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Calculating G-code for CNC machine using the Mamdani fuzzy logic inference system

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The widespread desire to automate the CNC machine control process and optimize it is leading to the development of new algorithms. The article presents both a novel approach to this task based on a fuzzy decision-making system as well as an evaluation of the proposed solution on a large database containing data from multiple machining processes and a comparison with the Reference Points Realization Optimization (RPRO) algorithm used in industry. In addition to achieving the intended accuracy of the machining process, the presented system is also easily interpretable for the expert operating the machine. It is also possible to manipulate the presented system easily and shape it according to specific needs.

Key words: CNC machine; G-code calculation; fuzzy logic

1. Introduction

Automation of technological processes used in many branches of the global economy requires solutions that will optimize aspects of product quality and energy intensity of production lines and manufacturing time [1, 2]. A special and widely used solution is the use of CNC machines in the manufacturing process. Optimizing the operation of CNC machines requires the prior preparation of a data set that unambiguously describes all aspects related to the dynamics of the machine, requirements arising from the technological processes for the workpiece to be fabricated, and economic aspects. These factors arise from the guidelines set for modern technical systems that are part of Industry 4.0. This requires the acquisition of a large number of geometric data describing the parameters

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of the manufactured parts and electrical data describing the energy state of the machine. Optimizing the operation of such the machine requires the cooperation of scientists from different fields [3]. The industrial experience of the authors, related to the application of modern computer methods and the operation of CNC machine tools, indicates that the development and implementation of new algorithms and the optimum selection of parameters describing the dynamics of the CNC machine, allowing the exact reflection of geometric points of the performed detail are still needed [4, 5].

One of the approaches available and operational in the industry for automatic G-code calculation is the Reference Points Realization Optimization (RPRO) algorithm proposed in [6]. This algorithm has as its main goal the fastest possible execution of the machining process, using the full capabilities of the dynamics of the CNC machine, while maintaining the intended average accuracy of the machining process as much as possible. However, this and similar solutions have some drawbacks [7, 8]. The first is high computational complexity: the need to check many combinations of machine dynamics parameters in order to find the one that achieves the targeted accuracy. The second one results from the way the machine is controlled based on the generated G-code, specifically the use of full spindle acceleration and deceleration (rapid movements). Such action leads to vibrations, which can result in loss of machining accuracy, and can also lead to faster wear of machine components. Machining in this way can, instead of the intended decrease in the price of the part's products, have the opposite effect of increasing the price [9, 10]. A final aspect worth mentioning is the fact that the operation of the available tools is not interpretable to the expert controlling the CNC machine. To answer the challenge posed, the authors, using the aforementioned RPRO algorithm, established a database of many different processing operations and proposed their own G-code determination system based on fuzzy logic. Fuzzy logic has been used before to solve other cnc machine tasks [11–13].

The remaining part of the article is organized as follows. Section 2 describes the proposed alternative motion planning system for a CNC machine. Section 3 describes the proposed versions of the system and the tests that were conducted, and considers the results. Finally, Section 4 summarizes the achievements and provides a plan for the future work.

2. Proposed method

The authors aimed to create a system that allows the determination of the G-code for given machine dynamics parameters and a specified sequence of reference points. This system should work in the offline mode and be easily understood and intuitive for the expert optimizing the machining process. Therefore, the proposed solution uses a fuzzy logic expert system based on the Mamdani first-type model. The authors considered the process of generating the G-code as a series of decisions concerning movement of the spindle in successive time steps. Between consecutive steps of performance quality evaluation, the expert can freely modify the set of rules representing the system's operating strategy. The proposed model requires the following information:

- parameters of machine dynamics,
- the actual spindle dynamics and its position referred to as the spindle state,
- the target reference point sequence.

Based on the above information, a simulation of spindle movement is executed, where in subsequent steps one of three discrete values is selected: Decelerate, DoNothing and Accelerate, which constitute the considered set of decisions. The simulation terminates when the spindle reaches the last of the reference points. The investigation allows to take a decision using Fuzzy Inference System (FIS) to focus on the movement of the spindle along a single axis without the possibility of reversing. A diagram demonstrating the proposed framework is shown in Fig. 1.

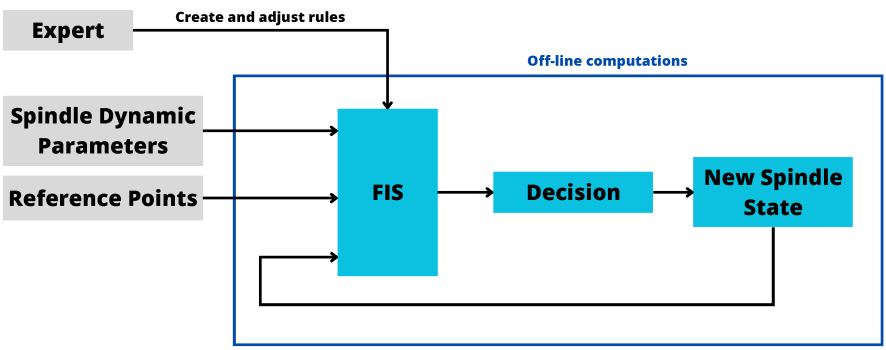

Figure 1: Proposed framework scheme

The authors proposed two different models shown in Fig. 2. The first model has two inputs: normalized spindle speed and normalized spindle distance to the next reference point. Each of the inputs of this model received values in the range $[-1; 1]$ and were covered with evenly distributed five features corresponding to the labels: "Very Small", "Small", "Medium", "Large", and "Very Large". These signals are analyzed according to 25 rules determined by the expert, each of which refers to every possible combination of input signals. The output of the system is a number in the range $[-1; 1]$ covered by 3 functions corresponding to possible decisions. The second model is an attempt to extend the perceptual abilities of the first model by supplementing its knowledge with a normalized spindle speed. This input is a number in the range $[-1.5; 2.5]$. It is covered by 8 functions corresponding in consecutive order to the labels: "Large backward", "Medium backward", "Small backward", "Very small", "Small", "Medium", "Large", "Very large". Consequently, the number of rules proposed for this model is 200.

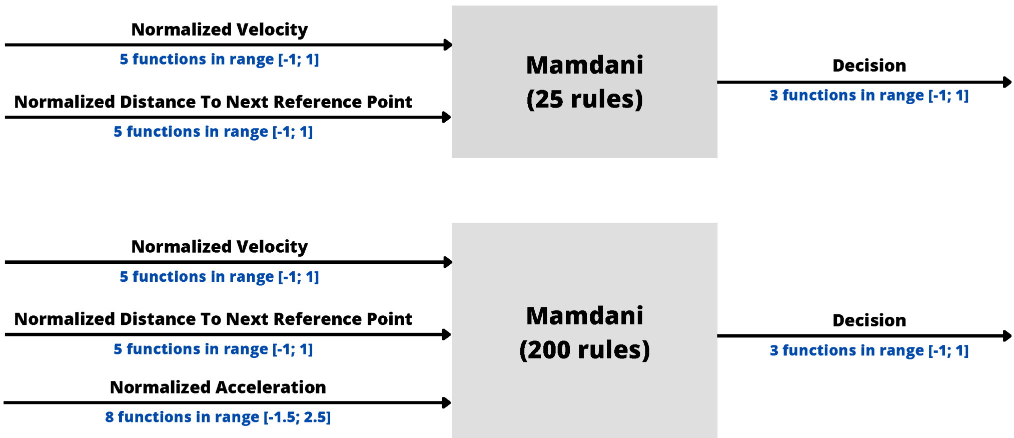

Figure 2: Proposed Fuzzy Expert Systems Models Diagram

Two shapes of the coverage function, namely the triangular function and the bell curve, were also considered in the conducted research. The proposed rule sets in the form of graphs are shown in Fig. 3 and Fig. 4. Individual symbols denote specific decisions of the system:

- *Decelerate* – red triangle,
- *DoNothing* – blue dot,
- *Accelerate* – green triangle.

Each point on the graph denotes one rule determined for a specific combination of input signals and indicating the corresponding decision of the fuzzy system. Subsequent numbers on the axes denote individual discrete values of the input signals in the same order in which they were given earlier in this paper.

As one can easily notice, the number of proposed rules is very large, especially for a model with three inputs. Therefore, the authors decided to reduce the number of rules using the mentioned graphs as an assist in finding dependencies. For example, eight rules containing three predecessors of the implication, represented by the column in the closer right corner of the graph, can be replaced by a rule with two predecessors "If Normalized velocity is Very Small and Normalized distance to next Reference Point is Very Big then Decission is Accelerate".

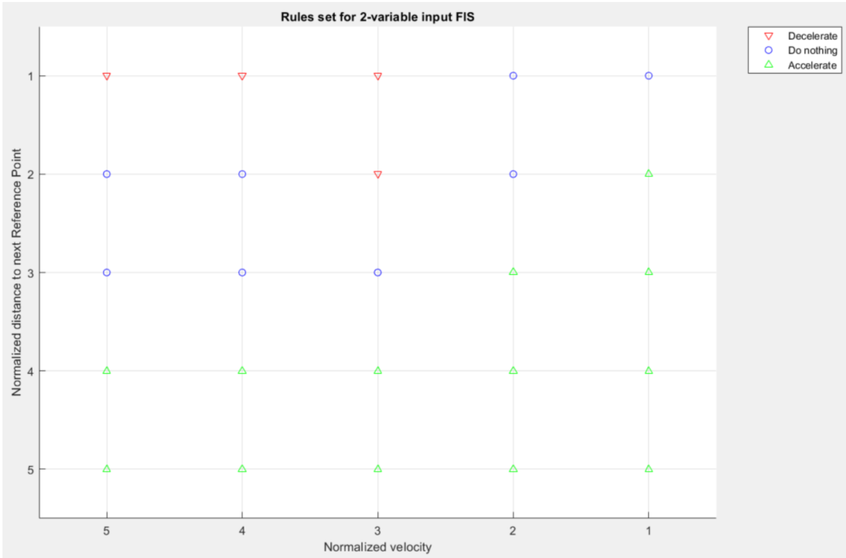

Figure 3: Rule set for 2-input model

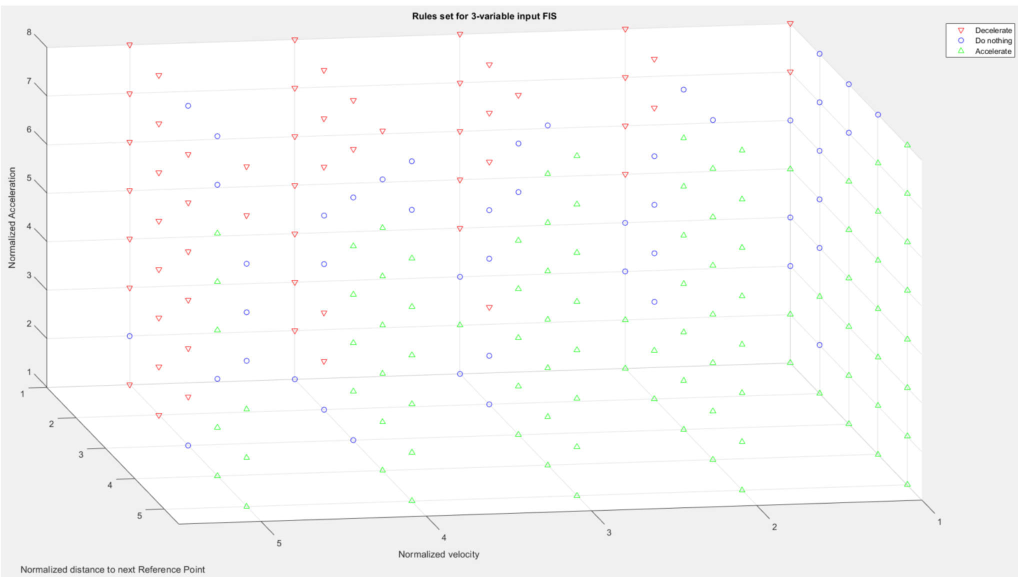

Figure 4: Rule set for 3-input model

Making equivalent transformations, one alternative set of rules was proposed for each model. The number of rules with individual successors and the total number of rules for each version of the system are shown in Table 1.

Table 1: Distribution of proposed fuzzy systems rules

Rules type	System type	Decelerate	Do nothing	Accelerate	Total rules number
full cover	2-variable	4	8	13	25
	3-variable	56	47	97	200
reduced	2-variable	4	8	4	16
	3-variable	21	23	32	76

3. Experiments

To check the quality of the 8 proposed fuzzy expert systems, extensive study was conducted using a set of processing proposed in [14]. The achieved results were compared with results obtained using the RPRO algorithm, with target accuracy set to 10 µm. This parameter describes maximum value of mean accuracy among all reference points. The database considered includes machining processes with different issues: reference path lengths (3), densities (3), trajectories (10), maximum spindle speeds (4), maximum spindle accelerations (5) and Jerk values (3). For convenience of analysis, they are assigned to 9 groups (combinations of length and density of reference paths) with 600 processes in each. A detailed description of the parameters can be found in [14].

Table 2 and Table 3 show the test results of the proposed fuzzy expert systems. The accuracy metric is measured as the average error of each of the 600 machining processes of a given group of trajectories and expressed in micrometers. In addition, the standard deviation is also given for each measurement, and the best and second best results are shown in bold. A metric indicating the number of time steps, each of which lasted 2 ms, was constructed similarly. In this case, only the best results were marked in bold for clarity. As expected, the RPRO algorithm provided shorter calculation time however, only for 3 of the 9 groups of trajectories it was able to achieve the intended accuracy. The proposed expert systems were successful in achieving satisfactory accuracy between 15 µm and 34 µm. The results of the number of steps indicate that the small machining error was achieved at the expense of not using the full potential of the machine dynamics. However, it should be noted that this behavior is fully dependent on the set of rules established by the expert that constitute the strategy of the fuzzy system controlling the machining process. Depending on the needs, the expert may propose a set of rules prioritizing the processing time. An interesting effect visible during the analysis of the results is the preservation of the stability of the system operation after minimizing the size of the rule set. This is a very advantageous effect that allows to significantly reduce the calculation time. An

Table 2: Test results – machining process accuracy as average error [µm]

Accuracy			Testing trajectory group number								
Number of input variables	Functions type	Rules type	1	2	3	4	5	6	7	8	9
2	bell	full cover	15.72±4.85	28.87±10.50	29.72±11.37	28.24±8.32	33.90±11.73	32.93±11.58	32.50±10.45	32.97±10.76	33.17±11.46
		reduced	15.92±5.19	28.90±10.53	29.70±11.21	28.38±8.68	33.80±11.61	32.93±11.58	**32.13±10.03**	32.99±10.78	33.14±11.31
	triangle	full cover	16.30±4.35	29.35±10.34	29.69±11.23	28.90±8.34	34.19±11.98	32.93±11.58	32.53±10.27	33.02±10.84	33.16±11.53
		reduced	16.21±4.46	29.45±10.42	29.69±11.23	29.00±8.53	33.91±11.71	32.93±11.58	32.53±10.46	33.16±11.02	33.16±11.40
3	bell	full cover	15.33±4.81	28.32±10.66	**25.29±11.16**	27.50±8.16	**33.69±12.06**	**28.12±11.99**	32.27±10.17	**32.96±11.02**	**28.68±11.74**
		reduced	**15.31±4.96**	28.74±10.37	30.46±11.82	27.60±8.08	33.99±11.86	33.13±11.46	32.16±10.07	33.22±10.89	33.79±11.74
	triangle	full cover	**15.28±4.34**	**28.54±10.39**	28.32±11.44	**27.39±8.24**	33.97±12.03	31.27±11.87	**32.07±9.94**	33.13±10.87	31.91±12.26
		reduced	15.41±4.74	28.73±10.21	30.40±11.55	**27.29±8.15**	34.21±11.94	33.28±11.51	32.14±10.05	33.10±10.82	33.91±11.84
RPRO			21.36±8.74	**15.39±15.85**	**3.67±1.47**	40.54±17.17	**19.21±16.88**	**3.88±1.27**	49.72±22.17	**16.23±14.32**	**3.95±1.29**

Table 3: Test results – number of processing steps

Time steps count			Testing trajectory group number								
Number of input variables	Functions type	Rules type	1	2	3	4	5	6	7	8	9
2	bell	full cover	201 ± 29	1126 ± 47	11484 ± 627	11700 ± 0	11700 ± 0	37120 ± 1681	40110 ± 0	40110 ± 0	73753 ± 2559
		reduced	201 ± 29	1126 ± 47	11484 ± 627	11700 ± 0	11700 ± 0	37120 ± 1681	40110 ± 0	40110 ± 0	73753 ± 2559
	triangle	full cover	201 ± 295	1126 ± 47	11484 ± 627	11700 ± 0	11700 ± 0	37120 ± 1681	40110 ± 0	40110 ± 0	73753 ± 2559
		reduced	201 ± 29	1126 ± 47	11484 ± 627	11700 ± 0	11700 ± 0	37120 ± 1681	40110 ± 0	40110 ± 0	73753 ± 2559
3	bell	full cover	201 ± 29	1126 ± 47	11484 ± 625	11700 ± 0	11700 ± 0	37131 ± 1673	40110 ± 0	40110 ± 0	73770 ± 2534
		reduced	201 ± 29	1126 ± 47	11484 ± 625	11700 ± 0	11700 ± 0	37131 ± 1673	40110 ± 0	40110 ± 0	73770 ± 2534
	triangle	full cover	201 ± 29	1126 ± 47	11484 ± 622	11700 ± 0	11700 ± 0	37132 ± 1674	40110 ± 0	40110 ± 0	73770 ± 2534
		reduced	201 ± 29	1126 ± 47	11484 ± 622	11700 ± 0	11700 ± 0	37132 ± 1674	40110 ± 0	40110 ± 0	73770 ± 2534
RPRO			**113 ± 21**	**578 ± 236**	**5542 ± 2529**	**273 ± 80**	**1934 ± 809**	**19436 ± 8856**	**470 ± 169**	**4052 ± 1717**	**37977 ± 17048**

additional advantage of the proposed system is the smoothness of acceleration and deceleration of the spindle movement. This phenomenon makes it possible to definitely reduce the level of vibration of the working CNC machine, and consequently extend its lifetime and definitely reduce operating costs.

To better observe the described behavior of the algorithm and to confirm that it also tackles mixed-density trajectories, a comparative simulation was conducted for trajectory [0.0, 0.6, 0.9, 1.3, 1.6, 1.97, 2.38, 2.45, 2.51, 10.0, 13.0, 22.0, 40.0, 100.0, 110.0, 111.0]. The RPRO algorithm achieved an accuracy of 26.83 μm during 431 steps, while the proposed expert system achieved an accuracy of 19.51 μm during 964 steps. As expected, the RPRO algorithm determined a significantly shorter G-code. As for the vibration level, on the other hand, the proposed solution provides an incomparably lower vibration level during the machining process. This can be observed by comparing the level of fluctuation of the velocity graph and spindle acceleration, which are shown in Fig. 5.

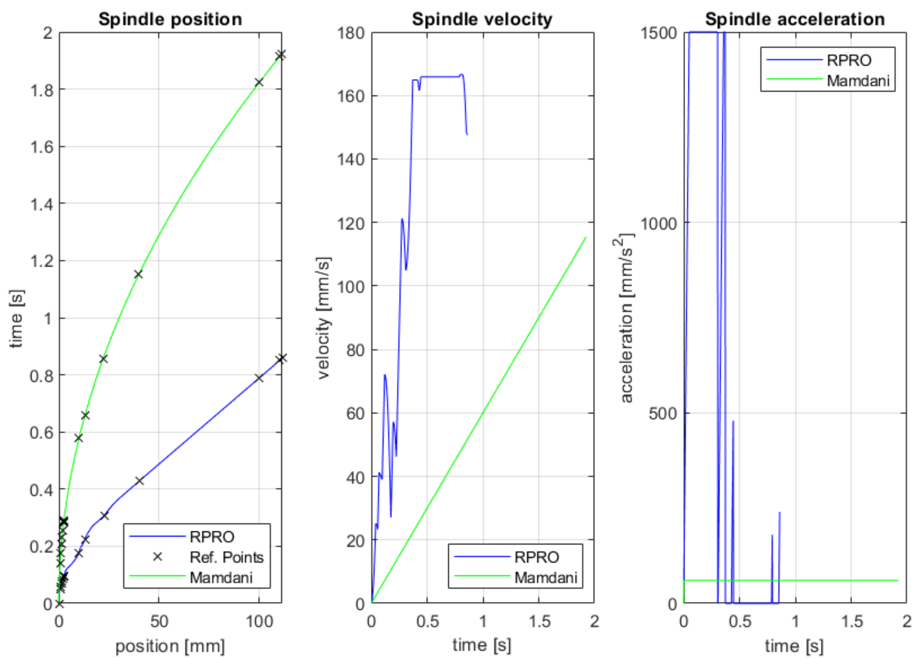

Figure 5: Comparative analysis for mixed density trajectory

4. Conclusions

The paper proposes a novel, off-line, Mamdani I-type algorithm that allows the generation of a G-code for given machine dynamics parameters and a specified sequence of reference points. Its capabilities and various versions have been tested during extensive experiments and compared with the results achieved by the RPRO algorithm used in industry. The proposed solution provides the possibility of personalizing the way of operation by appropriate construction of rules for the fuzzy system by an expert. In addition, by constructing the rules in a manner similar to that presented in the paper, it is possible to ensure an effective reduction in the level of machine vibration during the machining process. The authors also proposed a method for optimizing the set of rules while maintaining the stability of the algorithm's operation. Future work will focus on further optimizing the speed of the algorithm by using the Sugeno system, as well as other artificial intelligence methods.

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