Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 107 (2022) 734–739

www.elsevier.com/locate/procedia

55th CIRP Conference on Manufacturing Systems

Generation of identifiable CNC reference runs with high information content for machine learning and analytic approaches to parameter identification

Philipp Gönnheimer[a]*, Robin Ströbel[a], Markus Netzer[a], Jürgen Fleischer[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49 1523 950 2578; fax: +49 721 608 45005. *E-mail address:* philipp.goennheimer@kit.edu

Abstract

As a result of the change to Industry 4.0, the requirements for information models and digital twins are steadily increasing. Thus, reliable methods to identification and assignment of data sources in CNC machines are required. AI-based approaches are already capable of identifying individual signal groups but are increasingly reaching their limits due to the small size of existing datasets. Furthermore, the low information content of the timeseries used to build the learning datasets represents an additional limitation. In this paper, an approach is presented and examined by means of which identifiable CNC reference runs with particularly high information content can be generated to create a suitable database for machine learning approaches. Moreover, due to the uniqueness of the generated trajectories, the reference runs represent a particularly suitable basis for analytical methods to parameter identification.

Keywords: Artificial intelligence; Automation; Computer numerical control (CNC); Digital manufacturing system; Identification; Machine tool

1. Introduction

Today's production is characterized by high demands on Overall Equipment Effectiveness (OEE), consisting of the factors quality, performance and availability. To maximize these, Industry 4.0 applications which processing data from the environment of machines and equipment are increasingly being used. In the case of more recent machine generations, such applications are offered directly for purchase respectively as part of new digital business models, or the data sources are made available through accessible communication protocols.

In many cases, existing equipment in brownfield environments in particular poses a major challenge in this area [1]. On the one hand, this is the case due to the limited accessibility of proprietary provision types, and on the other hand, even in the case of more modern and accessible communication protocols such as OPC UA, due to unknown information models. Companion specifications such as the universal machine technology interface (umati) can provide some assistance here [2]. In many cases, however, companion specifications do not cover all the required parameters, e.g. component information, and although they represent at least a partial solution on new machines, they are not used on many existing machines either. In reality, the intended use of machine data in many cases results in technicians familiar with the equipment having to provide data analysts with the data in a laborious manual process.

1.1. Preliminary work

To date, there is no state-of-the-art application that offers a combined solution to extract and map data from various data sources in the environment of production machines [3]. Therefore, the objective of preliminary work was to provide

10.1016/j.procir.2022.05.054

users with an assistance system that supports them in the extraction from various data sources and the parameter identification and mapping based on this. In [3] and [4], such a system based on a three-step hybrid identification process with domain knowledge and Machine Learning (ML) was developed and presented.

To further improve this approach, this paper investigates the addition of identifiable Computerized Numerical Control (CNC) reference runs, both as a basis for an analytical approach for the identification and provision of machine control parameters and as a high information content database.

Nomenclature

AIP	Axis interpolation
BRK	Block change at the start of the breaking ramp
CF	Calculated feed rate
CNC	Computerized Numerical Control
CS	C-spline interpolation (CSPLINE)
DTW	Dynamic Time Warping
IF	Inverse-time feed rate
ML	Machine learning
NCU	Numerical Control Unit
OEE	Overall Equipment Effectiveness
PIP	Path interpolation
PLC	Programmable logic controller
QU	Quick acknowledgment
S0	No spindle movement
S1	Cubic B-spline spindle movement
SC	Piece-wise constant spindle movement
TOL	Block change with tolerance window 0.01 mm/deg
UMATI	Universal Machine Tool Interface

2. Own approach

Since conventional approaches are increasingly reaching their limits due to the size and quality of the datasets used, a new approach is being developed. Due to predefined and unique axis movements, the approach can be used for analytical signal identification. In addition to the large variability and a high information content of the generated movements, it can be ensured that all axes are always moved synchronously in time domain. Thus, the approach is particularly suitable for creating datasets for ML-approaches.

In a first step, an ID system will be introduced representing the basis of the generated reference runs and ensures their uniqueness. Furthermore, a methodology will be developed by which axis and main spindle movements can be derived from these IDs and executed synchronously. Depending on the movement type, a distortion can occur between the reference and the executed movement in the time domain. To investigate the influences, different approaches to CNC-based axis movements are presented and analyzed. Since these distortions can vary, the similarity of the recorded position signals to the specified movement is evaluated using Dynamic Time Warping (DTW). The aim of the investigation is to be able to execute the movements derived from the IDs with minimal distortion on a machine to preserve their uniqueness and thus enable signal assignment. Finally, it is shown that an oscillation state with a particularly high information content can be generated on the experimental machine.

3. Generation of identifiable trajectories

The basis for the uniqueness of the generated runs is an ID system through which each movement exists only once. This is intended to ensure that the generated datasets contain as different signals as possible and thus represent as many cases as possible. The uniqueness of the runs also enables them to be specifically identified and associated signals can be assigned to the respective axis. Therefore, the support points for a spline interpolation are to be generated by a bit sequence which represents the direction of two consecutive points. For this, an ID pool of binary sequences is generated, from which an ID is assigned to each axis according to the following rules:

- The first as well as the last ID (only 0 or only 1) are not assigned to get at least one change of movement direction.
- If more than 50% of the IDs have already been assigned, the next ID is assigned randomly.
- If the ID pool still contains more than 100 free IDs, a randomly generated subset containing 100 IDs is created, otherwise all IDs are used. From this subset, the ID with the maximum hemming distance to all assigned IDs will be assigned to the axis.

For this paper, IDs with a length of 12 bits were used. Once the ID has been selected, the next step is to use this as the basis for determining the relative location of the support points for an interpolation on a random basis. Thus, the ID determines whether the next point is set above (next bit is 1) or below (next bit is 0) the previous point. Therefore, the local environment of the previous point is divided into three areas and the relative location of the new support point is generated based on an exponential distribution. As shown in Fig. 1, this ensures that two consecutive points have a minimum distance. The probability of a support point is very high on the left side of the middle area and decreases sharply towards the right area due to the density function. This is intended to ensure that points have a high probability of being similarly spaced but not too close to one another. However, this should still vary so that different movements are generated even with the same directional specification.

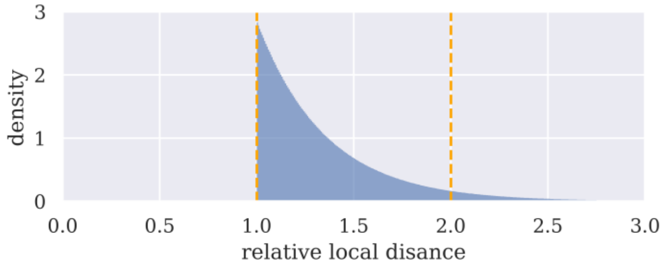

Fig. 1. Density function of the exponential distribution

Finally, the axis movement path is fitted using the support points. Since complex trajectories can be generated from a limited number of support points, the movements should be interpolated by cubic B-splines. Additionally, the movement of the spindle will be interpolated by piece-wise constant functions. Piece-wise constant spindle movements have the advantage that significantly less changes in movement must be defined. To ensure that the movement is within a specified range of values, the points created are converted with respect to the range of each axis. Shown in Fig 2., for the experimental machine 10 mm for translatory axes, 2° for rotary axes and 200 rpm for the spindle were selected.

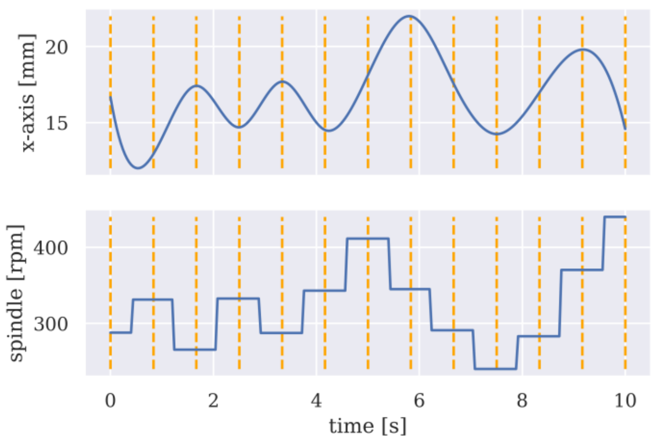

Fig. 2. Example movements for x-axis and spindle with the times of the values specified by the ID (vertical lines)

To meet the requirement of the lowest possible occupancy of the machine, all movements should run at the same time, i.e., synchronously. This is also intended to achieve the lowest possible downtime if the identifiable reference runs are to be used specifically to analyze machines that are already in operation.

4. Time domain based distortion of the axis movements

Movements in machine tools are interpolated with respect to the given location. Thus, the smallest possible contour deviations are achieved. As a result, the movement is interpolated and the axis drives are controlled regarding the current location coordinates. This leads to the distortion of the movement with respect to the time domain and the total duration does not match with the predefined. However, since the signals are recorded in time domain and information about the location is not available, this is problematic. To derive the IDs reliably from the recorded movements or to compare them with the specified movement, the distortion must be minimized. Therefore, the purpose of this paper is to clarify which type of axis movement causes the signals to be as close as possible to the predefined movement.

Fig. 3 shows the predefined and the recorded signals normalized to their sampling length, so that the distortion of the signal can be seen. Since a longer or shorter total duration compared to the given movement has no influence on the similarity of the overall movement, the sample length is not an important target criterion. However, the time domain based local distortion of the signals represent the decisive variable for similarity and is to be used in the following as the main criteria for the generated runs.

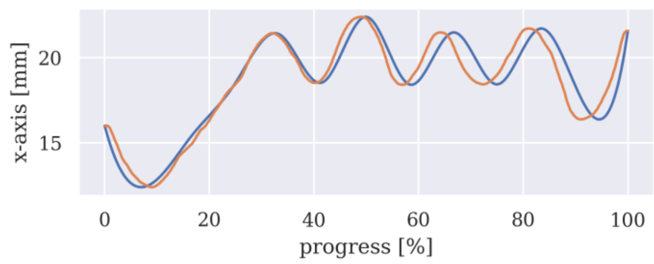

Fig. 3. Comparison of the predefined movement (blue) and the recorded signal (orange) (DTW-distance= 14.143mm)

5. Experimental setup

All tests were carried out on a DMC 60H - HDM machine with a SINUMERIK 840D control system. This is a retrofitted brownfield machine which is equipped with a new SINUMERIK control system as well as sensors for data acquisition. The milling machine has three translatory axes (X/Y/Z), a rotary axis (B) and a spindle.

6. Approaches for axis movement based on G-Code

To investigate the resulting distortions in the time domain, different approaches for generating the runs are to be investigated. For this purpose, they are derived from the created movements and their derivatives, from which the feed rate is calculated. The movements were generated with respect to a total duration of 10 seconds.

The first criterion to be examined is the number of calculated G-Code blocks. For this purpose, the predefined movement is calculated as a G-Code block at defined points, which is equivalent to down sampling. In this case, a larger number of blocks leads to more predetermined support points of the trajectories, which results in a more precise movement with respect to the location. However, since the blocks must be processed by the Numerical Control Unit (NCU), there is an increased computational effort and thus an increasing overall duration, which represents a conflict of objectives.

The spindle movement is also a source of influence, as it is carried out by the Programmable logic controller (PLC). Either none (S0), a piece-wise constant (SC) or a spindle movement generated with cubic B-splines (S1) were examined. With SINUMERIK, the QU(...) (QU) command can be used to switch to the next block with quick acknowledgment of an auxiliary function. [5]

The type of interpolation also represents a source of influence. Here, the path interpolator (PIP), which is common for machine tools, is examined, in which all path axes are interpolated together regarding their respective location. In case of a movement in rapid traverse (G00), no feed must be specified. With linear interpolation (G01) and using continuous path mode with a look-ahead function (G64), however, a feed rate must be specified. Inverse-time feed rates (IF) as well as feed rates calculated according to

$$F = \sqrt{F_x{}^2 + F_y{}^2 + F_z{}^2 + F_\alpha{}^2} \qquad (1)$$

(CF) are examined. With SINUMERIK, using the CSPLINE command (CS) the NCU additionally interpolates between the specified points with a cubic spline. [6,7,8,9,10,11,12]

Using positioning axis with axis interpolation (AIP), each axis is interpolated individually, which is why block change criterions must be specified. A block change at the start of the breaking ramp (BRK) and with an additional tolerance window of 0.01 mm/deg with respect to the actual position (TOL) is examined. [13,14]

7. Experiments on how to generate minimal distorted movements in time domain

The types of axis movement described above were examined in a series of measurements. For this purpose, 30 recordings were made for each movement (experiment 4 and 5, three runs each) and the average values were determined. The evaluation of the temporal distortion of the axis movements shall be done using the DTW-distance according to [15]. This is calculated for each recording between the specified movement and the recorded position signal at the points predefined via the G-Code blocks. For each experiment, the average duration of the recordings, the percentage of location signals which could be assigned by the ID and the DTW-distance for all assigned axes (X, Y, Z, B and spindle) were determined. The results of the tests are shown in Table 1.

The experiments can be divided into 4 groups. The first group consists of movements resulting from a path interpolation with linear interpolation and a very high feed rate (F50000) as well as movements in rapid traverse, which should have a similar effect on the machine used. Movements with the spindle switched off result in a strong temporal distortion for all axes, which is shown by the high DTW-distance. Since in experiment 2 a strongly distorted signal of the z-axis was assigned via the ID, the distance here is significantly higher on average. Experiment 4 can show minor errors in all axes, but the duration is high, and the average spindle error is increased. The results of Experiment 5 are average in all areas.

In the second group the movements were created by an axis interpolator. In this group, the duration of the movement is increased throughout, but the average DTW-distance is very small for all axes. Regarding the distance, this group represents the optimum. Only test 6 is an exception since it has an average DTW-distance of approximately twice as high for all axes with a shorter duration. In this group, test 11 stands out because, compared to test 8, there is approximately half the error of the spindle movement and a significantly shorter duration.

Table 1. Results of the first test series to minimize time domain based distortion.

experiment data					avg. duration [s]	identified [%]	average DTW-distance				
number	interpolator	movement	blocks	spindle			x-axis [mm]	y-axis [mm]	z-axis [mm]	b-axis [deg]	spindle [rpm]
1	PIP	G01	5000	S0	31,74	99	23,68	22,60	26,89	4,65	
2	PIP	G01	500	S0	7,18	80	20,94	22,99	307,87	4,40	
3	PIP	G00	1000	S0	8,62	88	18,87	23,32	20,43	4,01	
4	PIP	G00	1000	S1	48,85	100	3,41	3,33	2,75	0,67	261,96
5	PIP	G00	1000	SC	8,59	100	10,57	10,45	11,18	1,46	291,19
6	AIP	BRK	1000	S0	10,88	98	8,09	7,16	7,01	1,46	
7	AIP	BRK, TOL	1000	S0	31,18	100	4,43	4,49	4,79	0,85	
8	AIP	BRK	1000	SC	30,02	99	3,93	4,34	4,34	0,78	251,72
9	AIP	BRK	500	S0	19,16	100	4,51	3,76	4,09	0,94	
10	AIP	BRK, TOL	500	S0	19,35	100	4,68	4,76	4,58	0,91	
11	AIP	BRK	500	SC	19,49	100	4,48	4,33	4,69	0,93	122,58
12	PIP	G64, IF	1000	S0	5,06	97	8,48	8,77	8,33	1,56	
13	PIP	G64, IF	1000	SC	6,26	99	9,41	9,93	9,97	1,77	308,06
14	PIP	G64, IF	500	S0	3,34	71	9,70	8,86	7,47	1,60	
15	PIP	G64, IF	500	SC	4,84	79	10,55	10,33	10,13	2,26	180,18
16	PIP	G64, IF, CS	500	S0	3,43	80	14,45	8,38	7,78	1,66	
17	PIP	G64, IF, CS	500	SC	4,73	81	11,59	10,60	11,19	1,80	172,47
18	PIP	G64, CF	1000	S0	5,01	100	8,85	8,09	7,75	1,68	
19	PIP	G64, CF	1000	SC	6,25	99	9,82	8,32	9,56	1,96	303,21
20	PIP	G64, CF	500	S0	3,38	79	8,45	8,40	9,04	1,65	
21	PIP	G64, CF	500	SC	4,73	87	9,82	10,04	9,86	2,10	172,53
22	PIP	G64, CF	500	SC, QU	6,10	99	8,81	9,47	8,46	1,90	303,41

The last two groups lead to comparable results with low duration. It is particularly noticeable that using 500 blocks, significantly fewer signals could be assigned via the ID. The average DTW-distances in the experiments are in a medium range for all axes. As in group 2, the error in the spindle movement also decreases with a decreasing number of blocks. However, if you compare experiments 13 and 19 with experiment 8 and experiments 15, 17 and 21 with experiment 11, an increased DTW-distance can be recognized. A comparison of experiment 21 with 22, in which quick acknowledgment was used, shows that the number of recognized signals has increased from 87% to 99% and the DTW-distance of the spindle has almost doubled.

8. Optimization of the number of G-Code blocks

As shown above, experiment 11 is the most promising because all average DTW-distances are low, and all location signals could be assigned via the ID. Therefore, movements generated with an axis interpolator and BRK are to be examined in more detail regarding the effect of the number of blocks used. All movements are generated with a piece-wise constant spindle movement.

Table 2. Results of the second test series to minimize time domain based distortion.

experiment data					avg. duration [s]	identified [%]	average DTW-distance				
number	interpolator	movement	blocks	spindle			x-axis [mm]	y-axis [mm]	z-axis [mm]	b-axis [deg]	spindle [rpm]
23	AIP	BRK	1000	SC	30,02	99	3,93	4,34	4,34	0,78	251,72
24	AIP	BRK	500	SC	19,49	100	4,48	4,33	4,69	0,93	122,58
25	AIP	BRK	400	SC	17,80	100	4,95	5,42	4,55	1,04	98,73
26	AIP	BRK	320	SC	16,33	97	5,12	5,81	5,07	0,99	83,49
27	AIP	BRK	250	SC	14,91	100	5,11	5,18	5,30	0,90	66,68
28	AIP	BRK	200	SC	13,95	100	6,14	5,74	5,19	1,12	51,64

As can be seen in Table 2, the duration of the recordings decreases as the number of blocks decreases. The reason for this is that there are fewer block changes and, as a result, fewer blocks must be processed by the NCU. In almost all cases, the signals could be assigned to the respective axes via the ID. If this was not the case, it can be assumed that this is the result of an incorrect recording and that it is therefore an outlier.

In case of the translatory axes, the average DTW-distance increases as the number of blocks decreases. It can be assumed that this effect is caused by an increasing discrediting error because of down sampling during the block generation. The same trend can also be seen with the rotary axis. The distortion of the spindle signals increases almost linearly in the opposite direction.

Considering the opposite effects of duration and DTW-distance of the spindle on the one hand and DTW-distance of the axes on the other hand, it can be deduced that under the existing boundary conditions a number of blocks in the range of 400 to 250 sentences leads to the best results.

9. Analysis and discussion of the generated runs

In the following, the signals of the test machine generated with a specification of 250 blocks are to be examined in more detail. In this case, the runs created according to section 3 are specified by 250 points. In each step the respective point of all axes is approached simultaneously. The block change takes place as soon as all axes have initiated the braking process, which results in a point-to-point interpolation. As can be seen in Fig. 4 using exemplary curves, a clear reduction in distortion can be achieved in comparison with Fig. 3. Even with x-axis 3, which represents a run with strong distortion, a clear improvement and a smoother signal can be recognized. X-axis 1 shows a curve with very little distortion, which shows that in the ideal case, almost distortion-free curves can be generated.

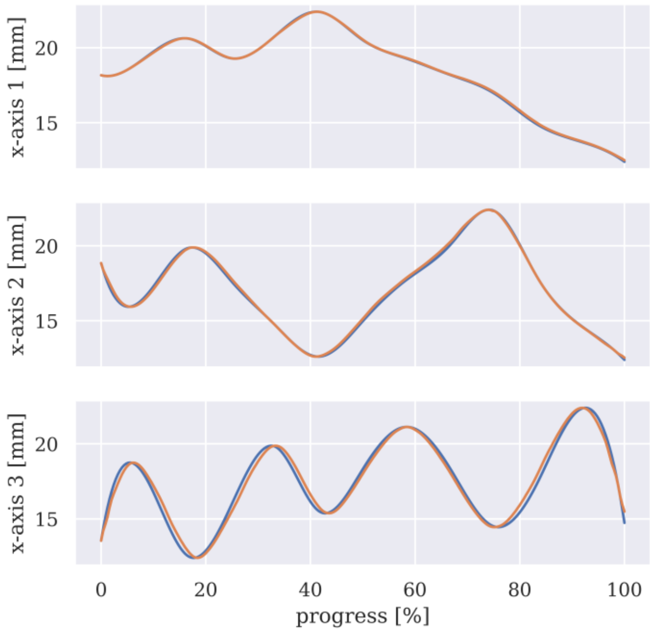

Fig. 4. Comparison of the given movement (blue) and the recorded signal (orange) for a good (top, DTW-distance=3.388mm), an average (middle, DTW-distance=5.112mm) and a strong distorted (bottom, DTW-distance=11.846mm) movement generated with 250 G-Code blocks

In addition, on closer inspection of the signals, an oscillation state can be recognized on the experimental machine which. As can be seen in the Fig. 5, this is also present in the associated signals such as current, torque or control deviation.

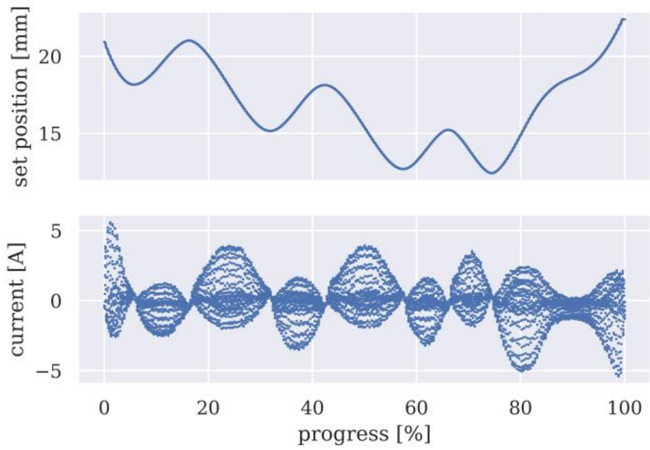

Fig. 5. Set position after fine interpolator and current signal for movements generated with 250 G-Code blocks

A closer examination of a section of the overall movement shows that the axis drive starts braking because of the block change criterion. However, since the block change is time consuming due to the operations to be performed by the NCU, the axis continues to slow down. This continues until the movement of the following block results in a renewed acceleration, which causes the oscillation state.

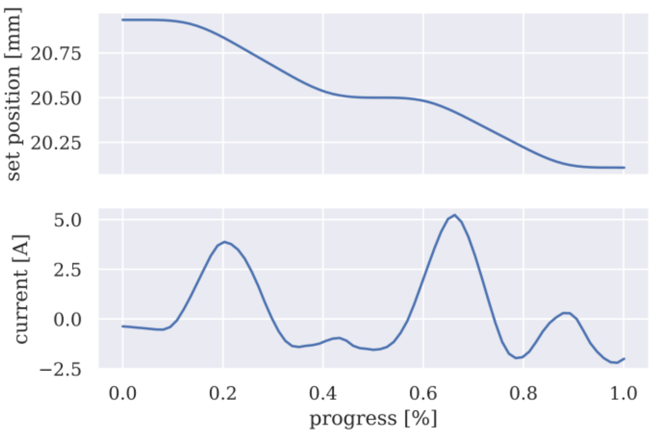

Fig. 6. Set position after fine interpolator and current signal for movements generated with 250 G-Code blocks (detailed view)

However, there is a need for further research to investigate the reproducibility of this oscillation state in more detail. If this state can be reproduced on other machines, this type of movement generation offers additional potential in addition to the low distortion in the time domain. The advantages of oscillating movements are:

- They are still unique due to the underlying ID.
- Due to the oscillation, they have a very high information content and thus offer an optimal basis for data intensive processes such as ML-approaches.
- They represent a good basis for finding analytic connections between signals, since both the global course and the individual oscillations and therefore statistical methods can be used. This could include parameter identification or the determination of system parameters.

10. Conclusion and outlook

This paper describes an approach for the generation of unique and identifiable reference runs, which can be used for the systematic identification of signals or the creation of databases with the highest possible variability for e.g., ML-approaches. The problem of signal distortion in the time-domain was introduced. In a first experiment, it could be shown that the error due to the time domain based distortion can be minimized on the experimental machine by using an axis interpolation with a block change at the start of the braking ramp. Based on this, the behavior regarding the number of G-Code blocks, which represents the number of specified interpolation points, was examined. Under the existing boundary conditions, a synchronous movement with minimal distortion could be achieved for all axes including the spindle when using 250 to 400 G-Code blocks.

Overall, the approach offers an advantage especially for the creation of datasets with high variability and reduced downtime. In addition, the experimental machine developed a state of oscillation, which offers great potential for data-driven approaches to parameter identification. Due to the uniqueness of the movements and their minimized distortion, the signals can be assigned by directly deriving the ID. This offers the possibility to automatically assign signals from machines of any manufacturer and age in production plants of any size to a digital representation.

Further research will focus on investigation to what extent this oscillation state can be reproduced on other machines as well as the comparison between analytical parameter identification based on the introduced reference runs and the existing ML-based approach.

Acknowledgements

We extend our sincere thanks to the German Federal Ministry of Economic Affairs and Climate Action (BMWK) for supporting this research project 13IK001ZF “Software-Defined Manufacturing for the automotive and supplying industry” (SDM4FZI).

References

[1] Netzer M, Begemann E, Gönnheimer P, Fleischer J. Digitalisierung im deutschen Maschinen und Anlagenbau – Aktuelle Studie zur Digitalisierung im deutschen Maschinen- und Anlagenbau und Bedarfsanalyse. In: wt Werkstatttechnik online, Vol. 111; 07/08; 2021. p. 525-530.
[2] Goerisch G. OPC UA for Machine Tools – Part 1. Machine Monitoring and Job Overview. 2020.
[3] Gönnheimer P, Karle A, Mohr L, Fleischer J. Comprehensive Machine Data Acquisition through Intelligent Parameter Identification and Assignment. In: Procedia CIRP, Vol. 104; 2021. p. 720-725.
[4] Gönnheimer P, Puchta A, Fleischer J. Automated Identification of Parameters in Control Systems of Machine Tools. In: Production at the leading edge of technology, Springer Berlin Heidelberg, 2020. p. 568-577.
[5] Siemens. SINUMERIK 840D sl / 828D Basic Functions: ; 08/2018; p. 438-439.
[6] Siemens. SINUMERIK 840D sl / 828D Basic Functions; 08/2018; p. 705.
[7] Siemens. SINUMERIK 840D sl / 828D Basic Functions; 08/2018; p. 257.
[8] Siemens. SINUMERIK 840D sl Fundamentals; 12/2018; p. 194.
[9] Siemens. SINUMERIK 840D sl / 828D Basic Functions; 08/2018; p. 201.
[10] Siemens. SINUMERIK 840D sl / 828D Basic Functions; 08/2018; p. 1392.
[11] Siemens. SINUMERIK 802D sl/840D/840D sl/840Di/840Di sl/810D Programming Manual ISO Milling; 04/2007; p. 1.19.
[12] Siemens. SINUMERIK 840D sl Job Planning; 12/2018; p. 244-246.
[13] Siemens. SINUMERIK 840D sl Extended Functions; 12/2018; p. 683-985.
[14] Siemens. SINUMERIK 840D sl Extended Functions; 12/2018; p. 699-707.
[15] Salvador S, Chan P . FastDTW: Toward Accurate Dynamic Time Warping in Linear Time and Space; 2004.