DEVELOPMENT OF A SYSTEM FOR HSM (HIGH SPEED MACHINING) PERFORMANCE MONITORING

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***Abstract.**. The need to implement a monitoring system for high speed machining has increased due to the high performance and security levels required of machine tools. The parameters of NC programming are traditionally based on manuals or on user experiences, which do not exploit the full capacity of the machine tool. The concept of open architecture CNC is a means to integrate the customized functions of the user; however, a common standard has not been established for open architecture which is accepted by CNC manufacturers and used on a large scale within the industrial context. With the specific objectives of monitoring the feed rate and axis acceleration, identifying the optimum parameters of the NC program and evaluating the implementation of the monitoring function of the open CNC, an open architecture CNC data monitoring system was developed. Tests which considered different NC programming parameters for tool path interpolation were carried out and the results demonstrated that one can identify the optimum parameters for NC programming by examining the monitored data. The level of implementation of monitoring functions of an open architecture CNC was evaluated, demonstrating the limits for the development of customized functions.*

***Keywords**: Monitoring system, open architecture CNC, high speed machining*

1. INTRODUCTION

High Speed Machining (HSM) is widely used in the mold and die industry for the manufacture of complex surfaces and in the aeronautic industry in the manufacture of non-ferrous alloys. Due to the high quality of the geometric surface and the high levels of material removal, a reduction in the time and cost of the machining process was achieved - a principal factor in increasing industrial competiveness. The impact of optimizing the machining process in the mold and die industry results in shorter product development cycles, thereby contributing to a reduction in time needed for launching a product in the market (Lartigue et al. 2004; Tzeng and Chen, 2005).

The options for integration and flexibility proposed by the new generation of machine tools are one of the primary characteristics for optimizing the machining process. The need to produce small lots of pieces within reduced timeframes and the capacity of the manufacturing system to quickly absorb modifications in the existing products, makes system flexibility, integration and reconfiguration important factors in the productive context. However, there is a gap between integrative technologies and the intelligence needed to receive information for optimizing the process through the monitoring and control systems. In addition, there is often a limitation in the level of function customization offered by the manufacturing system (Wang et al., 2004; Haber, Alique, 2007).

The openness that is offered by modern machine controllers allows for the development and application of a high level of user functions. In many cases, this openness is sufficient for the application of the monitoring process. At a low level, as in the access of velocity and current control data, the development of customized functions is not possible (Pritschow, Kramer, 2005).

According to Park, Kim and Cho (2006), the use of the middleware concept (a program that communicates among other softwares) in the kernel software module, makes the compatibility of communication between controllers possible, thus providing for the integration of geographically distributed CNC machines. Previous open architecture systems have the same purpose and functionality; however, they are logically incompatible.

Based on this information, it is possible to identify that the open architecture CNC allows for data access and manipulation without the need to modify the hardware. However, open architecture CNC does not offer a data interface method at all information levels. New hardware and software configuration methods are proposed to permit this opening (Pritschow and Kramer, 2005; Park, Kim and Cho, 2006; Erol, Altintas, and Ito, 2000; Pritschow, et al., 2001; Yun, Min and Pasek, 2007).

Based on this scenario, this paper presents the development of an open architecture CNC data monitoring system that can be applied to the HSM process to:

- Monitor the feed rate and acceleration of the axes;
- Identify the optimum program parameters of the tool path interpolation methods;
- Evaluate the open architecture interface of a commercial CNC.

The open architecture interface will be evaluated by the level of access to the data and by the level of function customization. Through this evaluation, the limits and the possibilities will be identified for the implementation of data monitoring systems in the open CNC. It is not within the objectives of this paper to evaluate the precision of the data provided by the CNC. The concept involving the application context of the monitoring system is illustrated in Figure 1.

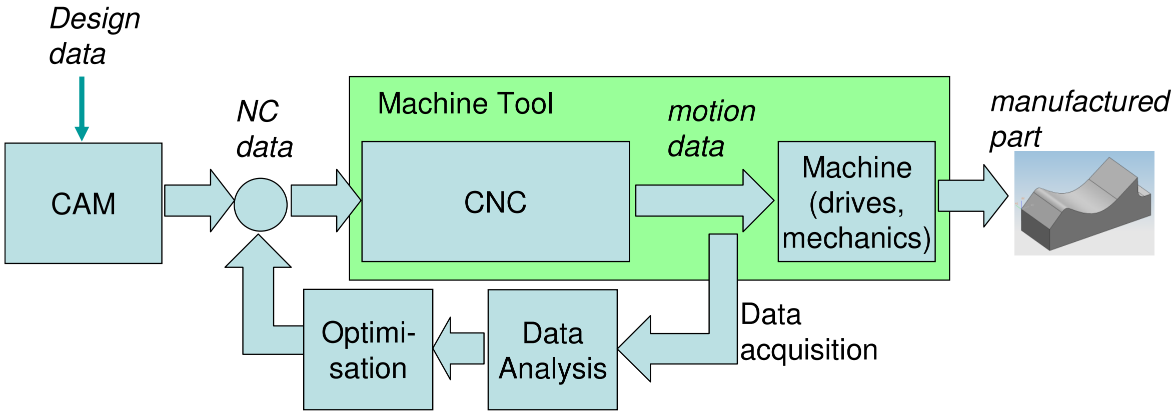


Figure 1: Concept of the CNC data monitoring system

Figure 1 shows the association of components involved within the concept of a feedback control system. The diagram of blocks represents the application of monitoring the machining process in order to provide the function of an interface that makes access and analysis of machine data coming from open architecture CNC possible. The analysis of signals that are made available for communication characterizes the machine tool behavior, which is influenced by the CAM program parameters.

1.1 Open architecture controller

The concept of the open architecture controller received more attention in the 1990s when the flexibility demanded by the manufacturing systems and the need to implement functions customized by users required a neutral interface for data access.

The requirements for the levels of accessibility and customization of the open architecture CNC functions are different for the end user than for the manufacturer of the numeric commands. For the end user the requirements are: access and customization of all levels of communication in standardized form without the need to buy additional modules for such an objective. For the machine tool builders, the level of accessibility is largely limited to customization of the man machine interface. In case there is a need for the implementation of interpolator or server control functions, the user depends on information/modules of CNC manufacturer (Erol, Altintas, and Ito, 2000).

The IEEE institute defines open architecture system as follows: “An open system has characteristics that enable the implemented applications to be carried out in various platforms of different manufacturers, interoperable with other systems and with an interaction consistent with the user.” (IEEE, 1998).

According to the definition above, a set of specifications is needed so that the controller manufacturers use it. While many such initiatives have already arisen, a consensus among manufacturers for the adoption of certain standards has not been reached.

The initiatives described in (Pritschow, et al., 2001) demonstrate that all of them have a common objective of defining a standard for the open architecture controllers. The main characteristics of this standard are neutrality in relation to the manufacturers and the customization of functions through modularization and the use of Application Programming Interface (API). However, there is no compatibility between these proposed standards. That is to say, although they have a common objective, these associations compete among themselves. The result of this lack of integration is that these standards are not used on a large scale within industry.

1.2. Experimental research method

The experimental method of this research attempts to identify the variables that influence the object, define the forms of control and analyze the effects produced by the variables in the object of study.

Based on the deductive hypothetical method, the following premises were formulated for the data monitoring system.

Premise 1: It is possible to acquire the data of the monitored variable with adequate resolution.

- Sample: data collected with the monitoring system;
- Independent Variable: programmed feed rate;

- Dependent variable: resolution of the monitored variable. ;

Premise 2: It is possible to identify the parameters of the CAM program that result in optimizing the process

- Sample: Data collected from the monitoring system;
- Independent variable: Tool path interpolation methods;
- Dependent variable 1: Machining time;
- Dependent variable 2: Mean feed rate;
- Dependent variable 3: Behavior of feed rate;
- Dependent variable 4: Behavior of axis acceleration.

Experimental procedure consists in carrying out tests to verify premise 1 and 2. The tests are presented in section 2.5. To verify premise 2, the procedure consists in carrying out an NC program on a test part of the German Numeric Command Association (NC-Gesellschaft) and monitoring the variables in accordance with the established conditions.

2 DEVELOPMENT OF MONITORING SYSTEM

The system was developed with the use of the National Instruments LabVIEW$^{(R)}$ 7.1 software. The communication of the Intel Pentium II PC with 800MHz and the Windows XP operating system with CNC was carried out by the CP5611 card installed in the Peripheral Component Interconnect bus of the PC. For the connection between the CP5611 card and the CNC, the MPI (Multi Point Interface) cable was used. All three instruments were manufactured by SIEMENS (Del Conte, Schützer and Helleno, 2008). The communication data was made available by NCDDE (NC Dynamic Data Exchange), a data server which is part of the SIEMENS OEM (Original Equipment Manufacturer) packet (Siemens, 1997).

2.1. Data acquisition module

The purpose of a module for data acquisition is to create a buffer directly in the CNC for the storage of data at the control level of the server. This is an attempt to avoid delays in communication in data acquisition via the network and to increase the sample rate.

The implementation of this data acquisition strategy is done through the synchronized action functions of the open CNC used in this study. As defined in the manufacturer's manual (Siemens, 2005), "synchronized actions are instructions programmed by the user that are evaluated in the interpolation cycle synchronically with the execution of the NC program. If the programmed condition in the synchronized action is satisfied, or if no condition is specified, the actions determined by the instruction are activated synchronically with the NC program that is being used."

The condition determined in the synchronized action is evaluated in the interpolation cycle and the actions are carried out if the condition is satisfied. To build the buffer, the variables of the CNC, called R parameters, were used. In the R parameters, the data of the feed rate and machining time variables are stored. There are 100 R parameters that potentially can be increased to 1000; however, this increase was not necessary for the objectives of this experiment. Below is the synchronized action program developed for the data acquisition module. The synchronized action is included in the beginning of the NC program and activated automatically when the program is executed (Del Conte and Schützer, 2007).

```
ID=1 WHENEVER ($AA_IW[X1]>$AC_PARAM[1]) AND ($AA_IW[X1]<$AC_PARAM[2]) DO
$R[$AC_MARKER[1]]=SQRT($VA_VACTM[X1]*$VA_VACTM[X1]+$VA_VACTM[Z1]*$VA_VACTM[Z1]
) $AC_MARKER[1]=$AC_MARKER[1]+1 $AC_PARAM[1]=$AC_PARAM[1]+1
$AC_PARAM[2]=$AC_PARAM[2]+1
```

The programming described above is built in the following way:

- ID=1: is the identifying parameter for synchronized action;
- WHENEVER (condition) DO: establishes a condition for the synchronized action to be executed. In this case, every time that a specific condition between parentheses is reached, an action after the instruction DO is carried out;
- DO action: describes which action will be carried out;

The logic for the functioning of the synchronized action is presented below:

- Every time that a position of an X axis is larger than the value of the $AC_PARAM[1] parameter and less that the value of the $AC_PARAM[2] parameter, the action that calculates the value of the feed rate resulting from the X and Z axes and records the result in the R parameters with the $AC_MARKER[1] index is carried out. The values of the conditional parameters are initialized and increased to assure that for each 1 millimeter of displacement of the X axis, the action is carried out. The index of the R parameters is also increased for the storage of data.

2.2. Data transmission module

The data transmission module was developed with LabVIEW 7.1 software. The program logic of LabVIEW is based on the flow of programmable data. Within this logic, the user "builds" a block diagram with the program functions made available by LabVIEW and makes the connection between these functions. The operating sequence is from left to right in the diagram.

The data transmission module carries out the communication between the CNC and the CP. The LabVIEW program carries out the reading of the data contained in the 100 R parameters of the CNC. Figure 2 illustrates the block diagram developed in LabVIEW for the data transmission module (Del Conte and Schützer, 2009).

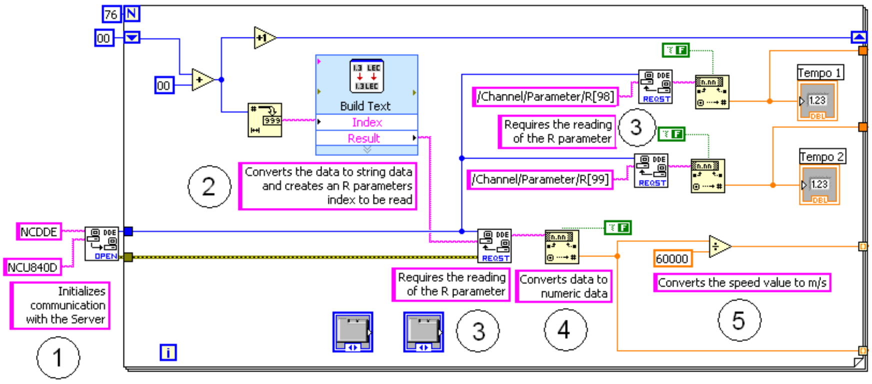


Figure 2: Block diagram of the data transmission module (Del Conte and Schützer, 2009)

As seen in Figure 2, the block diagram of the data transmission module functions in the following logical sequence:
1. The open DDE function initializes communication with the NCDDE Data Server;
2. The numeric data is converted to string data and creates the R parameters index;
3. The request DDE function requests the reading of values in the R parameters index;
4. The data is converted to numeric data;
5. The feed rate values are converted to meters per second for the calculation of the discrete derivative in the data analysis module.

The information transmitted to the PC is used by the data analysis module, which is presented in the following section.

2.3 Data analysis module

In the data analysis module the behavior of the monitored signal is visualized in the feed rate and axis acceleration graphs. The mean and median values of the feed rate, the machining time and the percentage of the optimization time are shown via the user interface. The user has the possibility of saving the monitored data in a text file. Figure 3 presents the part of the program that corresponds to the data analysis module (Del Conte, 2008).

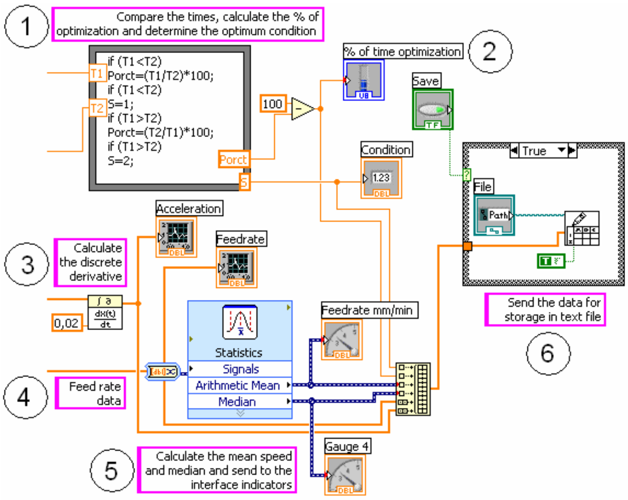
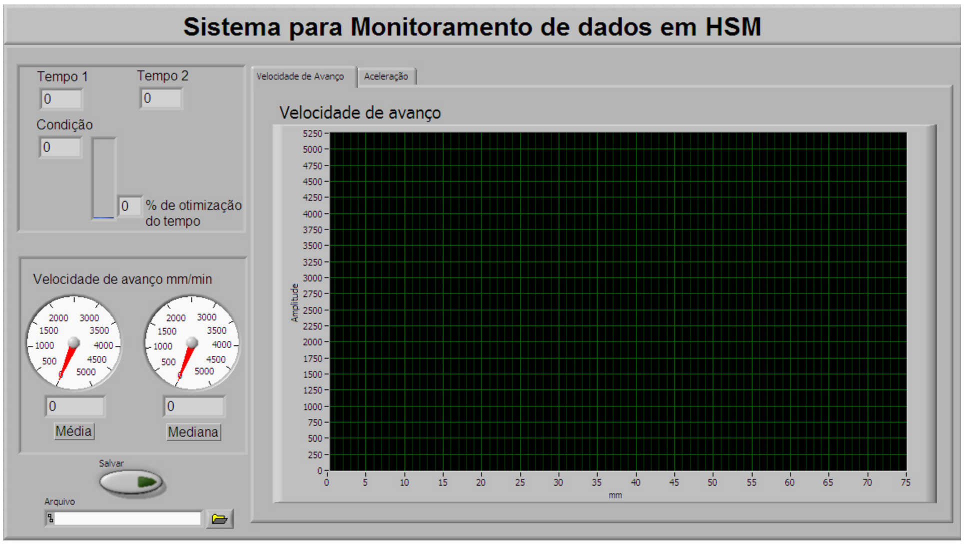


Figure 3: Data analysis module (Del Conte, 2008)

As seen in Figure 3, the machining time data is used to calculate the optimization percentage and determine the optimized condition. The feed rate data are used to calculate the axis acceleration. This calculation is carried out by the discrete derivative function of LabVIEW, which will be explained in topic 3.1. The feed rate and acceleration data are sent to the respective graphs. Through the LabVIEW statistic function the mean and median feed rates are determined. The presentation of the data is done by the interface with the user, which will be discussed in the following section.

2.4. Interface with the user

In the environment to design user interfaces of LabVIEW, controls and indicators for building the software are available. The indicators for the optimized condition (first or second) and the performance indexes as well as the graphs of the behavior of the feed rate and axis acceleration variables are visualized in Figure 4.



Sistema para Monitoramento de dados em HSM

Tempo 1: 0
Tempo 2: 0
Condição: 0
% de otimização do tempo: 0

Velocidade de avanço mm/min
Média: 0
Mediana: 0

Figure 4: User Interface of the monitoring system (Del Conte, 2008)

As seen in Figure 4, the indicator is visualized which corresponds to the optimized condition of the NC program parameters and the machining time values, the percentage of time optimization and mean and median rates. In the graph the behavior of the feed rate and the axis acceleration in relation to the distance run by the X axis of the machine tool. The feed rate variable and the performance indicators can be saved in text file. To save the data, file path should be specified and the save buttoned activated. The tests for the verification of the premises formulated in section 1.2 are presented in the next section.

2.5. Tests for the verification of the premises

To verify premise 1, the experiment was carried out in a three axis machining center with the CNC Siemens 810D. Data was acquired for the position of the X axis variable, defined by the internal CNC variable with the name $AA_IW[X1]. The data acquisition module was executed in two different conditions. In the first condition, the programmed feed rate was 1000 mm/min and in the second condition it was 6000 mm/min (Del Conte and Schützer, 2007). The NC programming parameters used in the tests were based on the studies of Helleno (2004) and Nunes et al. (2007). The CNC program presented below was used for this experiment (Del Conte and Schützer, 2009).

```
G54 D1
G1 X0 F1000
$AC_MARKER[1]=0
$AC_PARAM[1]=0
$AC_PARAM[2]=1
ID=1 WHENEVER ($AA_IW[X1]>$AC_PARAM[1]) AND ($AA_IW[X1]<$AC_PARAM[2]) DO
$R[$AC_MARKER[1]]=$AA_IW[X1] $AC_MARKER[1]=$AC_MARKER[1]+1
$AC_PARAM[1]=$AC_PARAM[1]+1 $AC_PARAM[2]=$AC_PARAM[2]+1
X100
M30
```

The NC program executes a linear movement on the X axis from 0 to 100 millimeters of distance. Always when the condition described in the synchronized action is reached, the value of the X axis position is stored in the R parameters of the CNC. The established condition assures that one value for the position of the X axis is recorded during the displacement interval of 1 millimeter of the X axis (Del Conte and Schützer, 2009).

To verify premise 2, an NC program for the NCG test part was generated. The NC programs were elaborated using the CAM system Unigraphics NX 3. For the test, the NC programming code was used which corresponds to a length of displacement for the finishing operation. This length corresponds to 1 displacement of the X axis of the initial coordinate until the final coordinate of the part. The monitored data of the feed rate and acceleration come from the X and Z axes.

The NC program parameters used for the tests were:

- Condition1: linear interpolation and CAM tolerance of 0.005 mm;
- Condition 2: polynomial interpolation and CAM tolerance of 0.005 mm.

The machining time data was acquired through the $AC_TIMER[1] parameter. This parameter was programmed directly in the NC code that corresponds to conditions 1 and 2 respectively as presented above.

3 ANALYSIS OF RESULTS

The data acquisition rate for programming the acquisition module directly in the open CNC is limited to the cycle time of the CNC interpolator. In the CNC utilized, the cycle time of the interpolator is set at 10 milliseconds, resulting in an acquisition rate of 100 points per second.

As stated earlier, the interpolator cycle time is the minimum time for the acquisition of data internal to the open CNC that was used in the experiments. Based on the equation proposed by Arnone (1998) for calculating the time for processing the blocks the Eq.(1), which determines the influence of the programmed feed rate on the resolution of the monitored variable, was obtained.

$$V_{a\max} = \frac{\Delta_x}{BPT/60} \tag{1}$$

Where:
V_{amax} = Maximum feed rate [mm/min]
Δ_x = Distance between data acquisition [mm]
BPT = Block Processing Time [s]

According to Eq.(1), the maximum feed rate for securing the condition of acquiring one value of the monitored variable for one millimeter of displacement is calculated below:

$$V_{a\max} = \frac{1}{0{,}010/60} \qquad V_{a\max} = 6.000\,mm/\min$$

Therefore, for the CNC Siemens 810D with an interpolator cycle time of 0.010 seconds, the maximum feed rate is 6000 mm/min.

As in the previous work from Del Conte and Schützer (2009) that shows the influence of the different interpolator cycle times on the resolution of the monitored variable, can be observed that the resolution of the monitored variable decreases proportionally with the increase in feed rate. For example CNC B, with a feed rate of 10000 mm/min, the specific condition is assured. With a value of 20000 mm/min the resolution is affected proportionally. In this case, the data is collected each 2 mm of displacement of the X axis.

3.1 Identification of the optimum parameters of the NC program

The optimum parameters of the NC program were identified as a result of the experiments described in section 1.2 for the verification of premise 2. The results in relation to the machining time are presented in Table 1. As seen, the machining time monitored by the system varies between two conditions in the NC program. There is a 30% optimization of machining time with the use of polynomial interpolation when compared with the linear interpolation time.

Table 1: Machining time (Del Conte, 2008)

Interpolation	Time (s)
Linear	2.19
Polinomial	1.53

The results in relation to feed rate are presented in Table 2 and in Figure 5. The mean and median feed rate increased by about 25% and 29% respectively with the use of polynomial interpolation.

Table 2: Feed rate (Del Conte, 2008)

Interpolation	Mean speed	Median speed
Linear	3,375 mm/min	3,498 mm/min
Polynomial	4,500 mm/min	4,953 mm/min

In Figure 5 the behavior of the feed rate monitored by the system is presented. The behavior of the feed rate is altered with the different interpolation methods used. The graph provide a visual comparison, showing that with the use of polynomial interpolation, the feed rate behavior is more stable and closer to the programmed value of 5000 mm/min, when compared to linear interpolation.

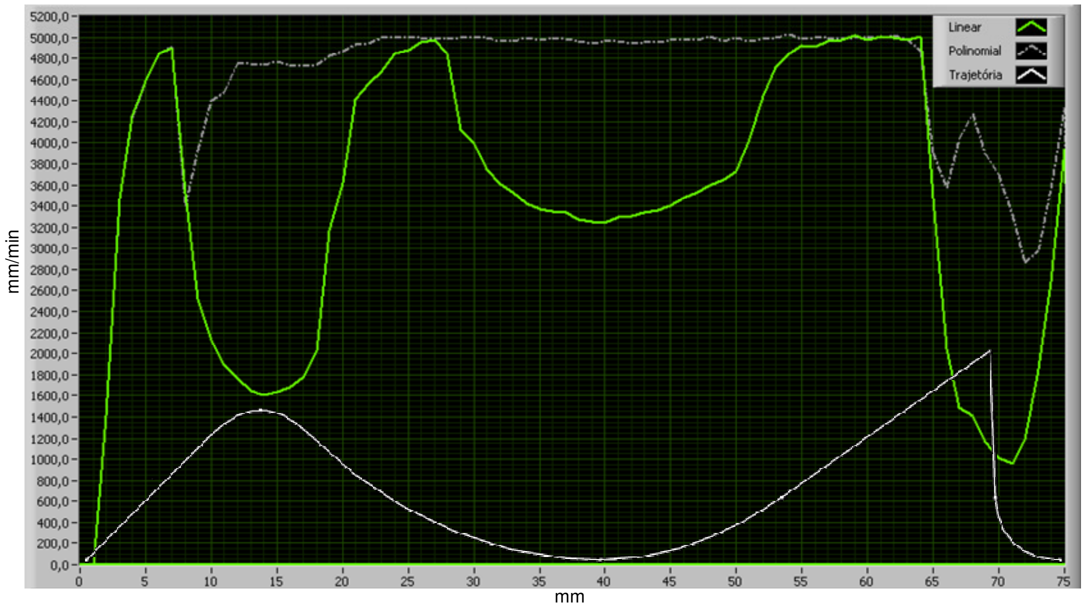


Figure 5: Behavior of the feed rate for linear interpolation (Del Conte, 2008)

In Figure 6 the behavior of acceleration obtained with the system is shown. To calculate the acceleration, a discrete derivative function of LabVIEW was used. This function carried out the discrete derivative of the feed rate using the method-centered approach for the first derivative. This approximation method is shown in Eq.(2) (Ruggiero and Lopes, 1996).

$$y'(x_i) \approx \frac{y_{i+1} - y_{i-1}}{2dt} \tag{2}$$

According to Ruggiero and Lopes (1996), the error due to the centered approximation is equal to the square of the discrete interval. For the discrete interval of 0.020 s, the error of the centered approach is 0.0004.

The discrete interval was obtained by considering the mean time between reading of feed rate data during the initial 5 mm of the test part. This stretch was chosen because it has a rectilinear path that results in feed rate and time behaviors between readings that is approximately equal for the two conditions of the NC program.

To determine the discrete interval, data was collected on the time between readings, using a data acquisition module. The monitored variable was the time counter $AC_TIMER[1] and the collected data was saved in a text file. The graph for acceleration for both NC program conditions is presented in Figure 6.

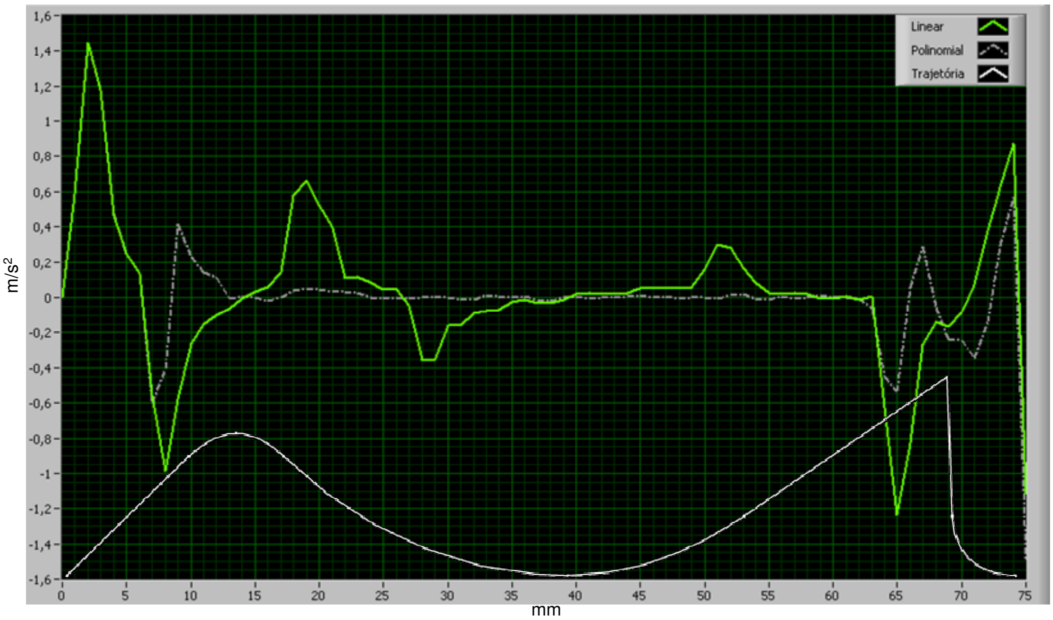


Figure 6: Acceleration behavior for linear interpolation (Del Conte, 2008)

As seen in Figure 6, the acceleration behavior for the 5 initial millimeters of the test part for both interpolations are practically the same. This occurs due to the rectilinear path of this stretch. During machining, the acceleration behavior for polynomial interpolation is softened. This can be verified by comparing the acceleration and deceleration peaks. Comparing the area between 13 and 60 millimeters, the acceleration is almost constant for polynomial interpolation.

The results obtained demonstrate that the system has the capacity to identify the optimum parameters for the NC program, by monitoring the machining time and the behavior of the feed rate and axis acceleration.

3.2 Access and customization of functions in the open CNC

In this section the levels of access and customization of the open CNC functions are analyzed. The limits found can vary with other CNC manufacturers, but this study did not set out to make this comparison. As stated in the bibliographic overview, open architecture standards that are widely accepted and used by CNC manufacturers have not been established.

The level of data access and customization of functions is limited to the level of the interpolator. In this way, the maximum frequency in the manipulation of the data is given by the cycle time of the interpolator. This results in limiting the data acquisition rate and the implementation of the monitoring systems in real time for high speed machining.

The permitted level for the customization of functions is also at the level of the interpolator cycle. For the development of functions at this level, a programming function from the manufacturer of the CNC should be used, as seen in section 2.1.

4 CONCLUSION

The specified condition for data acquisition for the collection of 1 value of the monitored variable per 1 millimeter of X axis displacement is assured by the system, as long as the feed rate value does not exceed the minimum time for data collection, which for the open CNC used, is 0.010 s. As the feed rate exceeds the minimum data acquisition time, the resolution of the monitored variable decreases proportionally.

The machine time was optimized by 30% and the mean and median feed rate were optimized by 25% and 29% respectively with a change from linear interpolation to polynomial interpolation.

The identification of the optimum parameters for the NC program is visualized by graphs that describe the behavior of the feed rate. By comparing the graphs, the behavior of the speed rate for polynomial interpolation is maintained closer to the value of 5000 mm/min (programmed feed rate) for most of the tool path displacement.

In the graph on acceleration, it was evident that the polynomial interpolation softened the acceleration profile, making it more stable when compared to the acceleration obtained from linear interpolation. The origin of the great variation in the feed rate and acceleration of the two conditions could be explained by the different tool path segments length. When the linear interpolation is programmed, the tool path is broken in small segments that cause the limitations observed.

The development of the data monitoring system for an open architecture controller depends on the level of openness of the architecture and the objective for applying the system. In this study, it was verified that for the level of openness of the CNC used, the monitoring objectives of the feed rate and identification of optimum parameters of the NC program were reached within the established limits of programmed values for the feed rate.

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