which is either exposed to environmental influences, like dust and fluids, or is close to the body and is therefore exposed to sweat, without destroying the electronics.

The ErgoJack uses the IMUs to detect the pose and movement of the worker and uses the vibration unit to give a feedback in real-time when the wearer performs potentially body harming actions. Details on the algorithm are published by Kuschan et al. [14]. Using this strategy, the wearer has a long-term learning effect, but is not restricted in his movements. By using the vibration unit the feedback is also only recognized by the wearer him- or herself.

8. Natural human-machine interface

Non-intrusive, contact free hand gesture detection can be beneficial for many human-computer interactions [15] and lately has also been implemented in human-robot interaction scenarios [15, 16]. In our use case we apply a simple 3D finger position to allow easy to use position or path definitions and manipulations of a projected interface directly within the working area. Thus no additional devices which may easily be destroyed in an robot assisted production space are needed. The user can naturally interact with the robot and show him where to perform which milling process. GUIs are still the well-established solution to interact with a machine and especially suitable to ease the transfer from a monitor to an augmented reality interface in a workplace. Instead of using a controller we allow users to naturally and efficiently use his/her fingers for 3D pointing interactions. Selection method is dwell time based and supported with projected visual feedback directly at the fingertip. The hand/finger detection is implemented as a mixture of traditional computer vision and machine learning approaches. Gesture recognition is based on the volumetric scene reconstruction data (see section 10) and a 3D separation of scene and the users hand. Parallel to that a hand and fingertip detection is processed based on a Yolov5 neuronal network. After recognizing hand and fingertip region, the exact position of the fingertip is computed using a hough transformation specially adapted to the finger geometry. The gesture recognition process is running on CPU not interfering with the GPU intensive volumetric scene reconstruction. In addition to GUI based human-machine interactions, the operator pass on elementary information, such as the approach path of the milling head, to the subsequent processes by means of finger gestures and can thus significantly reduce tedious CAM programming steps.

9. Robot Integration

To improve and automatize the scan, we mounted an UR5 on top of the scan-station facing downwards with the camera integrated at the end of the robot arm. The working area of the robot is predefined to prevent collisions. Trough a rough 3d reconstruction of the blade or form

recorded by the finger tracking cameras the robot path is adapted to the ideal working distance between scanner and object.

10. Scanning and Processing

In a two step process the object on the plate is detected and for this purpose the previously mentioned volumetric scene reconstruction is used. First, the plate itself is detected in the scene by simply fitting a plane around the origin of the work environment in the point cloud. If the plate is successfully detected, the objects on the plate can be detected and their poses estimated. The object pose detection is of importance for the AR projected scene and for the interaction with the scene (e.g. for the gestures) and scanning. The pose estimation by means of point cloud registration is based on the approach described in [17]. The point cloud is segmented based on the plane representing the plate and all voluminous objects over the plate are extracted. By using the CAD models of the known objects, the objects can be registered to the segmented point clouds and their poses estimated. The limitations of our approach is based on the reconstructed objects and/or scene. If the objects are too small or if objects occlude each other it may result in an unsuccessful pose detection. Since the plate can be fixated in four different orientations (shifted in 90° steps) a global reference frame is introduced by means of a QR code (containing the plate identification), which can be detected in a 2D or 3D scene. The status of detection of the plate and object as well as object's pose is stored in variables on the OPC UA server for other software modules to access and to trigger the process flow.

The workflow for generating the difference model is divided into five steps: scanning, filtering the point cloud, registering the target and actual model, cutting out the region of interest (ROI) and generating the difference volume. This is followed by an interface to the CAM software, which includes an automated globally oriented positioning in the virtual installation space. The process of data acquisition has already been described in detail above. Therefore we start here at the process step of filtering. Due to error detections and unnecessary data points, such as the base plate, the data set must first be repaired and filtered. This process is necessary to create a continuous even waterproof and also reduced actual model. Therefore, we integrated PCL based functions to reduce the model and to detect and filter out the baseplate. In the following, the simplified actual model and the corresponding target model are first roughly aligned with each other by means of RANSAC registration (Random Sample Consensus) and then finely aligned with each other by means of ICP registration (Iterative Closest Point). Correspondences of points between the registered actual and target models are also calculated. Points that have no corresponding point in the other model are extracted. From this a correspondence point cloud is generated, which can be divided into many clusters based on Euclidean distance. Many clusters are created at this point because there are production-related deviations between the target and actual model. Since these are irrelevant for the repair of the defect area, it is necessary to determine the cluster which covers the relevant defect area. With the coordinates of the Point of Interest (POI), which is read by the OPC-UA server, the next cluster to the POI is selected as the point cloud of the Region of Interest (ROI). An oriented bounding box is then calculated, which we use as a tool for cutting the ROI mesh. After cutting the ROI mesh, existing disturbances, e.g. overlapping models, are removed. From this, a difference volume between actual and target model is calculated quickly and cleanly with the Boolean difference in FreeCAD Software. However, the difference volume cannot be processed directly by the CAM software because of its irregular base area. Therefore, a common volume of the cut ROI of the target model and the oriented Bounding Box of the ROI is created using a Boolean operation to create a flat and rational base. This allows the toolpaths to be built in the CAM software. The interface between the data processing and the CAM software consists of a Python script that opens the CAM software and a macro that calls the CAM software functions. The parameters for additive manufacturing are then entered manually to generate the tool path and

the corresponding NC code.

11. Additive and subtractive Manufacturing

Based on the calculated tool paths from the previous process step and defined process parameters such as laser power, feed rate, track widths or track overlap, the defective areas of the component are prepared in CAM software and then welded on using the DED process. A zero-point clamping system is used to clamp the component. To repair the defective volumes, a metallic powder is fed through the nozzle of the DED processing head to the surface of the component, where it is melted by a laser. By moving the head, weld beads and 3D structures are formed, resulting in a near-net-shape geometry. This geometry is specifically manufactured with material allowance which results in an oversized geometry for post processing.

For components with large tolerances, the accuracy of the DED system may already be sufficient, but for the repair of a turbine blade presented here, accuracies in the lower μm range are required. Fig. 3 shows the turbine blade machined by DED. In the subsequent machining post-processing, the repair-welded component is also picked up using a zero-point clamping system, thus ensuring that the component is referenced. The repaired defects are specifically reworked, whereby the oversize is removed from the DED process to produce the target geometry.

Figure 3. Blade tip before (left) and after (right) repair process



12. Conclusion

The presented system combines different technologies and shows the gained value of combining them by an interdisciplinary team. The use-case of repairing the tip of a blade was reduced from three hours by programming the DED machine by hand to one hour preparation time and 15 minutes machine time. Integrating all hard- and software components into one workshop environment saves unnecessary transit times and enhances efficiency of the process. Our specially adjusted augmented reality interface with three dimensional hand-interaction provides better user experience and options for on the job training, as well as operation of the system by non expert workers. Such body-gesture controlled, projected or glasses based AR interfaces are applicable to many industrial applications. They are beneficial in spatial tasks and compared to buttons and keyboards less breakable in heavy duty tasks. Currently, we have not included a milling machine, which will be the next step to finish the processing. Also, this strategy is not restricted to blades. Many objects, especially forms, where the CAD is available can be repaired using this process chain.

Acknowledgement

The research described in this article was carried out as part of the "Berlin Center for Digital Transformation" project (project numbers: EFRE 1.8/20). The authors would like to thank the

Berlin Senate and the European Union for funding. Without this funding, it would not have been possible to carry out the work.

References

- [1] I. Alfred, M. Nicolaus, J. Hermsdorf, S. Kaielerle, K. Möhwald, H.-J. Maier, and V. Wesling, “Advanced high pressure turbine blade repair technologies,” *Procedia CIRP*, vol. 74, pp. 214–217, 2018.
- [2] M. Leino, J. Pekkarinen, and R. Soukka, “The role of laser additive manufacturing methods of metals in repair, refurbishment and remanufacturing—enabling circular economy,” *Physics Procedia*, vol. 83, pp. 752–760, 2016.
- [3] M. Fishedick, J. Roy, A. Acquaye, J. Allwood, J.-P. Ceron, Y. Geng, H. Kheshgi, A. Lanza, D. Perczyk, L. Price *et al.*, “Industry in: Climate change 2014: Mitigation of climate change. contribution of working group iii to the fifth assessment report of the intergovernmental panel on climate change. technical report.” 2014.
- [4] B. Graf, S. Ammer, A. Gumenyuk, and M. Rethmeier, “Design of experiments for laser metal deposition in maintenance, repair and overhaul applications,” in *Procedia CIRP*, 2013, pp. 245—248.
- [5] Z. Geng and B. Bidanda, “Review of reverse engineering systems—current state of the art,” *Virtual and Physical Prototyping*, vol. 12, no. 2, pp. 161–172, 2017.
- [6] F. Buonamici, M. Carfagni, R. Furferi, L. Governi, A. Lapini, and Y. Volpe, “Reverse engineering modeling methods and tools: a survey,” *Computer-Aided Design and Applications*, vol. 15, no. 3, pp. 443–464, 2018.
- [7] S. Mönchinger, M. M. Schmidt, S. Dreßen, P. Wissmann, and R. Stark, “Automatized 3d-scanning application for the virtualization of large components,” in *Gas Turbine India Conference*, vol. 83532. American Society of Mechanical Engineers, 2019, p. V002T11A002.
- [8] O. Heimann and J. Guhl, “Industrial robot programming methods: A scoping review,” in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1, 2020, pp. 696–703.
- [9] Z. Xia, Q. Lei, Y. Yang, H. Zhang, Y. He, W. Wang, and M. Huang, “Vision-based hand gesture recognition for human-robot collaboration: A survey,” in *2019 5th International Conference on Control, Automation and Robotics (ICCAR)*, 2019, pp. 198–205.
- [10] L. Yang, Z. Li, Q. Lei, J. Xu, Y. Deng, and Y. Zhong, “Teaching a robot to draw: hand gesture demonstration based on human-robot interaction,” in *International Conference on Machine Vision*, 2020.
- [11] G. Bolano, C. Juelg, A. Roennau, and R. Dillmann, “Transparent robot behavior using augmented reality in close human-robot interaction,” in *2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, 2019, pp. 1–7.
- [12] Y. Gao and C.-M. Huang, “Pati: A projection-based augmented table-top interface for robot programming,” in *Proceedings of the 24th International Conference on Intelligent User Interfaces*, ser. IUI '19. New York, NY, USA: Association for Computing Machinery, 2019, p. 345–355. [Online]. Available: <https://doi.org/10.1145/3301275.3302326>
- [13] J. Kuschan, A. Beleke, O. Heimann, V. Müller, S. Mönchinger, C. Niebuhr, and J. Krüger, “Mehrwert der digitalen vernetzung für den reparaturprozess von freiformbauteilen / modellerstellung für additive und spanende verfahren,” *wt Werkstattstechnik online*, vol. 11/12, 2020.
- [14] J. Kuschan, H. Schmidt, and J. Krueger, “Improved ergonomics via an intelligent movement and gesture detection jacket,” in *Proceedings of ISR 2016: 47th International Symposium on Robotics*. VDE, 2016, pp. 1–6.
- [15] R. de la Barré, P. Chojecki, U. Leiner, L. Mühlbach, and D. Ruschin, “Touchless interaction—novel chances and challenges,” in *International Conference on Human-Computer Interaction*. Springer, 2009, pp. 161–169.
- [16] P. Tsarouchi, A. Athanasatos, S. Makris, X. Chatzigeorgiou, and G. Chryssoulouris, “High level robot programming using body and hand gestures,” *Procedia CIRP*, vol. 55, pp. 1–5, 2016.
- [17] D. Holz, A. E. Ichim, F. Tombari, R. B. Rusu, and S. Behnke, “Registration with the point cloud library: A modular framework for aligning in 3-d,” *IEEE Robotics & Automation Magazine*, vol. 22, no. 4, pp. 110–124, 2015.