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A Survey of Control Methods for Electrical Discharge Machining Process

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Abstract: Electrical Discharge Machining (EDM) is a well-established machining process in which material is gradually removed during an electrical discharge process to form a desired shape. There are a number of factors that impact the efficiency and surface finish quality of the EDM process. In this paper, background of the EDM and such factors are discussed, followed by a review of different control methods that have been proposed in the literature for the EDM process. The control methods are categorized into four classes, namely the methods that are based on electrode movement control, on-time power control, pulse number control, and cracks prevention. The most commonly used EDM control methods belong to the family of methods that work based on directly controlling the movements of electrode. In such methods, the control is mainly based on direct comparison of some measured signal(s) such as voltage or current with some references. More recent designs include pulse discrimination methods and fuzzy logic controllers.

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I. INTRODUCTION

Electrical Discharge Machining (EDM) is a well-established machining process in which material is gradually removed during the discharge process to form the desired shape. It is commonly used where the material is extremely difficult to
machine by conventional machining processes. Applications of this technology are commonly found in mold-making and tools production such as drill pieces and in manufacturing engine parts for aircraft, e.g. in tool manufacturing where material is removed from a metal rod to form drill pieces or in precise cutting of materials such as drilling small holes or openings that are less than approximately 0.06 inches. Another advantage of EDM over traditional machining processes is that with EDM, it is possible to cut pre-hardened steel in intricate contours or cavities without the need to soften the pre-hardened steel through heat treatment, and then re-harden it later.

A. Historical Background

The erosive effect of electrical discharges was first studied by English physicist Joseph Priestley back in 1770. Later, two Russian scientists, Dr.B.R.Lazarenko and Dr.N.I.Lazarenko invented a controlled process for machining of metals based on the destructive effects of an electrical discharge in 1943. In order for the electrical discharge to take place, they devised a discharge generator named Lazarenko circuit, as well as a controller for the process [1]. The first manufacturer of a system involving the complete spark machining process was Charmilles who presented their product at the European Machine Tool Exhibition in 1955. [2]

Since 1955, different types of electric discharge machines have been developed. Nowadays, there are three common types of EDM technology in use:

(1) Traditional EDM, also known as spark machining, spark eroding or die sinking.

(2) Wire EDM, also known as wire erosion.

(3) Electric Discharge Grinding (EDG)
Traditional Electrical Discharge Machining

In traditional EDM, material is removed from the workpiece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. When the voltage is applied to the electrode, and the gap between the two electrodes (one being the material to be machined) is reduced as controlled by the CNC. With the gap shrinking, the electric field within the gap space intensifies until it allows plasma to be formed. Once plasma is formed, electric current flows through the gap from the electrode to the workpiece. This phenomenon is known as current discharge. The discharge generates heat and removes the material. During the discharge and material removal, the voltage across the gap (gap voltage) drops to a low value called burning voltage. As shown in Fig. (1), in traditional EDM, usually an inflow of a dielectric liquid (flushing) takes away the removed material (debris) from the workpiece.
Wire Electric Discharge Machining

Wire EDM is similar to traditional EDM. The workpiece is submerged in deionized water, and as shown in fig. (2), a thin single-strand metal wire composed of brass is fed through the workpiece and held between an upper and a lower diamond guides. The movement of the diamond guides are controlled by a CNC controller. The controlled movements of the guides are usually in the x-y plane, but in some cases, e.g. when a shape of circle is required to be cut on top of the workpiece and a square at the bottom, the guides are moved in x, y and z directions. Here, flushing also takes place to take away the debris.

Fig. (2). Machining process for wire electrical discharge machining.

Electric Discharge Grinding

Electric Discharge Grinding (EDG) is similar to EDM except that the electrode is a rotating graphite wheel. Here, the workpiece is fed to the wheel by a servo-controlled worktable. The workpiece is cut by the action of a stream of electric sparks between a negatively charged wheel and a positively charged workpiece immersed in a dielectric fluid – see Fig. (3). When spark discharge occurs, it melts or vaporizes a small amount of metal from the workpiece surface, producing the removal of material from the workpiece. Similar to traditional and wire EDM, flushing (inflow of dielectric liquid) takes away the removed material.
B. Factors that affect the EDM Process

The performance of the EDM process, in terms of material removal rate and surface finish quality, depends on various factors. The most important of such elements are:

1. density of debris in the working zone during machining;
2. thickness of the workpiece;
3. material of the workpiece, particularly its conductivity;
4. the dielectric fluid used; and
5. arc discharges and short circuits that can cause damage to the workpiece surface or electrode tool.

The first 4 factors listed above are manually controlled and the best options are usually chosen via experiments to choose the best dielectric fluid, the most appropriate voltage and current levels (depending on the material and size of the machined workpiece). However, to obtain the highest material removal rate and best quality of machining in terms of surface finish, it is important to meet the requirements mandated by the last above listed factor, i.e. minimum number of short circuit and arc pulses. Thus, optimal control of the discharge pulses (in terms of the
timing of switching on and off the voltage and current within the EDM process) is a crucial component of any EDM process design.

There is a relatively large body of recent literature on different aspects of EDM such as actual machining techniques [3-7], process modelling [8-13], material properties [14-17] and machining parameter optimization [18-21]. However, the problem of designing effective control and monitoring systems that are tailored to the particular needs of EDM and EDG technology has attracted limited attention.

In this paper, different solutions developed in the literature for control and monitoring of the EDM process will be explored. Existing EDM control methods focus on real-time regulation and tuning of various quantities during the machining operation, such as the gap voltage and/or current, gap size, on-time and off-time, and feed rate (relative speed of the workpiece or electrode). The existing EDM control and monitoring methods (surveyed in this paper) can be categorised as methods based on:

1) electrode movement control;
2) on-time power control;
3) pulse number control; or
4) crack prevention.

Our literature review has concluded that the most common form of EDM process control is via controlling the movement of the electrode during the machining process. In the next section, the most common methods belonging to this category are reviewed, along with a few control methods based on on-time, pulse number and crack prevention control.
II. CONTROL AND MONITORING METHODS

A. Electrode Movement Control

The control method in this category generally work based on improving the machining performance by controlling the relative movements of electrode versus workpiece in a direct or an indirect manner.

Electrode control based on relative velocity of electrode

Martin, and Dingy en Vuache [22] developed an EDM control method based on controlling the speed of the EDM machine servo motor using two signals: one signal is a function of the machining condition and the other signal is the difference between the relative position and reference relative position. The relative reference position is continuously varied in the same direction as machining so that the movement is within the predetermined speed/limits. The main propose of the design is to prevent the damage to the workpiece due to short circuits. The design of the system is shown in Fig. (4).
Before the machining takes place, the counter 16 that counts a number proportional to the advance of the electrode tool and the pulse counter 17 is set in a way that both counters are showing the same number, for example set both counters to zero, so that there are no output signal at the digital numerical comparator 14. The maximum advance speed is set according to the encoder 24, and the final dimension of the workpiece is set according to the encoder 22.

At the start of the machining process, the input to the Schmitt trigger is set to zero. While the counter 16 counts a number proportional to the advance of the electrode tool, the pulse counter 17 is set to zero. The digital comparator 14 detects the difference between the number of the pulse counter 17 and the counter 16. The signal from the Schmitt trigger enables the AND gate which then passes the pulses supplied by the output of the frequency multiplier 20. The reference magnitudes supplied by the pulse counter 17 increases at a predetermined speed depending on the
feed rate. If the machining is operated at a feed rate greater than the reference determined by the pulse counter, the signal from the digital to analogue converter will be increased so that the actual electrode feed speed is held equal to the reference feed rate. If the machining feed rate is the same as the predetermined speed, then there is no change necessary. Moreover, if the feed rate is lower than the reference, then Schmitt trigger will stop the variation of the reference speed, permitting the counter 16 to count up towards the reference value. The pulse counter 17 will then define a feed speed limit which allows the storing and memorising of the position of the electrode tool. When the electrode tool is moved towards the workpiece, the feed rate will be decreased as soon as the memorised position is reached.

The Schmitt trigger may have a short delay so that it can have a braking effect on the electrode when the electrode reaches the memorised position, and no delay is allowed while resetting of the Schmitt trigger.

This developed EDM control method is an important improvement on the system disclosed by F. Balleys and J. Dupraz [23], in which the electrode is slowed or stopped when the displacement passed the reference position, while maintaining electrical discharges across the gap.

*Electrode control based on gap voltage.*

Control of the movement of the servo motor, hence the movement of the electrode in the EDM process, can be performed by using the variable voltage signal across the machining gap as the feedback signal. More precisely, the gap voltage can be directly utilized to change the velocity of the electrode tool to move closer or further away from the workpiece during the machining process.
An improvement of the general control circuit for the feed of the electrode tool in a servo feed system for EDM was developed by Ball et al. [24], in which a dither circuit arrangement is connected in series with the servo valve coil so that AC pulses are supplied to the servo valve directly with constant pre-settable amplitude that changes according to machining conditions. The gap voltage is compared with the reference voltage signal and depending on the comparison result, changes are made to the servo feed system to control the movements of the electrode tool. When the gap voltage is smaller than the reference signal, in the case of a short circuit, the electrode is adjusted to reduce the movement and the velocity of the electrode tool towards the workpiece. On the other hand, in the case of an open circuit, when the gap voltage is larger than the reference signal, the electrode velocity is increased so that the electrode tool moves towards the workpiece. The design of the dither circuit arrangement is shown in Fig. (5).

Before the machining takes place, the servo voltage potentiometer 30 is initially adjusted to result in a stable cutting and normal movement on the electrode tool towards the workpiece. During the machining process, the gap voltage signal is measured. There are two feedback control shunt networks that are connected to the operational comparator amplifier 34. The output from the operational comparator amplifier 34 is either larger or smaller than the voltage drop across the diodes 42, 48, to provide the current flow in one of the shunt networks that provide the feedback.
The servo potentiometer 30 is connected on a common shaft to the potentiometers 38 and 44, so the movement of these potentiometers are inter-related. When the measured gap voltage approaches the ground voltage (zero), the backup gain is increased to reduce the movement of the electrode tool moving towards the workpiece. To increase the backup gain, the servo potentiometer 30 decreases the series resistance in the potentiometer 44, which in turn would increase the backup gain and the potentiometer 38 is increased which would reduce the movement of the electrode tool towards the workpiece. Vice-versa, if open circuit is detected, the potentiometer 30 will increase the series resistance in the potentiometer 44 and 38, which will result in decreasing the backup gain that would lead to the increased movement of the electrode tool towards the workpiece.
The arrangement of this servo feed system also includes a signal amplifier stage comprising a push-pull amplifier 46, which consists of an upper NPN transistor 48, and a lower PNP transistor 50. The positive and negative DC voltage sources are connected to them indicated by B+ or B- in the schematic diagram of the circuit. This servo feed system also includes a dither circuit that consists of a source of AC operating potential 52, a voltage adjusting potentiometer 54 connected across the source 52, and a step-down type filamentary transformer 56. To adjust the magnitude of the current flow to the servo coil 28, an additional potentiometer 58 is included in the circuit, which is connected to the secondary winding of the step-down type Filamentary Transformer.

*Electrode control based on ignition voltage control*

Arcing during the EDM process usually results in an undesirable finish on the workpiece, as well as reduced efficiency of material removal. To prevent arcs, an arc protection circuit has been proposed by Syria et al. [25] which monitors the value of the ignition voltage applied across the gap between the electrode and the workpiece, assumed to be indicative of arcs occurrence.
The schematic of the arc protection circuit design is shown in Fig. (6). The design includes a voltage comparator. The ignition voltage signal from the signal conditioning circuit is connected via a resistor 27 to the negative input of the voltage comparator. The primary cut-off reference voltage is generated by a biased positive potentiometer 32 that is serially connected with resistor 34. The secondary cut-off reference voltage is generated by the potentiometer 32 and serially connected resistors 36 and 38 which are connected to the positive input of the voltage comparator.

A transistor 40 is connected serially to the resistor 38 to control the operation of primary or secondary cut-off reference voltages. When the transistor is in off state (operating in blocking mode), the primary cut-off reference voltage is applied to the positive input of the voltage comparator. On the other hand, if the transistor is on, the secondary cut-off reference voltage is applied to the positive input of the voltage comparator. During operation, if the ignition voltage level is above the primary cut-
off voltage, the voltage comparator will act as open switch, which results in the transistor 40 being turned off.

If the ignition voltage level at the negative input of the voltage comparator is below the primary cut-off reference voltage, then the voltage comparator will be act as an open circuit which will generate a large voltage control signal at the output of the voltage comparator. In this situation, the transistor 40 will be turned on, causing the secondary cut-off reference voltage to be applied to the positive input of the voltage comparator, which will generate a drive signal to drive servo mechanism to increase the gap between the electrode tool and workpiece, as well as a signal to increase the off time between successive electrical discharges. After this occurs, the ignition voltage will decrease below the secondary cut-off reference voltage. Because of the change in the duty cycle and the increased gap between the electrode tool and workpiece, the ignition voltage will again increase until it reaches a level greater than the secondary cut-off voltage. When this happens, the voltage comparator will be in open circuit status, and second control signal will appear at the output that causes the transistor to be turned off and the primary cut-off reference voltage is again applied to the positive input of the comparator. The servo drive mechanism in this case, will move the electrode tool towards the workpiece, and the duty cycle of the pulse generator is increased back to the normal operating level.

In summary, when the ignition voltage is decreasing, the primary reference cut-off voltage operates as reference, and when the ignition voltage is increasing, to provide a dynamic reference voltage change which prevents the electrode from moving away from the workpiece, the secondary cut-off voltage operates as the reference.
In adoption of this design, better cutting times can be achieved, due to its capability of providing a dynamic reference voltage change, hence on the electrode to eliminate the contamination problem.

Electrode control using acoustic signals

During each cycle of the machining process, the machining pulse (comprising the time-varying voltage across the gap and the time-varying current flowing through the gap) can belong to one of the following four possible pulse types:

- open-circuit pulse (too wide gap, no current, no material removed);
- short-circuit pulse (gap being too narrow);
- sparking or normal pulse (the right gap width); and
- arc pulse (due to increased density of debris, inefficient machining).

Ideally, we want all pulses to be of normal type. This would guarantee maximum efficiency in terms of material removal and surface finish quality. However, arc and short-circuit pulses are most harmful to the workpiece and can damage it (open-circuit pulses would reduce the efficiency). Arc pulses are the most challenging pulses to detect and differentiate from normal pulses. Indeed, short-circuits and open-circuits can be detected by thresholding the current and voltage signals. We will review methods developed for this task later.

El-Menshawy et al. [26] proposed an innovative and easily implementable technique to detect arc pulses. Instead of monitoring the voltage across the gap and/or the current flowing through the electrode and the workpiece to control the EDM machining process, they process the sound signals emitted from the gap between the electrode tool and the workpiece. They observed that during sparking, the level of
emitted sound energy is different from the sound energy emitted during arcing. This
discriminable difference is evident from the experimental results shown in Fig. (7).

![Sound Spectrum](image)

**Fig. (7). Sound Spectrum of Sound Energy Emitted Vs Frequency (KHz) [26]**

El-Menshawy et al. [26] suggested an acoustic transducer to be coupled to an
amplifier and utilized to detect the sound when installed near the machine. The
amplitude of the ultrasonic signal recorded by the transducer would be then smaller
when arc were occurring—see Fig. (8). The schematic design of the transducer
suggested by El-Menshawy et al. [26] is shown in Fig. (9).
Fig. (8). Waveforms occurring in an EDM machine and in amplifier coupled to a piezoelectric transducer in the vicinity of the machine [26].
The developed transducer can be placed in a number of locations to detect the sound energy level; one way is to place it anywhere in the dielectric liquid, but not at the gap between the electrode tool and the workpiece. The other way is to place the transducer outside the tank but in contact with it. The transducer can also be strapped to the workpiece or the electrode tool.

The design of the transducer consisted of 2mm thick and 9mm in diameter transducer disc made from piezoelectric ceramic as well as modified lead zirconate titanate ceramic PZT-4 which is placed inside an insulated tube filled with insulating material such as an epoxy resin. The whole insulated tube is then placed in a thin plastic envelope for protection, when the transducer is placed with the dielectric liquid. A direct electrical connection is made to the disc to obtain measurement signals. This transducer design can be used for frequencies ranging from 10Hz to 2 MHz. For higher frequencies, a thinner transducer disc must be used.

The signal obtained from the transducer is amplified by an amplifier with its bandwidth covering frequencies from 2KHz to 70KHz. The input signal amplitude determines the output signal amplitude preferably with a linear gain. The output form the amplifier is then processed by a diode detector that consists of a series diode and a shunt capacitor 41.
The designed transducer and its amplified output signal can be used in different ways to control the EDM process. One way suggested by El-Menshawy et al. is shown in Fig. (10). The output from the detector of the transducer is fed to a comparator 52 which compares the monitor signal from the designed transducer with a reference level given by the potentiometer 53. If the monitored signal is high, sparking is happening during the machining process and the comparator sends a signal to the OR gate 54 and then to the AND gate 55. The signal is combined with the output from the oscillator 56 through the AND gate to form a synchronised command delivered to the drive circuit to drive the semi-conductor rectifier into conducting condition. In this arrangement, the oscillator 56 provides 10 μs pulses followed by 5 μs gaps that allow the 10 μs pulses to reach the drive circuit 57 and drive the gate of the semi-conductor rectifier into conducting condition.

On the other hand, if the monitored signal is low, either arcing is occurring, or the signal is very low/zero due to short or open circuits. In this case, no signal will be sent to the OR gate 54, which results in no output from the AND gate 55 and no drive signal sent to the drive circuit.

The semi-conductor rectifier is connected in series with the parallel connected groups of transistors and DC power supply that control the movement of the electrode tool during the machining process. After a certain interval or start up of the process, the timer/pulse generator 58 under the control of the output from comparator 52 and inverter 59, will produce a start pulse that allows the semi-conductor rectifier to conduct again.
An alternative arrangement is shown in Fig. (11), in which the output from the detector of the transducer is connected to a comparator 52, which compares the monitor signal from the designed transducer with a reference level given by the potentiometer 53. If we have a sparking pulse or a start up pulse (generated by the oscillator 58), the monitored signal is high and the comparator sends a signal to the
OR gate 54 then the AND gate 56. The signal is combined with the output from the oscillator 22 through the AND gate to form a synchronised signal delivered to drive circuit that drives the groups of transistors at 18, so that machining takes place.

On the other hand, if the monitored signal is low due to short circuits or open circuits, no signal will be send to the OR gate 54, which results in no output from the AND gate 56 and no drive signal.

The advantage of this method allowed visual indication on whether sparking or arcing is taking place, as well providing a monitor and control parameters for EDM machining.

_Electrode control based on Pulse Discrimination._

Pulse discrimination control method is usually based on obtaining the gap status by direct discrimination of pulse types, and using the pulse type information to control the servo motor. The purpose of obtaining the gap status is to detect harmful pulses during machining and making changes to the EDM machining process to achieve stable and efficient EDM machining process.

Different pulse discrimination methods have been developed for different types of EDM Machines such as conventional EDM machine, micro-EDM machine, wire-EDM and EDG, as each type has its own operation condition. However, the classification of pulses during the discharge process is quite similar. As it was mentioned earlier, the four types of pulses are:

— Normal spark pulses – pulses during normal machining and the pulses during the build up of the plasma channel (ignition delay time) before the current starts flowing through the gap.
— Short circuit pulses – pulses during the period when EDM machine is in short circuit state, i.e. when the electrode is directly in contact with the workpiece, or when the gap voltage drops to zero while gap current remains at a typical short circuit value.

— Open circuit pulses – pulses during the period when the electrode tool and the workpiece are far apart, and no machining takes place.

— Arc pulses – pulses during the period when a small amount of debris is not fully flushed by the dielectric. The debris creates subsequent discharge at the same location that forms a relatively deep crater on the workpiece and damages the workpiece or the electrode tool.

Behrens et al. [27], [28] proposed a pulse discrimination method based on utilizing the relative frequency of short circuits and open circuits during an inspected period as input value to control the movement of the electrode. The threshold for different conditions such as open circuit threshold, ignition delay threshold, burning voltage threshold and short circuit threshold need to be determined experimentally. In one of the experiments conducted, the values were chosen at 80 V, 60 V, adjustable between 15 V and 33 V, and short circuit threshold of 5 V, respectively, as shown in Fig. (12).
Based on these levels, the relative frequency of short circuits and open circuit are inspected and compared with the threshold for relative frequency of open-circuits and short-circuits. If the measured relative frequency of open-circuits and short-circuits are below the defined relative frequency thresholds respectively, then no change will be made to the movement of the electrode tool. If the measured relative frequency of open-circuits is greater than the relative frequency threshold of open-circuit, the electrode tool will be moved towards the workpiece to decrease the size of the gap according to the defined proportional factor for open-circuit. In contrast, if the measured relative frequency of short-circuits is greater than the relative frequency of short-circuit, then the electrode tool will be moved further away from the workpiece to increase the size of the gap according to the defined proportional factor for short-circuit.
Behrens and Ginzel [27] also proposed to use the pulse discrimination outcomes in a fuzzy logic scheme to control the movements of the electrode. The details will be discussed in the next section.

In micro-EDM Wire EDM systems, usually RC type power supplies are used which is different from the types of power supply used in normal EDM. With RC power supplies, the pulse characteristics mandate specific pulse discrimination methods to be used.

Yan and Liao [29] proposed the following method for pulse discrimination with Wire EDM processes. The method utilizes the ignition delay time and the level of gap voltage information by comparing the instantaneous gap voltage. If the instantaneous gap voltage is higher than a predetermined reference voltage after a pre-set time delay, then the pulse is classified as normal discharge. On the other hand, if the detected voltage is lower than the reference voltage, the pulse is classified as abnormal discharge (arc or short circuit). Yan and Liao [29] also proposed to use the discriminated signal within a Fuzzy Logic scheme to control the feed-rate of the servo mechanism and the power settings such as the pulse off-time to achieve high metal removal rate and at the same time stabilize the machining process. The details will be discussed in the next section.

Liao et al. [30] proposed the following pulse discrimination technique for micro-EDM systems that uses the gap voltage and the pulse duration. In their method, three different voltage levels are classified as High ($V_{\text{high}}$), Medium ($V_{\text{medium}}$) and Low ($V_{\text{low}}$). Corresponding to these levels, duration of the pulses are represented by $t_{\text{high}}$ (the period during which the pulse is less than $V_{\text{high}}$), $t_{\text{medium}}$ (the period during which the pulse is less than $V_{\text{medium}}$) and $t_{\text{low}}$ (period during which the pulse is less than $V_{\text{low}}$).
During the machining process, the voltage values and the duration of the pulses are analysed and calculated, as shown in Fig. (13).

![Fig. (13). Pulse diagram under different time durations [30]](image)

The pulses are classified according to the calculated ratio of the pulse durations. If the ratio of \( t_{\text{medium}} / t_{\text{high}} \) is less than 0.2, then the pulse is classified as a complex pulse. When \( t_{\text{low}} / t_{\text{high}} \) is zero, the pulse is classified as an effective arc discharge. If \( t_{\text{low}} \) is not equal to zero and the \( t_{\text{medium}} / t_{\text{high}} \) is more than 0.7, the pulse is classified as transient short circuit pulse. When \( t_{\text{low}} \) is not equal to zero and \( t_{\text{medium}} / t_{\text{high}} \) is in between 0.2 and 0.7, the pulse is classified as normal discharge. The step-by-step flowchart of this method is presented in Fig. (14).
Tee et al. [31] have recently proposed a pulse discrimination method for Electric Discharge Grinding (EDM with rotating electrode) which is based on analysing the gap impedance. The gap impedance can be measured based on jointly analysing the detected gap voltage and the current signals. In this method, the detected gap voltage is compared with 4 thresholds: open circuit threshold \( (V_1) \), normal discharge threshold \( (V_2) \), arcing threshold \( (V_3) \) and short circuit threshold \( (V_4) \), and the current flowing through the gap is compared with 2 thresholds; open circuit current threshold \( (I_1) \) and short circuit current threshold \( (I_2) \) in real-time. The waveforms and thresholds are shown in Fig. (15).

Fig. (14). Flow chart of the pulse discrimination program.
Fig. (15). Gap Voltage and Gap Current Thresholds of the proposed pulse discrimination

[31]

Pulse discrimination is performed based on the following rules (\( I \) and \( V \) denote the gap current and voltage):

**Rule 1.** If \( I < I_1 \) and \( V > V_1 \) for longer than a pre-set off time, then the pulse is classified as an *open circuit* pulse.

**Rule 2.** If \( I_1 < I < I_2 \) and \( V > V_2 \), then the pulse is classified as a *normal pulse*.

**Rule 3.** If \( I_1 < I < I_2 \) and \( V_1 < V < V_2 \), then the pulse is classified as an *arc pulse*.

**Rule 4.** If \( I > I_2 \) and \( V < V_4 \), then the pulse is classified as a *short circuit* pulse.

Figure (16) shows a step-by-step flowchart of the pulse classification algorithm proposed in [31]. The voltage and current thresholds used in such methods vary with the workpiece material and preset current and voltage values. Thus, the optimum thresholds need to be determined by trial and error through experiments.
To explore the performance of the developed method, Tee et al. [31] had setup a simulation in Matlab Simulink environment with synthetic signal waveforms similar to the actual data of different pulse types contained in long train of EDM current and gap voltage pulses, that generated by the signal builder block.

Within the simulation, there are three main modules: Comparators, Pulse Train Processing (Pulse Discrimination) and Counter, as shown in Fig. (17).
The comparator module is responsible for processing the analogue signals generated from signal builder block, by comparing the values with the four voltage thresholds and two current thresholds by various comparators.

When the voltage and current are classified according to different threshold levels, a pulse train data will be generated for different thresholds, as shown in Fig. (18).

The Pulse Train Processing Module is responsible for discriminating the pulse according to the proposed pulse discrimination method shown in the Flow chart of the pulse discrimination method in Fig. (16).
Finally, the counter module is responsible for counting the number of occurrence of different discriminated pulses obtained from output of pulse train processing module.

Tee et al. [31] have evaluated their method in a set of simulations using real measured data. A snapshot of the results is shown in Fig 18. By comparing the ground truth with the classification results of the method, method proved to successfully classify all the input pulse waveforms. The simulations show that the method has two main advantages, one is computational efficiency due to requiring only a few comparator and counter units, and the other one is being suitable for discriminating pulses with narrow width which are usually generated by EDM machines with rotating electrodes.

Fuzzy logic-based electrode control

Fuzzy logic was inspired by fuzzy set theory introduced by Zadeh back in 1965 [32], [33]. Fuzzy logic allows to mathematically represent (otherwise vague) information that are given in linguistics terms such as low, medium and high, by making use of human approximate reasoning. Using this theory, effective decisions can be made on the basis of available imprecise linguistic information. Mamdani [34] was the first to use the fuzzy logic framework for control purposes in 1974. Since then, fuzzy controllers have been extended and applied in different applications including EDM control. When utilised for EDM control, fuzzy logic is usually combined with another control method such as pulse discrimination to improve the performance of the original controller.
The pulse discrimination method proposed by Behrens et al. [27], [28] was reviewed earlier in this paper. They used the pulse discrimination outcomes as inputs to a fuzzy controller to control the movement of the electrode. In their proposed scheme, the relative frequency of open-circuits and relative frequency of short-circuits are fuzzified using the fuzzy membership functions shown in Fig. (19)-(21).

![Fig. (19). Membership-functions of the input relative frequency of open-circuits. [27][28]](image1)

![Fig. (20). Membership-functions of the input relative frequency of short-circuits. [27][28]](image2)

The fuzzy controller output is then determined by combining the two fuzzified variables using the fuzzy rules shown in Table 1.
Table 1: Fuzzy Rules for the fuzzy values of the controller output [27] [28]

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<th>AND Operation</th>
<th>Relative open-circuit frequency</th>
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<tbody>
<tr>
<td></td>
<td>VL</td>
</tr>
<tr>
<td>Relative VL</td>
<td>Medium</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Very High</td>
<td>Very Low</td>
</tr>
</tbody>
</table>

When the controller output is low or very low, short-circuit pulses are being detected, so the electrode tool should move away from the work piece. If the controller output is medium, there are small number of open-circuits and short-circuits being detected, so there is no movement required for the electrode tool. If the controller output is high or very high, open-circuit pulses are being detected, so the controller should control the electrode tool to move towards the work piece.

The proposed pulse discrimination method Short Circuit/Open Circuit (SC/OC) based and the output from pulse discrimination method combined with Fuzzy Controller was tested against ignition delay time ($t_d$) based controller in terms of removal rate and electrode wear during roughing and finishing application to compare the effectiveness of the method.

Setup of the method:

The work piece used in the test is steel (56NiCrMoV7), and the property of the Electrode is Cu(+). The machining parameters that had been used in the test are shown in Table 2.
A Survey of Control Methods for EDM

The electrode lift-off movement triggered by a separate arc detection module performs the normal cleaning of the gap, so no external flushing for all tests. In treatment of the arcs, the current was first switched off, and if arcs still exist, then combination of an oscillating and retrieval movement of the electrode is performed to clean the gap. The arc detection and flushing mechanism is independent of the gap-width control. A number of experiments have been undertaken and the results have been reported by Behrens et al. [27], [28]. The results of the removal rate and electrode wear for roughing application from the test is shown in Fig. (21), while the removal rate and electrode wear for finishing application from the test is shown in Fig. (22).

<table>
<thead>
<tr>
<th></th>
<th>Finishing</th>
<th>Roughing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_e$ [A]</td>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>$U_0$ [V]</td>
<td>200</td>
<td>160</td>
</tr>
<tr>
<td>$t_e$ [$\mu$s]</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>$t_0$ [$\mu$s]</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Number of Arcs for flushing</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>depth for flushing</td>
<td>varying</td>
<td>10 mm</td>
</tr>
<tr>
<td>Time for testing</td>
<td>60 Min.</td>
<td>varying</td>
</tr>
</tbody>
</table>

The electrode lift-off movement triggered by a separate arc detection module performs the normal cleaning of the gap, so no external flushing for all tests. In treatment of the arcs, the current was first switched off, and if arcs still exist, then combination of an oscillating and retrieval movement of the electrode is performed to clean the gap. The arc detection and flushing mechanism is independent of the gap-width control. A number of experiments have been undertaken and the results have been reported by Behrens et al. [27], [28]. The results of the removal rate and electrode wear for roughing application from the test is shown in Fig. (21), while the removal rate and electrode wear for finishing application from the test is shown in Fig. (22).
The experimental results obtained by Behrens et al. [27], [28] demonstrate that their proposed method combined with Fuzzy controller gives better removal rate as well as minimum electrode wear on both roughing and finishing application, compared to SC/OC-based methods which in turn is better than the $t_d$-based method in terms of material removal rate and less electrode wear during roughing and finishing application. The reason that the proposed fuzzy controller outperforms the delay time ($t_d$) based controller is due to its advantage of reduced number of arcs caused by increased number of open-circuits during the process.

M.T. Yan and Y.S. Liao [29] had proposed a fuzzy control method for wire EDM, in which their proposed pulse discrimination method for wire EDM (reviewed earlier in this paper) with a fuzzy logic-based reasoning method to control the EDM process. In the fuzzy controller design, there are three inputs which are calculated from the outcomes of the pulse discrimination. The first input, denoted by $e_1$, is the error of sparking frequency (number of sparking pulses per second, in Hertz) from the
reference value defined for the sparking frequency. The second input, denoted by $e_2$, is the error of ab\textit{normal ratio} (cumulative ratio of short-circuit and arcing pulses in percent) from its reference value. The third input is the change of abnormal ratio error, denoted by $ce_2$. The input $e_1$ is fuzzified using three fuzzy sets labelled as positive (P), zero (ZO), and negative (N) which refer to safe, critical, and wire rupture regions, respectively. These regions are relevant to the control of the movement of the servo mechanism and the power settings. The second and third inputs, $e_2$ and $ce_2$, are fuzzified using five fuzzy sets labelled as negative big (NB), negative small (NS), zero (ZO), positive small (PS) and positive big (PB). The above mentioned fuzzy sets are defined by the membership functions shown in Fig. (23).
Fig. (23). Membership functions used to fuzzify the three inputs of the fuzzy EDM controller proposed in [29].

The fuzzy controller uses an ensemble of fuzzy if…then… rules to generate its two outputs: $\Delta u_1$ and $\Delta u_2$, where $u_1$ represents federate, $u_2 = 1/t_0$ is the inverse of the pulse off-time, and

$$u_1(kT) = u_1((k-1)T) + \Delta u_1(kT)$$

$$u_2(kT) = u_2((k-1)T) + \Delta u_2(kT)$$

where $kT$ is the $k$-th sampling time instant. Each fuzzy rule has the following general form: If $e_1$ is $A$ and $e_2$ is $B$ and $ce_2$ is $C$ then $\Delta u_1$ is $D$ and $\Delta u_2$ is $E$. The parameters $A$, $B$, $C$, $D$ and $E$ are each, one of the fuzzy sets using which the inputs or outputs are fuzzified. Indeed, for the inputs, we have: $A \in \{N,ZO,P\}$, $B \in \{NB,NS,ZO,PS,PB\}$, $C \in \{NB,NS,ZO,PS,PB\}$. The two outputs are also hypothesised to belong to fuzzy sets similar to the inputs $e_2$ and $ce_2$, i.e. $D \in \{NB,NS,ZO,PS,PB\}$ and $E \in \{NB,NS,ZO,PS,PB\}$. The fuzzy membership for output variables are exactly same as the ones shown in Fig. 23 (b).

The ensemble of if…then… fuzzy rules are listed in Tables 2-4. These rules are designed based on experimental observations. For instance, when the sparking frequency is in the safe region (that is, $e_1$: Positive) and the abnormal ratio is far larger than the predetermined value (that is, $e_2$: PB) but it decreasing fast (that is $ce_2$: NB), then the feedrate should slightly increase ($\Delta u_1$: PS) and the pulse off-time should slightly increase as well (so its inverse should slightly decrease, i.e. $\Delta u_2$: NS). This rule is abstracted as below:
If $e_1$ is P and $e_2$ is PB and $ce_2$ is NB, then $\Delta u_1$ is PS and $\Delta u_2$ is NS, as shown in the top-right elements of the $\Delta u_1$ and $\Delta u_2$ tables shown in Table 3.

In the above Fuzzy rules, the fuzzy reasoning on the linguistic control rules is determined using max-min inference method. The defuzzification process is done based on the center-of-area method. And it can be presented as:

$$
\Delta u_1 = \frac{\sum_{j=1}^{n} \mu_p(u_j) \times u_j}{\sum_{j=1}^{n} \mu_p(u_j)} \times GU_1
$$

(3)

$$
\Delta u_2 = \frac{\sum_{j=1}^{n} \mu_x(v_j) \times v_j}{\sum_{j=1}^{n} \mu_x(v_j)} \times GU_2
$$

(4)

where $u_j$ and $v_j$ are the support values when the membership function reaches the maximum value of $\mu_p(u_j)$ and $\mu_x(v_j)$ respectively, $n$ is the number of quantification levels and $GU_1$ and $GU_2$ are scaling factors.

Table 3: Fuzzy if…then… rules for the case when $e_1$: Positive [29]

<table>
<thead>
<tr>
<th>$e_2$</th>
<th>$e_1$</th>
<th>$\Delta u_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
</tbody>
</table>

Table 4: Fuzzy if…then… rules for the case when $e_1$: Zero [29]

<table>
<thead>
<tr>
<th>$e_2$</th>
<th>$e_1$</th>
<th>$\Delta u_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>NS</td>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
</tbody>
</table>
B. On-time Power Control

In terms of the depth of cutting, electric discharge machining is performed on the workpiece in a number of phases. In the initial phase, the machining operation performs the cut on the workpiece to some initial depth. The workpiece is then cut increasingly deeper in the next phases until the desired material removal is achieved.

During each phase of machining, debris is formed and the dielectric fluid flowing through during flushing may not be able to flush away all the debris before
the next phase of machining takes place. In such a case, in the next phase of machining, the machining will be performed on the debris that are formed near the cutting area before taking place on the workpiece for a deeper cut, and this will significantly reduce the efficiency of the machining process.

By controlling the rate of the debris produced, or controlling the average particle size of the debris, the efficiency of the machining process would be greatly increased, due to the fact that the cutting spark is able to perform the deeper cut on the workpiece rather than removing the debris formed near the cutting area before performing the deeper cut on the workpiece. Jarlabek [35] has stated that the amount of debris formed during machining is directly related to the average power level which in turn depends on the on-time power levels supplied to the cutting spark. Thus, an EDM control scheme was proposed in [35] based on the following experimental observation: reducing the on-time power setting would generally reduce the average particle size of the debris, resulting in a deeper cut on the workpiece in each phase of machining and better surface finish.

Jarlabek [35] also observed that although the length of the off-time could affect the average particle size of the debris formed during machining, but no significant effect was observed on the characteristics of the cutting spark, e.g. the size and the finish of the cut. More precisely, by increasing the off-time, the rate of debris production could only be reduced by as much as one quarter to half.

To reduce the on-time power level, it was suggested that one or more of the working gap voltage, the peak current or the on-time should be reduced. However, it is not possible to determine the optimum parameters at the start of the machining process, as each phases of machining are independent. Therefore, controlling the on-time power level is performed through an iterative process. The distance between the
electrode and the workpiece is monitored during the machining process, and it is compared with a predetermined distance. Once it reaches the predetermined distance, the power to the electrode is cut off. The process is repeated until machining is complete.

The advantage of this proposed method is the ability to reduce the debris, hence a deeper cut in each phase of the electrical discharge machining process by reduce the on-time power level.

C. Pulse Number Control

Another way of controlling the EDM process, suggested by Dauw [36], is to adjust the pulse generator as a function of the volume of the material removed which is related to the rate of wear of the electrode tool. Dauw [36] invented a method and an apparatus for measuring the rate of wear of an EDM electrode tool. By utilising this information, a control signal is supplied to the pulse generator which in turn controls the number of pulses applied to the electrode during the machining process that leads to controlling of the EDM machining process.

To measure the rate of wear of an EDM electrode tool, the speed at which the voltage drops from no-load to cutting voltage is taken into account by measuring the time taken for voltage to drop from no-load to state to cutting voltage state. The measured time is then used to determine the amount of the material removed in a single discharge as follows:

\[
\Delta q = e^{t_f/k}
\]

where \(\Delta q\) is proportional to the quantity of the material removed in the course of one discharge, \(t_f\) is the time taken for the voltage to drop from the open-circuit value
(\(U_i\)) to the cutting (burning) voltage (\(U_2\)), and \(k\) is a constant which is a function of the voltaic cell formed by the metals.

The electrode wear rate (\(U_R\)) is then accumulatively calculated for every set of \(n\) consecutive pulses as follows:

\[
U_R = K_R \frac{\sum_{i=1}^{n} e^{-t_e(i)/k}}{\sum_{i=1}^{n} t_e(i)}
\]

where \(K_R\) is the constant depending on the couple of metals of the positive and the negative electrodes, and \(t_e(i)\) is the duration of the discharge current for the \(i\)-th pulse.

In the control method of Dauw [36], a control signal is generated based on the computed electrode wear rate (\(U_R\)) then sent to the pulse generator to improve the sparking efficiency. This invention includes unique experimental concepts that depart from the EDM traditional sparking phenomenon. Despite a range of different approaches, this new research shares the same objectives of achieving more efficient metal removal coupled with a reduction in tool wear and improved surface quality.

### D. Cracks Prevention

Recently, the use of EDM on non-conductive material has become a trend. Non-conductive materials are usually exceptionally hard or brittle, fragile or intricate, such as ceramics. Thus, cracks can be formed on the workpiece surface or just beneath the surface during the EDM process, especially when arcing condition occurs which leads to the material being detached from the workpiece as a result of the cracks, causing undesirable machining on the workpiece.
Huddleston and Hill [37] found out that useful information regarding the state of the EDM process can be provided by acoustic emissions that can be detected on or below the surface of the workpiece. Based on this finding, they developed a feedback control mechanism which makes use of the characteristics of the acoustic emissions in conjunction with the current flow information to control the machining process. The design consists of an acoustic sensor coupled to a workpiece during the machining process. The sensor receives acoustic emissions during machining and provides an output signal which can be used to determine if cracks are formed on the workpiece, and whether the material is being detached from the workpiece as a result of cracks. This method can be applied to more recent techniques involving the machining of non-conductive workpiece such as the methods involving special electrolytes in place of the dielectric fluid or using a specially coated workpiece as well as traditional machining techniques. The schematic diagram of the design is shown in Fig. (24).
The electrode tool (head 21) are connected to a position control system 33 and current delivery and control system 34 that supplies the electrical discharge current to the electrode during the EDM process. The acoustic sensor can be coupled to the workpiece in a number of ways. One way is to couple it to the workpiece and to the position control system 33 which provides the relative movement according to the machining process. The other way is to couple the acoustic sensor using the acoustic conduction properties of the dielectric fluid 10 that provides the sparking or discharge medium between the electrode tool and the workpiece. The acoustic coupling may also be enhanced by a coupling gel between the acoustic sensor and the workpiece.

The output of the signal from the acoustic sensor is the input to an amplification and filtration system 24 which amplifies the acoustic sensor output and removes unwanted noise and interferences during the machining process.

If the acoustic sensor output frequency is below 100 kHz, it will be removed before the signal is processed using selective signal amplification or an acoustic transducer resonant sensitivity. A signal from the current control system 34 that represents the electrical current delivered to the EDM is fed into the differentiating and amplification circuit 26 which generates a current signal and a current derivative signal as a function of \( \frac{dl}{dt} \), where \( l \) is the electrical current comprising the electrical discharge signal and \( t \) is the time. The current signal, the current derivative signal from the amplification circuit 26 and the acoustic sensor signal (passed the amplification and filtration system 24) are fed into a signal processing circuitry 25, then captured and stored in the computer memory in the decision making circuit 27.

Based on the received signals, the decision making circuit 27 determines the state of the EDM process, by determining whether the acoustic emission relates to a
A Survey of Control Methods for EDM

spark discharge or an arc discharge or a cracking event. To decide which of these events is occurring, the decision making unit 27 processes the amplitude and/or acoustic energy values recorded during a time window that is equal or close to the duration of the current discharge pulse or pulses applied on the material.

Depending on the state of the EDM process, different procedures will be followed. If the state of the EDM process is determined as a spark discharge or arc discharge, operation will be carried out by the spark detection module 30. If the state of the EDM process is a cracking event, operation will be carried out by the cracking detection module 29. The operation can be changing the position of the electrode tool or the workpiece, reduction of the current delivered by the electrode or the time interval of the discharge or even changing the electrical discharge machining operation mode.

During the control of the EDM process, a hardware module 28 may be used to control and/or interrupt parameters to be used based on the detected acoustic and current characteristics. The operation output from either (1) spark detection module 30, (2) cracking detection module 29 or (3) hardware module 28 is fed into a machine control circuit 31, that checks whether the operation is it within the desired parameters and if required, the control signal may be changed by providing specified control parameters or overridden by the user control unit 32 which is connected to the machine control circuit 31 before being applied to the position control system 33 and the current control system 34. Another way to make changes or overrides is to directly interface with the decision making circuit 27.

With this feedback and control mechanism, the ability to detect the occurrence of cracking on the workpiece and modify the electrical discharge to prevent or inhibit further cracking is possible.
III. CONCLUSIONS

In this paper, different ways of controlling the EDM process were surveyed. The control methods were categorized into four classes, namely the methods that are based on electrode movement control, methods based on on-time power control, methods based on pulse number control, and methods based on cracks prevention. A summary list of the surveyed methods is presented in Table 6.

Out of four types of control methods, the most commonly used is the family of methods that work based on directly controlling the movements of electrode. Within this category, different designs were reviewed. In the early stage of the developed electrode movement control methods, the control was based on direct comparison of the measured signal such as voltage or current with some reference signals. Later on, the designs were enhanced and the measured signals were processed before being used to control the electrode movement. For instance, in pulse discrimination techniques, the type of the discharge was categorized and the pulse statistics were used to control the machining process. In most recent methods, pulse discrimination methods were combined with fuzzy logic controllers to control the electrode movements towards achieving better machining performance.
Table 6: Summary list of the surveyed EDM/EDG control and monitoring methods.

<table>
<thead>
<tr>
<th>Category</th>
<th>Method</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Movement Control</td>
<td>Electrode control based on relative velocity of electrode [22]</td>
<td>The electrode is slowed or stopped when the displacement passes a reference position, while maintaining electrical discharges across the gap.</td>
</tr>
<tr>
<td></td>
<td>Electrode control based on gap voltage [24]</td>
<td>An improved general control circuit for the feed of the electrode tool in a servo feed system for EDM.</td>
</tr>
<tr>
<td></td>
<td>Electrode control based on ignition voltage control [25]</td>
<td>Better cutting times can be achieved with this method, due to its capability of providing a dynamic reference voltage change, hence eliminating the contamination problem.</td>
</tr>
<tr>
<td></td>
<td>Electrode control using acoustic signals [26]</td>
<td>This method allowed visual indication on whether sparking or arcing is taking place, as well as providing monitoring and control parameters for EDM machining.</td>
</tr>
<tr>
<td></td>
<td>Electrode control based on Pulse Discrimination [27-31]</td>
<td>Discriminating normal, arch and short-circuit pulses based on voltage and current levels and comparing them with thresholds, then using the pulse type statistics for electrode movement control.</td>
</tr>
<tr>
<td></td>
<td>Fuzzy logic-based electrode control [27-29]</td>
<td>Combines pulse discrimination method with a fuzzy controller for electrode movement control.</td>
</tr>
<tr>
<td>On-Time Power Control</td>
<td>Method of Jarlabek [35]</td>
<td>Based on controlling the on-time power level, which allows to reduce the debris, hence a deeper cut in each phase of the electrical discharge machining process.</td>
</tr>
<tr>
<td>Pulse Number Control</td>
<td>Proposed by Dauw [36]</td>
<td>Measuring the rate of wear and utilizing rate of wear information to supply a control signal to the pulse generator which in turn controls the number of pulses applied to the electrode during the machining process.</td>
</tr>
<tr>
<td>Cracks Prevention Control</td>
<td>Feedback and control mechanism proposed by Huddleston and Hill [37]</td>
<td>Based on detecting the occurrence of cracking on the workpiece and modify the electrical discharge to prevent or inhibit further cracking.</td>
</tr>
</tbody>
</table>

IV. CURRENT & FUTURE DEVELOPMENTS

From the literature review, we have identified a number of possible avenues for further research and development in the field of designing and developing control and monitoring techniques for electrical discharge machining technology. With the recent proliferation of low-cost high speed and memory-rich processing platforms, it is envisaged that a new generation of intelligent real-time control methods can be developed. In such methods, complex signals can be processed and optimal control
methods can be employed to use those processed signals based on the physics of the plasma created within the discharge gap.

Another avenue for further research and development work is to devise and develop pulse controllers based on the physical principles of plasma created within the gap between the electrode tool and work piece. Such principles have not been investigated in the literature for their utilization within the controller design process.

The literature has well demonstrated that machining quality and material removal rate improve when pulses with shorter on-time are used for electrical discharge grinding. Implementing shorter on-times requires faster processing and data acquisition system. High speed processor and acquisition systems can also be utilized in an adaptive, non-linear controller such as the piecewise linear controller shown in Fig. (25). But with the help of faster processor and data acquisition systems, it is also possible to explore the possibility of multi-variable input applied to non-linear control.

![Piecewise Linear Curve](image-url)
ACKNOWLEDGEMENTS

This research was supported by Advanced Manufacturing Corporate Research Centre under the Australian Government’s Cooperative Research Centres Program as Project No. 2.2.1.

REFERENCES


Fig. (25). Piecewise linear controller curve
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