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# EDM GAP WIDTH CONTROLLER BASED ON THE RELATIVE FREQUENCY OF SHORT CIRCUITS METHOD

# REGULATOR SZCZELINY DLA PROCESU EDM OPARTY NA METODZIE WZGLĘDNEJ CZĘSTOTLIWOŚCI ZWARĆ

A b s t r a c t

Electrical discharge machining is a process of machining a work-piece to a desired shape by using the eroding effect of electric spark discharges. A gap width controller is one of the key components of each electrical discharge machine. It is gap width controllers that mainly determine the machining speed and accuracy. This article describes a gap width controller based on fuzzy logic. The control algorithm operates according to the number of short circuits, open circuits and normal pulses that occur within a control period. A specially developed PC application allows for accessing and modifying electrical discharge machining parameters.

*Keywords: electrical discharge machining process, gap width controller, fuzzy logic*

S t r e s z c z e n i e

Obróbka elektroerozyjna (ang. *EDM – Electric Discharge Machining*) jest to proces nadawania żądanego kształtu materiałowi obrabianemu przez wykorzystanie erozyjnych właściwości elektrycznych wyładowań iskrowych. Jednym z głównych elementów każdej obrabiarki elektroerozyjnej jest regulator szczeliny międzyelektrodowej. W głównej mierze decyduje on o szybkości i dokładności obróbki. W artykule przedstawiono rozwiązanie regulatora szczeliny oparte na logice rozmytej. Algorytm regulacji działa na podstawie liczby zwarć, liczby przerw i liczby poprawnych impulsów, które występują w ciągu cyklu sterowania. Zmiana parametrów i odczyt charakterystycznych wielkości związanych z drążeniem jest możliwy za pomocą specjalnie opracowanej do tego celu aplikacji na komputer PC.

*Słowa kluczowe: proces elektroerozyjny, regulator szczeliny, logika rozmyta*

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## 1. Introduction

An important consideration in discharge machining is the utilization, to a maximum extent, of the generated pulses. A decisive factor in this regard is the ability to continuously maintain optimum gap width between the surface of the workpiece and the tool electrode. Figure 1 shows several examples of gap width and its impact on the erosion process. If this width is too large (Fig. 1a), no discharges will occur despite the fact that the generator is generating electric pulses, and that across the material being machined as well as the tool electrode, there is a potential difference, i.e. the so-called ignition voltage. If the width is decreased, e.g. from $x_1$ to $x_2$ (Fig. 1b) first discharges will occur – this means that the electrode is within the machining space. Initially, normal discharges account for only a fraction of the pulses produced by the generator. As the tool electrode continues to move from $x_3$ towards $x_4$ (Fig. 1b and c), it enters the space where almost all pulses produced by the generator trigger electrical discharges. As the electrode continues to advance towards the workpiece, e.g. to position $x_5$, momentary short circuits occur in between normal discharges. When gap width reaches value $x_6$, a short circuit occurs between the electrode and the work-piece.

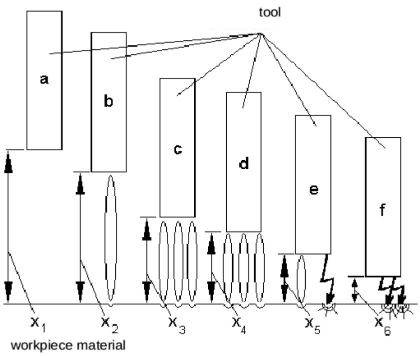


Fig. 1. Effect of gap width $x_1$–$x_6$ between the work-piece and the tool electrode on the intensity of discharges and short circuits

When a short circuit condition arises, almost all the energy provided to gap space is used up in spot heating and melting of the tool electrode and workpiece – and this is a very undesirable effect from the perspective of the EDM machine operator. In order to prevent these harmful short circuits from occurring during the machining process, strict requirements are imposed on tool electrode feed control systems. Such controllers are primarily designed to keep the optimum gap width, while conditions in the gap change in a dynamic manner.

### 1.1. Review of electrode gap width control methods

Appropriate control of electrode movement is a key aspect of the electrical discharge process and control quality determines key parameters, such as material removal rate, surface roughness and electrode wear ratio. The main difficulty affecting gap width control is a non-linear and non-stationary character of the electrical discharge process occurring between the electrodes. It is not possible to develop a precise mathematical model of an electrode gap because its parameters will change as the shape of the electrode changes and as the process continues (e.g. the rate of eroded debris removal will decrease as the electrode advances deeper into the work-piece). There is no possibility, either, of directly measuring the width of the gap; one can only make an estimate based on e.g. voltage across the gap.

Over the past years, various gap control methods and algorithms have been developed and tested. As a result of these developments, EDM process efficiency has increased significantly compared with old solutions. In many cases, details of the developed technologies, such as the construction and setting of controllers, are kept secret, as EDM machine manufacturers will not publish details of their work. For the most part, gap controllers operate based on the measurement:

- average gap voltage,
- average gap voltage within a specified range,
- ignition delay time [1],
- number of short circuits, open circuits and normal pulses [1],
- spectral content of electromagnetic interference emitted during the machining process [7],
- of voltage across the gap using continuous wavelet transform [8].

Controllers used in EDM machines can be divided into the following groups:

- PI controllers,
- adaptable controllers [9],
- fuzzy logic-based controllers,
- controllers based on artificial intelligence.

Historically, first controllers used in EDM machines were PI controllers; however, the control quality offered by such a control system is low in the case of non-linear objects, in which parameters additionally change in a random mode [5]. In the case of non-linear objects, fuzzy logic controllers prove to have good control capabilities; this is true of EDM machines, which are non-linear objects. The authors of publications [1] and [2] claim that the use of fuzzy controllers contributes to a tangible increase in the machining rate and a decrease in electrode wear. Numerous tests have been carried out to develop controller models that utilize artificial intelligence methods other than fuzzy logic, such as neural networks, neuro fuzzy controllers (Adaptive Neuro Fuzzy Interference System – ANFIS), genetic algorithms as well as combinations of these and other methods. The performance of all of these models is determined by electrode material, work-piece material and the type of EDM machine being used [6]. Fuzzy logic controllers are very familiar and have been extensively described in various articles and books. The difficulty involved in the use of those algorithms is the selection of input and output signals, number of inference rules and controller fuzzy set setting in relation to a specific object.

### 1.2. Description of the control algorithm selected

The controller developed by the authors uses a SC/OC algorithm to control the movement of the tool electrode [1]. The acronym stands for *short circuits open circuits*. During the machining process, the controller counts instances of short circuits, open circuits and normal machining operations by means of a counter system, such as a micro-controller. Gap voltage is used to differentiate between short circuits and normal pulses. Next, at specific intervals, the counters are read from, counter data are transferred to the memory and the counters are reset for the next measuring cycle. Based on values read from the counters, the control function is activated and modifies the position of the electrode.

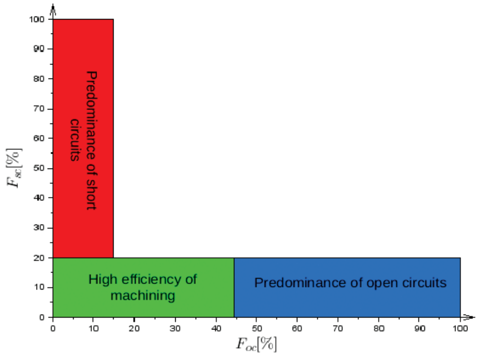


Fig. 2. Concept of control algorithm based on the short circuit relative frequency method [1]

Relative frequency SC/OC is calculated as a ratio of the number of instances of a given condition to the number of all pulses within a pre-set interval. The idea of control consists in minimizing both short circuits (by moving the electrode away) and open circuits (by feeding the electrode towards the work-piece) (Fig. 2). What is prioritisedprioritized here is the objective of minimizing short circuits, as they lead to accelerated electrode wear and may cause the destruction of the work-piece. The controller is an MISO object (*multiple input, single output*) as, based on the two parameters mentioned, a control signal is generated that moves the electrode. A single control signal from two inputs is created while the linguistic control rules are being processed by means of an AND logical operation. The determination of a control signal is carried out in three stages:
1. Fuzzification of input data,
2. Inferencing,
3. Defuzzification (sharpening).

## 2. Actual gap controller implementation

The gap controller has been adapted for use with the existing electrical discharge machine, installed in the laboratory of the Institute of Machines Technology and Production Automation at the Faculty of Mechanical Engineering, Cracow University of Technology. Figure 3 shows the laboratory station and the EDM machine.

On the left-hand side (Fig. 3), the mechanical part of the machine can be seen (an *X*, *Y* table for holding a work-piece, a rotary chuck for holding an electrode, servo system motors). On the right-hand side, there is a control panel with the original controller, while the power generator is located in the center. The EDM machine in the picture can move the table along axes $X$ and $Y$, and the chuck moves along axis $Z$, and can also perform rotary movement. During the erosion process, gap width adjustment is carried out only along one axis, selected by the operator. The new controller uses input/output signals that are available in the power generator and measuring system of the original controller. The block diagram of the new controller is shown in Fig. 4.

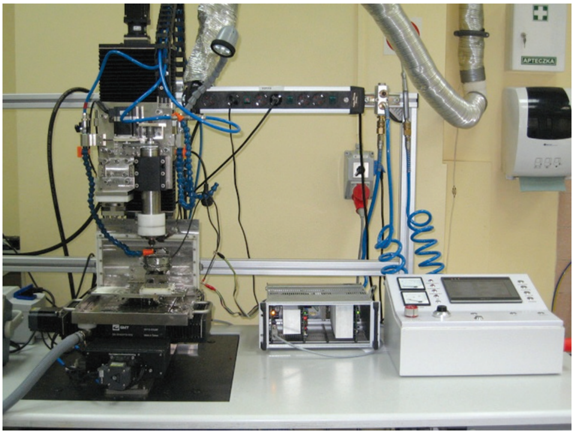

Fig. 3. Laboratory station with the erosion machine

Key properties (features) of the new gap controller include:

- operation according to the number of short circuits and open circuits read,
- cooperation with a laboratory erosion machine. The controller uses input signals provided by the power generator: PULSES, SHORT CIRCUIT, SPARK; an input signal from the servo-drive: SERVO_ALARM; signals from the control panel: START/STOP and LIMIT_SWITCH,
- An output signal from the controller controls the servo-drive; these are two signals: SERVO_STEP (number of steps and SERVO_DIR (movement direction),
- two available algorithms: simple (DEMO mode) and one based on fuzzy logic (FUZZY mode),
- two modes of operation: manual (electrodes are positioned manually) and automatic mode (eroding with automatic control) – operational status communicated with LED, STOP and OPERATION diode indicators,
- in the manual mode, control is effected by an external manipulator,
- selection of inference rules and fuzzy set ranges (for the fuzzy logic algorithm),
- carrying out electrode withdrawal during the machining process in order to provide for more effective gap flushing,
- in the manual mode – capability to move the electrode using UP or DOWN buttons, with the feed rate being set with the Speed adjust potentiometer,
- a feature allowing the operator to read controller input values (number of short circuits, of open circuits and pulses per unit of time),

- a feature allowing for reading the position of (the electrode) servo-drive and the average number of short circuits and of open circuits,
- a feature allowing for setting controller parameters and monitoring its operation by means of a PC application, communication with a PC via RS232 interface.

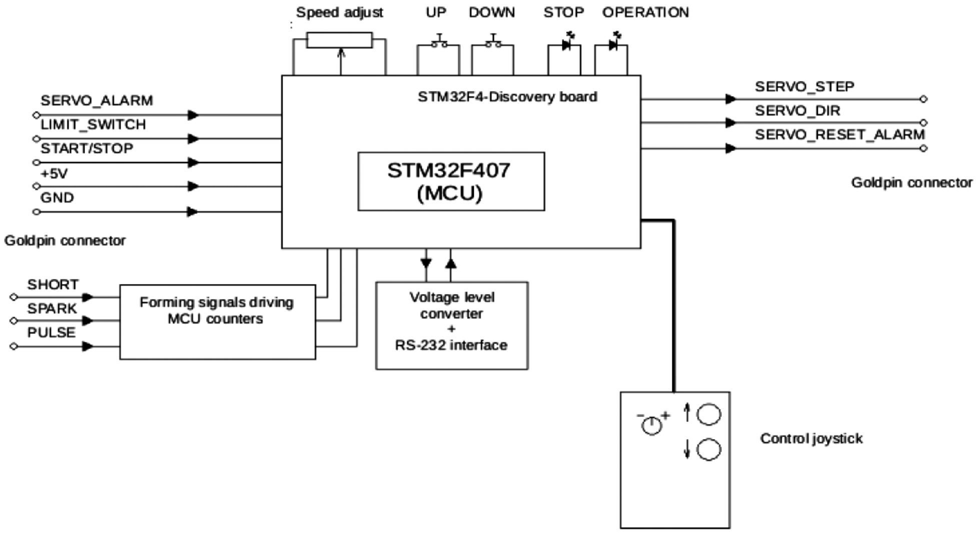


Fig. 4. Block diagram of the gap controller

SHORT and SPARK signals are provided by the gap voltage comparators incorporated in the power generator. A SPARK signal will take on a low value if gap voltage falls below 5 V. A SHORT signal is used in manual mode operation to detect the zero position of the electrode (i.e. the electrode and the work-piece making actual contact). The signal causes electrode movement to stop when a short circuit occurs. In automatic mode operation, SHORT signals are counted by the counter system upon each pulse being generated by the generator and taken into account in the control algorithm. A SPARK signal will take on a low value if gap voltage falls below 40 V. During machining, the active status of a SPARK signal is considered a normal pulse. A PULSES signal is a signal that turns on the transistors in the power generator (active state ‘1’). The gap controller controls an Ezi-SERVO drive, manufactured by the company Fastech. Motion conditions are set using SERWO_STEP and SERWO_DIR signals. The first signal determines the number of steps by which the shaft will turn, the other signal determines the direction of servo-drive rotation. One SERWO_STEP pulse from the controller causes the electrode to move 1 μm. The controller also responds to a SERWO_ALARM signal that communicates servo-drive failure, e.g. if the motor is blocked. A START/STOP control signal is provided by the control panel, and causes machining operation to start or stop (starting supplying/ceasing to supply voltage to the gap). A LIMIT SWITCH signal is provided by the axis Z position sensor and causes the servo-drive to stop if the electrode moves too high.

To build their controller, the authors selected a 32-bit micro-controller with an ARM Cortex M-4F core, type STM32F407, made by the company STMicroelectronics. SHORT, SPARK and PULSES signals are fed to an additional logic circuit (Fig. 5) from which signals are transmitted to the counter inputs inside the STM32F407 micro-controller.

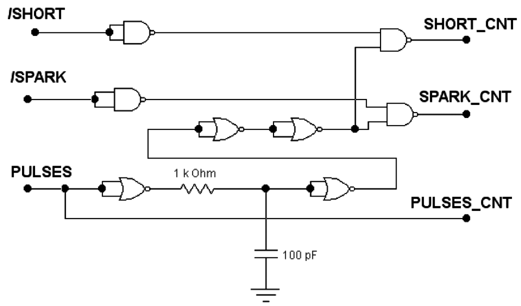


Fig. 5. Schematics of the additional logic device to count pulses by the micro-controller

The internal counter, triggered by a SHORT_CNT signal, counts all short circuits, the counter triggered by a SPARK_CNT signal counts all generator pulses, whereas the counter triggered by a PULSES_CNT signal calculates a total of pulses in which machining is carried out or a short circuit occurs. The number of short circuit and open circuit conditions and the relative frequency of the occurrence of these conditions should be calculated using the following formulas:

$$\text{pulses} = \text{CNT}_{\text{pulses}}$$

$$sc = \text{CNT}_{\text{short}}$$

$$oc = \text{CNT}_{\text{pulses}} - \text{CNT}_{\text{spark}}$$

$$f_{sc} = \frac{\text{sc}}{\text{pulses}}$$

$$f_{oc} = \frac{sc}{\text{pulses}}$$

$\text{CNT}_{\text{pulses}}$, $\text{CNT}_{\text{short}}$, $\text{CNT}_{\text{spark}}$ symbols refer to the state of counters counting relevant events. Symbols $f_{SC}$ and $f_{OC}$ designate the average frequency of the occurrence of short and open circuits. In each control period, the counters are read from and then are reset.

## 2.1. Controller software

The controller software has been written in ANSI C language (uVision environment, by the company Keil). The project is comprised of a dozen or so *.c files grouped by function performed. The micro-controller software performs the following functions:

- communication with the application installed on a PC via a serial port: setting parameters,
- implementation of a communication protocol ensuring control of the correctness of data transmitted,
- counting short and open circuits based on signals provided to the controller,
- implementation of a control algorithm based on fuzzy logic,
- servo-drive emergency stop when contact is made with the limit switch,
- stopping the machine after detecting the electrode makes contact with the work-piece in the manual mode,
- operating the manipulator buttons and eliminating contact vibrations,
- generating signals that control the servo-drive and responding to alarm signals.

### 2.2. Fuzzy logic library and PC software

In the controller, fuzzy control has been implemented using eFLL library [3]. The library was written in C++ for the Arduino platform and comprises 9 classes; it allows for easy implementation of Mamdani's fuzz inference method in a wide spectrum of embedded devices. The maximum method is used for calculating the logical sum, while the logical product is calculated using the minimum method. Sharpening is carried out using the center of gravity method [3]. It has been necessary to make slight changes to the library in order to be able to use it in the micro-controller. The modifications were related to the capability to change settings of fuzzy set parameters and inference rules while the program is running. The original version of the eFLL library provided for working with fuzzy set values that are fixed. The PC application for managing the gap controller has been written in C++ language, using libraries Qt, version 4.8 [4].

Key functions performed by the PC application include:
- communication with the controller through an RS232 serial port (at 115200 bps),
- monitoring software errors in the controller,
- selection of the control: simple or fuzzy logic based,
- setting the control period duration (1, 2 or 5 ms) and the electrode feed rate, from 5 mm/s to 150 μm/s,
- configuring fuzzy inference rules and fuzzy set values,
- reading servo-drive positions and alarm count reported by the servo-drive,
- reading data from the controller: number of short circuits (SC), number of open circuits (OC), of all pulses from the generator in a given control period,
- saving servo-drive positions to file in csv format,
- configuring electrode withdrawals during the machining operation,
- reading average values and variations from an offset signal set by the controller,
- reading the average value of the number of short circuits, open circuits and normal pulses for the last 1000 control periods.

The application window has five tabs that allow for configuring a connection between the PC and the application, for setting controller parameters, setting fuzzy sets, and reading measured data from the controller. One of the tabs is shown in Fig. 6.

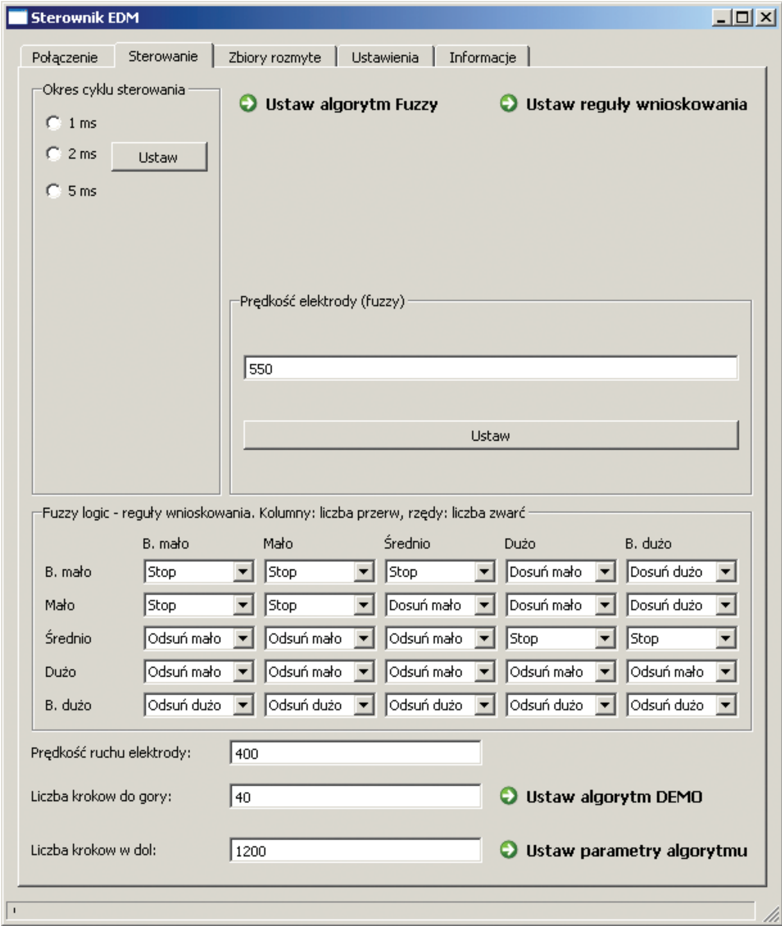


Fig. 6. Sample PC application tab used for setting: inference rules, control period duration, electrode feed rate, for both the manual mode and the automatic mode

### 3.1. Laboratory tests

Testing and selecting rules and gap controller settings for an EDM machine is a very difficult and time-consuming task. As the course of the EDM process depends on multiple factors, controller settings should be tested and selected individually with respect to at least a few machining parameters: operating current, ignition voltage, work-piece material, electrode material, gap flushing rate, type of dielectric. The tests discussed below were carried out using the same generator parameters. After each series of measurements, the servo-drive position was monitored and, after the electrode plunged into the work-piece to the set depth of 200 μm, the time that elapsed since the start of the machining operation was measured. The work-piece was made of acid-resistant steel PN 0H18N9 (AISI 304, DIN-X5CrNi18-10, GOST 1.4301, EN-1.4301), and the electrode used was a copper one, with a circular cross section and diameter of 1 mm. The test results presented relate to the following generator settings: ignition voltage in the generator was set at 120 V and total operating current was 5 A, the duration of pulses and the interval between pulses was 50 μs. In order to comprehensively verify the operation of the controller, it is necessary to operate it at various operating current, pulse duration and interval duration settings.

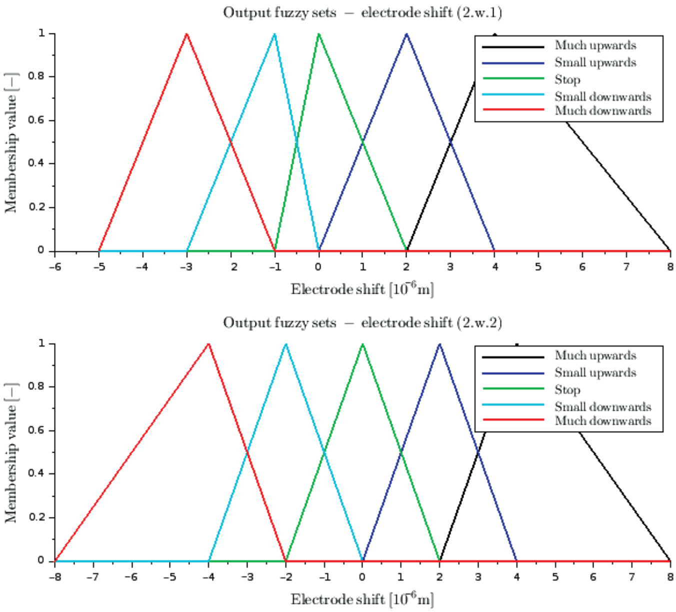


Fig. 7. Two specimen input sets for controlling the servo-drive

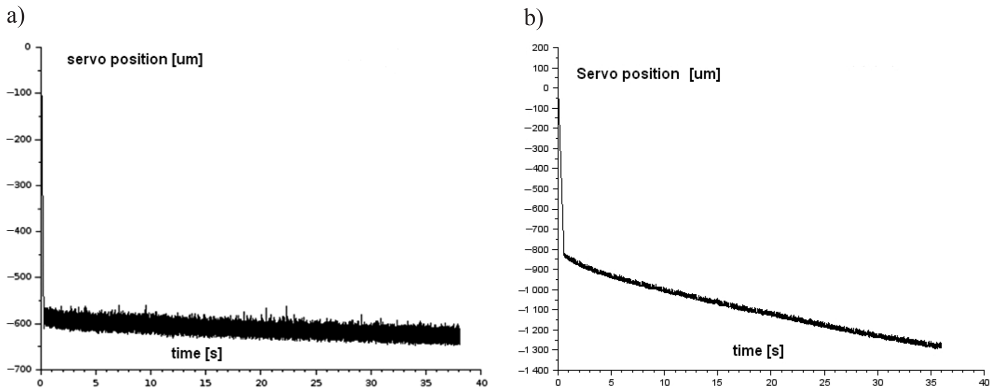


Fig. 8. Sample graphs movement of the servo-drive (tool electrode) during machining. Graph a) shows slow movement of the tool electrode; graph b) represents faster tool electrode movement. The graphs show electrode positions as read from the controller during the machining process)

## 3.2. Comparison of test results

The main objective of the tests was to find such optimum settings and sets for fuzzy logic that the machining rate should be highest and electrode wear should be minimal. The results shown are only a portion of the results obtained during the controller tests. The first measurement series confirmed that the controller was operating properly – machining times obtained were comparable to those of the original controller (which we replaced with our fuzzy logic controller), operating according to average gap voltage; however, during machining a large number of short circuits occurred. The number of normal pulses was ca. 2%. The electrode moved very rapidly, constantly advancing towards and shifting away from the work-piece, along the maximum pre-set distance. Such operation is not acceptable for a regular machining cycle due to power losses

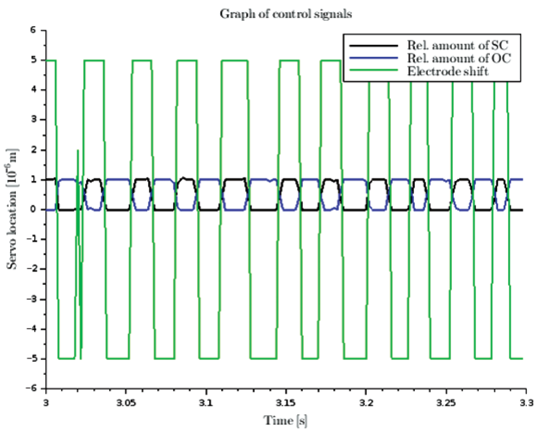


Fig. 9. Graph showing controller input and output signals during operation with initial settings

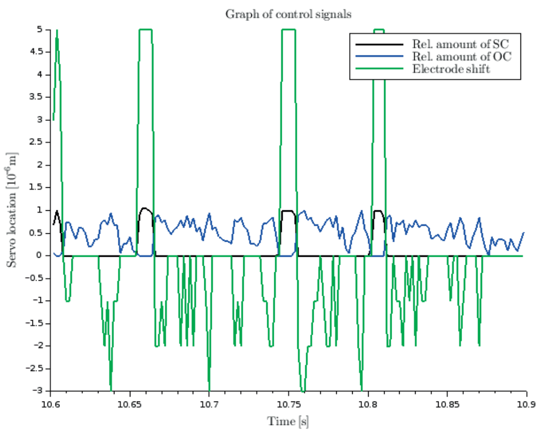


Fig. 10. Graph showing controller input and output signals during operation with optimum controller settings

and the workpiece being overheated. The servo-drive positions and relative number of short circuits and open circuits are shown in Fig. 9. These data were read from the controller by the application installed on the PC. As can be seen, servo-drive movement was quite jerky.

In order to improve the control quality, additional sets have been added to the three fuzzy sets on the input side, totaling five for the relative frequency of short circuits, and five for the relative frequency of open circuits. It is important to configure such settings whereby the electrode shift away from the work-piece is larger than towards it (so that the fuzzy sets should be non-symmetrical relative to zero). After the controller parameters had been modified several times, a minimum number of short circuits was obtained, with a short machining time to a depth of 200 μm and minimum electrode wear. In the other cases, as electrode wear decreased, the machining time increased and vice versa. After several attempts, the best results were obtained, with the electrode being moved by a small number of steps, compared with the other settings. A graph showing electrode movement during machining and the relative number of short circuits (SC) and relative number of open circuits (OC) is presented in Fig. 10. As can be seen, the results shown are significantly better than in Fig. 9.

## 4. Summary

After the authors had selected appropriate fuzzy sets for the controller input and output, laboratory tests demonstrated that the machining process was correct. During the tests, such settings were selected that allowed for reducing the number of short circuits and ensuring stable controller operation with minimum electrode wear. An analysis of the test results allows a tentative conclusion that the controller should respond to the occurrence of short circuits as quickly as possible, by withdrawing the electrode. On the other hand, if no short circuits occur, the electrode should advance slowly, by a small number of steps. It would also be advisable to simplify the operation of the entire machine by redesigning the control program. Entering each parameter for all the fuzzy sets is a burdensome task and it is easy to make errors leading to improper or un-optimal operation of the equipment. The controller can be successfully used in industry applications, but it would be advisable to make certain improvements and develop a complete table with settings for other workpiece materials, other electrodes and for various power parameters of pulses provided by the generator.

## References


[1] Behrens J. Ginzel, *A comparison of different input values for gap-width controllers used in electro discharge machining*, http://erosion.de/Wissenswertes/paper_regler.pdf. (access: 01.07.2016).

[2] Boccadoro M., Dauw D.F., *About the application of fuzzy controllers in high-performance die-sinking EDM machines*, Annals of the CIRP, vol. 44/1/1995.

[3] eFLL library documentation available on the Internet: http://www.zerokol.com/2012/09/arduinofuzzy-fuzzy-library-for-arduino.html (access: 01.07.2016).
[4] Qt library documentation available on the Internet: http://qt-project.org/doc/qt-4.8 (access: 01.07.2016).
[5] Kuo-Ming Tsai, Pei-Jen Wang, *Predictions on surface finish in electrical discharge machining based upon neural network models*, 2001, Department of Power Mechanical Engineering, National Tsing Hua University.
[6] Pawade M.M., Banwait S.S., *A Brief Review of Die Sinking Electrical Discharging Machining Process towards Automation*, American Journal of Mechanical Engineering, Vol. 1, No. 2, 2013, 43–49.
[7] Bhattacharyya S.K., El-Menshawy M.F., *Monitoring the EDM process by radio signals*, Int. J. Mfr Res. 16 (5), 1978, 353–363.
[8] Yi Jiang, Wansheng Zhao, Xuecheng Xi, Lin Gu, *Adaptive control for small-hole EDM process with wavelet transform detecting method*, Journal of Mechanical Science and Technology 26 (6), 2012.
[9] Yih-Fang Chang, *VSS Controller Design for Gap Width Controller*, JSME International Journal 2003, Series C, Vol. 35, No. 3.