Controlling Electrochemical Machining By Using a Fuzzy Logic Approach

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Abstract
New trends and the effect of key factors influence the quality of the holes produced by ECM processes. Researchers developed a fuzzy logic controller by adding intelligence to the ECM process. Maintaining optimum ECM process conditions ensures higher machining efficiency and performance. This paper presents the development of a fuzzy logic controller to add intelligence to the ECM process. An experimental ECM drilling was improved through the integration of a fuzzy logic controller into the existing control system. Matlab (Fuzzy Logic Toolbox) was used to build a fuzzy logic controller system, which controls the feed rate of the tool and the flow rate of the electrolyte. The objective of the fuzzy logic controller was to improve machining performance and accuracy by controlling the ECM process variables. The results serve to introduce innovative possibilities and provide potential for future applications of fuzzy logic control (FLC) in ECM. Hybrid controllers that integrate fuzzy logic into the control system allow for "human like" decision-making intelligence to be incorporated into ECM controllers.

1. Introduction
One of the tools for integration of design and manufacturing is expert systems. An expert system (also called a knowledge-based system) is, generally, defined as an intelligent computer program that has capability to solve difficult real-life problems by the use of knowledge base and inference procedures. The goal of an expert system is the capability to conduct an intellectually demanding task in the way that a human expert it. The field of knowledge required to perform this task is called the domain of the expert system. Expert system utilizes a knowledge base containing facts, data, definitions, and assumptions. They also have the capacity for heuristic approach that is making good judgment on the basis of discovery and revelation, and making high probability guesses just as a human expert would [1, 2]. Electrochemical machining (ECM) uses electrical energy to remove material. An electrolytic cell is created in an electrolyte medium, with the tool as the cathode and the workpiece as the anode. A high-amperage, low-voltage current is used to dissolve the metal and to remove it from the work piece, which must be electrically conductive. ECM is essentially a depleting process that utilizes the principles of electrolysis. The ECM tool is positioned very close to the work piece and a low voltage, high amperage DC current is passed between the two via an electrolyte. Material is removed from the work piece and the flowing electrolyte solution washes the ions away. These ions form metal hydroxides which are removed from the electrolyte solution

by centrifugal separation. Both the electrolyte and the metal sludge are then recycled. Unlike traditional cutting methods, work piece hardness is not a factor, making ECM suitable for difficult-to-machine materials. It takes such forms as electrochemical grinding, electrochemical honing and electrochemical turning. Characteristic of ECM machining are: a) there is no tool wear during electrochemical machining. b) The components are not subject to either thermal or mechanical stress. c) Complex shapes can be machined repeatedly and accurately. d) Electrochemical machining is a time saving process. e) There is no contact between the tool and work piece. f) Hard and also brittle material can be machined easily. g) During drilling, deep holes or several holes at once can be made. h) ECM deburring can debur difficult to access areas of parts. i) Surface finishes of 25 μ in. can be achieved. Researchers developed electrochemical micromachining EMM setup mainly consists of various sub-components and systems, e.g., mechanical machining unit, micro tooling system, electrical power and controlling system and controlled electrolyte flow system, etc. All these system components are integrated in such a way that the developed EMM system setup will be capable of performing basic and fundamental research in the area of EMM fulfilling the requirements of micromachining objectives [3]. Other researchers discussed about the latest advances and the principal issues in ECM development and related research are raised. Developments in tool design, pulse current, micro-shaping, finishing, numerically controlled, environmental concerns, hybrid processes, and recent industrial applications, are covered [4]. Mount et al. analyzed current transients during electrochemical machining (ECM) at a planar workpiece planar tool configuration results in the determination of the important parameters for the ECM process. These have been used in finite difference simulation of the ECM process, which allows simulation of the current transients and tool and workpiece configurations at any time for non-planar configurations more applicable to industrial ECM. Small differences in the simulated and experimentally observed current transients are often observed, which can be attributed to variation of the combined ECM parameters [5]. Mohan Sen and Shan highlight the recent developments, new trends and the effect of key factors influencing the quality of the holes produced by ECM processes [6]. Labib et al. developed a fuzzy logic controller to add intelligence to the ECM process. An experimental ECM drilling rig, at University of Manchester, was improved through the integration of a fuzzy logic controller into the existing control system. Matlab (Fuzzy Logic Toolbox) was used to build a fuzzy logic controller system, which controls the feed rate of the tool and the flow rate of the electrolyte. The objective of the fuzzy logic controller was to improve machining performance and accuracy by controlling the ECM process variables. The results were served to introduce innovative possibilities and provide potential for future applications of fuzzy logic control (FLC) in ECM. Hybrid controllers that integrate fuzzy logic into the control system allow for "human like" decision-making intelligence to be incorporated into ECM controllers. They focused on feasibility of FLC in ECM [7]. In other words, electrochemical machining (ECM) is a non-traditional process used mainly to machining hard or difficult to machining metals, where the application of a more traditional process is not convenient. In traditional processes, the heat generated during the machining materials is dissipated to the tool, chip, work piece and environment, affecting the surface integrity of the work piece, mainly for those hard materials. In ECM, there is no contact between tool and work piece. Electrochemical (electrolysis) reactions are responsible for the chip removal mechanism [8]. The difficulties to cut

super alloys and other hard-to-machine materials by conventional process have been largely responsible for the development of the ECM process. The main components of ECM system are a low voltage and high current power supply and an electrolyte. The electrolyte is normally solutions of salts, like sodium chloride (NaCl) or sodium nitrate (NaNC3). It is also necessary pumps, filters, heat exchanger and an enclosure where the reactions occur [9-12]. There are basically numbers of parameters that affect the work piece tolerances such as current, electrolyte type, concentration, flow rate, inter electro gap etc. [13]. In the electronic industry, electrochemical micro-machining (ECMM) is received much attention for fabrication of micro components: by dry etching material which is removed at very precise resolution. In recent years, ECM has received much attention in the fabrication of micro parts [14-19]. Electrochemical micro machining ECM is an electrochemical anodic dissolution process [20]. Direct current is passed between a workpiece (the anode) and a pre-shaped tool (the cathode), with electrolyte flowing through the gap to complete the circuit. The tool shape is copied (formed) into the anodic workpiece surface through the metal being dissolved into metallic ions by electrolytic action. Hence ECM changes the shape of the workpiece by removing metal through electrolytic action. EMM has evolved from ECM due to miniaturization developing as a future trend in production demands. Researchers comment that because of the inherent machining advantages ECM has over other processes, ECM appears to be very promising as a future micromachining technique [21, 22]. These authors state that, ''In EMM the inter-electrode gap control plays an important role.'' It follows that the inter-electrode gap has a major role in the accuracy of the machining process [22- 25]. In conclusion, Bhattacharyya et al. comment that further work is required into EMM inter-electrode gap control and machining parameter control [2]. Bhattacharyya and Munda continued their work into EMM and presented further findings from their experimental EMM rig set-up [22, 23]. They discuss features such as inter-electrode gap control, which consists of a Boolean logic-based control system that compares power input signals to a reference voltage. The performance of ECM is affected by many inter linking machining process variables [24]. Optimum process conditions allow for high ECM performance in terms of surface finish and rate of machining. It follows that optimum process variables are desirable in order to ensure optimum machining conditions and performance. Process deterioration is identified through indirect interpretation of a process variable moving out of the acceptable operational range. The interlinking variables are highly nonlinear and complex in nature and it is therefore very difficult to develop an exact mathematical model to control the machining process. The result is that conventional linear control strategies become extremely complex to construct and may still not adequately model the ECM process. Existing operational procedures for ECM machines are mainly based upon in-house ''trial and error'' experiments to achieve process parameter optimization. ECM parameters and tool design still rely very much on the input by the human expert based on his personal knowledge and experience. It seems that an industry standard, in terms of ECM/EMM optimum process parameters, may not be so straightforward. Gap conditions in ECM are random in nature due to the variable state of the electrolyte condition and the machining process itself is subject to various practical complications (e.g. debris in the gap causing sparking) that affect machining performance [25]. Also, critical operator machining decisions are based upon the operator's knowledge and experience from using ECM machining. For this reason the application of fuzzy logic is well suited for such a control problem, as the fuzzy if-then rules provide the

foundation for an expert knowledge-base and inference engine. This inference engine can then be incorporated into a control system to provide real-time decision-making intelligence to monitor and control the machining process. It was thus the main objective of the research to create a fuzzy logic controller to be integrated into the ECM rig Visual Basic (VB) control system, enabling the control system to act 'intelligently' throughout the machining process. Creating a fuzzy logic controller will serve two purposes: (1- to investigate the concept of integrating fuzzy logic into the experimental ECM drilling; and (2) to investigate the potential of fuzzy logic control (FLC) to ensure higher levels of machining performance through inter-electrode gap control. Zadeh in1965 introduced fuzzy set theory in the 1960s [26]. Here cognized that many shades of grey found in the real world were not covered by Boolean logic. In fuzzy logic instead of something being 100% true or false, it deals in degrees of membership ranging from zero to one and so something can be partially true and false at the same time. Classical Boolean logic prevailed before fuzzy logic, the idea being the whole universe could be either A or not A and so everything is accounted for wholly either by one group or another. However, it was proven by Kosko in1994 that Classical Boolean logic is just a special case of fuzzy logic [27]. Fuzzy logic allows nonlinear functions to be modeled; it is easy to use, to understand and to implement. Based upon the present authors' research findings, FLC is ideally suited to ECM, as FLC is an effective control strategy for nonlinear/uncertain process applications. Applications of fuzzy logic have been proposed by the first author of this paper in a variety of applications such as maintenance [28], design [29], reconfigurable manufacturing [30, 31], and production scheduling [32], as well as applications of fuzzy sets in design. In recent times, published work relating to the application of fuzzy logic to ECM is limited. However, FLC has been applied to other members of the non-conventional machining processes family, e.g. electro-discharge machining [33, 34]; applied a fuzzy logic controller to electro-polishing of cobalt chromium dental cast alloys. They presented a fuzzy logic controller with 16 fuzzy rules, which completely automated the polishing process. The fuzzy logic controller approach is used to extract key interlinking machining process features, capturing this knowledge in a fuzzy rule-base to be used as the control system's inference engine. The addition of FLC to ECM provides expert real-time operational intelligence, which may result in more consistent levels of machining performance.

2. Electrochemical Machining

The following section presents three annotated pictures to enable the reader to gain an appreciation for the ECM. Figure 1 presents a picture of the whole ECM; the major parts are identified as the control PC, the power supply and the ECM. Figure 2 presents a more detailed look at the ECM machining chamber. All physical drilling takes place within the machining tank. The tool is fed backwards and forwards manually using the stepper motor, which is controlled through the VB program on the PC. The tool is hollow to allow electrolyte to be pumped through it. It also has the negative electrode connected to it, which allows it to take a negative charge during machining. The positive electrode is also shown, which is attached to the vice that clamps the workpiece. The machining tank encases all machining activity and prevents the electrolyte from escaping. It also has two flow back tubes to allow process electrolyte to return to the main electrolyte tank. On some occasions electrolyte spray may escape from the tank and so a screen has been installed around the whole chamber to protect neighboring rig components form the electrolyte, which is a 20% by

weight sodium chloride (NaCl) solution. The ECM machining chamber is mounted upon a trolley table, which also has the conductivity meter on it. In this picture, the 0.75 Kw pump and automatic valve are shown. This draws electrolyte from the electrolyte tank and pumps it up.
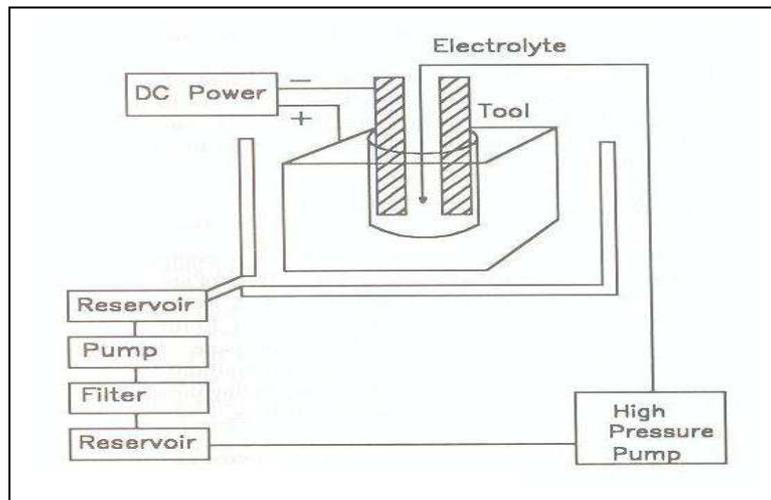
Figure1. Schematic diagram of Electrochemical Machining
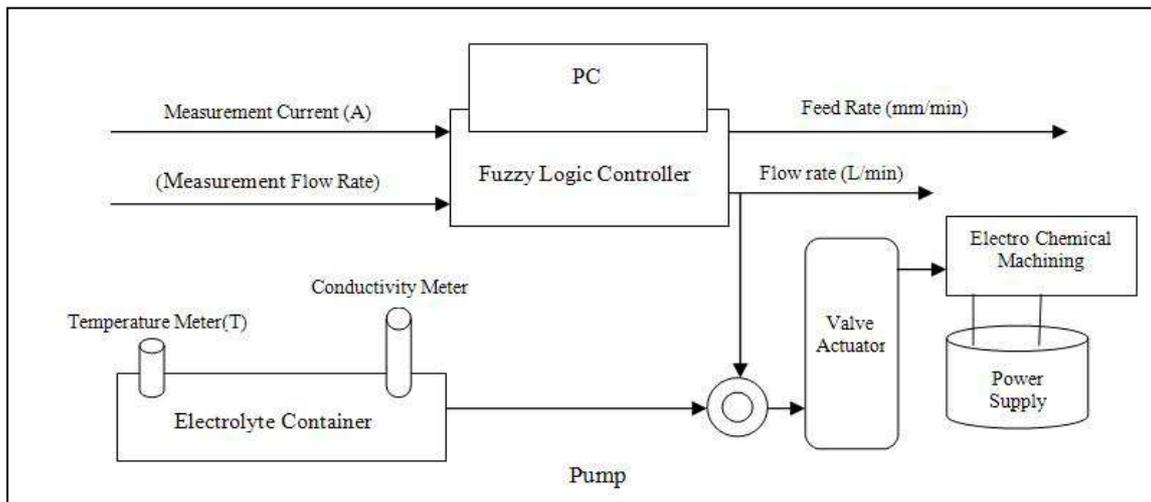
Figure2. Elements of fuzzy logic controller and ECM machining chamber

3. The Fuzzy Logic Controller: Design Methodology

1. Analysis and partition of the control system previously, machining decisions were subject to interpretation from the machine operator, as the machine operator managed the VB controller and rig manually through indirect interpretation of process variable measurements (e.g. If the flow rate of the electrolyte reduces, then the manual flow valve is opened). In order to control the ECM drilling process, the following input variables were identified and measured: voltage, current, measured flow rate, electrolyte conductivity and electrolyte temperature. These are used to monitor the ECM drilling process and give the operator an indication of process conditions. As this was the first attempt at integrating FLC into the experimental ECM drilling rig, a simple fuzzy logic

controller was created; but one that would still provide the means to investigate research objectives. The fuzzy logic controller was created in Math works (2004) Matlab Fuzzy Logic Toolbox. Two fuzzy logic controllers, consisting of two inputs and one output each, were created to monitor and control both the feed rate and the flow rate (valve position) of the ECM process. Both could be combined together producing one fuzzy logic controller, consisting of two inputs and two outputs. However, the first author built two separate controllers because it was easier to investigate their robustness and accuracy when separate. This is not to say that they cannot be combined, but that they are separately constructed and later implemented as one fuzzy logic controller into the physical system. In the combined fuzzy logic controller there are two input variables, but they can be considered twice, giving four input variables. This is because in each case although the input variables are the same, they are constructed differently depending on the output they are mapped to. This is understood as the operator relating the inputs to the output, in each case, using different linguistic terminology, and so the Membership Functions (MFs) are different.

2. Defining the input and output membership functions: After deciding upon the inputs and outputs of the Fuzzy Inference System (FIS), the next step was to define all the MFs and universe of discourse for each variable. The number of MFs defines the precision of the system. The more MFs, with smaller scope, acting over the same universe of discourse, the more precision is built into the system. The trade-off here is that more MFs result in more rules, and one may come to a point where computer processing time is slow because of the number of rules the controller has to evaluate. Fuzzy logic allows precision to be traded off against significance and so depending upon the situation the number of MFs can be reduced with the system still yielding the desired output result. The universe of discourse of the MF, for each variable, was defined through previous experiments and operator rig experience/knowledge. For example, as the valve actuator is controlled through a 0–10 V input range; the universe of discourse is set from0 to 10 V. Other universes of discourse are: Input current is 0–50 A; Input measured flow rate is 0–11 l/min; and output feed rate is1.0–1.0 mm/min. The valve position, as mentioned previously, can be between 0 and 10 V. For output variable, feed rate, one MF allows for the control system to output reverse feed rate values. It also acts as a counter balance, in that when the FIS applies the COG method of areas that include MF, optimal and reverse feed rate, smaller feed rates are the resulting output. In terms of the objective of this research to use fuzzy logic to maintain the inter-electrode gap, one can see that a more gradual change in output feed rate will result in process variables change. Input and output of the fuzzy controller is demonstrated in Figure 3.

3. Development of the rules: Table 1 shows the 31 rules generated, of which the first nine manage the electrolyte flow rate through the control of the ECM valve/actuator set. Rules 23–31, control the tool feed rate, pump conductivity, meter machining, stank stepper, A motor automatic valve flow back tubes screen accounts for the tool moving in either a positive (away from the workpiece) or negative (towards the workpiece) direction. All rules were generated through operator experience and then fine-tuned to provide the desired effect, which accounts for the number of rules being used.
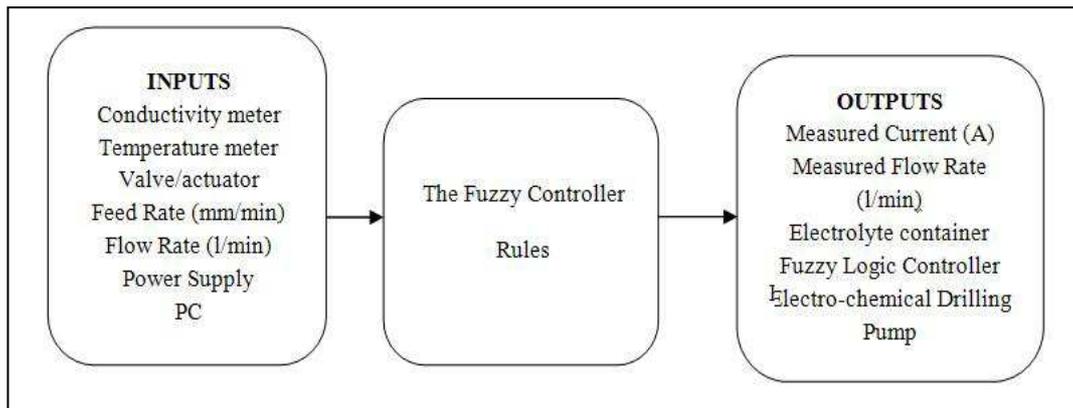
Figure3. Input and output of the fuzzy controller

4. Output control surfaces: This discussion aims to explain key control areas of the output surfaces generated from the FIS built in Matlab, relating this back to the physical ECM process. As the machining process begins the tool fed towards the workpiece, current starts to increase and the flow rate either stays the same or drops slightly. This is recognized by the transient stage on the control surface. Once the equilibrium position is reached, the inter-electrode gap should remain reasonably constant, which is the optimum machining area of the control surface. It is the objective of the fuzzy logic controller to keep the ECM process within this optimum machining area of the control surface and so if flow rate reduces and/or the measured current increases, the controller will output a result to bring conditions back to optimum analysis and partition of the control system previously, machining decisions were subject to interpretation from the machine operator, as the machine operator managed the VB controller and ECM manually through the transient stage and the optimum machining area is also indicated on this surface. In the case where the measured flow rate drops and the measured current increases due to the tool moving too close to the workpiece, the output result is for the valve position to open to a maximum, i.e. 10 V, increasing the flow rate.

4. The Fuzzy Logic Controller (FLC): Design Methodology
FLC integration into the VB controller: The existing controller consisted of in-house software developed in VB to control the tool feed rate and collect real-time probe data every second. The introduction of the new valve/actuator set allowed for the electrolyte flow rate to be controlled using an upgraded version of the VB controller. The final upgrade phase for the VB controller was the integration of the FLC. Specific to this research project, the best way would be to make the VB program directly interrogate the FIS created in Matlab. This would be possible with further investigation into Matlab and Dynamic Data Exchange (DDE). Due to the research project timescales (Keasberry, 2004), this was not possible and an alternative method was used to integrate FLC into the existing VB controller. The method used was to generate look-up tables directly from the FLC based output control surfaces, within Matlab itself. The look-up tables contain the data points that describe the output surfaces created. So by integrating them into the VB controller, they serve as the controller knowledge-base (inference engine), as the VB program was upgraded to compare process readings with values in the look-up tables, and then 'decide' upon what tool feed

rate and electrolyte flow rate (valve position) to set as the output. The authors acknowledge that this has its limitations. Matlab will always generate the same number of surface data point. The problem here is when the physical process returns a reading in-between data points. In this situation, the VB program looks for the nearest data point to the reading, to acquire what action output value to take. The FLC aspect of the PC controller acts as a 'Black box' within the VB controller, as it maps input space to output space using FLC.

5. Experimental Results and Discussion

Critical test results: It can be observed that on three occasions the fuzzy logic controller brought the machining process back to optimum conditions (measured current and flow

Table1. The electrolyte management system

No	Fuzzy rules for managing the electrolyte flow rate through controller
1	IF Current is below 15 AND Measured Flow Rate is Operating THEN Flow Rate is 5.
2	IF Current is 16 AND Measured Flow Rate is Operating THEN Flow Rate is 5.
3	IF Current is 17 AND Measured Flow Rate is Operating THEN Flow Rate is 5.
4	IF Current is 18 AND Measured Flow Rate is Operating THEN Flow Rate is 5.5
5	IF Current is 19 AND Measured Flow Rate is Operating THEN Flow Rate is 5.5
6	. IF Current is 20 AND Measured Flow Rate is Operating THEN Flow Rate is 5.5
7	IF Current is 21 AND Measured Flow Rate is Operating THEN Flow Rate is 6.
8	IF Current is 22 AND Measured Flow Rate is Operating THEN Flow Rate is 6.
9	IF Current is 23 AND Measured Flow Rate is Operating THEN Flow Rate is 6.5
10	IF Current is 24 AND Measured Flow Rate is Operating THEN Flow Rate is 6.5
11	IF Current is 25 AND Measured Flow Rate is Operating THEN Flow Rate is 6.5
12	IF Current is 26 AND Measured Flow Rate is 4 THEN Flow Rate is 7.
13	IF Current is 27 AND Measured Flow Rate is 4 THEN Flow Rate is 7.
14	IF Current is 28 AND Measured Flow Rate is 4 THEN Flow Rate is 7.5
15	IF Current is 29 AND Measured Flow Rate is 4 THEN Flow Rate is 7.5
16	IF Current is 30 AND Measured Flow Rate is 4 THEN Flow Rate is 7.5
17	IF Current is 31 AND Measured Flow Rate is 3 THEN Flow Rate is 8
18	IF Current is 32 AND Measured Flow Rate is 3 THEN Flow Rate is 8
19	IF Current is 33 AND Measured Flow Rate is 3 THEN Flow Rate is 8.5
20	IF Current is 34 AND Measured Flow Rate is 3 THEN Flow Rate is 8.5
21	IF Current is 35 AND Measured Flow Rate is 3 THEN Flow Rate is 8.5
22	IF Current is 35+ AND Measured Flow Rate is 3 THEN Flow Rate is 9.
23	IF Current is 35+ AND Measured Flow Rate is 2 THEN Flow Rate is 10
24	IF Current is 35+ AND Measured Flow Rate is 1 THEN Flow Rate is 10.
25	IF Current is 30-35 THEN Flow Rate is 9.
26	IF Current is Dangerous THEN Feed Rate is Reverse Feed Rate.
27	IF Current is Too High THEN Feed Rate is Very Slow.
28	IF Current is Operational AND Measured Flow Rate is Operating THEN Feed Rate is Optimal.
29	IF Current is Too Low THEN Feed Rate is Optimal.
30	IF Measured Flow Rate is Critically Low THEN Feed Rate is Reverse Feed Rate
31	IF Current is Operational THEN Feed Rate is Optimal

Rate of approximately is 20.0 – 25.0 A and 6.0 – 9.0 l/min (respectively) without any operator intervention. Critical conditions triggered the tool feed rate to reverse and also the automatic valve to open. Although the fuzzy logic controller slightly over-compensates for the critical current occurrence, this can be adjusted through 'fine tuning' of the MF. What these results serve to prove is that FLC can be used to gradually control the ECM process. This next result was created by a machining run that was totally managed by the fuzzy logic controller. This was the last machining run of this research project, and as a result the electrolyte was in its worst condition. The measured current increases to its highest recorded level during the machining run. This result shows that the fuzzy logic controller ensured that the machining process finished without any sparking incidences. The FLC approach to inter-electrode gap control is different from other gap control methods.

6. Conclusions
FLC was successful integrated into the electrochemical machining, using a look-up table method. Although it is acknowledged by the authors that it is not the most robust method, it is deemed acceptable due to the notion of FLC of ECM being feasibly assessed. The critical test performed resulted in the fuzzy logic controller showing encouraging control performance. On three occasions, the ECM was forced into an artificially created short circuit situation. The fuzzy logic function of the controller was then turned on and in all three cases it brought the system back to optimum process conditions. This in itself was an encouraging result as it suggests that the application of FLC to ECM has potential. The encouraging result was that the fuzzy logic controller showed signs of maintaining the inter-electrode gap and stopped any occurrences of sparking. What is concluded is that FLC is shown to automate the ECM process, eliciting human knowledge and integrating it into the ECM controller to give it 'intelligence'. There is potential in FLC for the maintenance of process conditions within optimum ranges, and thus the potential for better machining performance. Further work needs to be done to establish what role FLC should take within the ECM controller, as related to the above discussion

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