Accurate vibration-free robotic milling electric discharge machining

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Abstract

Traditional computer numeric control (CNC) machines have high accuracy but are limited by workpiece size and axes. Therefore, many researchers attempted to equip six-axis industrial robots (IRs) with milling end-effectors to explore the robot’s large and flexible working envelope. However, IRs lack stiffness and have limited force, resulting in low accuracy, poor surface roughness (SR), and low material removal rate (MRR). On the contrary, electric discharge machining (EDM) is a non-conventional process capable of shaping complex profiles in any conductive material. Since the EDM process has no physical contact between the electrode and the workpiece, it can machine diverse hard-to-cut materials accurately and free of vibration. However, to this day, EDM is found in limited conditions of CNC machines only. Thus, this research investigates a synergistic combination of IR and milling EDM. Adopting advanced CAM tools and offline programming, it examines pre-designed electrodes working analogue to conventional milling to perform the desired machining by intricate cutting paths. The results deliver a robotic machining technique able to cut hard materials using small industrial robots yet free of vibration and not pose dependent.

Keywords Milling EDM · Robotic machining · Robotic vibration · Compensation · Adaptive fuzzy control

1 Introduction

Six-axis machining robots have replaced computer numeric control (CNC) machines to process large workpieces. Compared to CNC, industrial robots (IRs) are economical and flexible due to their reconfigurability [1]. However, IRs in conventional machining has been severely limited by the lack of stiffness combined with the high forces of traditional machining [2]. As a result, robotic machining is mainly applied in low accuracy and soft materials.

Parallely, electric discharge machining (EDM) is found in different variants, while die-sinking is the one that refers to the fundamental EDM principle. In die-sinking EDM, a block electrode is previously machined with the negative shape of the cavity. Next, the electrode is connected to the machine head to perform linear up and down movements towards the workpiece until a small distance gap where the sparkles can occur. The process will gradually melt portions of the workpiece surface by repeating this kinematic several times to deploy high-frequency electric discharges [3]. Unlike traditional machining, EDM offers nearly no cutting forces, while mechanical stresses, chatter, and vibrations are eliminated [4]. However, the characteristics of a customised electrode tool and one-axis linear kinematic configure the main limitations for die-sink EDM. Thus, equally large electrodes are necessary to machine complex and significant parts [5]. As a solution, an EDM variant called milling EDM (MEDM) has been studied. Unlike sink EDM, MEDM uses smaller electrodes shaped in primitive geometries such as cylinders, cones, and prisms [6]. Next, analogous to traditional milling, the electrode acts as a tool that performs layer-by-layer cutting paths [7].

Therefore, this study investigates a synergistic combination of MEDM and IR machining to overcome weaknesses in sink-EDM and IR machining by achieving a novel process able to cut large and complex workpieces of hard-to-cut materials. The research is organised as follows. Section 1 presents the background that motivates the research. Section 2 retrieves state-of-the-art literature.
Section 3 describes the materials and methods, Sect. 4 presents the findings and discussions, while Sect. 5 is the conclusion.

2 Literature review

This section explores previous research in both robotic machining and MEDM fields.

2.1 The application of robotics in electrical discharge machining

Industrial robots have successfully replaced many manufacturing techniques [8]. Compared to CNC machines, IRs offer many advantages, thus attracting research interest aiming for cost-efficiency, flexibility, and multi-functionality [1]. IRs can be defined as a series of interconnected bodies and joint mechanisms with 6 degrees of freedom (DOF) [9]. Thus, IRs can perform machining trajectories in 3-dimensional space while keeping arbitrary positions and orientations [10]. However, the high forces of conventional machining techniques combined with the lack of stiffness of IRs limit their use as machining tools [11]. While CNC machines have stiffness greater than 50 N/μm [12], IRs usually have less than 1 N/μm. Also, even IRs with a large mass have a natural frequency of around 10 Hz and cannot be compared with hundreds to thousands of hertz of CNC machines [12]. To overcome robotic machining deviations, researchers have studied cutting path strategies coupled with dynamic identification methods embedded in offline programming [13]. The main advantages are a better use of the time [14], precise conversion of the 3D workpiece into less force [15], or less vibration cutting-path [16] while avoiding collision and singularities [17], achieving stiffer robot pose [18–21] and error compensation [19].

Although no previous research has been found providing experimental data on EDM robotic machining, at this point becomes possible to suggest a synergistic combination where the intrinsic characteristic of minimal forces and vibrations of MEDM can amend or potentially solve the biggest IR machining obstacle of low stiffness and vibration. Both fields share similar approaches, suggesting that methods can be adapted to make MEDM suitable for IR machining free of vibrations.

2.2 Benefits and pitfalls of robotic Milling EDM

As in any EDM technique, MEDM works by high-frequency discharges in the dielectric fluid between a conductive workpiece and an electrode [22] with no contact and minimal pulse forces resulting in neglectable vibrations [4]. Examples in Micro-EDM suggest that using appropriate kinematic control of different electrode types and wear compensation can be machine complex shapes [23]. Hence, MEDM feasibility has been demonstrated in both micro [24] and macro scales [25].

With primitive shaped electrodes, MEDM can machine slots, revolute, grooves, pockets, and 3D cavities [26]. However, low material removal rate, complex kinematic control, and electrode wear have limited MEDM to micro applications [27]. Since wear is more significant on a large scale, researchers have focused on MEDM wear compensation under two approaches. First, offline cutting path strategies are designed to forecast and dictate the amount of compensation before starting the process [28]. Second, the continuous monitoring, quantification, and online correction [29].

Offline compensation can solve path control problems by simplifying three-dimensional electrode wear into a linear problem [30]. Also, it was demonstrated that the electrode corner wears to a radius equal to the cutting plunge if the depth is not superior to 2 mm [7]. Thus, the active diameter and length of the electrode can be determined by adding the effective gap distance.

Yu et al. [6] analysed and quantified the wear rate during conical and spherical micro-cavities machining to find that MEDM with appropriate wear compensation can deliver better precision than sink-EDM [30].

Parallelly, other researchers have approached the problem with indirect and continuous measurement through electrical sensing circuits. This method works through an online tool wear sensing of the effective and accumulated normal discharge pulses to calculate the volumetric wear of the electrode [29]. Because of online strategies, improved accuracy can be achieved when machining larger and more complex workpieces [31].

In drilling operations, it was proven that a small rotating hollow-tube electrode with the intern dielectric flow could achieve higher MRR and improved surface roughness (SR) [32]. In addition, the workpiece no longer needs to be submerged in dielectric but rather through external nozzles or the electrode itself [33].

Lastly, MEDM is exclusively found in constrained rigid bed-based CNC machines [7]. Therefore, the synergistic combination is again confirmed, while cutting path and wear compensation are found as crucial aspects to be taken into consideration.

3 The design of the 6-axis robotic milling EDM system

Firstly, it is necessary to evaluate the theory that MEDM low forces will not generate prohibitive vibrations on the robot. Therefore, both robot and MEDM end-effector will be specified to next perform finite element analysis (FEA) to test the assumption of no vibrations.
3.1 Adopted 6-axis robot

Aiming to test the boundaries of robotic MEDM vibration, we conduct the experiments on a lightweight ABB-IRB120 robot, the smallest IRs in the market, weighing 25 kg, and a payload of 3 kg, nonetheless with a significant working space envelope of 0.7 m³ [34].

Next, the 3D robot model was acquired and imported into CATIA V5-6 [35] CAD software to position its six axes and the MEDM end-effector. Figure 1 presents the robot 3D model and illustrates the working envelope with the predominant robot pose for the experiments.

3.2 Milling EDM end-effector

Using Catia CAD software, the MEDM end-effector was designed and configured to weigh 1.685 kg. The spindle is a 24 VDC–0.25 kW electric motor with ER20 tool holders, driven by a variable frequency drive, delivering up to 10,000 RPM and a maximum of 0.5 Nm of torque.

The holder case is 3D printed using a modern Stratasys printer with carbon fibre and lattice structure to achieve rigidity, lightweight, and electric insulation (Fig. 2).

The spindle chuck is connected to a closed-loop controlled piezo actuator model Thorlabs PAZ015, able to
stroke 100 µm in a resolution of 25 nm. Such adoption has two main reasons: (1) achieving precise electrode calibration towards the workpiece and (2) providing rapid move back in case of short circuits.

The selected electrode is a round bar of brass with 7 mm diameter and 30 mm of useful length. The electrode has a central hole of 2 mm in diameter to improve flushing, resulting in a useful machining area of 35.3 mm² (Fig. 3). The dielectric type is deionised water, while the workpiece is made of tool steel class P20-DIN 1.2738.

3.3 Simulating robot vibration in Milling EDM

Since even low forces can induce a harmonic response, the robot and end-effector tool arrangements were investigated using FEM. We focused on vibrations along with the Z-axis, which represents the gap between the electrode and the workpiece and may result in short circuits. The risk of vibration is assessed using ANSYS R19 [36] and the steps of Almeida et al. [37], however adapted to consider a rotating electrode that vibrates due to the eccentric mass of the spindle [38]. Since the vibration force is proportional to the square of the rotation rate, the spindle rotation will be fixed at 1800 RPM. The EDM reaction forces acting on the electrode are caused by bubble formation [39], and the adopted value of 0.11 N is calculated according to Adachi et al. [40]. Finally, Table 1 presents the material properties for each simulated component.

As shown in Table 2, the natural frequency modes of the system were mapped. At the same time, Fig. 4 depicts the effect of vibrations for the lowest (B) and highest (A) amplitudes.

By focusing on the electrode Z-axis, Fig. 5 shows that the amplitude decreases with the increase of pulse frequency. Thus, even light forces of EDM combined with low pulse frequencies present a real risk of prohibitive vibrations, short circuits, and poor accuracy in robotic MEDM. In other words, for the system here presented, frequencies below 528.42 Hz will generate prohibitive

| Mode | Natural frequency (Hz) | Total deformation range (mm) |
|------|------------------------|-----------------------------|
|      |                        | Minimal | Maximal |
| 1.   | 54.301                 | 1.3684e−017 | 29.485 |
| 2.   | 60.484                 | 1.0069e−017 | 22.988 |
| 3.   | 85.046                 | 2.8108e−017 | 28.98  |
| 4.   | 108.63                 | 1.6191e−017 | 40.514 |
| 5.   | 148.82                 | 1.017e−017  | 64.114 |
| 6.   | **166.85**             | 1.5228e−018 | **72.821 (highest)** |
| 7.   | 180.01                 | 4.0202e−017 | 45.075 |
| 8.   | 385.02                 | 2.556e−016  | 21.402 |
| 9.   | 398.46                 | 5.3439e−016 | 16.059 |
| 10.  | **528.42**             | 1.3407e−015 | **15.205 (lowest)** |

**Table 1** Material properties for the robot simulation

| Component description          | Material                  | Young’s modulus (MPa) | Poisson’s ratio | Bulk modulus (MPa) | Tensile strength (MPa) | Tensile yield strength (MPa) |
|--------------------------------|---------------------------|-----------------------|-----------------|--------------------|------------------------|------------------------------|
| End-effector housing           | Plastic, ABS              | 1628                  | 0.4089          | 2978.4             | 36.26                  | 27.44                        |
| Robot structure                | Cast iron                 | 1.22e+05              | 0.275           | 90,370             | 426                    | 234                          |
| Robot gearboxes                | Structural Steel          | 2e+05                 | 0.3             | 1.6667e+05         | 460                    | 250                          |
| Spindle                        |                           |                       |                 |                    |                        |                              |
| Bolts and nuts                 |                           |                       |                 |                    |                        |                              |
| Ball bearings                  |                           |                       |                 |                    |                        |                              |
| Spindle chuck and stator       | Aluminium Alloy           | 0.71 e+05             | 0.33            | 69,608             | 310                    | 280                          |
| Pulleys                        |                           |                       |                 |                    |                        |                              |
| Timing belt                    | Polyisoprene, hard rubber| 397* longitudinal direction | 0.499 | 15,000             | 25                     | 47                           |
| MEDM electrode tube            | Brass                     | 1.12 e+05             | 0.31            | 140,000            | 338                    | 133.3                        |
vibrations, while frequencies above 460 Hz can offer a feasible electrode gap oscillation lower than 0.06 μm. Since EDM can be performed in a broad range of frequencies from 2 kHz to 0.5 MHz, the experiment’s amendments consist solely of keeping the pulse frequency above the natural frequencies.

A triaxial piezoelectric accelerometer Kistler 8694M1 was attached to the end-effector to capture the range of vibrations using a decoder type 5134B. The sensor weighs only 2.5 g and has a frequency response from 10 to 20,000 Hz. Lastly, the accelerometer is grounded, isolated, and sampled at 1500 Hz.

3.4 Robotic milling EDM control

This section approaches two main controlling aspects: (1) cutting-path programming and (2) EDM adaptive robot speed control.

3.4.1 Adaptive fuzzy EDM controller

EDM process is characterised as stochastic and capable of abrupt change. Fortunately, fuzzy controllers can capture knowledge and make reasoning to simulate human intellect for controlling stochastic processes such as EDM.
Fig. 6 WEDM process pulse discrimination by voltage and current waveforms. Adapted from [49]

| Normal Discharge | Delayed Discharge | Arcing |
|-------------------|-------------------|--------|
| ![Normal Discharge Voltage Waveform](image1) | ![Delayed Discharge Voltage Waveform](image2) | ![Arcing Voltage Waveform](image3) |
| ![Normal Discharge Current Waveform](image4) | ![Delayed Discharge Current Waveform](image5) | ![Arcing Current Waveform](image6) |

Fig. 7 Fuzzy input variables membership functions where (A) stand for the frequency error $= e_1$ and (B) is used for both abnormal ratio error $= e_2$ and change of abnormal ratio $= ce_2$. 

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**Fig. 8** Fuzzy output variables membership functions where (X) stands for Δ\(u_1\) = change in the feed control and (Y) is Δ\(u_2\) = change in pulse off-time

**Table 3** Fuzzy rules for a MIMO three-region robotic EDM fuzzy controller

| \(e_2/ce_2\) | PB | PS | ZO | NS | NB |
|---------------|----|----|----|----|----|
| PB            | PB | PB | PB | PB | PS |
| PS            | PB | PB | PB | ZO | PS |
| ZO            | PB | ZO | NS | NS | NS |
| NS            | NB | NB | NB | NB | NB |
| NB            | NB | NB | NB | NB | NB |

| \(e_2/ce_2\) | PB | PS | ZO | NS | NB |
|---------------|----|----|----|----|----|
| PB            | PB | PB | PB | PB | NB |
| PS            | PB | PS | PS | PS | NB |
| ZO            | PS | ZO | NS | ZO | NB |
| NS            | NB | NB | NB | NB | NB |
| NB            | NB | NB | NB | NB | NB |

| \(e_2/ce_2\) | PB | PS | ZO | NS | NB |
|---------------|----|----|----|----|----|
| PB            | ZO | ZO | ZO | NS | NS |
| PS            | ZO | ZO | ZO | ZO | NS |
| ZO            | NS | NS | NS | NS | NS |
| NS            | NB | NB | NB | NB | NB |
| NB            | NB | NB | NB | NB | NB |

| \(e_2/ce_2\) | PB | PS | ZO | NS | NB |
|---------------|----|----|----|----|----|
| PB            | NS | NS | NS | NS | NS |
| PS            | NB | NB | NB | NB | NB |
| ZO            | NB | NB | NB | NB | NB |
| NS            | NB | NB | NB | NB | NB |
| NB            | NB | NB | NB | NB | NB |
However, the current range of industrial robots needs from 0.3 to 0.5 s to implement a speed change command. Such delay is considered significant for the EDM. Suppose the robot runs at 5 mm/min, and the controller sends a strong reduce speed command (nearly a stop). If the delay is 0.5 s, the robot will continue moving towards the workpiece of 41 μm before adjusting the speed. Since the discharge gap is found at 20 μm, a collision followed by short circuits will happen without premonitory control capabilities. Therefore, an adaptive control improved with predictive capabilities is crucial, and different researchers have demonstrated that the abnormal pulse frequency rise helps predict process deterioration. Therefore, to develop the adaptive control that captures the expertise of experienced EDM operators, we adapt a multiple-input vs multiple-output (MIMO) three-region fuzzy controller initially designed for wire EDM. The three main changes focus on (1) fuzzy rules that are experimentally adjusted to emphasise premonitory frequency characteristics and better cope with slow robot response. (2) The range of pulse-off time adjusting output is no longer limited to increase or decrease 2 μs. Instead, we use the generalisation made by Juran and Godfrey pp. 5.20–24 for the postulate of Pareto. In context, a minor change of up to 20% of the total pulse-off time represents most process change. (3) The fastest way to make online robot speed adjustments is by speed override. Thus, the fuzzy scale is changed to accommodate an output from 0 to 100% of a pre-determinate maximal robot speed.
The control’s objective function is to optimise material removal rate (MRR), which means that the robot’s speed is controlled to be as fast as possible, while the constraint is to keep stable process sensed by pulse frequency (kHz) together with bad pulses percentage (i.e., arcing and shorts) to modulate both pulse-off time (μs) and robot speed (mm/min) every 10 ms sampling interval. It is worth noting that the cut-off percentage of bad pulses can be adjusted so that MRR can increase as a compromise over SR. In other words, it is possible to choose a percentage value that falls in between a fine cut to a rough cut.

The gap status is continuously read and discriminated by the percentage of pulses classified as a normal, arcing, and short circuit. Each pulse is individually analysed by concurrently measuring gap voltage and gap current curves to achieve pulse discrimination. It is possible to classify the pulse according to the combined behaviour of current and voltage along with pulse time. Figure 6 shows a typical example of different pulse classifications available at the ITRI pulse generator.

According to Fig. 6, each pulse discrimination is summarised as follows:

- A normal pulse is the desired and useful pulse. In it, gap voltage drops from maximal value only after the programmed pulse-off time, while the current rises proportionally until the pulse is once more turned off by the programmed pulse-off time.
- Arcing occurs when several pulses hit the same area resulting in continuous material removal. It is caused by inductive reactance in one ionisation point, preventing the dielectric fluid from deionising. It is a harmful effect since it creates larger craters, increasing surface roughness. Nonetheless, it is frequently unavoidable yet should be kept low as possible as a trade-off with the intended SR vs MRR.
- A short circuit occurs when the wire electrode touches the workpiece by (1) direct contact or (2) indirectly by debris accumulation. A short circuit is identified when the current curve is found at maximum while the voltage is at minimum. Also, a short pulse does not remove material.

On the other hand, disturbances in pulse frequency are controlled by modulating pulse-off time. The main causes of frequency peaks are as follows:

- Robot speed running faster than MRR, increasing short pulses.
- Flushing is inefficient, causing debris accumulation and lower dielectric resistivity, resulting in unstable pulse-off time between cycles.
- Insufficient pulse-off time causes arcing. Since a series of involuntary pulses characterise arcing, frequency peaks will occur.

Lastly, regarding the functionalities of the ITRI pulse generator, it has four pulse protection options: (1) none, (2) shorts, (3) shorts tuned, and (4) shorts arc tuned. However, we have selected option 1 (no protection) to evaluate the fuzzy controller performance unbiased.

In brief, the controller operates by identifying which of the three regions the frequency input ($e_1$) is operating, namely safe, critical, and dangerous region domains. The respective linguistic sets to identify the regions are positive (P), zero (ZO), and negative (N). Figure 7 presents the fuzzified input signals as to frequency error ($e_1$), abnormal pulse ratio error ($e_2$), and change of abnormal pulse ratio error ($ce_2$), while each of the crispy input values are calculated as follows:

![Fig. 13](image1.png) Inputs $e_1$ and $ce_2$ vs pulse-off time output in microsecond

![Fig. 14](image2.png) Inputs $e_2$ and $ce_2$ vs pulse-off time output in microsecond
abnormal pulses = short-circuit pulses + arcing pulses
\[ e_1 = (\text{reference frequency} - \text{sparking frequency}) \times GE_1 \]
\[ e_2 = (\text{reference abnormal pulse ratio} - \text{current abnormal ratio}) \times GE_2 \]
\[ ce_2 = (\text{current abnormal pulse ratio error} - \text{previous abnormal pulse ratio error}) \times GCE_2 \]

where \( GE_1, GE_2, \) and \( GCE_2 \) are scale factors respectively found, in this case, as 0.5, 1, and 10. The inputs are fuzzified using five linguistic variables of negative big (NB), negative small (NS), zero (ZO), positive small (PS), and positive big (PB).

Similarly, Fig. 8 presents the fuzzified output control signals of robot speed (\( \Delta u_1 \)) and pulse-off time (\( \Delta u_2 \)), both using the fuzzy linguistic variables of NB, NS, ZO, PS, and PB. Finally, the output values are calculated:
Robot speed (%) = \( \Delta u_1 \times \frac{1}{100} \)

Pulse-off time (μs) = \( \left( \text{pulse-off time set} \right) \times \Delta u_2 \times \frac{20}{100} \) + (pulse-off time set).

where \( GE_1, GE_2, \) and \( GCE_2 \) are scale factors respectively found, in this case, as 0.5, 1, and 10. The inputs are fuzzified using five linguistic variables of negative big (NB), negative small (NS), zero (ZO), positive small (PS), and positive big (PB).

The max–min inference method is adopted to perform the fuzzy reasoning on the linguistic rules, while the centre of the area method is used for defuzzification [45]. Table 3 presents the resulting fuzzy rules, while Figs. 9, 10, 11, 12, 13 and 14 depict the fuzzy input vs output relationships.

Finally, the fuzzy controller is coded using LabVIEW to capture input signals and output signal control for both robot speed and pulse-off time while performing accurate data acquisition, later used for experimental analysis. Figure 15 shows the fuzzy controller interface.

### 3.4.2 Offline cutting path programming and wear compensation

On a macro-scale, MEDM demands compensation, and the approach chosen is offline control. To generate robotic offline cutting path programming that includes compensation, the three-dimensional models for the robot MEDM cell were imported, positioned, and programmed within computer-aided manufacturing (CAM) software PowerMill [50]. Figure 18A depicts the virtual apparatus for offline programming, including wear compensation, collision, and singularity avoidance.

Aiming to verify robotic EDM capabilities in terms of pulse control, robot speed, and offline wear compensation, the chosen geometry to be machined is a circular pocket of 12 mm in diameter, varying in depth, position, and angle. Figure 16 depicts the three approaches.

The adopted strategy is a helical path with a pitch defined according to the electrode wear. Since wear in MEDM is a unique combination of materials, process parameters, and flushing conditions, to build the offline electrode wear model, a preliminary experiment was performed following the steps of Lee et al. [51]. As a result, the pitch of the helix was found as 0.009 mm. Next, to anticipate the wear of the electrode corner, the resulting radius is defined as 0.2 mm by approximating the cutting pitch as in Ding and Jiang [7]. Figure 17 exemplifies the cutting path strategy embedding offline wear compensation for electrode length and radius (Fig. 18).

### 3.4.3 Discharge gap calibration

To accurately follow the offline programmed path, it is vital to calibrate the gap voltage accordingly. Thus, the gap is experimentally measured as follows. First, with the pulse generator turned off, the electrode is aligned with the Z-axis and positioned to a contact (zero distance) from the workpiece. Next, it is moved away along the Z-axis to the distance of 500 microns so that a discharge spark cannot be generated. Next, the EDM parameters in the pulse

| Table 4 MEDM process parameters |
|---------------------------------|
| Parameter                        | Value                                |
| Electrode                        | Brass Ø7 × Ø2 mm                      |
| Workpiece                        | Tool steel P20–DIN 1.2738             |
| Dielectric fluid                 | Deionised water                       |
| Dielectric temperature (°C)      | 25                                    |
| Dielectric pressure (bar)        | 0.2                                   |
| Spindle rotation (RPM)           | 1800                                  |
| Cycling time of the fuzzy controller | 10 ms                               |
| Voltage (V)                      | 120                                   |
| Current (A)                      | 14                                    |
| Pulse on time (μs)               | 18                                    |
| Pulse off time (μs)              | 24                                    |
| Pulse frequency                  | ~ 23 kHz                              |
| Pulse mode                       | Iso-frequency                         |
| Polarity                         | Electrode (+) Workpiece (−)           |
| Maximal robot speed (mm/min)     | 15                                    |

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**Fig. 19** MEDM fuzzy controller

**Fig. 20** Robotic vibration in milling EDM (A: vibration baseline, and B: machining vibration)

**Fig. 21** Material removal rate of robotic MEDM
generator are all set together with the dielectric flow and pressure. Third, the distance between the electrode and the workpiece progressively decreases until a first spark is detected. Next, the found gap distance of 20 μm is added to the tool electrode in length and the diameter to update the cutting path and assure that the selected process parameters and offline cutting path are in agreement. The list of process parameters is summarised in Table 4.

4 Experimental results and discussion

This section describes the results of robotic MEDM by evaluating process and workpiece aspects.

4.1 Robotic MEDM adaptive fuzzy controller

The LabVIEW code runs in a 64-bit Windows 10 operational system in a microcomputer installed with an Intel Core i5 processor of 1.8 GHz and 8 Gb of RAM with a sampling time of 10 ms. Figure 19 depicts the captured process in a time window of approximately 11 s.

As shown in Fig. 19, the system automatically tunes both robot speed (purple and blue lines) and pulse-off time (black line), achieving a stable process with approximately 4.7 mm/min speed. Since pulse discrimination is found as normal pulses (86% – green line), arcing pulses (14% – orange line), and short circuits (nearly 0% – red line), the quality of the process can be classified as good.
Regarding the adaptive nature of the controller, it is possible to observe that the fuzzy controller reacts to changes in bad pulses (i.e., arcing and shorts) and outputs to the robot a speed command depicted by the purple line. Hence, the blue line shows that the robot responds to the robot speed command accurately; however, an expected delay was found from 0.25 to 0.3 s. Similarly, pulse-off time is also increased to attenuate process deterioration trends to be later restored.

Finally, since frequency (grey line) is found nearly unchanged and gap voltage (light-green line) is found stable, within the range from 26 to 32 V, the control is proved efficient.

4.2 Vibration assessment of robotic Milling EDM

Since vibration is the major obstacle in IR machining, in Fig. 20, the robotic machining vibration during MEDM is measured.
In Fig. 20A, the robot is static in an initial pose for MEDM machining, while both the spindle and pulse generator are off. Next, only the spindle is turned on to 1800 RPM, and the stable vibration pic is found for $X$, $Y$, and $Z$ as 2.3 g (green line), 1.8 g (blue line), and 1.4 g (red line), respectively. In Fig. 20B, the spindle is kept moving at the same speed, while the machining process is stable, with the robot moving at approximately 5 mm/min. Finally, the spindle is turned off, while the machining process is kept verifying if EDM pulses are creating significant vibrations, which was not observed and can be assumed as lower than 1 g. Thus, not EDM pulses but the spindle, together with electrode unbalance, is confirmed as the primary source of vibration, yet, not superior to 7 g, thus, feasible for the stiffness of the current robot.

As shown in Fig. 21, the average material removal rate (MRR) is close to a linear trend of 8.2 mm³/min. However, the machining time shows a significant difference with a
nonlinear trend. By analysing the potential causes for the time difference, offline programming was found as the root cause of deviation. It was possible to verify that empty path segments, consuming time but not effectively machining, explain the difference. That is why full pocket cut, corner cut, and lately half-cut present decreasing MRR efficiency.

### 4.3 Robotic MEDM machining characterisation

Figure 22 presents the resulting specimen from three machining approaches, namely (1) corner cut 45°, (2) full pocket 90°, and (3) half pocket 90°.

Next, each sample will be analysed regarding surface morphology and dimensional accuracy.

### 4.4 Morphological surface analysis

The roughness and surface morphology were analysed using a non-contact 3D microscope Alicona Infinite Focus equipped with an ×50 magnification lens.

While corner cut 45° (Fig. 23) and full pocket 90° (Fig. 24) find similar results, the half pocket 90° (Fig. 25) reveals an average surface roughness ($Ra$) 37% lower, which is corroborated by the root-mean-square roughness ($Rq$) 40% inferior. Hence, measuring and averaging five samples of the distance difference from the vertical highest peak to the lowest valley reveals the $Rz$ value also smaller by 35%. Such findings suggest that the open geometry of the half pocket 90° allows improved flushing, thus, improving surface roughness and more uniform morphology. Figure 26 depicts the roughness values.

Finally, to verify the microstructure of the MEDM surface, a scanning electron microscope (SEM) is adopted, while Fig. 27 presents the results.

As depicted in Fig. 27, the morphology can change significantly despite adopting the same sparking parameters. As in any EDM process, robotic MEDM relies on correctly flushing debris. Therefore, the machining surface aligned with the top surface of the electrode presents a less uniform surface, where the full pocket 90°, machined with the dielectric flow trapped within the machined pocket, presents the poorest

| Table 5 Electrode surface roughness Ra. Note: Dimensions are expressed in microns |
|---------------------------------|-----------------|-----------------|-----------------|
| Cutting path | Machining surface (M) | Side surface (C) | Corner radius (S) |
| (1) Corner cut 45° | 6.62 | 0.47 | 0.197 |
| (2) Full pocket 90° | 2.52 | 1.66 | 0.293 |
| (3) Half pocket 90° | 6.01 | 0.54 | 0.215 |

Fig. 28 MEDM electrode morphology: (1) corner cut 45°, (2) full pocket 90°, and (3) half pocket 90°

Fig. 29 Robotic MEDM sparkle interruption by dielectric pressure (A: 1 bar, and B: 0.2 bar)
result. On the other hand, it becomes clear that the vertical surfaces of the three cuts, where the electrode performs an indirect cut, also known as finishing cut, result similar and with a more uniform surface, with shallower craters, lower accumulation of debris, or re-deposited material.

4.5 Electrode wear and surface morphology

To evaluate the surface morphology and potential influences on electrode wear, once more, the Alicona microscope is adopted. This time, the primary machined surface
is analysed, and the lateral surface of the electrode and the corner transition in between the two surfaces. Figure 28 depicts the findings being M machined surface, C the electrode corner, and S the side surface of the electrode.

According to the findings in Table 5, the corner cut 45° and half pocket 90° reasonably confirm the theory that the electrode wears as per the path step downs, adopted as a pitch of 0.2 mm. On the other hand, the full pocket 90° presents a significant increase in corner wear, which can be explained by the increased difficulty in flushing the debris since the cut is performed in a vertical position with low dielectric pressure. In this sense, the dielectric pressure coming from the electrode’s centre can create enough force to push back the electrode and disturb or even interrupt the machining sparkle. Next, Fig. 29 demonstrates this phenomenon.

In Fig. 29A, dielectric pressure above 1 bar pushback the electrode along with the Z-axis and sparkles are interrupted. On the other hand, in Fig. 29B, once the flow pressure is reduced to 0.2 bar, in this robot case, the sparkle is restored. Therefore, only low dielectric pressures of up to 0.2 bar are possible for the presented robot.

4.6 Three-dimensional metrology analysis

To analyse the accuracy of robotic MEDM, a three-dimensional scanning of the workpiece was performed using a high-resolution scanner with an accuracy of 10 μm. Next, both three-dimensional CAD files and resulting cloud points acquired during the scanning process were compared using metrology software Geomagic Control and the best-fit algorithm. The accuracy findings are depicted in Figs. 30, 31 and 32.

Since the EDM is set to a rough cut and the scanner accuracy is 10 μm, the analyses are carried out with an accepted cut-off of ± 20 μm, depicted by the green colour. In all cases, the bottom surface of all pockets is found within the cut-off criteria, suggesting good agreement with the offline wear compensation. On the other hand, significant dimensional deviations are concentrated in corners and sidewalls. Since the vibrations mapped in Fig. 20 are mainly detected when the spindle is on, each of the three electrodes was evaluated to verify rotational unbalance. Figure 33 depicts the mapped errors, while Table 6 presents the findings.

According to Table 6, all electrodes have some degree of eccentricity. Nonetheless, the electrode used to perform the corner cut 45° presents the smallest deviation resulting in a practical diameter of 7.016 mm. By comparing with the metrological results of Fig. 30, it becomes clear that the resulting diameter and corner accuracy are superior to the other two cuts. On the other hand, full pocket 90° and half
pocket 90° present higher centre deviation resulting in practical diameters of 7.19 mm, and 7.22 mm, respectively. Such errors corroborate the deviations found in Figs. 31 and 32.

5 Conclusions

This paper introduced a novel robotic milling electric discharge machining system. The system’s novel design and control allow even small and low stiffness six-axis industrial robots to machine accurately hard-to-cut materials free of unsolved harmful vibration. The specific contribution of this research is summarised as follows:

- A fuzzy logic strategy has been developed and implemented successfully for adaptive control of robotic electric discharge machining substantiated with experimental results. This outcome represents a new manufacturing system that can machine hard-to-cut workpieces in complex shapes within the large and complex capabilities of industrial robots working envelopes.
- Extremely challenging vibration and robot pose are solved problems making robotic milling EDM an excellent technique to overcome robotic chatter in machining hard-to-cut materials. The experimental results show that the EDM surface morphology and accuracy do not deteriorate. Nonetheless, shorter electrodes and the appropriate rotational balance calibration may improve the remaining minor vibrations and machining accuracy.
- The research shows that the EDM process does not generate forces or vibrations beyond the low stiffness of the robot, even with the presence of dielectric pressure to support the EDM process. In other words, adopting a flowing dielectric from the centre of the electrode through a reduced gap distance of 20 μm creates forces that can push the electrode away from the workpiece, creating disturbances or even interrupting the discharge. Furthermore, the ability of complex robot movements can be explored to preferably approach the machined area so that the gravitational field helps to flush debris and improve MRR and SR.
- Offline programming, including compensation, is proved effective. Since this manufacturing process is new, no CAM software has the post-processor to generate the necessary robot control code suitable for this research. Thus, it reveals a research opportunity to develop CAM software to generate complex milling EDM cutting paths with embedded compensation as an opportunity for future research.
- Lastly, even though current industrial robots are designed for fast speed movements of thousands of millimetres per second, it was found feasible to operate at EDM speeds as slow as 0.5 mm per minute. Also, the robot time response limitation of up to 0.3 s delay to implement a commanded movement was found acceptable for EDM purposes once predictive aspects of frequency monitoring and pulse off time adaptive online modulation are in place.

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Declarations

Ethics approval The authors state that the submitted work is original, the manuscript in part or in full has not been submitted or published anywhere, and it will not be submitted elsewhere until the editorial process is completed. The authors affirm that the results are presented without fabrication and ensure that all the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication. All named authors agree on the order of authorship.

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Table 6 Electrode unbalance error. Note: Dimensions are expressed in millimetres

| Cutting path       | Measurement length (M) | Bottom error (B) | Corner error (C) | Unbalance error (U) | Electrode diameter (Ø) | Practical diameter (P) |
|--------------------|------------------------|------------------|------------------|---------------------|------------------------|------------------------|
| (1) Corner cut 45° | 50                     | 0.001            | 0.001            | 0.008               | 7.0                    | 7.016                  |
| (2) Full pocket 90°| 50                     | 0.007            | 0.007            | 0.095               | 7.0                    | 7.19                   |
| (3) Half pocket 90°| 50                     | 0.008            | 0.008            | 0.112               | 7.0                    | 7.22                   |
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