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Computer Aided Inspection Planning For Automation Of On-Machine Inspection Of Customised Milling Parts

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Abstract

Customised products force manufacturing systems to operate efficient at batch size one. Automation in upstream processes and on shop floor increase productivity. Besides value-adding processes, quality management to sustain product quality must be considered regarding automation and consistency from 3D model to the execution on shop floor. Computer aided inspection planning addresses the automation of measurement operations. The inspection planning starts with a customised 3D model and realises a simple execution of the measurement task on shop floor level. A method for implementation of computer-aided inspection planning for tactile on-machine inspection will be presented to realise potentials like tool deviation and work piece correction based on measurement results. The developed method focuses on ensuring automation of computer aided inspection planning and sets up the basis for a self-controlling manufacturing system of customised milling parts. A validation was performed at a manufacturing company for customised drilling tools and enabled less downtime and rework time for milling machines.

Keywords

Computer aided inspection planning; on-machine inspection; automation; CAx

1. Introduction

Mass personalisation forces manufacturing companies to face the challenge of producing customised products economically of consistent or increased quality [1-3]. In addition to the value-adding process of production, quality management is also part of the production process, which must cater to the individuality of the products [4]. Production and quality management need to be automated for the sake of high quantities despite batch size one in order to ensure economic efficiency [5].

1.1 Initial situation

Quality assessment of products contains various steps of assessment. The production processes is the determining factor of product quality. Therefore, the focus will be on the quality of production processes. Based on the assumption that manufacturing steps for product manufacturing take place in a CNC machining centre. The contours realised by machining vary based on customer requirements [6]. The focus is set on milling operation due to the higher complexity of milled geometry compared to turning operation and its higher wear compared to 3D printing. Consequently, the objective is the quality assessment of personalised milled products down to batch size one. As quality assessment, the result of the performed milling operation are in need of evaluation.

Inspections of milled parts operate within the machine or in a separate measurement work station by the use of measurement equipment. At the current state measurement operation are performed in or around the machine manually [7]. The worker themselves decides whether the quality is good enough and what kind of

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steps to rework are necessary. In specific measurement workplaces, automation of measurement task is state of the art, but due to the spatial separation of production and measurement, decisions for rework are delayed and errors can occur [8].

1.2 Solution modules

Cost efficient mass personalisation is in need of automation to reduce cost extensive manual process steps. For products with high likelihood of quality issues on-machine Inspection (OMI) is suitable. OMI provides the possibility to rework parts in exactly the same clamping situation, because of the measurement equipment being connected to the machine control system. Therefore, time for setting up rework is eliminated. Due to batch size one of rare occurring repeating parts, automation solutions are still challenging. The challenge is to operate inspection for each customer-individualised part at the right location of the part and provide the suitable inspection strategy. The scope will be set on tactile OMI via tactile probing. Tactile measurement tends to be the most robust way in a milling environment influenced by coolants and lubricants.

Computer aided inspection planning (CAIP) plans measurement operations based on the CAD-model of products. An automation of CAIP is still lacking and done manually when used. CAIP solves worker biased quality assessment and reduces machine-programming times for measurement operations. Nevertheless, the highest potential exists in automating the planning and the measurement itself.

This paper focuses on the automation of OMI using CAIP for machining. With the help of OMI, the manufactured contours are measured by the tactile measuring probes in the machining centre and thus enable the quality assessment of the work piece and the direct conclusion on the production-determining variables. Subsequently, existing CAIP approaches will be examined and further developed with regard to OMI and fitness for automation.

2. State of the art

2.1 On-machine inspection

OMI is used when advantages result from the fact that the measuring operation takes place in the same clamping situation as manufactured. A significant advantage is the possible immediate subsequent correction of the work piece based on the measuring operation without the influence of a changed clamping situation. The tool correction is based on the result of the machining operation and the performed measurement operation afterwards [9]. Furthermore, handling times of the work piece are reduced compared to a measurement on a coordinate measuring machine (CMM). This is done at the expense of availability of machinery time for value-adding activities [10-11].

The accuracy and reproducibility of tactile OMI is within the range of the machine tolerances on the installed machine tool. Currently, the range of reproducibility for 5-axis turning and milling centres on the market is within few µm. Consequently, the reproducibility decreases with increasing machine wear due to machine crashes with necessary alignment of the axes. Especially for older machines, the necessary reproducibility should be checked before installing OMI [12].

In general, OMI is suitable for use with correction-intensive work pieces, as it takes place directly after the measuring operation in the same clamping. Tool correction is made by the production result and not only by the tool wear, which increases production quality.

2.2 Computer aided inspection planning

ElMaraghy et al. describe CAIP as the ability to automatically obtain an inspection plan [13]. The inspection plan enables feedback into the design and manufacturing process and provides the basis for handling a large number of product features. The focus is on tactile measurement with a coordinate measuring machine and is based on the computer aided design (CAD) model of the component to be measured. The process for CAIP (“Fig. 1”) includes feature extraction or construction of elements to be measured. A feature is understood here as one or more geometry elements that have a reference to the component or among each other. These features are analysed with regard to their use on a CMM and the measurement sequence is subsequently planned. After selecting the inspection equipment, the inspection path is planned and simulated in order to derive the measurement programme [14].

Wong et al. define CAIP as a module that recognises geometry features to be measured, plans the measurement task, and integrates it into the inspection planning. This process is automated or semi-automated and can be tolerance- or geometry-driven [15].

Zhao et al. summarise the literature on CAIP approaches for coordinate measuring machines and OMI [10]. For this purpose, they define CAIP as a system that contains the following modules (“Figure 1”):

- Selection and sequencing of inspection features,
- Selection and optimisation of the measuring points,
- Measurement path planning and measurement programme generation,
- Execution of the measuring operation

Sources earlier than the year 2000 almost exclusively address measurement on CMMs. CAIP research for OMI therefore builds on these approaches and extends them in the areas of inspection feature extraction and measurement path optimisation. However, gaps exist for the interaction of CAIP and manufacturing in the context of OMI. The interaction is insufficiently considered. This also applies to the integration of the measuring operation into the measuring programme to be executed and the lack of uniform standards regarding numerical control (NC) code and CAD format [16].

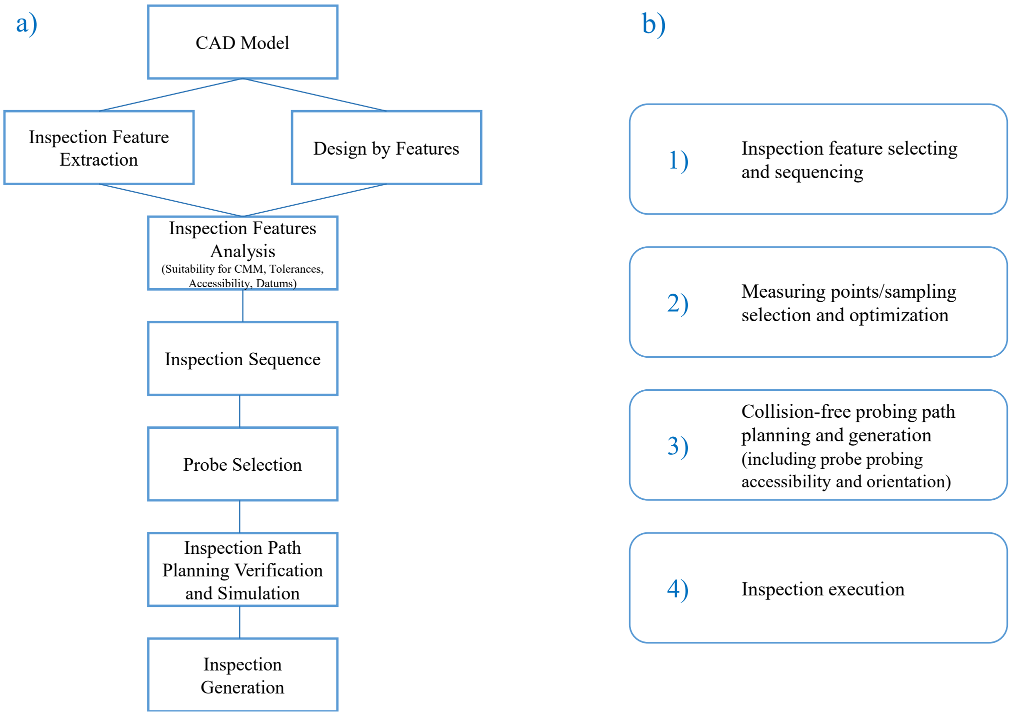


Figure 1: a) Process of CAIP by ElMaraghy et al. [13], b) Modules of CAIP by Zhao et al. [10]

3. Method for implementing computer aided inspection planning for on-machine inspection

The presented approaches for a CAIP are mostly based on the CMM target system and thus do not consider the necessary modules for the application of OMI. Based on the direct interaction of OMI and production on shop floor, the NC programming of the production task must also be taken into account. This includes the necessary interfaces to be implemented on the shop floor. The aim is to show a method for implementing a tactile OMI that can subsequently be automated (“Figure 2”).

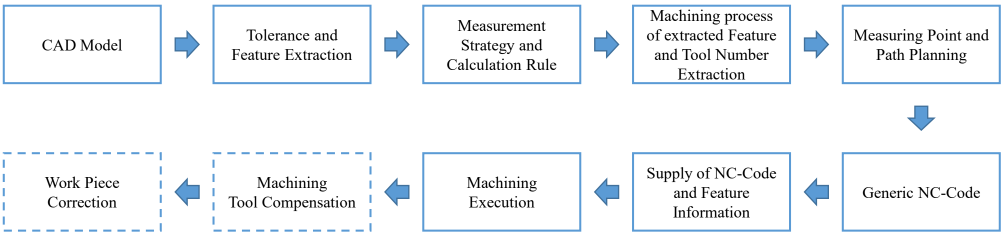


Figure 2: Method for OMI to connect CAIP and manufacturing

As prerequisite for the developed architecture a 3D-CAD-model need to be available. The geometry to be inspected is within a extracted feature. The feature is a geometric shape within the part, which can be described by an explicit parameter set, and contains tolerances due to quality requirements. The feature can be freely configured in its dimensions and position on the work piece. To reduce complexity it will be assumed that all tolerances regarding the size of the feature are given and are not subject to any changes.

The first step contains the analysis of the CAD-model to derive the feature, its position and size. This is important information to evaluate the results of the measurement and address the suitable inspection strategy based on the feature and its shape. Based on the feature shape the measurement strategy is defined beforehand. For each strategy a generic calculation scheme exists, which calculates the tolerance equivalent based on the inspection points to evaluate the quality. The strategy defines the number of inspection points, their location within the feature and the start point for each inspection path.

Besides the 3D-model, the operation planning of the process steps in manufacturing is a major information source. Within the CAM-setup and the NC-code the information about the tool, which performs the manufacturing operating, and the corresponding operation are stored. This information is needed in order to evaluate in which section of the NC-code the inspection operation has to take place and which tool need adjustment when failing the quality assessment. Based on the chosen inspection strategy the measurement points can be set in the 3D-model to calculate starting points and provide a file with all inspection points to be checked and their travels to each other.

A necessary condition to automate the whole inspection for customer individual parts is to provide a modular machine-readable inspection code. The modular structure of the generic NC-code allows using varying inspection strategy based on different calculation schemes, varying inspection points and operating with varying information about the quality assessment like tolerances and tools. The generic NC-code is written in G-code and can be easily scaled and updated regarding the information mentioned.

Before operating the CNC machining centre, the architecture needs to be set up to supply the machine with all created files during CAIP (for example: files containing inspection point). In this stage has to be taken care of the enabling inspection on all possible CNC machining centres on shop floor level without creating redundancy or differing file versions across machines.

The last step is the operation on the machine at shop floor level. It is important to provide a feedback of the quality assessment to the worker and the quality management department for further use. If the quality assessment evaluates a good part, the process is terminated at this point. If on the other hand the quality does not fit the expectations, the tool need to be adjusted. Using manual inspection the adjustment process has to be iterative. Because of the CAIP process beforehand and automation of the measurement task, the necessary adjustment can be calculated and executed by the measurement programme. The adjusted tool will fulfil the quality assessment next time being used. Based on the adjusted tool there is the possibility to rework parts directly in the same clamping right after the inspection operation with the adjusted tool. This work piece correction will not be objective of the paper and is meant for future research.

The novelty of this approach is based on the interaction of inspection and manufacturing. The combination of manufacturing planning and inspection planning due to its joint execution on shop floor is solved by the presented method. Based on this framework a self-controlled manufacturing system is enabled by computer aided inspection planning. The results will be presented for each step of the presented method. In the end, all results will be put in the overall perspective of automation of inspection planning.

4. Results

The method presented in the methodology is now exercised for an example part and the results when applying the architecture are presented. Each step of the described architecture in chapter 3 will be executed and ways of implementation and existing hurdles are pointed out. The starting point is the CAD model, which contains the geometries to be inspected. The sample component is shown in Figure 3, was produced with varying features and measured within a project at a tool manufacturing company for customer individual tools. At the current state, the customised tools are produced and manually checked in the clamping of the milling machine, because of a high likelihood of violating tolerances. Workers decide on their impression whether rework is necessary. This actual quality check prevents the manufacturing process to be automated. The introduced method enables automation via OMI and reduce preparation time for measuring operation.

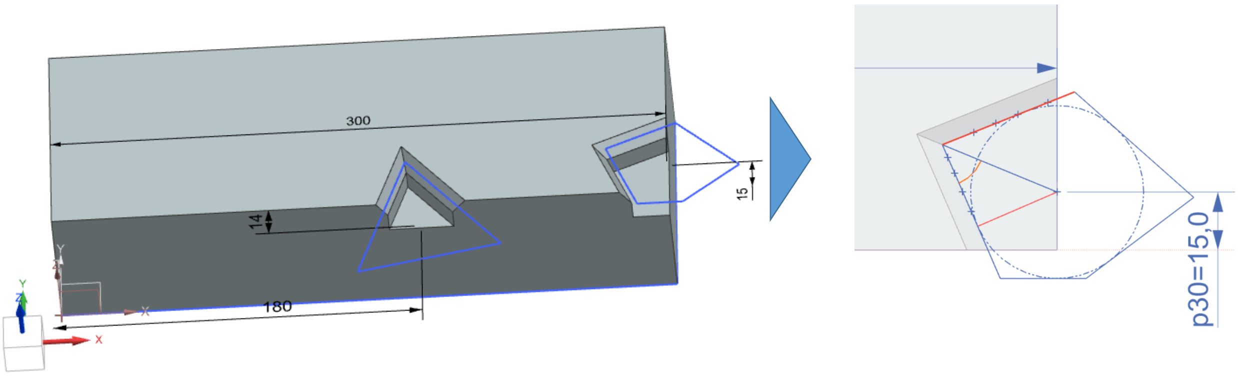


Figure 3: Sample part for execution CAIP for OMI at tool manufacturing company

The assumption is made that the base body is a cuboid into which subtracting features are placed. The feature is a polygon, which can be described by the size of a circle touching all sides of the polygon. The design, size and position within the basic body can vary. Thus, a customer-specific component is available.

Following the method, the first step is to examine the component with regard to the design suitable for production. This step is essential in the production environment, since deviations between the digital model and the real component will be measured. However, if there is a systematic error due to unequal centricity tolerances between tool and part, this will always falsify the measurement result, because of discrepancies of digital model and produced part.

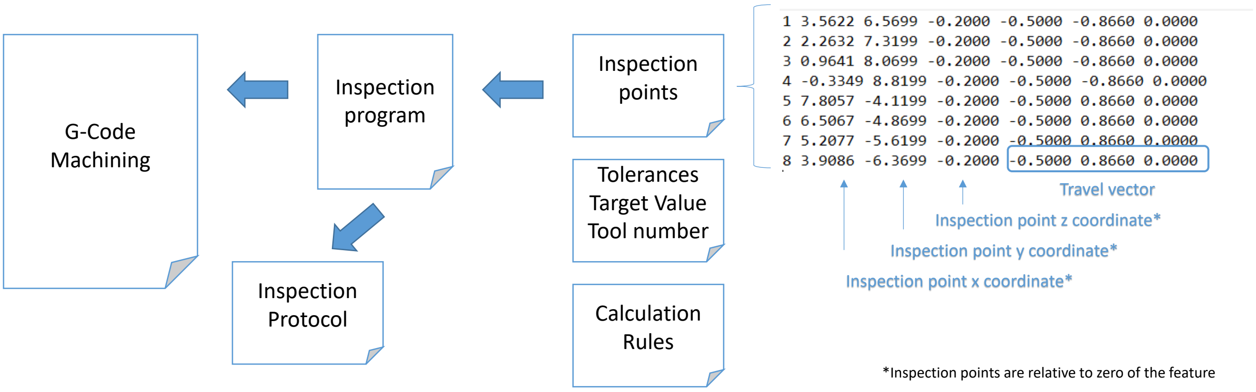
The features are presented in the example part by the milled polygon structures, which can be configured. The configuration of the features is represented within the CAD model by parametric design. The parametric design enables the features to be adjusted within the parameters and placed anywhere on the part. The assumption is made that the size of the feature is the parameter to be inspected and the regarding tolerance is always the same for each configuration and known beforehand. Thus, the feature does not need to be extracted separately in the process, since the model of the feature is already created by customer specific input beforehand.

The measurement strategy is based on the fact that each feature size can be described by a circle touching the edges of the part surface (Figure 3, right side). Therefore a calculation logic is necessary, which calculates the circle radius on basis of inspection points. It is assumed that at least two edges are created by the feature. It is possible that more edges exists due to the polygon structure, but this will not interfere with the calculation logic. Based on the assumption, two edges can be measured by four inspection points each and the position of the edges can be determined by a regression function. Using the two regression lines, the angle and intersection between the two edges could be determined. By knowing the angle and the intersection point, the radius of the circle could be calculated. The visualisation of the geometry for calculation is shown in Figure 3 on the right side.

Computer Aided Manufacturing (CAM) must identify the process, which will manufacture the feature to enable an automated process of inspection and production. It is necessary to obtain the section of NC-code where the measurement operation must be inserted. The tool, which performs the machining, could be adjusted afterwards, must be known. In the present case of the example part, a machining operation with a fixed tool is already attached to the surfaces of the feature. For this reason, the tool is not to be identified forcibly in the process and can be taken over directly into the NC-code. The machining steps performed on the example part are exclusively to the milling of features, therefore the position in the NC-code for the measuring programme is also determined.

Since the parametric model for the feature is already available, it can be used directly for planning of the inspection points. Four points each are placed on two visible edges of the polygon at an equal distance. The position of the points results from the length of the visible edge subtracted with a safety distance to the next edge. The approach vectors are always orthogonal to the edge from the centre of the feature. Thus, the points automatically adjust with each configuration and can subsequently be derived as a spf. file. A spf. file can be read and processed directly by the machine control system.

The probe used is a TC52 from BLUM with application on a CTX Beta with Sinumerik control. The inspection programme was developed together with BLUM and has a modular structure. Within the inspection programme, the position of the feature is transferred and set as temporary zero point. Based on the new zero the inspection points and travels can be extracted from the generated inspection points file and are measured by the probe. The machine control processes the measured values and executes the calculation on basis of the measured values within the subprogram containing the calculation rules. The result of the calculation is returned to the inspection programme. In this case, the calculated circle radius is derived and compared with the default values from the corresponding subprogram. The tool number is transferred in case of tolerance or meshing limit violation and corrected by the deviation from the target value. Finally, the output is a protocol with measurement results and corrections made. The entire structure is shown in Figure 4 with an example of the measuring point file with 8 measuring points on 2 edges.



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1 3.5622 6.5699 -0.2000 -0.5000 -0.8660 0.0000
2 2.2632 7.3199 -0.2000 -0.5000 -0.8660 0.0000
3 0.9641 8.0699 -0.2000 -0.5000 -0.8660 0.0000
4 -0.3349 8.8199 -0.2000 -0.5000 -0.8660 0.0000
5 7.8057 -4.1199 -0.2000 -0.5000 0.8660 0.0000
6 6.5067 -4.8699 -0.2000 -0.5000 0.8660 0.0000
7 5.2077 -5.6199 -0.2000 -0.5000 0.8660 0.0000
8 3.9086 -6.3699 -0.2000 -0.5000 0.8660 0.0000
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Figure 4: Modularity of inspection programme

The modular structure enables execution of other measuring tasks, since the measuring points, tolerances and calculation logic can be easily exchanged, since they are located in separate subprograms. Preventive correction is used for tool adjustment. Preventive correction sets intervention limits depending on the tolerances, consequently the tools are corrected in time and scrap material is avoided. These intervention limits are also variable and editable in the subprograms of the inspection programme. Based on this solution, no work piece correction is needed and provided for the example component.

Overall, the inspection programme was set up and enabled for the production of the example component. Four different components were produced on the CTX Beta, for each a call for the inspection programme was integrated in the machining programme. Two features on the components were deliberately manufactured too large and two too small. The inspection programme detected the derivation and the machine control automatically corrected the corresponding tool. This provides proof of the functionality of the mounted method.

5. Discussion

The established on-machine inspection at the tool manufacturer is not yet fully automated. Actually, there is a break in CAM programming and there is no feature recognition; instead, parametric models are used. These offer the advantage of simple and automatic adaptation with customer parameters when a basic similarity of the products is given. It also ensure the quality of the digital twin of the product. On the other hand, effort is required to create the models and to determine the dimensions to be parameterised in advance. Within the implementation of CAIP, the quality of the digital model, which describes the target shape, was a critical factor. If the digital model does not have the target shape, a deviating component will be created at shop floor level. Therefore, the path via the parametric models is the best choice if the features to be measured are available in a high number with a basic similarity that can be described via a manageable number of parameters.

One hurdle for the implementation was the various functional areas involved within the manufacturing company. The implementation links the areas of development (parametric modelling), design, CAM programming, production and quality. Based on existing implicit knowledge as well as missing interfaces and insufficient information flow, it is necessary to remove hurdles, create consistency and take a large number of stakeholders into account. On a technical level, skills from design, programming of software automation and programming on the machine tool are needed.

In summary, hurdles have to be overcome in the area of organisation and overarching competence in order to connect the areas that are not yet automated and sequentially integrated. Nevertheless, the potential of automating a previously performed manual subjective inspection was replaced by an automatically controlling inspection process on shop floor. This enabled a reduction in rework and gains in productive machine time. The method shows a way to avoid costly measurement preparation for customised tools, which can then be successively automated.

6. Conclusion

In summary, it can be stated that for tactile measurement with OMI, the CAIP approaches, which are primarily designed for the purpose of CMM, cannot solve the implementation satisfactorily. The weakness lies primarily in the unconsidered dependencies between CAIP and integration into manufacturing. An automatic tool correction based on the measurement results and the integration of OMI into an autonomous manufacturing can only be lifted after considering the interface between CAIP and manufacturing.

The method presented in this paper shows a possibility to design CAIP for tactile OMI for customised milling products. The methods requires a customer based CAD model, on which the inspection paths, calculation rules and underlying tolerances are planned. A modular structure of the NC-programme for a tactile probe realises the creation of a feature specific inspection programme. The inspection programme evaluates the inspection results and adjusts the tool for machining as necessary.

The method is largely validated based on a tool manufacturer. The validation shows hurdles for implementation in the area of interdisciplinary communication and interfaces. Current weaknesses regarding the integration of feature recognition and automation of the CAIP approaches also become apparent. These will be subject to future research to further develop automation of CAIP.

References

[1] R. Ogunsakin, C. A. Marin, and N. Mehandjiev, “Towards engineering manufacturing systems for mass personalization: a stigmergic approach,” International Journal of Computer Integrated Manufacturing, vol. 34, no. 4, pp. 341–369, 2021.

[2] D. Mourtzis and M. Doukas, “Design and Planning of Manufacturing Networks for Mass Customisation and Personalization: Challenges and Outlook,” Procedia CIRP, vol. 19, pp. 1–13, 2014.

[3] S. J. Hu, “Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization,” Procedia CIRP, vol. 7, pp. 3–8, 2013.

[4] F. Z. Fang, Z. Li, A. Arokiam, and T. Gorman, “Closed Loop PMI Driven Dimensional Quality Lifecycle Management Approach for Smart Manufacturing System,” Procedia CIRP, vol. 56, pp. 614–619, 2016.

[5] S.-L. Jämsä-Jounela, “FsUTURE TRENDS IN PROCESS AUTOMATION,” IFAC Proceedings Volumes, vol. 40, no. 1, pp. 1–10, 2007.

[6] B. Stump, F. Badurdeen, “Integrating lean and other strategies for mass customization manufacturing: a case study”, J Intell Manuf 23, p. 109–124, 2012

[7] S. Sahoo, C.-Y. Lo, “Smart manufacturing powered by recent technological advancements: A review”, Journal of Manufacturing Systems, vol. 64, p. 236-250, 2022

[8] Y. Jin, H. Pierson, H. Liao, “Scale and Pose-Invariant Feature Quality Inspection for Freeform Geometries in Additive Manufacturing”, J. Manuf. Sci. Eng., vol. 141, 121008, 2019

[9] S.-M. Wang, Y.-S. Chen, C.-Y. Lee, C.-C. Yeh, and C.-C. Wang, “Methods of In-Process On-Machine Auto-Inspection of Dimensional Error and Auto-Compensation of Tool Wear for Precision Turning,” Applied Sciences, vol. 6, no. 4, p. 107, 2016.

[10] F. Zhao, X. Xu, and S. Q. Xie, “Computer-Aided Inspection Planning—The state of the art,” Computers in Industry, vol. 60, no. 7, pp. 453–466, 2009.

[11] S. G. Wang, Y. J. Wang, and Y. L. Fu, “Study on On-Machine Inspection Technology of Machining Center Based,” AMR, vol. 97-101, pp. 4282–4286, 2010.

[12] J. Mou and C. Richard Liu, “A method for enhancing the accuracy of CNC machine tools for on-machine inspection,” Journal of Manufacturing Systems, vol. 11, no. 4, pp. 229–237, 1992.

[13] H. A. ElMaraghy and W. H. ElMaraghy, “Computer-Aided Inspection Planning (CAIP),” in Advances in feature based manufacturing (Manufacturing Research and Technology 20), J. J. Shah, M. Mäntylä, and D. S. Nau, Eds., Amsterdam, New York: Elsevier, 2010, pp. 363–396.

[14] H. A. ElMaraghy, P. H. Gu, and J. G. Bollinger, “Expert System for Inspection Planning,” CIRP Annals, vol. 36, no. 1, pp. 85–89, 1987.

[15] F. S. Y. Wong *, K. B. Chuah, and P. K. Venuvinod, “Automated extraction of dimensional inspection features from part computer-aided design models,” International Journal of Production Research, vol. 43, no. 12, pp. 2377–2396, 2005.

[16] P. Lei and L. Y. Zheng, “A STEP-NC Compatible on-Machine Measurement System with Automated Correlation of Inspection Data,” AMM, vol. 397-400, pp. 1772–1777, 2013

Biography

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