Optimization of Computer Aided NC Programming System for NC Wire Cutting Machine

Haitao Wang[1], Gang Liu [2], Qing Liu[3], Qian Wu[4] and Jiahui Wang[5]

[1]Center of Engineering Technology Education, Henan Institute of Technology, Xinxiang City, Henan, 453000, China, wanghaitao2100@163.com
[2]School of Vehicle and Traffic Engineering, Henan Institute of Technology, Xinxiang City, Henan, 453000, China, gliu14@mails.jlu.edu.cn
[3]Department of Transportation, Hami Vocational and Technical College, Hami City, XinJiang, 839000, China, liuqing1997xfm@163.com
[4]Department of Transportation, Hami Vocational and Technical College, Hami City, XinJiang, 839000, China, suizailh@126.com
[5]Department of Transportation, Hami Vocational and Technical College, Hami City, XinJiang, 839000, China, wjh940320wjh@163.com

Corresponding author: Haitao Wang, wanghaitao2100@163.com

Abstract. With the continuous development of computer-aided control technology, traditional manufacturing has gradually entered the modern manufacturing model. Now the core of manufacturing technology is computer digital computer-aided control technology. This paper studies the interpolation algorithm of the numerical control system, and discusses the realization of the computer-aided control of the trajectory and the computer-aided control of the feed motion of the CNC WEDM system. The computer-aided control methods of the interpolation motion of the numerical control system are compared, and the improved interpolation method of the point-by-point comparison method is used to realize the computer-aided control of the trajectory of the machine tool; at the same time, the stepper motor is controlled by the torque-frequency characteristics of the stepper motor. The computer-aided control method of speed acceleration and deceleration is described for the computer-aided control of sports. The computer-aided control method of curve acceleration and deceleration is adopted to realize the computer-aided control of automatic speed acceleration. The design of the overall framework of the system software is completed, and the multi-task parallel processing of the system is realized by using the multi-thread mechanism of the Windows operating system. The threads use global variables to communicate, and the threads coordinate and cooperate with each other to realize the motion computer-aided control function of the CNC system. The main functions of computer-aided control of motion are realized. Motion computer-aided control mainly realizes the various functional modules of machine tool movement, such as returning to the starting point of the original path, returning to the broken wire point of the original path, etc.; this part of the function is the soul of the motion of the machine tool, and its function directly reflects the automation level of the machine tool.

Keywords: CNC Wire Cutting Machine; CNC Programming; Computer Aided; Contour Interpolation
DOI: https://doi.org/10.14733/cadaps.2022.65-75

1 INTRODUCTION

The number of CNC wire-cutting machine tools is growing at a rate of more than 10,000 units per year, and the market capacity of wire-cutting machine tools is very large [1]. Although high-speed wire cutting machine tools are widely used, compared with low-speed wire cutting machine tools, the former shows many shortcomings, such as poor precision maintenance of the machine tool, and the wire transport system cannot maintain constant tension cutting [2]. The reliability of the computer-aided control of the electrical cabinet is poor, and the programming and memory cannot meet the user's convenient use. The machining accuracy of the machine tool and the surface roughness of the workpiece are limited, which is far below the level of the low-speed wire cutting machine tool. As far as the current level of technology is concerned, in order to greatly improve the performance of high-speed wire-cutting machine tools in a short time, the difficulty is relatively large. The increase in the development cost of the machine tool leads to the increase in cost, thereby reducing the cost performance, which is not realistic from the perspective of technology and market [3].

In EDM, the factors that affect the processing effect are far more and more complex than other processing methods, and it is also increasingly difficult for users to train skilled operators who are proficient in technology [4]. The ability to have high-performance intelligent computer-aided control is not only an important manifestation of the development level of the machine tool, but also the key to whether the machine tool can give full play to its technical level when in use and whether it can be welcomed by users [5]. Ramnath et al. [6] pointed out that the performance indicators of WEDM-LS are processing speed, processing surface roughness, electrode loss and processing accuracy. With the gentrification of processing objects, the indicators begin to subdivide. For example, the surface roughness requires a uniformity requirement under the premise of surface flatness. This is the requirement of the integrated circuit IC module mold and the quality requirement of the high-end mobile phone shell mold. Yin et al. [7] believe that micro-EDM is an important field of modern manufacturing technology, which generally refers to the machining of holes, slots, shafts and cavities with a size less than 300 μm. The principle of its processing is not unique. Its main feature is that the processing unit is very small, including tiny single pulse discharge energy, fine electrodes and tiny discharge gaps. Manoj and Narendranath [8] believe that in many cases where the processing accuracy is not very high, the fast-moving wire-cutting machine tool can fully reflect its advantage of high processing speed. However, due to the high wire speed and the repeated use of the metal wire for processing, the metal wire cannot be fixed, and the diameter of the metal wire will change after repeated use, so it is difficult to improve the processing accuracy. The foreign low-speed wire cutting machine has a slow processing speed and the metal wire will not be used repeatedly, so its processing accuracy can be guaranteed. Padhi and Tripathy [9] pointed out that the computer-aided control platform of WEDM has been transplanted from the DOS platform to the Windos platform, and the performance of the PC is becoming more and more high-end. The traditional high-speed wire cutting machine has a big gap in processing accuracy compared with the modern one. Therefore, how to improve the processing accuracy of the high-speed wire cutting machine is an important development direction for the wire cutting machine in the future. Shen et al. [10] have found that the low-speed wire cutting machine is processed in deionized water, and the processed parts are prone to oxidation and corrosion to produce metamorphic layers and microcracks, which reduce the hardness and service life of the processed surface. For this reason, various companies have introduced different forms of non-electrolytic pulse power supplies, which have alternating voltage waveforms that eliminate the effect of anodic oxidation. Marani et al. [11] have introduced a low-speed wire cutting machine tool driven by AQSSOL linear motor. Because the linear motor drive and the main shaft are the same part, there is no screw connection, no backlash, accurate movement, high response and high tracking. And the high-precision position computer-aided control can maintain stable processing in the best discharge state, improve discharge efficiency and processing accuracy, and overcome surface streaks in wire cutting.

This paper uses the point-by-point comparison method to realize the computer-aided control of the trajectory of the CNC wire-cutting machine processing motion. The computer-aided control method of curve speed rise and fall is used to control the feed speed of the system. The computer-aided control of trajectory realizes the complete processing computer-aided control process. In the process of realizing the acceleration and deceleration of the system, relatively speaking, the constant-speed operation occupies most of the working time. The parameter interpolation method can be used to provide the acceleration, deceleration, and constant-speed operation speed, so as to realize the computer-aided control of automatic speed increase and decrease. Because this computer-aided control system is a two-axis linkage system, the process of adopting the point-by-point comparison method is clear and simple, and the system work intensity is average, so the stepper motor drive signal can be directly obtained from ARM. According to the computer-aided control function requirements of the system, the tasks of the system are reasonably divided. At the same time, the functional requirements of the system software are analyzed, and the modular programming idea is adopted to divide the functional modules. The design takes into account the real-time and interoperability of the monitoring module and the processing module. In the design process of the user’s main interface, modular methods are also adopted: preparation modules, information modules, execution modules and graphics modules; obviously the modular method is the most suitable method for large-scale system development. The independence of each other allows the entire development team to carry out their tasks at the same time without interfering with each other.

2 CNC PROGRAMMING COMPUTER-AIDED CONTROL OPTIMIZATION OF CONTOUR INTERPOLATION AND FEED MOTION

2.1 Optimization Analysis of Point-by-point Comparison Method

Data sampling interpolation is to divide the given contour curve into the feed section of each interpolation cycle according to the feed speed of the user program, namely the contour step length. You perform an interpolation operation in each interpolation cycle, calculate the coordinates of the next interpolation point, and calculate the feed amount of each coordinate in the next cycle, and then get the command position of the next interpolation point. The difference from the reference pulse interpolation method is that the calculated feed is not the feed pulse but the feed expressed in binary, that is, in the next interpolation cycle, the feed segment on the contour curve is divided into each coordinate axis. Through the position sensor, the computer regularly samples the actual position of the coordinates, compares the sampled data with the command position, and obtains the position error, and then performs computer-aided control of the servo system according to the position error to eliminate the error and make the actual position follow the command position. The interpolation period of the data sampling method can be equal to the sampling period or an integer multiple of the sampling period. A linear segment of interpolated periodic motion approximates a circular arc with a chord line. Data sampling and interpolation mainly include time division method, extended DDA method, double DDA method and so on. This type of interpolation algorithm is suitable for closed-loop or semi-closed-loop numerical control systems with DC or AC servo motors as actuators.

Every time the interpolation program is called, it calculates the position increment of the coordinate axis in each interpolation cycle, and then obtains the corresponding position reference value of the coordinate axis, and then compares it with the sampling station. The actual position feedback value obtained is compared to obtain the position tracking error. The position servo software calculates the given speed of the feed axis according to the current position error, and outputs it to the drive device, and then drives the lead screw and the worktable to move in the direction of reducing the error through the motor.

Since the principle of the point-by-point comparison method is based on the different positions of the interpolation points as the judgment basis, the next step is determined, regardless of the distance between the new position to be reached and the standard contour. For arcs, the degree of interpolation effect approaching the standard contour curve is different, as shown in Figure 1.

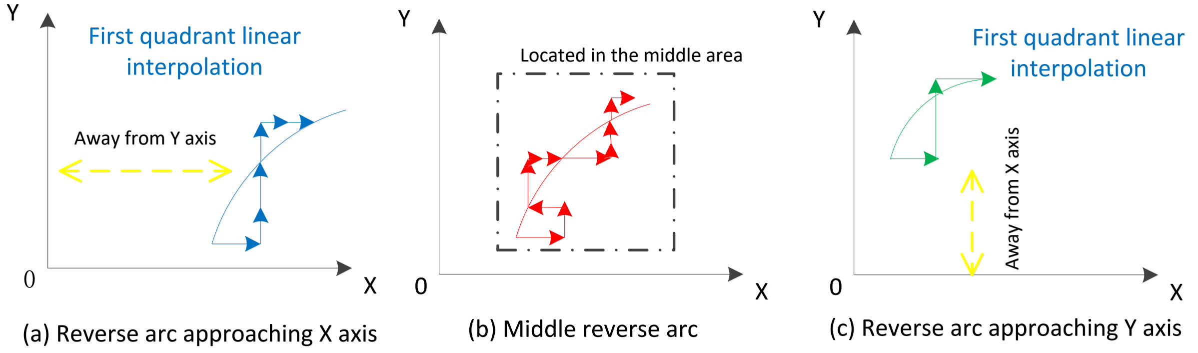

Figure 1: The degree of arc approximation is different in different positions.

2.2 Computer-aided Control of Feed Motion

1) Selection of stepper motor

Stepping motor is a computer-aided control motor that converts electrical pulse signals into corresponding angular displacement or linear displacement. It can be used to form a simple and practical servo system, and does not require feedback links, so it has been extremely successful in the open-loop CNC system.

Stepping motor is the main executive element in the open-loop computer-aided control system, and its performance directly affects the performance of the CNC system. Therefore, it is necessary to fully consider its characteristics when designing and manufacturing a stepper motor system, and choose a stepper motor reasonably. The parameters related to the selection of stepper motors mainly include step angle, starting frequency, maximum operating frequency and so on. The step angle is:

$$\theta = 360 \bullet i \bullet \delta / h \tag{1}$$

Among them, δ is the pulse equivalent of the open-loop CNC system (mm/pulse); i is the reduction gear reduction ratio, that is, the transmission ratio; h is the pitch of the ball screw (mm).

The two axial stepping motors of the feed drive system of the CNC wire cutting machine transmit motion to the lead screws in their respective directions through the two-stage reduction gear, and the lead screws drive the worktable to move. Under normal circumstances, first you select the stepper motor type according to the load characteristics, the maximum feed speed and other conditions. Then you determine the parameters according to the system accuracy and machine tool stroke. When the preliminarily selected θ, δ, and h cannot meet the constraint requirements, a gear must be added between the stepper motor shaft and the lead screw to reduce speed to achieve mutual coordination. Since the starting frequency of the stepper motor will be reduced when starting with a load, the equivalent load inertia JZ on the motor should be calculated first. Because only the pinion gear is directly connected to the stepper motor, J2, J3 and Jw need to be converted. The calculation formula is as follows:

$$J_Z = J_1 + {(J_2 + J_3)}\big/{i^2} + W \bullet \delta / \theta \tag{2}$$

In the formula, J1 and J2 are the moment of inertia (Nms2) of the small gear and the large gear respectively; J3 is the moment of inertia of the lead screw (Nms2); W is the total weight of the carriage and the table; δ is the pulse equivalent (mm/pulse).

We select the value of f st according to the starting frequency f stm required by the machine tool as follows:

$$f_{stm} = f_{st} \bullet \sqrt{\frac{1 + M / M_Z}{1 - J_Z / J}} \tag{3}$$

In the formula, J is the moment of inertia of the motor rotor, and M is the torque determined by the pitch-frequency characteristic curve at the starting frequency. Because of the non-linear relationship between M and fst in the formula, it can only be completed by trial and error combined with curve approximation. In addition, it can be approximated by the following formula based on experience:

$$f_{stm} = 0.45 \bullet f_{st} \tag{4}$$

According to the maximum operating speed of the machine tool table, the size of f max is selected according to the following formula.

$$V = 60 f \bullet \delta \tag{5}$$

2) Computer-aided control of automatic speed reduction

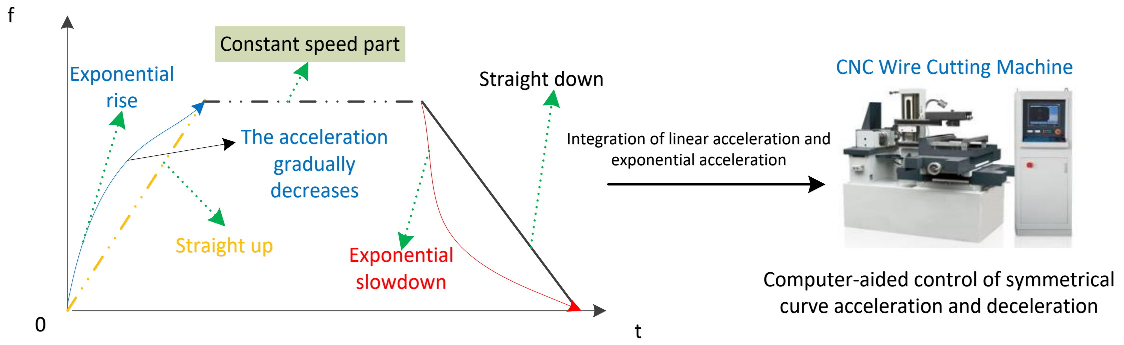

Figure 2: Computer-aided control of stepping motor speed of CNC wire cutting machine.

As shown in Figure 2, when the speed is increased and decreased according to the linear law, the acceleration value is theoretically a constant value, but in fact, the output torque decreases when the motor speed increases, resulting in a change in acceleration. When carrying on the computer-aided control of speed increase and decrease, the acceleration is gradually reduced, which is closer to the law of stepping motor output torque changing with speed. Taking into account that the linear acceleration and deceleration does not conform to the speed change law of the stepping motor, the exponential acceleration and deceleration computer-aided control has poor balance when the speed changes greatly.

Using this kind of symmetrical curve acceleration and deceleration computer-assisted control of the stepping motor's automatic speed reduction method, the specific application can adopt two kinds of timing method or fixed step method. The timing method is to change the operating frequency of the stepper motor at a certain time interval (Δt), so as to realize automatic speed increase and decrease computer-aided control; while the fixed step method is to change the operation of the stepper motor according to a certain step interval (Δp), that is, when the stepper motor completes a fixed number of steps, it changes the frequency once, so as to realize automatic speed increase and decrease computer-aided control. Regardless of the timing method or the fixed step method, the principles followed when choosing the time interval (Δt) and the step interval (Δp) are the same. The change in the operating frequency of each stepper motor is:

$$\Delta f_i = \left| f\left[(i+1)\Delta t\right] - f(i\Delta t) \right| \tag{6}$$

This article adopts the fixed-step method to realize the process of automatic speed increase and decrease in the process of stepping motor rapid feed. Assuming that Δp=100 steps, the kick frequency of the motor is 15Hz, the total number of steps required for the motor's forward feed to be N, and the discretization interval of speed increase or decrease is n, then the automatic speed increase and decrease process can be given, as shown in Figure 3.

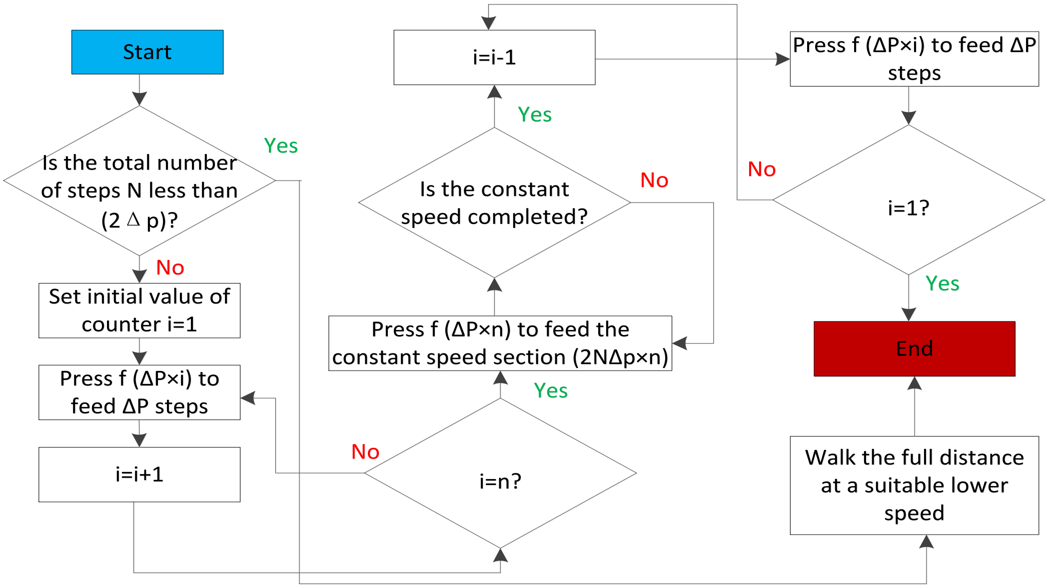

Figure 3: Flow chart of automatic speed increase and decrease.

3 SIMULATION EXPERIMENT AND ANALYSIS OF COMPUTER-AIDED CONTROL FUNCTION OF CNC WIRE CUTTING MACHINE MOTION

3.1 Analysis of Computer-aided Adaptive Speed Control Function

Because of the modular programming method, and according to the multi-task priority preemption mode of Windows, an independent thread is used to complete the entire motion computer-aided control function module (processing thread). In this thread, the processing mode is switched by the detected processing status flag. If the broken thread symbol appears during normal processing, the computer will immediately record the broken thread point and switch the processing state to pause mode so that the machine tool can re-use wire. In the pause mode, the machine tool can execute the fast-starting point and the original path starting point. After threading the wire, it can execute the fast breakpoint, original path breakpoint and other functional operations.

The motion computer-aided control process is to make a plan for the machining operation process of the machine tool, that is, to clarify the relationship between the computer-aided control functions. The software structure of the motion computer-aided control function is an important means to determine the relationship between the computer-aided control functions. Each motion computer-assisted control function is placed in the processing thread, that is to say, the processing thread summarizes the function functions, and it uniformly allocates the execution order and execution conditions of each function. Because there are inter-related relationships between functions, without a good overall structure, the logical relationship in the future will become very complicated. The gap adjustment function of EDM is realized by the movement of forward and backward directions. In this development system, the gap adjustment function can be realized by the package function dmc3000_change_speed provided by the motion control card. According to the comparison between the gap voltage value detected by Advantech and the servo reference voltage, it is determined whether the current movement is to increase or decrease the processing speed. If the gap voltage value is smaller than the servo reference voltage, it indicates that the current discharge state is arcing or short circuit. The DMC3000 motion computer-aided control card immediately reduces the operating speed during processing to increase the distance between the tool electrode and the workpiece, thereby avoiding. The occurrence of arcing or short-circuit phenomenon. If the current discharge state value is greater than the servo reference voltage, it indicates that there may be an open circuit between the tool electrode and the workpiece. The DMC3000 motion computer-aided control card immediately increases the running speed during processing to reduce the distance between the tool electrode and the workpiece. Therefore, the DMC3000 motion computer-aided control card completes the gap adjustment between the tool electrode and the workpiece by changing the processing speed in operation, so that the processing process is always in an effective discharge state. Among them, the servo reference voltage is a voltage band, that is, the servo reference voltage cannot be a small amount, otherwise the processing speed during processing will constantly change, which will reduce the processing stability and the processing quality.

3.2 Experimental Analysis of Computer-aided Control Function of CNC Wire Cutting Machine

Some CNC machine tools, such as EDM and CNC wire cutting machines, will cause a short circuit when the feed speed is greater than the erosion speed and there are impurities between the tool electrode and the workpiece. When a short circuit occurs, it is necessary to reduce the processing rules and quickly retreat along the original track to eliminate the short circuit to prevent wire breakage. The key to the realization of short-circuit retraction is to retreat in the opposite direction of the original processing direction, and to return to the original path after retreat. In the low-speed wire EDM machining, the retreat distance is usually set to 0.45 mm.

If a short circuit occurs at the corner, it is likely that the running distance of the current segment is less than 0.45 mm. You write down the coordinate position at the time of short-circuit and calculate its total length; call the motion function and add a negative sign to the motion displacement of each axis. If the short-circuit state is eliminated, you call the motion function, cancel the negative sign on each axis, return to the short-circuit point and continue processing. The short-circuit state is not eliminated, the pointer points to the previous section, and the displacement of each axis in this section is calculated. Figures 4 and 5 show the effect of short-circuit back-off. It is inevitable that the wire will be interrupted in the wire cutting process of the electric spark. After the wire is broken, the wire must be re-threaded, and the difficulty of threading through the workpiece will increase as the thickness of the workpiece increases. Therefore, in order to solve the problem of the difficulty of threading through the workpiece, there must be a return in the slow wire cutting process. Both the original path return to the starting point and the rapid return to the starting point can achieve the requirements of returning to the starting point.

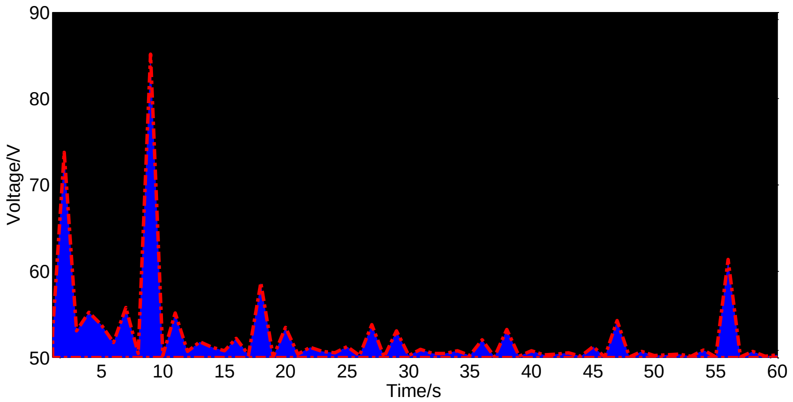

Figure 4: Short-circuit back-off voltage experiment.

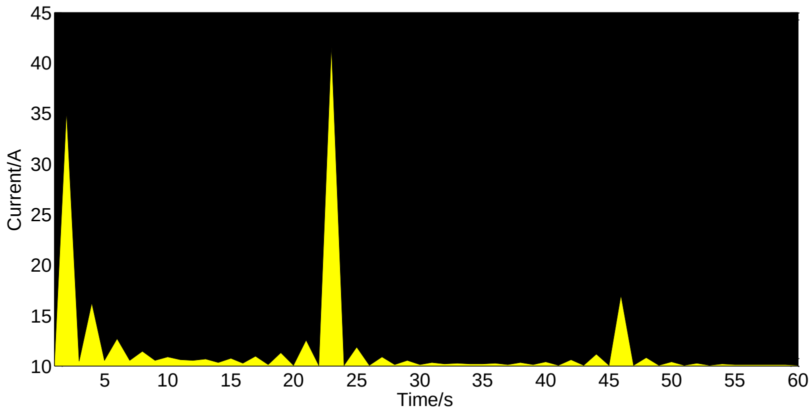

Figure 5: Short-circuit back-off current experiment.

Generally, when cutting a workpiece with a long running track like a gear, it is more time-saving to choose the quick return to the starting point. Sometimes after processing a part, you don' t want to continue processing, and you don' t want to rethread the thread before the next cutting (or you don' t want to break the thread after processing), you must have the function of returning to the starting point. If you want to continue cutting after re-threading the wire, you need to use the original way to return to the broken wire point function. The realization of these two functions requires the use of double-linked list pointers. For example, if you take the original path back to the starting point, you need to create a new linked list pointer to point to the current processing breakpoint pointer, and then make the pointer point to the previous segment. The motion function of the control card executes the return motion. When one segment of the return motion is completed, you make the pointer point to the next segment, and then call the motion function of the computer-aided control card to execute the return motion, and then loop until it returns to the starting point. Figure 6 is an effect diagram of the user interface of returning to the starting point of the original route. From the figure, it can be seen that this method can effectively perform the function of returning to the original route.

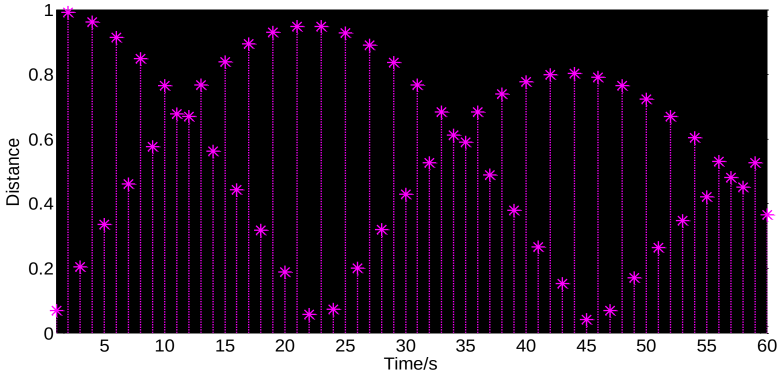

Figure 6: Back to the starting point experiment.

After returning to the origin, the program needs to return to the broken wire point in the original path. At this time, the monitoring thread scans the original path to the broken wire point and the status is valid. When the pointer points to the judgment condition in the processing thread, the internal related functions are executed when the condition is met. Figure 7 and Figure 8 are the effect diagrams of the broken wire point of the original route.

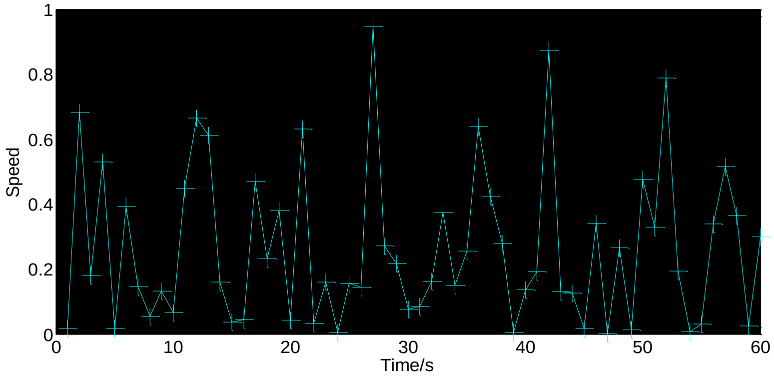

Figure 7: Computer-aided speed control experiment of CNC wire cutting machine returning to the broken wire point in the original path.

Single-segment running is mainly used in the trial cutting stage of the program to check whether the program code meets the requirements of part processing. The basic idea is to pause after each line of program code is run, and the execute button needs to be pressed again to run the next segment. It is to put an M01 auxiliary function code after the code segment that needs to be paused; when the program detects M01, after the current segment of the program is completed, it will be placed in the paused state.

4 CONCLUSION

This paper realizes the computer-aided control of the motion trajectory of automatic speed increase and decrease. The parameter interpolation method needs to update the interpolation frequency parameters in real time, which is relatively complicated to implement. In a high-speed running system, the method of segment interpolation can fully satisfy the system. The constant speed section occupies the main body of the computer-aided control of the entire operation, which can ensure the high-speed operation of the system, so as to realize the real-time trajectory and speed computer-aided control of the CNC WEDM system and meet the design requirements of the system.

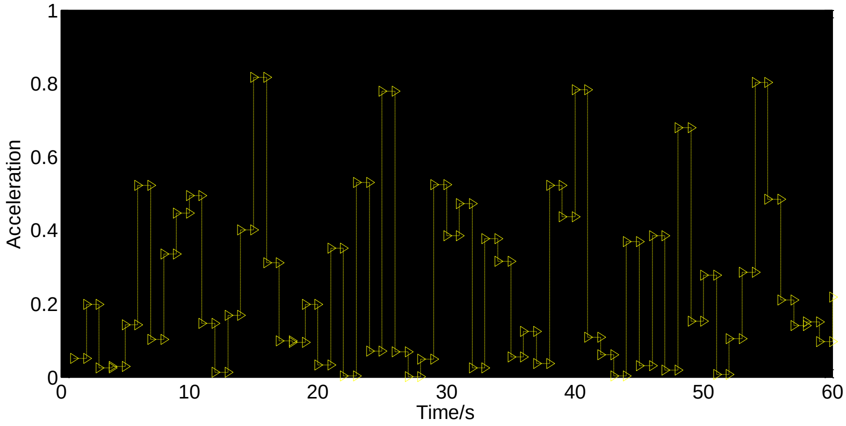

Figure 8: Computer-aided acceleration control experiment of CNC wire cutting machine returning to the broken wire point in the original path.

According to the functional requirements of the low-speed wire cutting machine, the tasks of the system are reasonably divided, and the multi-task technology of the Windows operating system is used to realize the multi-task parallel processing of the computer-aided control system. Taking into account the real-time and non-interference of the monitoring module and the processing module, the monitoring thread and the processing thread are used to achieve their independence. In the design process of the main user interface, a modular approach is also adopted. Due to the limitation of experimental conditions and practice, the system developed in this paper only performed a small amount of experiments, and there is no detailed understanding of the cutting quality. There is still some distance from practicality. The commercialization of any CNC system will not work without a large number of process tests. This is the main work in the future. In addition, it is necessary to strengthen the research on the theory of software and hardware reliability, testing methods and standards, as well as the research on system reliability and anti-interference design methods. At the same time, it is necessary to strengthen the research on open computer-aided control systems. Only by providing convenient and friendly support tools, users can ultimately benefit from the automated processing optimization system.

ACKNOWLEDGEMENTS

New engineering research and practice project of Henan Province in 2020，Construction and exploration of curriculum system of Automobile Specialty under the concept of new engineering，Project number：160217；Henan Province Education Science 13th five year plan 2020 education aid Xinjiang special topic，"Internet +" promotes the practice teaching in Xinjiang Higher Vocational Colleges，Project number：2020ZY010.

Haitao Wang, https://orcid.org/0000-0003-3080-7887
Gang Liu, https://orcid.org/0000-0001-8849-169X
Qing Liu, https://orcid.org/0000-0002-3836-5430
Qian Wu, https://orcid.org/0000-0003-4344-2864
Jiahui Wang, https://orcid.org/0000-0002-4429-1503

REFERENCES

[1] Özkan, E.; Öz, O.: Determination of appropriate cutting parameters depending on surface roughness by Taguchi method in milling of marbles, Arabian Journal of Geosciences, 13(13), 2020, 1-10. https://doi.org/10.1007/s12517-020-05380-0

[2] Wszołek, G.; Czop, P.; Słoniewski, J.; Dogrusoz, H.: Vibration monitoring of CNC machinery using MEMS sensors, Journal of Vibroengineering, 22(3), 2020, 735-750. https://doi.org/10.21595/jve.2019.20788

[3] Zhao, G.; Cao, X.; Xiao, W.; Liu, Q.; Jun, M. -B. -G.: STEP-NC feature-oriented high-efficient CNC machining simulation, The International Journal of Advanced Manufacturing Technology, 106(5), 2020, 2363-2375. https://doi.org/10.1007/s00170-019-04770-3

[4] Selvakumar, G.; Balasubramanian, V.; Lenin, N.: Investigation on corner accuracy in wire cut EDM of AISI D3 tool steel, International Journal of Rapid Manufacturing, 9(1), 2020, 58-70. https://doi.org/10.1504/IJRAPIDM.2020.104426

[5] Butola, R.; Kanwar, S.; Tyagi, L.; Singari, R. -M.; Tyagi, M.: Optimizing the machining variables in CNC turning of aluminum-based hybrid metal matrix composites, SN Applied Sciences, 2(8), 2020, 1-9. https://doi.org/10.1007/s42452-020-3155-8

[6] Ramnath, S.; Haghighi, P.; Venkiteswaran, A.; Shah, J. -J.: Interoperability of CAD geometry and product manufacturing information for computer integrated manufacturing, International Journal of Computer Integrated Manufacturing, 33(2), 2020, 116-132. https://doi.org/10.1080/0951192X.2020.1718760

[7] Yin, X.; He, G.; Meng, W.; Xu, Z.; Hu, L.; Ma, Q.: Comparison Study of Low-Heat-Input Wire Arc-Fabricated Nickel-Based Alloy by Cold Metal Transfer and Plasma Arc, Journal of Materials Engineering and Performance, 29(7), 2020, 4222-4232. https://doi.org/10.1007/s11665-020-04942-3

[8] Manoj, I. -V.; Narendranath, S.: Variation and artificial neural network prediction of profile areas during slant type taper profiling of triangle at different machining parameters on Hastelloy X by wire electric discharge machining, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 234(6), 2020, 673-683. https://doi.org/10.1177/0954408920938614

[9] Padhi, P. -C.; Tripathy, D. -K.: Multi-response optimisation of machining parameters in wire EDM process using grey relational analysis, International Journal of Manufacturing Technology and Management, 34(4), 2020, 376-394. https://doi.org/10.1504/IJMTM.2020.108019

[10] Shen, N.; Zhao, C.; Li, J.; Xu, Y.; Wu, Y.; Deng, Z.: A parameterized automatic programming solution for composite grinding based on digital image processing, The International Journal of Advanced Manufacturing Technology, 110(9), 2020, 2727-2742. https://doi.org/10.1007/s00170-020-05984-6

[11] Marani, M.; Songmene, V.; Zeinali, M.; Kouam, J.; Zedan, Y.: Neuro-fuzzy predictive model for surface roughness and cutting force of machined Al – 20 Mg 2 Si – 2Cu metal matrix composite using additives, Neural Computing and Applications, 32(12), 2020, 8115-8126. https://doi.org/10.1007/s00521-019-04314-6