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Collision avoidance and adaptive path planning in machine tools by matching live image data with a geometric simulation

Malte Hansjosten[a,*], Jürgen Fleischer[a], Markus Frings[b], Sven Odendahl[b], Marc Stautner[b]

[a]*Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany*
[b]*ModuleWorks GmbH, Henricistraße 50, 52072 Aachen, Germany*

* Corresponding author. Tel.: +49 1523 9502597; *E-mail address:* Malte.Hansjosten@kit.edu

Abstract

A major cause for unplanned downtime in small-series machining are collisions. While there are solutions to avoid collisions using geometric simulations, these do not cover collisions caused by setup errors. To address this problem from batch size one, a system has been developed which matches a geometric simulation with image data to detect deviations, modify the simulation and recalculate NC-Code to fit reality. Building on previous work regarding image-preprocessing, an iterative matching algorithm is developed, as well as a microservice based system-architecture which allows the integration of matching, adaptive path planning and collision avoidance simulation. The system is validated on a machining center.

Keywords: Machine tool; Simulation; Sensor

1. Introduction

Success in the modern, global market hinges more and more on the effectivity and efficiency of production systems. One standard metric to measure this is the Overall Equipment Effectiveness (OEE) [1]. The OEE is the product of the three following components:

- Availability (percentage of time that a machine is available for operation)
- Performance (percentage of speed at which a machine runs in relation to its designed speed)
- Quality (percentage of good parts produced)

One major cause of unplanned downtime and therefore loss of availability in machine tools are collisions and one major cause for collisions are setup errors [2,3,4]. This fact gains in importance if one considers the trend towards more product variety which results in turn in smaller batch sizes up to single part production [5]. In such cases the worker has little to no experience in setting up a particular workpiece making the process especially prone to errors.

To address this problem, the system presented in this paper was developed. The system matches a geometric collision avoidance simulation with image data obtained from the workspace of a machining tool. It is not only able to detect deviations between simulation and reality but also to modify the simulation to fit the sensor data and recalculate the NC-Code accordingly. In addition, the system is able to stop the machining process if significant deviations between simulation and reality are detected or if an upcoming movement would lead to a collision. With these functionalities the system does not only increase availability by reducing unplanned downtime but also aids the setup-process thus increasing performance as well.

This paper is divided into six major sections. After an overview of the state of the art in collision avoidance, a brief recap of previous publications on the developed system is given, which address the basic system architecture as well as the preprocessing of the image data. Building on these works

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the developed matching algorithm is described, followed by the recalculation of the NC-Code and the functionality during the machining process. Finally, the complete system is validated with the production and subsequent measurement of several test workpieces. This shows the overall functionality of the system as well as its limitations, leading to the conclusion of this contribution and possible future developments.

2. State of the Art

A basic approach to limit damage to machine tools due to collisions is to detect such collisions and stop the machining process as quickly as possible. Monitoring motor current, acceleration or force signals allows the detection of impacts or generally unexpectedly high loads. These usually indicate collisions or unexpected contact between tool and objects besides the workpiece. [4]

There are also several existing solutions to not only detect collisions but also actively avoid them, usually utilizing some form of simulation or sensor.

Simulation-based approaches can be divided into offline approaches which check for collisions during process planning and online approaches where a simulation is running parallel to the actual process. Offline approaches are wide-spread and commercially available as part of the CAD-CAM process chain. After planning the machining steps, a geometric and kinematic simulation of tool, workpiece fixture and machine tool is used to simulate the toolpath and checking for contact between tool and geometries other than the defined workpiece [6]. Online approaches use a similar simulative model, but utilize live position values as well as look-ahead data transferred from the machine control unit to check for collisions in the current position as well as during the next few machining steps [7].

Sensor based solutions can be divided into camera-based approaches and systems based on distance measuring. The Camera-based solution presented in [8] overlays an image of a geometric simulation on the real situation in the machine and subsequently rely on an operator to check for discrepancies. While this system does provide an intuitive way for the operator to compare simulation and reality it still needs human input and is not able to automatically detect possible errors. Other Systems, like the one presented in [9] rely on a reference image from previous parts of the same type and setup, thus limiting its usefulness in small-batch manufacturing.

Monitoring solutions based on distance measurement check the distance between moving machine parts (like the main spindle) and static parts like workpiece and fixture. To measure the distance ultrasound, laser triangulation or inductive measurement can be used. While these systems represent a very general approach, the position and number of measurement points is limited due to high cost and available mounting space. [10]

In conclusion the presented approaches either only limit the damage of collisions, are susceptible to setup errors, are not fully automated, need at least one successful machining run as reference or cannot cope well with complex geometries. Furthermore, none of the presented systems allows for an adaptive path planning to handle setup errors without the need to physically correct them.

3. Approach and previous work

To address the deficiencies listed in the previous paragraph the system presented in this work was developed with the aim to combine the advantages of sensor and simulation-based collision avoidance to allow for safe machining up from lot size one.

The general approach, the system architecture and the image preprocessing (especially the image segmentation) has already been described in previous publications [11, 12]. Since the work presented in this paper is building up from there and the validation described at the end of this paper concerns the system as a whole, a short recap is necessary.

3.1. General approach and system architecture

The developed system combines the ModuleWorks Real-Time Collision Avoidance System (CAS) with real world image data obtained in a machine tool. CAS consists of a geometric simulation of machine, fixtures, workpiece, tool, and material removal. The simulation is constantly updated during machining based on the axis positions provided by the machine control unit. The axis data obtained from the control unit contain the necessary information to simulate the current and future state of the machine and the in-process-workpiece (IPW) within a given time span. This enables CAS to detect future collisions and stop the process before those collisions actually occur.

To work properly, the simulation has to match reality which makes the system very susceptible to setup errors (i.e. wrong placement of workpiece or fixture). To address this issue, the real-world image data is used to detect such deviations and adapt the simulation accordingly (see section 4). Since simulation-based collision avoidance systems typically allow for a safety clearance of about 3mm, the presented system therefor aims for an accuracy <3mm. Higher accuracy demands can be met by implementing an additional probing cycle (see section 6).

To test and validate the approach, the system was implemented on a DMC 60H machining centre. To observe the machine workspace single camera with a resolution of 1920x1080 pixels is used. The camera provided by Rotoclear GmbH is specifically designed for applications in machining tools by protecting the camera lens with a clear disc rotating at high speeds as well as a pressurized air cushion, making additional protective measures unnecessary.

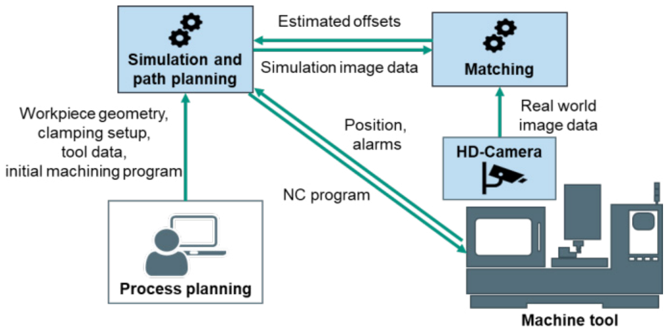

Fig. 1: Basic system architecture [12].

To maximize flexibility and allow for easy expansion of the system in the future, a micro-service-based approach was used to implement all necessary software components. For communication between the separate components, http-interfaces were used. This architecture allows the easy integration of the different components as well as the possibility to physically distribute services on different hardware systems. An overview of the resulting system architecture can be seen in Fig. 1. The user has to input an initial machining program as well as an initial setup (workpiece and fixtures) into the simulation environment. Pre-processed image-data is automatically passed to the matching-service along with the simulated image data of the initial setup. If an offset is detected the simulation is adapted accordingly (see section 4). After finding a good match the NC-Code is recalculated and automatically loaded to the machine tool where the user can start the machining process.

3.2. Image preprocessing

The goal of the image preprocessing is to generate a contour image which only shows workpiece and fixtures. Therefore, the first step is to identify this region of interest (ROI) in the image. For the presented system a deep learning model was developed, trained and validated [13]. The developed approach worked very well on known fixtures, with an Intersection over Union (IoU) of up to 0.936 and a F1-Score of up to 0.967, but was also able to accomplish good results on test data with previously unseen fixtures (IoU=0.796, F1-Score=0,883).

Since the images generated by the simulation are not photo-realistic the matching is done with contour images, thus eliminating the influence of color as well as most of the influence of illumination-changes. Therefore, the last step of the image preprocessing is to generate contour images of the ROI by applying the canny edge detector [13]. The canny edge detector provides a binary image containing detected edges (or contours) with a width of one pixel.

4. Matching and adaptation

Building on this work the system modules for matching the preprocessed real-world images to the simulation and adapt the simulation as necessary were implemented. While the main functionality is to detect setup errors before the machining process is started the implemented matching module is also able to detect deviations during the machining process.

4.1. Matching of simulation and reality

The matching algorithm is an iterative approach, that matches the simulation images of fixtures and workpiece against the segmented contour image provided by the preprocessing, detects offsets and adapts the simulation accordingly. These steps are repeated until either a good match is found or a maximum number of iterations is reached.

The matching process has to consider fixtures and workpiece separately. Therefore, the simulation image is first segmented by color into workpiece and fixtures and then converted into a contour image by applying the canny algorithm.

The simplest method to align images or image segments to each other is to shift them relative to each other and calculate a metric representing the quality of the match [14]. In the present case this means, that the contour image of the simulated fixtures (or workpiece) is laid over the real-world contour image and overlapping contour pixels are counted. This value is then divided by the number of contour pixels in the simulated image of fixtures or workpiece to account for different object sizes. This can be expressed by Equation 1, where M_{sim} is the overlapping area of the simulated contour image and M_{real} is the overlapping area the real-world contour image. Both represent n x m Matrices where each entry represents one image point. Contours are represented by the value 1 all other elements have the value 0.

$$q_{match} = \frac{\sum_n \sum_m M_{sim}(n,m) * M_{real}(n,m)}{\sum_n \sum_m M_{Sim}(n,m)} \quad (1)$$

This process is then repeated for each position in a defined search area. The result is a matrix of match-values for every possible offset in the search area. The maximum value of this matrix represents the likeliest offset of simulated object and reality.

To adapt the simulation to reality the detected offset has to be transformed from the 2D coordinate space of the image-plane to the 3D-coordinate system used in the simulation. Since only a single image and a single perspective was used true 3D-coordinates cannot be directly determined. However, we can reasonably assume, that the primary fixture and workpiece can only be offset in a single plane like the surface of the machining table or the mounting surface of a secondary fixture. With this assumption the problem simplifies and can be solved using images from a single camera/perspective. To accomplish this, real-world coordinate vectors for the examined plane have to be determined in image coordinates. Since they are not constant over the whole image area, this step is necessary for every adaptation cycle.

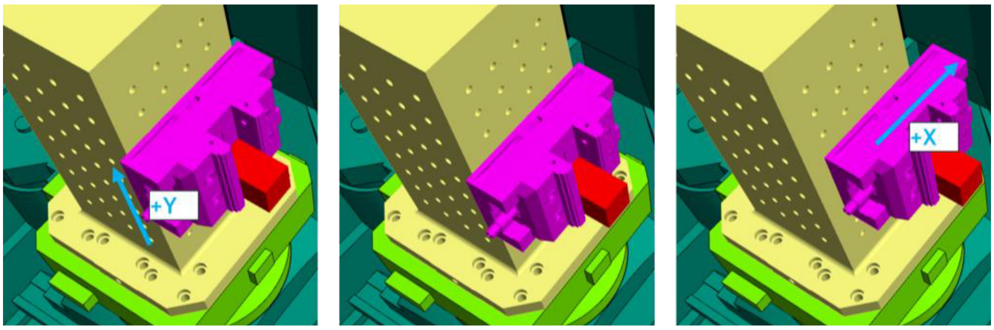

Fig. 2. Estimation of world-coordinate axis in image plane by translation of fixture and workpiece.

To determine the axis vectors, fixture and workpiece in the simulation are shifted by a defined length in each axis (see Fig. 2). The resulting offset in image coordinates can be used to calculate an approximate transformation from image to world-coordinates. This coordinate transformation can then be applied to the detected offsets between simulation and reality and the simulation adapted to fit. Since inaccuracies in this process are larger with larger offset-values an iterative approach is necessary to achieve the best possible results. An exemplary image sequence for the matching process of a fixture element can be seen in Fig. 3.

Although the assumption of offsets only in one plane is true for most cases, it is a restriction for the system as a whole and can be addressed in future works. Several possibilities for further development and expansion of the system to address this problem are described in section 6.

4.2. Recalculation of NC-Code

If a good match is found after the adaptation of the simulation, the geometries of workpiece and fixture can be passed to the ModuleWorks machining core. This core utilizes the initially user-defined machining setup to generate a new tool path with the updated geometry positions. The newly computed tool path is posted into a NC file. Subsequently, the NC file is automatically transferred to the machine tool and loaded to the NC controller via OPC-UA. There, the operator can start the adapted machining process without any manual adjustments.

In case no sufficient match is found, the feed release of the machine tool is blocked, and a corresponding error message is given to the user.

4.3. Machining process

After the machining process is started, the system switches to a continuous checking mode. Since simulation and reality already match each other, it is no longer necessary to search for matches in a large area but only to check whether simulated and real contours continue to match each other or not. This significantly reduces processing time to 1.8 seconds per image. While this is not sufficiently fast for safety-relevant functions, it is acceptable for stopping the process on the detection of significant abnormalities like a loose workpiece. In such a case the feed release is blocked as well and also an error message is given to the user.

5. System validation

To validate the whole system regarding functionality and accuracy, four different test-workpieces were defined, manufactured and measured (see Fig. 4).

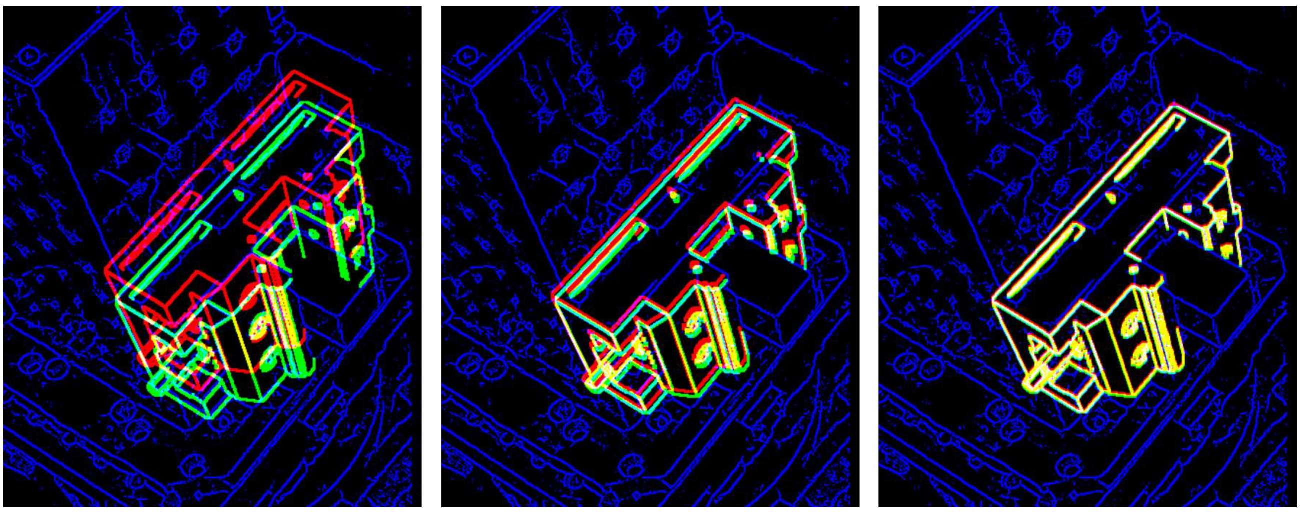

Fig. 3. Adaptive matching on the example of a fixture.

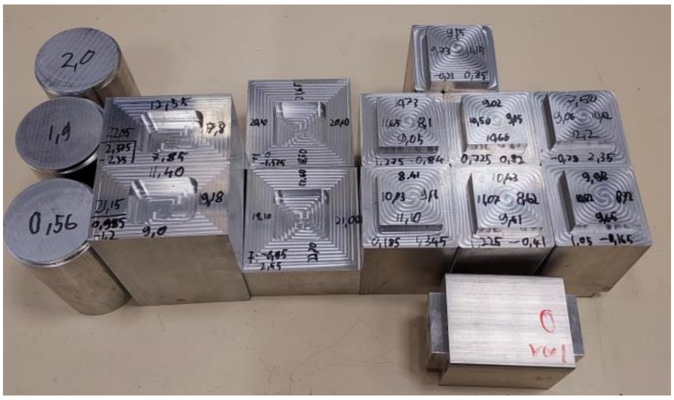

Fig. 4. Machined test-workpieces during the validation.

The defined test-workpieces have in common that the machined geometry is a dome or pocket in the center of the workpiece. Since the respective feature is expected to be directly in the center of the workpiece, the deviation from the center-position straightforward measure for the overall system accuracy. Although, the machined geometries are somewhat similar, they differ in their actual size and in the size of the initial workpiece. Furthermore, one of the specimens is a rotational workpiece which is machined using 4-Axis machining instead of 3-Axis machining.

For each machined workpiece, the position and/or orientation of the fixture and its position on the fixture was varied. In each case an offset error between 20-100mm from simulation to reality was introduced. All in all, a total of 16 workpieces were manufactured.

After manufacturing, the position of the dome or pocket in relation to the center of the workpiece was measured. Since the target accuracy set for the system is <3mm (see section 3) using a digital caliper for the measuring proved to be sufficiently accurate. An overview of the measured offsets for the 3-Axis machining parts can be seen in Fig. 5. The reached accuracy was [-0.95; 2.375] in x-direction and [-2.35; 2.55] in y-direction. It can also be seen, that the scattering of the measured offset values is not uniform around the mean offset and that the mean offset is not zero.

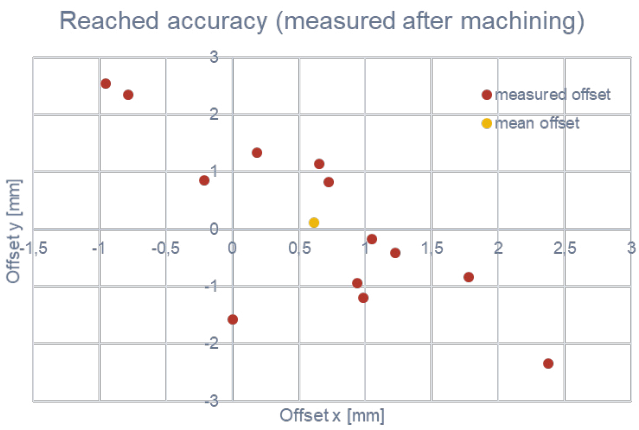

Fig. 5. Reached overall system accuracy.

To evaluate the repeatability of the system the initial offset in the simulation was randomly varied followed by a matching/adaptation cycle. This was done several times before the machining process was started and the actual part position was verified through subsequent measurement as described above. An exemplary result of this can be seen in Fig. 2. The system reaches a repeatability of [-0.58; 0.57] in x-direction and [-1.13; 1.46] in y-direction. It can also be seen that once again the scattering of the values is not uniform and the mean of all measurements is not the actual position of the workpiece.

The non-uniformity of the scattering is most likely a result of the non-orthogonality of the world axis in image coordinates. The difference of mean measured value and real position points to a systematic error. Most likely causes are faulty camera calibration or faulty calibration of camera and simulation to each other.

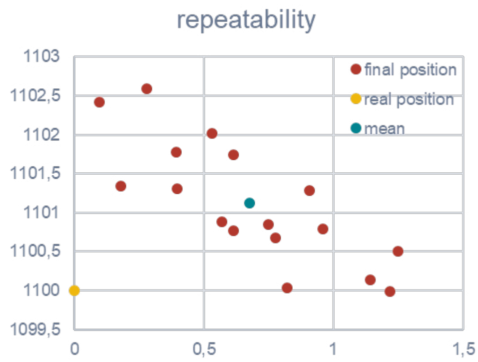

Fig. 2. Exemplary repeatability of measurements.

6. Discussion and outlook

Systems for avoiding collisions can significantly improve safety and availability of machine tools. Systems based on geometric simulations can detect collisions well in advance minimizing possible damage to the machine tool, but only if the simulation matches reality. Setup errors cannot be detected which is a problem, especially for small lot-sizes. To address this issue a system was developed, which matches real world image data against a geometric simulation enabling the system to detect deviations (mainly setup errors). Is such a deviation detected the system is then able to adapt the simulation to fit reality and subsequently recalculate the NC-Code based on the fitted geometry data. The system as a whole was implemented on a machine tool and the base functionality validated by producing several test workpieces.

The matching of simulation and reality by itself (meaning without any adaptation) already provides a benefit to potential users by adding an additional layer of safety, especially for small lot sizes with manual setup processes, by alerting users to possible setup errors. By enabling the system to adapt the simulation to reality and automatically recalculate NC-Code, the system can self-correct in case of errors increasing the overall productivity of a given machine tool. Since the system is mainly software based and only needs a single HD-camera to be installed in the machine tool, the costs of retrofitting this system to existing machine tools are affordable.

However, the system currently has several limitations which will be named in the following paragraphs along with possibilities of how to address these issues.

While the reached accuracy of <3mm is sufficient for collision avoidance applications it is not sufficient for actual machining processes which can have accuracy requirements <0.001mm. Nevertheless, to reach these accuracies the usual procedure in most machining applications is to use a probe to account for small deviations in the actual workpiece position. These probing cycles can already be automated and added to a NC-file. In such a case, possible setup errors pose significant risk of collisions and damage to the sensitive and expensive measurement equipment. This means, that they either have to be done very slowly to account for large margins for error or be closely monitored by an operator. Here, the developed system can significantly speed up and simplify the process.

Besides such an automated probing cycle, it would also be possible to increase the inherent system accuracy. Although, it is questionable if such high precision requirements can be met with relatively low-cost camera solutions. To fulfil the accuracy requirements for rough machining operations (around 0.1mm) it would be possible to increase image resolution either by increasing the camera resolution or by reducing the imaged area to a specified position within the working area of the machine tool.

Another issue that needs to be addressed in upcoming works is the systems inability to detect true 3D-coordinates. While it would be possible to substitute the HD-camera with an optical 3D-measurement-system (like a time-of-flight-camera) or add more cameras for a stereo-vision based approach, this would significantly increase the overall system cost. Another more feasible approach would be to add an intelligent imaging cycle before each machining program. By either moving workpiece and fixture relative to the camera or mounting the camera on the tool-spindle and then moving the camera it would be possible to generate images from different perspectives. Using established approaches from computer stereo vision true 3D-data could then be generated. This approach would also offer possibilities to increase the systems overall accuracy. The non-uniform scattering of measured values seen in the validation (see section 5) is most likely caused by the fixed perspective of the camera and the resulting non-orthogonality of the world coordinate axis in the image. Therefore, this problem could also be addressed by taking multiple images. Furthermore, overall accuracy could also be improved by first matching the working-area of the machine tool as a whole and then moving camera and workpiece closer together for detailed imaging and matching of selected features.

In conclusion, although there are limitations to the presented approach these are by far insurmountable, but rather represent excellent starting points for future works. The validity of the base-system concept was proven and the developed system addresses a key weakness of purely simulation-based collision avoidance systems. By matching geometric simulation with reality, detecting deviations like setup errors and adapting the NC-Code accordingly, the system enables safe and reliable machining up from lot-size one.

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References

[1] Seiichi N. (1988), Introduction to Total Productive Maintenance, Produktivity Press, isbn: 978-0915299232

[2] Abele, E., Brecher, C., Gsell, S.C. et al. (2012): Steps towards a protection system for machine tool main spindles against crash-caused damages. Prod. Eng. Res. Devel. 6, 631–642. doi: 10.1007/s11740-012-0422-6

[3] Pilland, U. (1986): Echtzeit-Kollisionsschutz an NC-Drehmaschinen. Springer, Berlin Heidelberg, iwb Forschungsberichte, Berichte aus dem Institut für Werkzeugmaschinen und Betriebswissenschaften der Technischen Universität München, 8. doi: 10.1007/978-3-662-06810-6.

[4] Rudolf, T., Brecher, C., Possel-Dölken, F. (2007): Contact-based collision detection—a new approach to avoid hard collisions in machine tools. In: International Conference on Smart Machining Systems.

[5] Piller, F., Kumar, A. (2006): Mass customization: Providing custom products and services with mass production efficiency, Journal of Financial Transformation, vol. 18, no. 3, pp. 125–131.

[6] Hehenberger, P. (2011): Computerunterstützte Fertigung, doi: 10.1007/978-3-642-13475-3.

[7] Armendia, M., Fuertjes, T., Plakhotnik, et al. (2019): Cyber-physical system to improve machining process performance. Twin-Control vol. 58. Springe, Cham. pp. 197–208. isbn: 978-3-030-02202-0. doi: 10.1007/978-3-030-02203-7_12.

[8] Sommer, P. (2018): iWindow - Intelligentes Maschinenfenster: Abschlussbericht Verbundforschungsprojekt. Fortschritt-Berichte VDI Reihe 2, Fertigungstechnik vol. 697, Düsseldorf: VDI Verlag, isbn: 978-3-18-369702-1

[9] Heidenhain GmbH (2019): Optionen und Zubehör für TNC-Steuerungen.

[10] Li, T., Wang, Y., Liu, K., et al. (2018): Virtual grid and BPNN based collision avoidance control of automatic fixture system. The International Journal of Advanced Manufacturing Technology, vol. 95, no. 5-8, pp. 2843–2853, doi: 10.1007/s00170-017-1432-5.

[11] Barton, D., Männle, P., Odendahl, S., et al. (2020): Concept for collision avoidance in machine tools based on geometric simulation and sensor data. In Forum Bildverarbeitung

[12] Barton, D., Hess, F., Männle, P., et al. (2021): Image segmentation and robust edge detection for collision avoidance in machine tools. tm-Technisches Messen, 88(6), pp. 374-385. https://doi.org/10.1515/teme-2021-0028

[13] Canny, J. (1986): A computational approach to edge detection. IEEE Transactions on pattern analysis and machine intelligence, (6), 679-698.

[14] Szeliski, R. (2022): Computer Vision. Springer, Cham. doi:10.1007/978-3-030-34372-9