Scientia Iranica B (2015) 22(5), 1813–1832

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions B: Mechanical Engineering
www.scientiairanica.com

Review on an electrical discharge machining servomechanism system

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Received 26 Ferbruary 2013; received in revised form 21 September 2014; accepted 16 February 2015

KEYWORDS
Electrical discharge machining;
Servomechanism;
Precise positioning system;
Micro machining.

Abstract. Electrical discharge machining is a non-contact process based on thermoelectric energy between the electrode and workpiece. It is an efficient machining process to machine an advanced, difficult-to-machine material with high precision, complex shapes and high surface quality. Realizing the advantages and abilities of this machining method, electrical discharge machining research has caught the interest of many researchers. This paper reviews the electrical discharge machining process, including recent research fields and inventions that have been developed in order to improve workpiece surface quality and integrity, machining time, tool wear and material removal rate. Electrical discharge machining apparatus and its servomechanism system, including mechanical structure developments using computer numerical control, a lead-screw mechanism and linear motor driven and piezoelectric actuators, are also reviewed. Furthermore, control strategies that are applied to electrical discharge machining systems, including servo-drive control and optimization techniques, such as fuzzy, genetic algorithms and artificial neural networks, are also discussed.

1. Introduction

Nowadays, machining processes are commonly used to produce complex shapes and micro features with high aspect ratios of various materials, such as metals, polymers and ceramics. Various factors, such as process capabilities, machining productivity, surface quality, dimensional accuracy and workpiece material, are key parameters used to select the required machining process [1].

Generally, conventional machining, such as milling, grinding and drilling processes, are chosen since the machined materials are relatively softer than the tool materials. However, according to Sen et al. [2], current advances in technology require the use of harder and more brittle materials. Since it is necessary that machining processes be improved in accuracy and surface finish, several factors should be considered. These include the surface integrity of materials, including mechanical, physical and metallurgical properties used to reduce defects that occur during the machining process. Thus, conventional machining is no longer suitable, as it does not provide a good performance in machining harder and more brittle materials. Furthermore, frequent tool resharpening, excessive drill breakage, the poor ability of hard alloys to withstand machining, and the formation of entry or exit burrs with mechanical drills, make

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conventional drilling almost impractical in micro-hole production [3].

Therefore, several non-traditional machining processes, such as electroforming, chemical milling, ultrasonic machining, laser machining, electro-beam machining and electrical discharge machining, have been introduced as alternative methods to improve the quality of the machined materials. Electrical Discharge Machining (EDM) is important and widely used among other non-traditional machining methods. In recent years, there has been an increasing interest in EDM research. EDM or spark erosion is known as a non-traditional machining process to remove an extremely hard and brittle material which cannot be machined using conventional processes [2]. This process is based on the spark and thermoelectric energy that are created between a workpiece and an electrode immersed in a dielectric fluid [4]. It is one of the earliest non-traditional processes discovered by B.I. Lazarenko and N.I. Lazarenko in 1943 [3] during the process of trying to remove a stuck drill bit from a hole using a pulsed electrical discharge.

In this process, electrical energy through sparking frequency is used to remove the materials [5]. This machining method could eliminate mechanical stresses and chatter vibrations during the machining process since it does not involve a contact process between the electrode and workpiece. Due to these advantages offered by EDM machining, many researchers have further endeavored to improve EDM performance. Developments in EDM technology can be referred to in several reviews by researchers. A review on current research trends on machining in EDM on ultrasonic vibration, dry EDM machining, EDM power additives, and EDM in water, has been carried out by Mohd Abbas et al. [6], while Ojha et al. [7] published a review on MRR improvement in die-sinking EDM. A review has been undertaken by Mahendran et al. [8] describing characteristics and parameters of MRR and tool wear essential in the micro-EDM process. So far, however, there has been little discussion and few reviews on the EDM servomechanism itself. Since EDM is a non-contact process, the adjustment of the gap between the electrode and workpiece that is controlled by the servomechanism system is important. An adequate knowledge of its servomechanism is also important for improving EDM machining. Therefore, this paper presents a review on the EDM servomechanism and control system.

2. EDM overview

2.1. EDM structures and components

Basically, the EDM machine is comprised of three block subsystems; a power supply power generator, a digital controller unit, and a servo system [9]. A power supply generator produces electrical spark discharges between the electrode and the workpiece [10]. This process removes metal from the workpiece by thermal erosion or vaporization. A microprocessor is used to control the generator to generate appropriate machining sparks for the machining operation. The microprocessor controls the power level and polarity to provide the desired value and direction of current flow across the gap [11].

The digital controller unit is a multi-loop control system made of multi-loops (inner current loop, speed loop and position loop and an outer gap voltage loop) [11], in order to ensure accurate position control of the tool electrode in relation to the workpiece. It consists of a servo position sensor as a device for measuring the actual depth of machined holes on the workpiece. The microcontrollers use the depth readings to terminate the cycle and execute a new operation if necessary. The EDM process does not involve physical contact between the electrode and the workpiece. Thus, EDM provides a servo system to control the optimum gap between the electrode and the workpiece automatically. The EDM servo system consists of two major subsystems; a servo motor and a lead screw load containing the tool electrode [9]. The control unit and servo system part will be discussed further in the next section. A basic block diagram of the general layout of an EDM system [12] is shown in Figure 1.

2.2. EDM process

In EDM, both electrode and workpiece must be electrically conducted, separated by a specific gap called a spark gap, and submerged in a dielectric fluid. The dielectric fluid acts as an insulator until the potential difference is sufficiently high. It also acts as a cooling and flushing medium to remove the debris in the gap. The dielectric medium is usually kerosene or deionized water. The workpiece and tool are connected to a

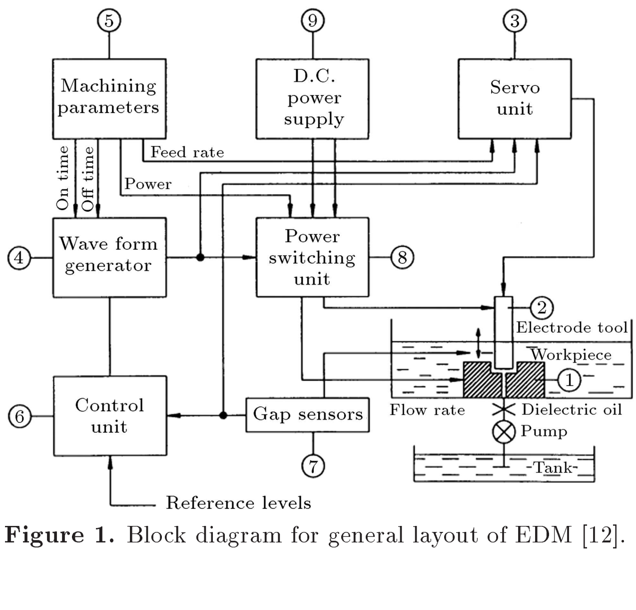

Figure 1. Block diagram for general layout of EDM [12].

power source via a cable. Generally, the tool is connected to the positive terminal of the generator while the workpiece is connected to the negative terminal [8].

During the machining process, the tool moves towards the workpiece and the gap is reduced to a very short distance (about 25 micrometer). Then, when current flows, the dielectric fluid breaks down, the gap is ionized [13], and electrons are emitted from the workpiece. The collision between atoms will increase the concentration of electrons. Thus, a plasma channel will start to form. A spark will then occur between the electrode and the workpiece, and the temperature will increases at the spark point on the workpiece. Thus, small quantities of metal will melt and evaporate. During the machining process, small metallic or conductive chips or particles will be carried away by the circulated dielectric fluid which floods the gap [14].

2.3. EDM researches

Recently, this machining technique has become more significant in mold and die manufacturing. It has caught the attention of many researchers [15] due to its broad industrial application, such as in the aerospace [16], and the automotive industries [17,18], medical device manufacturing [19] and others [20]. It also provides an alternative method to produce microstructures instead of using traditional (or conventional) machining process, such as drilling, milling and grinding. These traditional techniques involve a contact process between the tool and the workpiece. The factors that contribute to EDM application over conventional machining processing is their good performance and the versatile qualities of the EDM machine. These include its ability to remove machine materials of high hardness, poor machine ability and high tensile strength, fabricate parts that are too thin and fragile and also machine complex or irregular shapes and intricate cavities. This is because, for example, drill machining of holes of diameter 100 microns to 250 microns with an aspect ratio greater than 5 is very expensive by conventional means. It is also burr-free and stress free in the micro-machining process of conductive material [3] and yet is recognized as an effective machining to produce very small components that are smaller than 100 micrometers [21]. From given research [22,23], we can see many important variables and parameters, such as in Table 1, that need to be taken into consideration in order to get the desired response based on research objectives, respectively. Table 2 is a summary of several pieces of research that have been conducted to improve system performance.

Table 1. List of variables in EDM process.

On time	Open circuit voltage
Off time	Polarity of the workpiece
Current setting	Surface area of the cathode
Dielectric medium	Depth of machining
Dielectric pressure	Material of electrode
Speed of the cathode	Size of electrode
Anti-arc height	Material of workpiece

Besides, some research has also considered methods, such as powder metallurgy and diffused powder in dielectric. It has been found that this approach enlarges the discharge gap, widens the discharge passage and, lastly, forms evenly distributed and "large and shadow" shaped etched cavities that improve machining efficiency and surface quality. However, one major drawback of this approach is that it produces electrode wear [39]. The effect of powder on the machining performance can be varied depending on the different parameters used. Experimental studies by P. Singh et al. [40] describe the effect of aluminum powder concentrations and the grain size of powder on material removal rate, tool wear rate and the surface roughness of the machined materials. The performance of the machining can be achieved by proper parameter selection.

Since EDM is widely used in many productions, we can see that it has been modified in many ways to meet specific requirements for specific applications. However, all of the research and approaches have been undertaken mainly to improve the machining performance in terms of its surface quality, machining time, tool wear, and material removal rate.

3. EDM servomechanism

3.1. Mechanical structure

It is well-known that EDM is a non-contact process. Therefore, this servo system part of EDM plays an important role in predetermining gap spacing and executing the mechanical spark adjustment in order to maintain a consistent gap between the electrode and the workpiece, thus, preventing contact with each other. This mechanism is known as the servo-controlled feed mechanism [2] and mainly consists of a granite base, three-axis linear platform (X, Y and Z); some have an a-axis rotary table to rotate the workpiece at any angle, a rotary spindle and a grinding device [41]. Mostly, research has focused on the development and improvement of the EDM mechanical structure involving movement of the tool (electrode) in the Z direction [42] and the table in the X and Y direction.

3.2. Micro-machining

A schematic diagram of the machine tool is shown in Figure 2. In industry, a micro-hole having a diameter of less than 0.5 mm has a wide range of applications, including ink-jet printer nozzles, orifices

Table 2. EDM research fields.

EDM research fields	Problems	Research work
Surface quality and integrity	Crack susceptibility on workpiece material during machining	Relationship between EDM parameters and surface crack formation [24-27]
	Machining with accuracy and better surface finish	Development of technological table [28]
		Development of pulsed power DC supply for micro-EDM [29]
Machining time and speed	Electrode jump motion to maintain a suitable gap between tool and workpiece could affect machining speed of EDM machining	Study on electrode jump parameters and the development of electrode jump motion in linear equipment [30]
		Study on dimensional accuracy optimization of multi-stage planetary EDM [31]
Tool wear	Tool wear is one of the major source of inaccuracy	Development of linear motor equipped spindle for direct drive EDM [32]
		New wear compensation method based on real-time tool wear sensing to achieve machining accuracy [33]
Material removal rate	MRR in EDM operation is slower than traditional machining [22]	Study on different electrode materials to increase MRR [34]
		Study on electrical and physical parameters on MRR using dimensional analysis [35]
		Study on electrode geometries and designs to improve MRR [7]
		Hybrid model and optimization technique improve MRR [36]
		Combination of high-frequency vibration and rotation of electrode could produce high MRR [37]
		Flushing performance on EDM with bunched electrode [38]

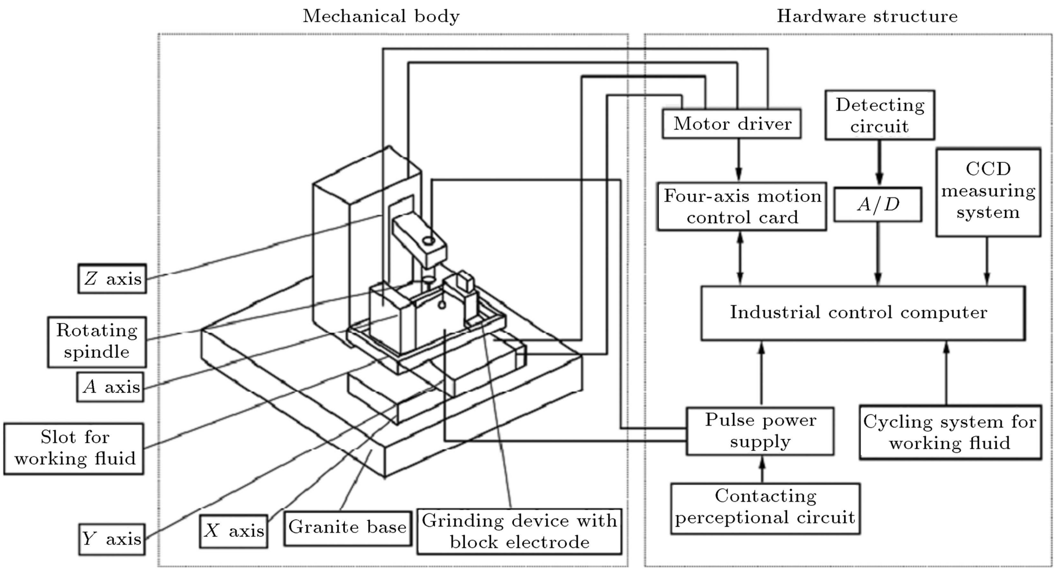

Figure 2. Schematic diagram of micro-EDM machine tool setup [41].

in bio-medical devices and diesel fuel injector spray holes. Micro-EDM is commonly chosen and currently widely used for these purposes as the holes can be machined with high repeatability without burrs and material alteration [17,43]. Furthermore, according to Ho and Newman [44], micro-EDM is capable of use in not only micro-holes and micro-shafts as small as 5 mm in diameter, but also for complex three-dimensional (3D) cavities. However, in micro-machining, accurate form measurements seem to be difficult, due to small diameters and high aspect ratio machining [45].

Precise positioning with high accuracy miniature components and microstructures are increasingly in demand too. Some approaches have been explored by Dehong et al. [46] in order to develop and improve machining characteristics, especially in multi-axis micro-machining, including the designing of 5-axis ultra-precision micro milling machines. In EDM, multi-purpose miniature machine tools for high precision micro-machining were developed by Asad et al. [47] to perform micro-EDM machining. Table 3 shows the commercially available micro-EDM systems and their capabilities [48].

3.3. Positioning and feed drives system

Since precise positioning is required for micro-machining, a Computer Numerical Control (CNC) system has been introduced and has been in use since 1978 [49] for many applications. This is because a CNC-controlled machine is able to machine different geometries and shapes, like angles at the end of the workpiece or conical structures [50] and also to help in multi axis machining to control the motor of each axis of the machine [51]. The same goes for EDM machining, which has been used widely in many applications, especially, micro-machining. With their own demands and requirements, the developments in EDM machining have led to integration of a new CNC system and advanced spark generators that have helped to improve the performance of multi axis EDM [52,53], machined surface quality [54,55], and micro-feature production [4,56].

According to the Electronic Industry Association (EIA), CNC is a system in which actions are controlled by direct insertion of numerical data at some point of which the system must automatically interpret at least some portion of data. In other words, CNC is a system which receives numerical data, interprets the data and controls the actions according to the interpreted data. This system consists of 6 major elements which are input devices, a machine control unit, a machine tool, a driving system, a feedback device and a display unit [57]. The traditional approach used in building machine tools is the use of rotary motion and drive screws to achieve motion. However, referring to Rui et al. [56], this type of motion has limitations in its maximum rotation speed, inertia, windup, backlash and hysteresis.

In positioning the electrode, lead-screw positioning mechanisms are normally used in EDM [9]. Figure 3 illustrates the mechanics of the lead-screw mechanism for EDM. In addition, most motion controllers are capable of performing lead screw compensation. Thus, this also allows for a table of corrections to be entered

Table 3. Micro-EDM system and capabilities for available commercial products [48].

Machine	Power supply	Motion control	Electrode size	User applications
Panasonic	Relaxation generator (RC circuit). 10 nsec pulse-width	0.1 μm resolution. 1 μm positioning accuracy.	Holes as small as 5 μm. WEDG makes electrodes on machine.	Three axes machining and WEDG allow gears, shafts, etc. as well as holes and complex cavities. Real 3D shapes.
Sarix	Undisclosed. 50 nsec pulse-width. 0.05-40 amp.	1 μm resolution. 1 μm positioning accuracy.	Electrodes as small as 12 μm diameter.	Holes. Shaped electrodes make shaped holes. Machining in three axes are possible but not demonstrated.
Pacific controls	555 multi slot (dual gap voltage). 2.5 μsec pulse-width. 0.002-100 amp	Monitored to 0.5 μm.	Electrodes as small as 2.5 μm diameter.	Holes only. No mention of electrode shapes. Machining only in z-axis.
Agie	Undisclosed.	0.1 μm resolution. 1 m positioning accuracy.	Wire as small as 25 μm diameter.	Any type of 2D part. Machining in -x and -y axes only.

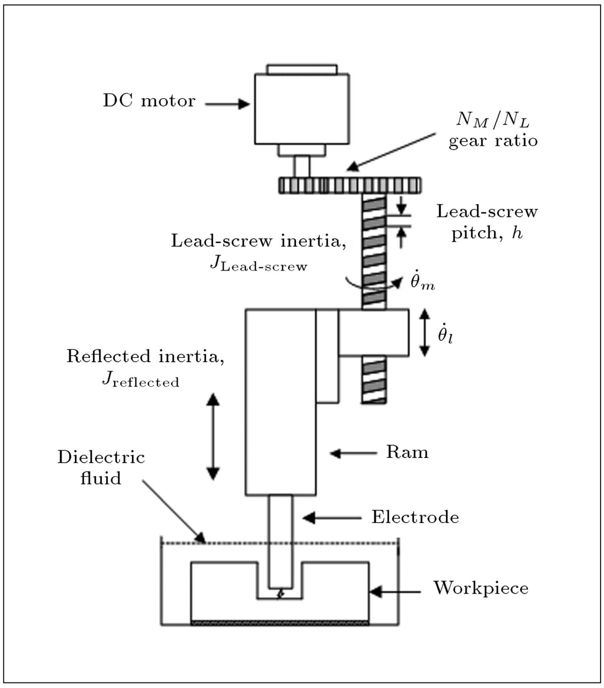

Figure 3. Ball screw in EDM machine [9].

into the controller as a function of motor position [56]. The quality of the lead screws would determine overall accuracy, while the nut design should help to eliminate backlash if it is properly executed [58]. However, although the lead screw would give an adequate performance in the electrode positioning system, the positioning response is quite slow to maintain discharge distance for the machining, due to the mass of stacked tables and the rotary inertia of the leadscrews [59].

The study of this problem is now of more interest in EDM machining. During the operation of EDM, the gap between the tool electrode and the workpiece changes continuously, due to continuous workpiece material removal. In order to maintain the ideal gap, which would provide ideal electrical discharge conditions, high speed and high precision re-positioning of the electrode are required. In addition, Ho and Newman [44] discussed that the debris around the electrode also has to be removed immediately to avoid abnormal electrical discharge.

Hence, there is an important requirement for high speed precision machining, which requires the capability of the twin parallel feed drives to follow the same command trajectories accurately in order to achieve satisfactory positioning accuracy and reduction of the synchronization error of the two motors [60]. Therefore, much research was conducted [61,62] to improve the positioning response and its accuracy by utilizing the actuators used in EDM. A linear motor system is simply an electromagnetic actuator composed of two rigid parts supported by a linear bearing. It is used as an alternative to the traditional drive

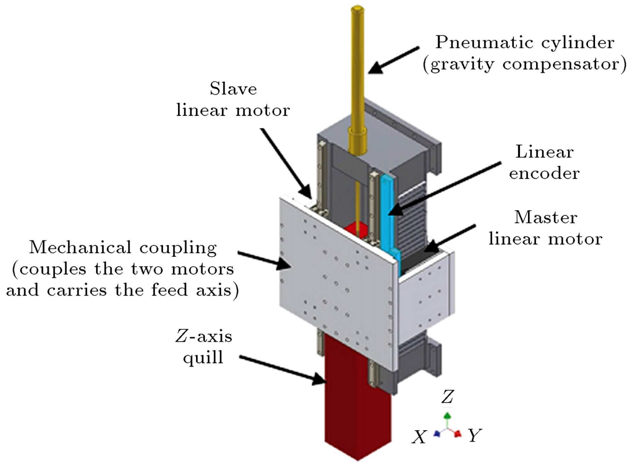

Figure 4. Linear motor driven [42].

system. Lead screws can serve as the linear actuating mechanism in the majority of positioning systems [58].

Development of the linear motor equipped direct drive EDM and its control strategy for high speed machining has been undertaken by Hsue et al. [32]. In high dynamic applications, linear motor drives are also used in precision machining [63]. Figure 4 shows an example of a custom-designed linear servo motor used in EDM. It does not require transmission elements to convert rotational movements to translational movements. However, it is found by Yan and Cheng [64] that it has less friction, no backlash, less mechanical limitations, acceleration and velocity, higher reliability and a longer lifetime. In addition, due to its simple mechanical arrangement and relatively low cost of linear drive technology, it is used widely as a basis for developing a table motion system for micro-EDM [56].

A crucial and difficult task for ultra-precision micro-machining applications is the development of tool feeding drives with high resolution, large strokes and high thrust motion performance [22]. Direct drive actuators, such as piezoelectric ceramic driven linear motors, have been studied for this purpose, due to their ability to eliminate backlash. They also have a faster transient response, better tracking capabilities than conventional lead screw drives and possess the attractive advantages of high resolution and high stiffness. Therefore, a linear electrostatic motor with large thrust capability and high positioning and tracking accuracy is proposed for electrode-feeding the servo-drive in micro-EDM. In the research, a linear electrostatic motor was used as a direct-electrode-feeding device, due to its quick response and ability to move with fine steps down to 0.05 micrometers. Figure 5 shows the control diagram of the system.

As there are high expectations for EDM to become important equipment for precise machining in many applications, a new local actuator module has been developed for highly accurate micro-EDM, which

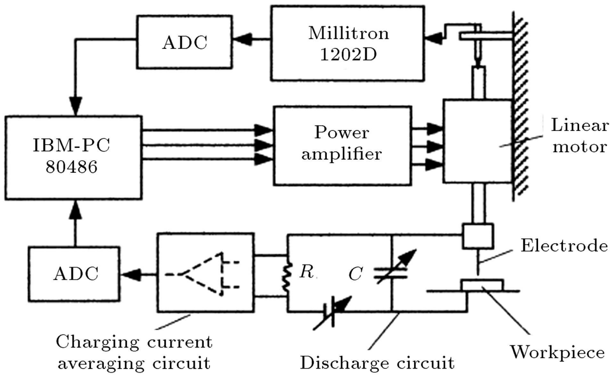

Figure 5. Control diagram of the micro-EDM system [22].

is able to drill a micro-hole approximately three times faster and produce less electrode wear. It is also has the capability of quick planetary motion for highly accurate machining. According to the diameter of the hole, by using this local actuator module, the machining was able to produce holes of almost the same size at the entrance and exit of the holes [65].

The speed and accuracy of conventional EDM are limited by the probability and efficiency of the electrical discharge. In order to achieve stable electrical discharge, the electrode should be speedily repositioned in order to maintain a suitable distance from the workpiece, and the debris that was produced around the electrode should be immediately removed. Thus, for that purpose, rapid retraction of the electrode is significant for the electrode actuator [59]. As an additional actuator, a piezoelectric actuator has been used by Kunieda et al. [61] to improve the positioning response of an electrode. It is known as a special kind of direct actuator feasible for high resolution (10 nm) and for stroke lengths of a few hundred microns, together with high actuator stiffness (300 N/micron) and high bandwidth (100 Hz) [66]. Figure 6 shows the schematic of the entire EDM system with the piezoelectric actuator.

However, the stroke of the piezoelectric actuator is insufficient to accommodate the periodic rapid retraction of an electrode, as it is needed to introduce fresh machining fluid into the machine hole to wash away the debris. Therefore, 5 Degree Of Freedom (DOF) motion using piezoelectric elements is required. The actuator is also used to maintain a suitable distance between the electrode and the work-piece in EDM. Besides, an improved maglev, wide-bandwidth, high precision, millimeter-stroke actuator for positioning the electrode in 5-DOF was developed by Zhang et al. [59] and attached to conventional EDM to realize high speed and accuracy in micro-EDM. Zhang had focused on this work for several years [67-69].

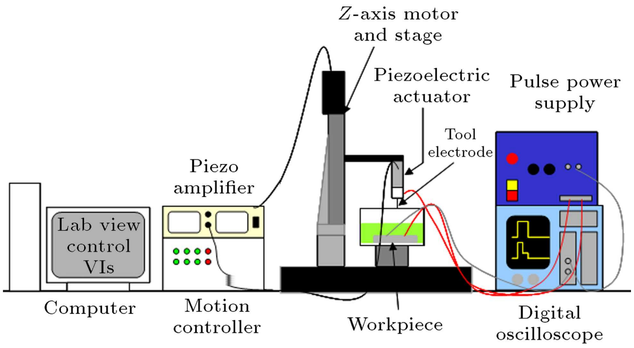

Figure 6. Schematic of the entire micro-EDM set up with piezoelectric actuator [48].

This development includes a magnetic coupling mechanism that transmits torque from the motor to the spindle shaft and feeds a discharge current to an electrode attached to the spindle shaft. Experiment results done by He et al. [70] showed that the Maglev Local Actuator (MLA) provided a sub-micron positioning resolution with an angular resolution of several microradians, bandwidths greater than 200 Hz in the 5-DOF directions, positioning strokes of 2 mm in the thrust direction, 180 micrometers in the radial direction and 3.6 mrad in a tilt direction. In addition, the spindle shaft can be rotated smoothly up to 2000 min^{-1} and its vibration amplitude less than 1.5 μmeter and 30 μrad. Figures 7-9 show the block diagrams of the EDM control system for thrust, radial and planetary direction machining [71].

Dynamic modeling of a micro-positioning workpiece table for an active surface grinding control utilizing a piezoelectric translator also has been developed. The workpiece table has a working area of 100×100 mm, with a resolution less than 20 nm and a nominal working range of 45 micrometer, with a natural frequency of 579.2 Hz. It was found by Gao et al. [72] that using the moving part of the reduced mass and a piezoelectric translator (PZT) could produce the high dynamic performance of a workpiece micro-positioning table. Figure 10 shows the schematic diagram of the workpiece micro-positioning table that has been developed.

4. Control strategies

4.1. Servo-drive control

The servo-drive control system is an important part of EDM, as it maintains the spark-gap between the tool and the workpiece at the desired level. Therefore, several control strategies have been applied in this system, in order to ensure a stable and effective machining. In general, all EDM machines use an automatic control in their servomechanism system, whose discharge gap is controlled automatically. During the machining process, the electrode will penetrate the workpiece and some parameters other than the spark gap will change. When this occurs, it is necessary to make an

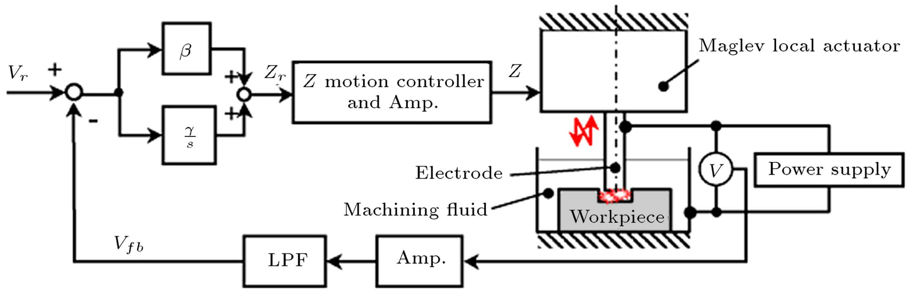

Figure 7. Block diagram of the EDM control system for thrust direction machining [71].

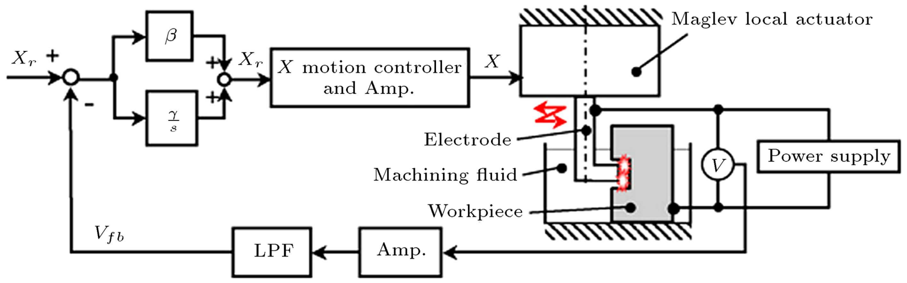

Figure 8. Block diagram of the EDM control system for radial direction machining [71].

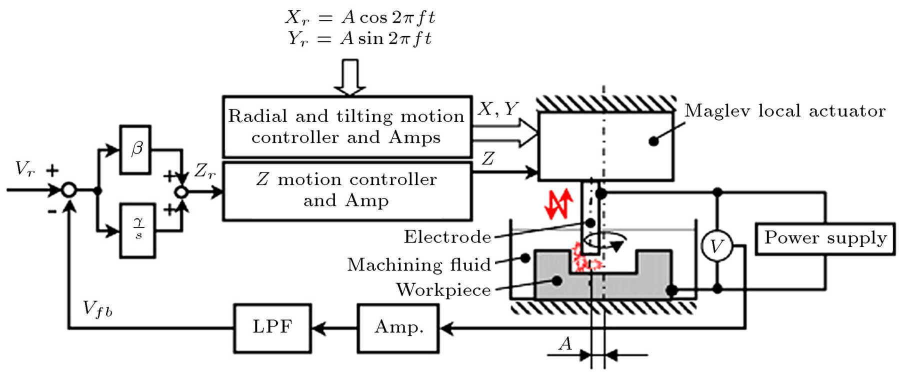

Figure 9. Block diagram of the EDM control system for planetary machining [71].

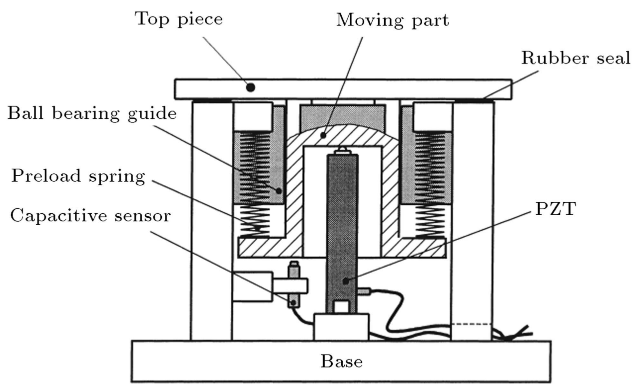

Figure 10. Schematic diagram of workpiece micro-positioning table [72].

adjustment to the generator setting in order to restore stable conditions. This process needs to be monitored and adjusted by skilled operators. However, since the machining process involves a stochastic process with more parameters that need to be controlled and high frequency pulses, it makes this operation extremely difficult [2]. Therefore, an adaptive control strategy is necessary to be implemented in EDM machining, which is able to detect and react to EDM status changes by continuously adjusting the system response based on feedback information [73].

4.1.1. Adaptive Control System (ACS)

In 1970, an Adaptive Control System (ACS) was introduced which was used to detect error signals and send correcting signals to the servo-drive mechanism. An error signal is measured by comparing the ideal output pattern as a reference with the actual output. This system improves the machining productivity by almost 50%, and, by avoiding arcing, reduced workpiece damage [74]. The main advantage of using an adaptive controller is the ability to modify its behavior in response to the timely varied gap state in the EDM process and to disturbance. However, in this technique, the process model and the controller

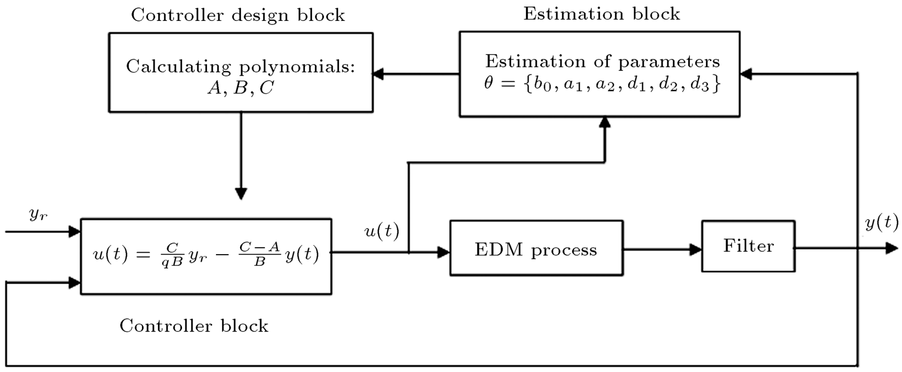

Figure 11. Block diagram of adaptive control system with self-tuning regulator for EDM process [75].

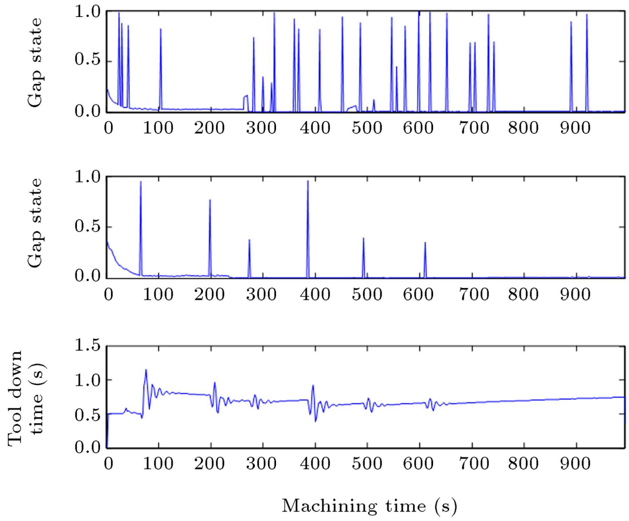

Figure 12. Upper figure shows the normal EDM process gap state, middle figures shows the adaptive controlled process while the lower figures shows tool-down-time adapted correspondingly to the above gap states in the middle figure [75].

parameter need to be determined. Therefore, the system that emerged in the EDM application was provided with a self-tuning regulator. It was designed to control the EDM operation so that the gap states would follow the specified gap state based on a real-time process [75]. Figure 11 below shows a block diagram of the ACS system with a self-tuning regulator for the EDM process. Comparison of a normal EDM process and an adaptive controlled process are shown in Figure 12. The adaptively controlled process shows the robustness of its capability to adapt to changing conditions.

4.1.2. Adaptive Control Optimization (ACO)

In 1979, an Adaptive Control Optimization (ACO) technique was introduced which enabled us to detect machining trends that lead to unnecessary conditions and to take appropriate actions before the conditions actually occurred. This system is divided into two categories; offline optimization and online optimization. In offline optimization, optimal selection of parameters such as pulse current, pulse duration or discharge current need to be set before the machine starts to operate, while, in online optimization, several parameters are left for in-process computer optimization and control, in order to achieve optimal performance [2]. This system was also implemented in EDM by Kruth et al. [76], in 1983, using mini computers, EDM-process-analyzer sensors and control devices and interfaces which automatically search for machine settings that coincide with optimal working conditions. However, the EDM process depends on multiple independent parameters which influence each other and which will make the machining process a typical random multiple parameter and time-variant nonlinear system [77]. Hence, due to poor gap control of the ACO system and the difficulty of on-line adjustment (because of the stochastic, non-linear and dynamic process that occurred during EDM machining), the fuzzy knowledge system was applied to the EDM system in 1995 by Marco et al. [78].

4.1.3. Fuzzy knowledge

A fuzzy knowledge system is widely used in EDM servo-system applications, as well as in micro-machining, because of its capability of handling a highly nonlinear process with only qualitative knowledge available. It is also well suited to the EDM environment in order to control the gap between the electrode and the workpiece. Further research has been made in this control to aid the operators, thus improving the machining process, as it has a faster response, is more robust and has a higher stability technique [23,79-82]. Figure 13 is a schematic diagram of self-adjusting fuzzy control [83] in order to decrease the influence of temporally unstable states to the fuzzy inference.

Kao et al. [80] developed a micro-hole EDM system with adaptive fuzzy logic control and a piezoelectric stage, and made a comparative study of system performance with and without the presence of a fuzzy logic controller. The results obtained are shown in Figure 14(a) and (b). It can be observed that

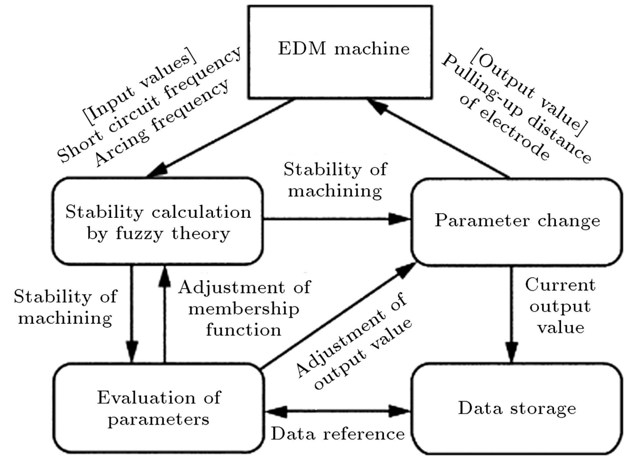

Figure 13. Schematic diagram of self-adjusting fuzzy control [83].

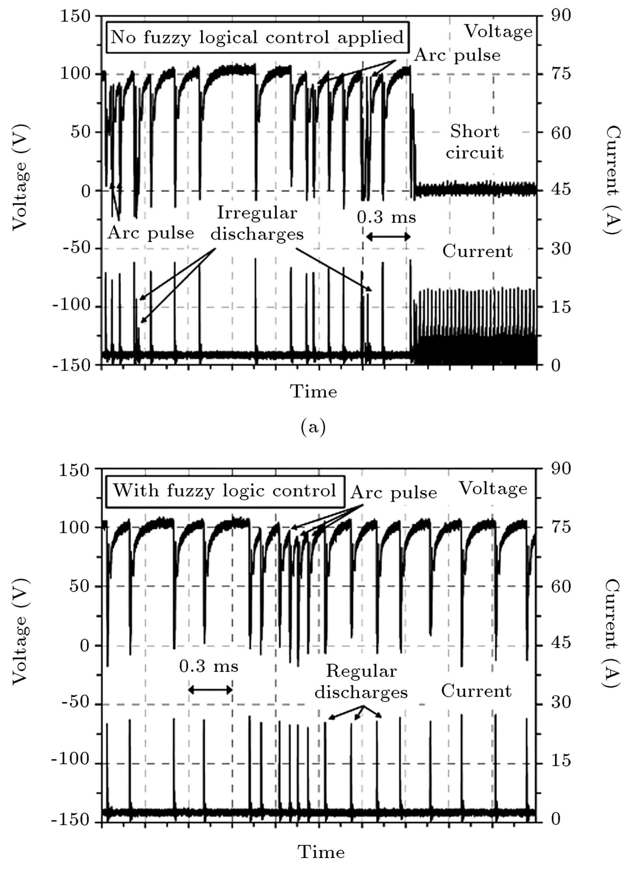

Figure 14. Gap voltage and current of the EDM pulse train with (a) no fuzzy logic controller applied, and (b) fuzzy logic controller applied [80].

frequent irregular discharges are generated during the EDM process due to inferior discharge gap conditions, compared with the presence of fuzzy logic. Thus, it can be deduced that the fuzzy logic controller is beneficial to maintain, smooth and stabilize non-deterministic processes, such as in EDM machining, as the discharge gap distance can be precisely controlled and almost no short circuit is observed. Furthermore, the unwanted arc pulses are also quickly suppressed to enable a stable and fast EDM process with regular discharge.

Although fuzzy logic is capable of dealing with the non-linear and time varying nature of the EDM process, the discrimination of pulses from the RC type power source is still an ill-defined problem relying on heuristics, as it is important to discriminate between different levels of pulses for proper operation in micro-EDM machining. Therefore, a tunable fuzzy logic based servo controller for monitoring and controlling the micro-EDM process was developed by Byiringiro et al. [84] in order to provide stable machining which improves the performance. The system has been developed by classifying the discharge pulses through measurement and analysis of voltage and gap current pulse characteristics.

The equipment used is a conventional PID controller, which will be discussed in a later section. Figure 15 shows the structure of the designed fuzzy logic control for the EDM servo motor.

4.1.4. P, PI, PD, PID controllers

In modern mechanical systems, such as machine tools, the robust, high speed and high accuracy positioning of the motion controller is necessary. The speed of response for the system, which determines how quickly a system responds to a change in input, is also important, the performance of which can be evaluated from the system step response. The graph of step response and its important parameters are depicted in Figure 16.

However, the linear range of the feedback element is generally limited, and the saturation feedback element would disturb the control performance during the control process. If the Proportional (P) controller is used to control the feedback system, the saturated feedback signals would increase the rise time. The gain value parameter needs to be increased whenever the travelling speed is large. It will lead to a substantially unstable system. In order to reduce the instability of the system, an Integral (I) controller can be connected, in parallel, to the P controller by reducing the rise time and eliminating steady state error. A robust variable structure system using a PI/P controller has been developed which can be applied to EDM to achieve a high precise positioning system [85]. In motion control, there are two major sources of uncertainty, which are friction and inertia [86]. Since the EDM operation needs to deal with random and uncertainty conditions during the machining process, the regulation of variance and stability of the stochastic process in real-time issues still needs to be discussed. It leads to the use of a proportional-integral, PI controller in EDM applications [71,87].

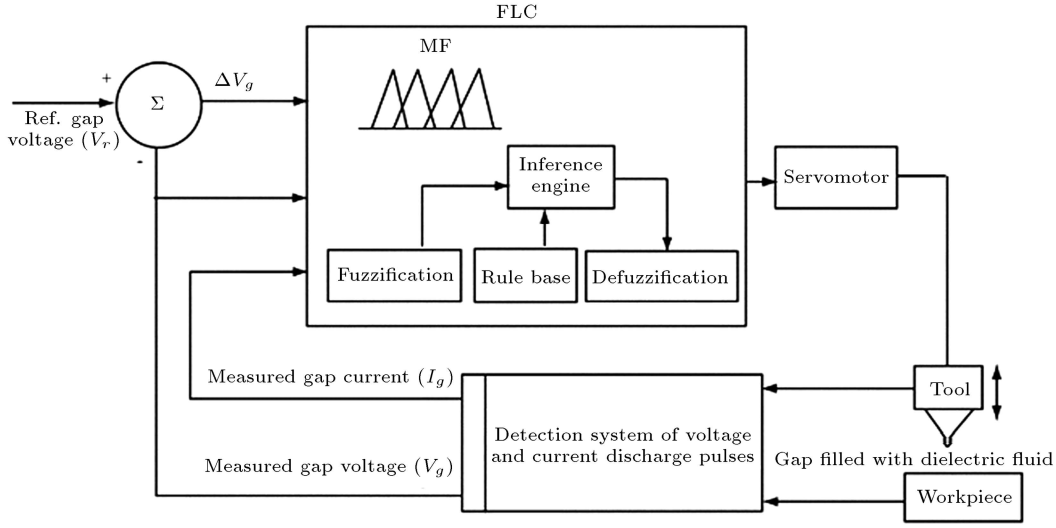

Figure 15. Structure of designed fuzzy logic control for EDM servo motor [84].

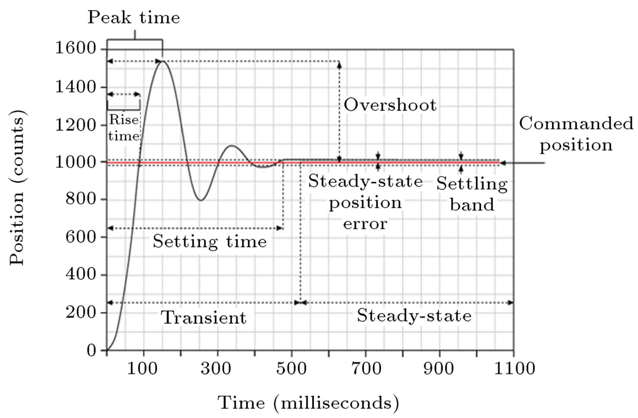

Figure 16. Step response.

In a multi-axis system, it is known that each of the axes has its own system dynamics. Therefore, a PI controller has also been used in designing a control system that involves four-axis position synchronous control [88]. Figure 17 illustrates the schematic diagram of the servo system, representing the concept of the control scheme for a multi-axis rotating system using a PI controller. The PI velocity servo is also used in traditional servo systems as an alternative approach, which regards the bounded non-linear friction term as disturbance. However, an I-action in the system may cause a limit cycle around a target position in point-to-point control, and magnifies the tracking error when the motion direction is reversed. Therefore, the introduction to the Proportional-Derivative (PD) controller has been made and it was used by Lee et al. [86] to utilize the linear feedback control theory in order to construct an asymptotically stable position feedback loop. As there are numerous methods in control processes, a comparative study has been conducted by Kumar et al. [89] to evaluate the real-time performance of a combination of several controllers,

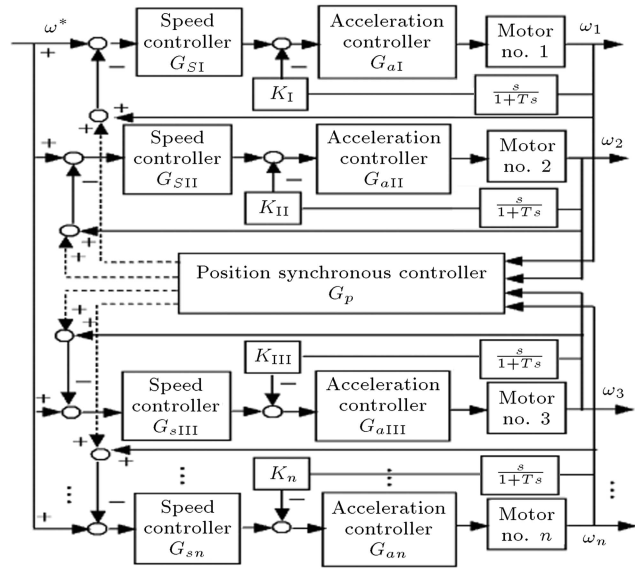

Figure 17. Schematic diagram of multi-axis position synchronous control system [88].

Fuzzy-PI and Fuzzy-PD. Table 4 shows a summary of the system performance obtained in these studies, in terms of their rise time, peak, overshoot, and settling time of the step response.

The Proportional-Integral-Derivative (PID) controller was then introduced and has been used in feedback control in most industrial and manufacturing application [90]. It utilizes a predefined mathematical model to dynamically adjust the servo movement according to the feedback sensor, and this controller is commonly used in EDM process control [73]. The values of parameters in this controller must be tuned according to the characteristics of the process, in order to yield satisfactory results [91] and optimize system performance. In addition, this controller could also have been cascaded with a differential controller,

Table 4. Comparison between fuzzy and conventional controllers for real time result (cascade) [89].

Type of controller	Rise time (sec)	Peak (cms)	Overshoot (%)	Settling time (sec)
Fuzzy PI + fuzzy PD (primary) + conventional PI (secondary)	194	41.8	4.5	194
Conventional PI (primary) + conventional PI (secondary)	183	42.5	6.25	364

Table 5. The effects of increasing each of controller parameters K_P, K_I and K_D [94].

Response	Rise time	Overshoot	Settling time	S-S error
K_P	Decrease	Increase	NT*	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_D	NT	Decrease	Decrease	NT

* NT: Not definite trend; minor change

as a differential-PID, DPID. This was implemented by Chung et al. [92] as the controlling strategy in the beginning and middle stages of die-sinking EDM machining and it increasing machining efficiency by 30%.

PID control, with its terms functionality, could improve both transient and steady-states response, thus, making it a simpler and more efficient alternative to many real world control problems. However, the processes involved are, in general, complex and time-variant, with delays and non-linearity, and often with poor dynamics. In addition, due to its simple structure and robustness, it is quite difficult to optimally tune the gains of this controller by conventional approaches of PID controllers [89,93]. Table 5 summarizes the effects of increasing each of the PID controller parameters, K_p, K_I, and K_D [94].

4.2. Optimization techniques

From the previous section, in time-variant or non-linear characteristics, such as in EDM operation, it cannot provide a general solution to all control problems, as it is difficult to be controlled with fixed controllers, such as PID controllers, based on the applications. This is due to the fact that a conventional PID controller may not suffice to provide high contouring accuracy, as well as adequate disturbance rejection and parameter variation robustness [64].

In order to solve this problem, optimization techniques that automatically tune such parameters in the control process are required, as this type of controller is still considered the most efficient, and is widely used as a feedback control strategy [95,96]. Hence, this type of controller has been integrated with adaptive features, such as self-tuning and gain scheduling. In gain scheduling, it is necessary to know the optimum PID parameter values under certain conditions. The values of parameters are stored and will be recalled in the controlling system according to operation requirements [91]. There is a variety of research that has been conducted to optimize the parameters for the controller using different optimization techniques.

The Genetic Algorithm (GA) is one of the optimization techniques proposed by professor Holland of American Michigan University, in 1975, which simulates the natural evolvement process in order to search for the optimal solution. The method has four important operations, including coding, selecting, crossing and variation [97]. It is the robust adaptive optimization technique and has been applied in EDM [87]. The Artificial Neural Network (ANN) has also been introduced, which is an effective method for solving non-linear problems. It has been used in some research, such as that conducted by Andromeda et al. [98] to predict the Material Removal Rate (MRR) in the EDM process. Neural network based modeling has also been used to get higher prediction accuracy in wire EDM, as the maximum percentage absolute error of the predicted value, with respect to the experimentally observed value, MRR, is not high [96,99]. A comparative study of the material removal rate between DA and ANN has also been conducted by Yahya et al. [100]. It was obtained that the ANN model gives better accuracy than the DA model. In research by Gao et al. [101], the GA and ANN have been combined to establish a parameter optimization model in EDM. The ANN model was used to represent the relationship between MRR and the input parameter, while GA is used to optimize parameters. The model is more effective and the Material Removal Rate (MRR) is improved.

Sandhu et al. [102] has made a comparative study regarding their percentage of error, which compares fuzzy performance without optimization techniques, and with the presence of an optimization technique which is a neural network and a GA. Based on the experiments, it was proven that fuzzy logic-GA is the best and most efficient compared to other algorithms used in the work for non-linear and complex engineering applications, such as control, inference and analysis. Hence, in EDM applications, a GA-based fuzzy logic controlled system has been adapted in wire EDM by Yan and Fany [103] for a retrofitted wire transport system. The results obtained satisfied the transient responses, steady state response and robustness, hence, improving flushing conditions.

On the other hand, there is a new optimization technique, Particle Swarm Optimization (PSO), which until now has rarely been applied to EDM machining. From previous research, it has been used for a non-linear curing process that was combined with fuzzy control [104], and also used in tuning PID controllers, such as in robot trajectory control [105], bar rolling processes [106], and controlling the speed of DC motors [107]. Research has also been conducted to compare the PSO and GA technique effects on system performance. From the research, although GA has a strong ability for global searching, it has low computation efficiency and high complexity. Thus, optimization speed also becomes low. Comparing PSO and GA, it can be found that PSO can be implemented simply, with less parameters and good global searching abilities, and is even faster than GA [97].

Nasri et al. [108] conducted a comparative study to compare the system performance of a GA and PSO based PID controller in the speed control of a DC motor; the result obtained is shown in Figure 18. From the result, it can be seen that PSO could give a better response, as it can perform an efficient search for the optimal PID controller, thus improving the dynamic performance of the system. Due to its strong abilities, this non-traditional optimization technique has also now been applied by Rao et al. [109] in WEDM to optimize the process parameters, in order to achieve maximum machining speed for the desired value of surface finish.

Generally, there are many other optimization techniques and controlling strategies that have been

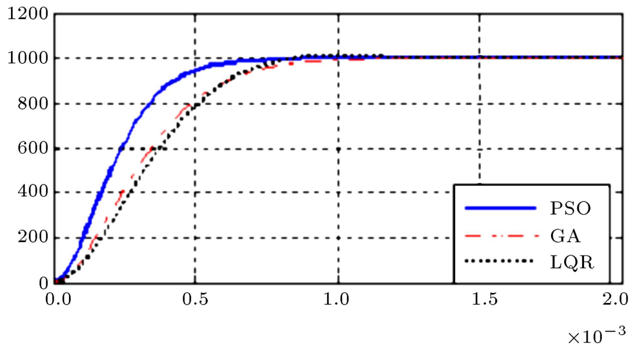

Figure 18. Comparison between GA and PSO based PID control in speed control of BLDC motor [108].

Table 6. Comparison of performance for fuzzy-PSO and PID-PSO [89].

Results	**Fuzzy-PSO controller**	**PID-PSO controller**
Rising time (Sec)	0.0087	0.00285
Overtaking (%)	0	0
Steady state error	0	0

previously developed and newly introduced until now. Due to the existence of various controller and optimization techniques, there have been combined controlling strategies used in order to optimize their performance, based on their applications, such as a combination of PID-neural networks [110,111], PID-genetic algorithms [112], fuzzy logic-PSO [113], PID-PSO [108,114], and fuzzy logic-neural networks [115]. In other research, it has been found that PID-PSO configuration improves system dynamic performance and possesses a good robustness, which has no overshoot, minimal rise time, and zero steady state error. Table 6 shows a comparison of the step response parameter between Fuzzy-PSO and PID-PSO controllers [93].

From the previous topic, there are various types of process control that have been previously applied and developed for EDM and other applications. Each of the techniques has been studied for different objectives and applications. A summary of several developed controllers and control processes is shown in Table 7.

5. EDM in biomedical applications

In medical device manufacturing, such as orthopedic implants, surgery devices and dental parts, besides requiring high geometrical accuracy, it also requires good surface integrity in the manufacturing process. In implants, especially, some requirements need to be taken into consideration [119], such as compatibility, mechanical properties and manufacturing process. In the manufacturing process, the surface should avoid pores and cracks, and not contain any toxic substances which can harm the human body. This is because any undesired machining could affect the workpiece of the implant material, thus, creating the risk of inflammatory reactions in the patient. It has been known that EDM can create complex shapes with high accuracy for hard materials and gives a good result in surface finish compared to the conventional methods. Since metallic biomaterials such as magnesium, alloy, titanium, stainless steel, cobalt, chrome etc. are used widely in implant manufacturing, due to their characteristics and biocompatibility [120], they are impossible to be machined using conventional machining. Thus, this medical field actually relies heavily on EDM machining for the manufacturing process [121]. In addition, research by Klocke et al. [19] was conducted

Table 7. Development of process control.

Type of controller	Process control research	Research findings
Fuzzy + GA/PI+GA	Comparison between Fuzzy+GA and PI+GA [103], 2004	Fuzzy+GA controller obtained an optimal performance in WEDM as it contributes to fast transient response and small steady-state error compared to PI+GA controller.
PI + GA	Development of PI controller to control system with fast eroding speed using GA to gain parameters in PI controller with optimal tracking performance [87]; 2007	A discharge process with fast eroding speed in EDM can be treated as first-order dynamic process with non-linear and time-varying perturbations by designing PI implemented with GA.
PSO/GA	Comparative study between PSO and GA optimization technique [97,108]; 2007,2010	PSO give a better performance as it has good global searching ability faster than GA and it is easier to be implemented.
Fuzzy + PI/ Fuzzy + PD	Comparative study for real-time performance of fuzzy PI + fuzzy PD with conventional PI controller [89]; 2008	Fuzzy PI + fuzzy PD controller could perform better in comparison with conventional PI controller.
PD-PI + GA/ PD-PI + PSO	Optimization techniques and evolutionary algorithms (GA and PSO) were implemented in PD-PI controller system, and system performances between the two models were compared [116]; 2008	The values of K_p, K_i, and K_d are quite high than using GA. However, simulation results proved that PSO technique is more effective and speed computations is better than GA.
Fuzzy + GA + Neural network	Development of a new method of fuzzy, optimization and control of EDM process using neural model predictive control and employed GA to optimize input parameters [23]; 2009.	EDM machining for WC-Co confirms capability of the system of predictive controller model based on neural network with 32.8% efficiency increasing in stock removal rate.
PID + GA	GA was implemented to PID controller for the DC motor position control system [117].	The designed PID with GA has much faster response than classical method in terms of rise time and settling time with less error.
Fuzzy + PSO/ PID + PSO	Comparative study between fuzzy-PSO and PID-PSO [93]; 2009	PID-PSO is better to improve the system performance in speeding up DC motor speed control.
Fuzzy-neural-network controller PI-/PD	Development of FNN PI-/PD controllers to replace the conventional PID controllers [118]; 2011	Favorable tracking performance including disturbance rejection and external loading

by including some modifications to the EDM system, so that it can be used to manufacture medical devices with better performance or surface finish.

6. Conclusion

EDM is now becoming a popular and effective method for micro-machining. This is due to its capability of producing a better surface finish on the machined materials. In order to maintain proper machining characteristics and performance, it is necessary to make sure that the optimum discharge gap between the electrode and the workpiece is achieved. This can be done by choosing the right servo mechanism and control strategies that are suitable to the application and desired product. From what has been discussed in this paper, it can be concluded that each method of control strategy developed has similar objectives, which is to improve system performance, especially by reducing machining time and improving the step response of the system. For the EDM control strategy, it is necessary to choose the right type of controller for controlling the process, while feed drive systems and their mechanical properties are important to provide smooth movements and improve machining time. These studies and research material have made several noteworthy contributions to many fields. Furthermore, it is recommended that further research be undertaken for improving EDM machining for biomedical applications. The biomedical field is becoming more important, especially in producing biomedical devices and medical implants, as this field requires accuracy in the machining of the material itself.

Acknowledgment

This research has received financial support from the Research Management Center (RMC) at Universiti Teknologi Malaysia.

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