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Conceptual Design of a High-Speed Wire EDM Robotic End-Effector Based on a Systematic Review Followed by TRIZ

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Abstract: Exotic materials such as titanium offer superior characteristics that, paradoxically, make them hard-to-cut by conventional machining. As a solution, electric discharge machining (EDM) stands out as a non-conventional process able to cut complex profiles from hard-to-cut materials, delivering dimensional accuracy and a superior surface. However, EDM is embodied in CNC machines with a reduced axis and machining envelope, which constrains design freedom in terms of size and shape. To overcome these CNC constraints, traditional machining using six-axis industrial robots have become a prominent research field, and some applications have achieved cost efficiency, an improved envelope, and high flexibility. However, due to the lack of stiffness and strength of the robot arm, accuracy, material rate removal, and surface finishing are not comparable to CNC machining. Therefore, the present study investigates the design of a novel WEDM combined with six-axis robotic machining to overcome the limitations of traditional robotic machining and enhance EDM applications. This study extends the work of a conference paper to confirm potential outcomes, quantifying and ranking undesired interactions to map technical problems and applying the TRIZ approach to trigger solutions. Finally, an effective robotic end-effector design is proposed to free EDM from CNC and deliver robotic machining as a flexible and accurate machining system for exotic materials.

Keywords: electric discharge machining EDM; robotic machining; wire EDM; end-effector design; TRIZ

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1. Introduction

During the past decade, exotic materials have received much attention, including superalloys, ceramics, composites, semi- and superconductors [1]. The most prominent industry examples are observed within the two groups. The first focuses on cutting tools (e.g., carbide and polycrystalline diamond), which are used, for example, to drill large diameter holes in airframes [2] or to machine composite materials [3]. The second group focuses on hard-to-cut metals, such as titanium, molybdenum, and superalloys, with applications in highly demanding aerospace, automotive, and military applications, and are also important in medical equipment [4] and bio-implants [5]. However, exotic materials are often characterised by poor thermal conductivity, high toughness, ultra-hardness, and extremely high hardening behaviour that, when combined, will lead to laborious machining [6]. Thus, exotic materials come under the category of hard-to-cut materials [7]. Due to the high strength of these exotic materials, cutting forces attain high values and generate vibrations, compromising the surface quality [8]. Residual stresses [9] resulting in fatigue [10], surface roughness, and dimensional integrity [11] will also provide substantial machining challenges. To improve the machining of hard-to-cut materials, conventional processes have been successfully replaced by electro-discharge machining (EDM). By definition, EDM consists of a non-conventional machining process that electrically removes any conductive material offering at least 0.01 S/cm of electrical conductivity [12]. The process will gradually melt and evaporate portions of the workpiece surface due to the thermal energy generated by a series of high-frequency discharges in the dielectric fluid between a conductive workpiece and an electrode [13]. There are no physical cutting forces between this electrode and workpiece in EDM machining, avoiding mechanical stresses, chatter, and vibrations [14]. To control the electrode path, EDM is configured on computer numerically controlled (CNC) machines [15]. However, CNC machines are characterised by limited available working space that often leads to the workpiece being segmented and processed in multiple stages, frequently demanding unique fixtures and techniques, resulting in the deterioration of dimensional precision and a substantial increase in costs and time [16]. Since CNC are robust machines, stiffness and vibration are frequently considered as variables of minor importance [17]. Within the CNC context, most of the related literature has focused on analysing EDM in different hard-to-cut materials with different process conditions [18], usually seeking less surface roughness (SR) or an increased material removal rate (MRR) [19,20].

On the other hand, the advantages of six-axis industrial robotic arms (IR) in digital fabrication are widely recognised. They have successfully replaced many manufacturing techniques [21] and are used in the processing of large and complex workpieces [22]. IRs have many advantages over CNC machines, such as flexibility, a lower price, and mechanical reconfigurability [23]. Furthermore, with IRs, it is possible to attach a great variety of end-effector tools (EE), sensors and control mechanisms to improve quality and productivity [24,25]. However, IR machining has been severely limited by problems originating from a lack of stiffness and from machining vibration [26].

This study aims to provide a comprehensive overview of recent advances in EDM and IR machining by investigating the conceptual design of a novel machining technique combining EDM with robotic machining. The research is organised as follows. Section 2 describes the adopted materials and methods. Section 3 presents the literature findings and discussion. Section 4 proposes and evaluates the proposed combination, while Section 5 is the conclusion.

2. Materials and Methods

During this section, the adopted methods will be briefly described, aiming to (1) scrutinise the literature within EDM and IR fields, (2) look at the results of the combination, and (3) extract design requirements while proposing conceptual solutions for the EDM end-effector.

2.1. Systematic Literature Review

To approach the literature, a two-stage systematic review was adopted [27], focusing on literature in the English language from 2009 to October 2019, and databases were chosen by affinity with WEDM as the first research axis and IR machining as the second research axis, including Springer Link, Science Direct, Scopus, Web of Science, IEEE Xplore, and Google Scholar engine. The latter focuses on industry articles, patents, and reports not included in the academic repositories [28]. To find appropriate keywords, Web of Science was first searched using preliminary keywords. After reading the titles and abstracts of the ten most cited papers, it was noted that other strings were better aligned. The keywords are summarised in Table 1.

Table 1. Research keyword strings.

Preliminary Research Strings		Final Research Strings	
E.D.M.	IR machining	E.D.M.	IR machining
Exotic material	Machining	Exotic material	Six axis robots
Electric discharge	Robotic	Hard to cut material	Industrial robot
Hard to cut	Hard to cut	Electric discharge	Wire cut
EDM		EDM	Machining
		Wire EDM	Grinding
		High-speed WEDM	

In the EDM research axis, the first selection round resulted in 672 samples. Next, by restricting each subject, parsing duplicates and categorisation, the sample resulted in 161 contributions. Next, each paper was reviewed twice. The first round has two objectives. (1) It intends to analyse the references to locate and include documents with potential contributions not detected in previous samples, and (2) to compose the list of criteria expressed in terms of new methods, processes, and tools (MPT) that will judge and categorise the literature. The second round selected and groups the final literature, and the EDM research axis was shortened to 83 samples. By following the same steps as the first research axis, for the second, the literature was first screened to 485 papers, then to 108, and finally to 41 samples.

2.2. Combination Scenarios

To capture human thinking and predict unbiased and plausible scenarios for the EDM and IR combinations, AHP and SWOT analysis will be combined as in the first step of Görener et al. [29]. However, this method will be adapted. Regarding SWOT, only the critical Strengths and Weaknesses of both research axes will be extracted to compose the group factors compared pairwise [30]. To retrieve values from the AHP comparison scale, instead of assessing "how important a certain factor is against others", the factors will be ranked according to "how likely one factor is to prevail against others".

2.3. Innovative End-Effector Ideation by TRIZ

It is broadly accepted that the engineering design process is performed by steps of problem formulation, conceptual solutions, solution evaluation, and comprisal design.

The theory of inventive problem solving (TRIZ) was developed by Genrich Altshuller while observing and mapping patterns of inventive thinking applied in a patent office in the former Soviet Union. In brief, TRIZ is a set of tools for guiding creative thinking yet avoiding trial and error.

Since TRIZ's main merit is to solve technical problems by guiding concept generation, it will be adopted to trigger an innovative proposal for an EDM end-effector by following the simplified algorithm as in Figure 1. For one looking for more in-depth explanations on TRIZ principles adopted here, we suggest Cameron's work [31].

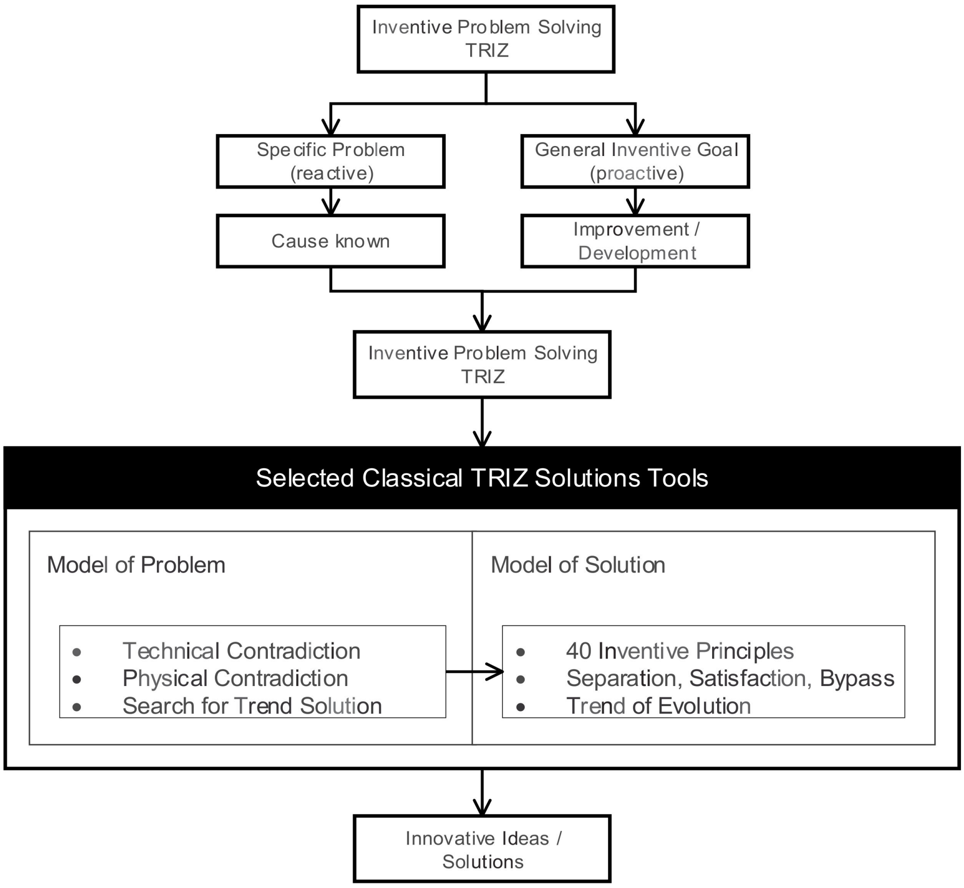


Figure 1. Simplified algorithm for the use of narrowed innovative TRIZ tools.

3. Results and Discussion

As engineering fields, for both EDM and IR, most of the best practices, advances, strengths, and limitation can be found in the form of methods, processes, and tools (MPT). As an outcome of a systematic review, we found the current opportunities and limitations in EDM and IR machining and how they have been addressed.

3.1. State of the Art in EDM Machining

EDM is a complex non-conventional process in which many parameters will drive the outcomes. Moreover, depending on the EDM process variant, other parameters can be added. Therefore, a proper understanding of EDM variants and the fundamentals concepts behind the usual main parameters is imperative and will be briefly described.

3.1.1. EDM Fundamentals

Discharge voltage (V) is the average difference of potential measured in volts along the gap between the workpiece and the electrode during the machining. V can influence the spark gap size and the overcut [32], with low V notably being used for highly electrically conductive materials. In contrast, materials with low electrical conductivity will use a high V [33].

Peak current (Ip) is the amount of energy defined by a flow of electrons during the discharge machining. The Ip will influence material removal rates (MRR), resulting accuracy, and electrode wear [34].

Pulse on time (Ton) is the time of each current discharge duration. The amount of energy generated during the Ton will affect the MRR being increased with more extended Ton [35].

Pulse off time (Toff) is the time in which the discharge remains interrupted. Toff is applied after each Ton to allow melted debris to be flushed away from the gap. Toff plays a crucial role in EDM stability since remaining debris may cause short circuits and compromise the next Ton cycle efficiency and surface roughness [36].

Polarity (P) refers to the assigned charges for the electrode and the working piece where one of the two charges must be opposite to the other. The current of electrons flows from the negative electrode (EDM tool) to the positive electrode (material being eroded). Concurrently, positive ions flow in the inverse direction. However, since the electron is lighter than an ion, it flows with lower acceleration resulting in dominant erosion on the positive electrode [37]. Lately, the electrode is often used as a reference to identify the polarity of the charge assigned to the system and is frequently found as positive polarity [33]. It is worth noting that, according to the working piece material and the machining purpose (i.e., faster but rough cut or better surface quality), the polarity may be changed [37].

Spark gap (G) refers to the distance between the workpiece and the electrode. Within G, the sparking will occur depending on the conductivity of the material [38]. Usually, G is found between 0.01 and 0.1 mm, and it decreases to a few microns in micro-EDM [39]. To achieve efficient machining and flushing, the G distance must be managed throughout the process [13].

Flushing (F) refers to the flow of the dielectric fluid injected against the machining area to clean away the machined debris and reduce the temperature of the machining area [33]. The fluids are characterised mainly by high dielectric strength, low viscosity and quick recovery [40]. The commonly used dielectric fluids are deionised water, kerosene, and hydrocarbon oil [41], noting that recent efforts have been made to find options (i.e., oil-based synthetics) to mitigate harmful effects to the worker and the environment [42,43]. The flushing parametrisation and the dielectric type will influence the MRR, the electrode wear rate (EWR), and surface roughness (SR) [44].

3.1.2. EDM Variant Processes

EDM machining principle is found in different variant processes that need to be identified to choose the most suitable process to combine into a robot. The main EDM processes can be summarised as follows.

Die sinking EDM refers to the first and fundamental EDM principle. EDM was invented by the English scientist Joseph Priestly in early 1770 [45], becoming more popular in 1955 when the Russian Lazarenko introduced the first EDM machine [46]. In sink EDM, an electrode is previously shaped with the desired cavity. Next, the electrode is connected to the machine head that moves in up and down vertical movements against the workpiece, fixed and submerged in a tank full of dielectric fluid.

Micro EDM refers to micro-scale applications such as biotechnology, medical, and miniaturised machines. In micro EDM, the spark gap (G) is limited to a few microns. Moreover, SR is more relevant than high MRR due to high aspect ratio demands [47]. Common challenges are related to difficult flushing conditions, accuracy, machine measurement, and control [48].

Milling EDM is analogous to traditional machining, where usually rotating cylindrical electrodes remove material along a defined cutting path [49]. Contrary to conventional die sink EDM, this technique does not need pre-shaped electrodes nor a submerged workpiece. A significant challenge arises from electrode wear in the corner or front, affecting accuracy [50]. Although some evidence suggests that this technique could be used in macro levels [51,52], it remains successfully used in microscale [48,51,53,54].

Dry EDM relies on the use of gases instead of conventional dielectric liquids. Since gas efficiency to flush debris is not comparable to dielectric fluid in a liquid state [55], it is common to find it combined with high pressure and rotating electrodes [1]. The main advantages of dry EDM are superior MRR, lower EWR and surface integrity [56].

Powder mixed EDM (PM-EDM) refers to fine electrically conductive abrasive powder particles added to the dielectric fluid aiming to improve SRR [57] to the point that mirrored surfaces can be achieved [58]. However, MRR is prone to be reduced [59], while most of the current powder EDM are considered harmful regarding environmental concerns [60].

Wired EDM (WEDM) does not require pre-machined electrodes. Instead, it uses straighten wire that cuts only the surrounding of the workpiece by feeding a wire-electrode that moves as a band saw [61].WEDM is the most used EDM application in the industry [62] and can vary according to the workpiece scale, the wire speed and wire reuse. The specificities and differences can be briefly explained as follows:

- WEDM, also known as low-speed WEDM (LS-WEDM), is characterised by an average wire speed of 7–10 m/min reaching an MRR of 500 mm^2/min [63]. However, the electrode wire is used only once, being next chopped and scraped [46].
- HS-WEDM refers to a new high-speed wire electrical discharge machining (HS-WEDM) and has been broadly adopted due to its cost-effectivity. It defers from conventional LS-WEDM due to the wire running faster and being reused [32]. In HS-WEDM, the wire performs a reciprocating motion with a speed up to 12 m/s, which is on average ten times more than LS-WEDM. The wire is usually made of molybdenum or tungsten molybdenum alloy with diameters from 0.08 to 0.25 mm [64]. As a drawback, while LS-WEDM can reach an MRR of 500 mm^2/min, the stable MRR in HS-WEDM is usually 100 mm^2/min, but no more than 200 mm^2/min [63].
- Micro-WEDM is used for machining complex micro-features since it subjects the workpiece to negligible forces [65]. However, the CNC table, wire size and type, and process parameters need to be scaled and tailored [47,66].
- Lately, cylindrical wire electrical discharge turning (CWEDT) is a particular form of WEDM where a submerged rotation spindle work as a clamping device for workpiece rotation to cylindrical machine parts [67].

Hybrid EDM refers to combinations of one classic EDM process with one or more processes [19]. The typical target is to find new forms to improve MRR and SR. The most prominent combinations combine grinding [68], abrasives [69,70], chemical reactions [71,72], and ultrasonic machining, the latter a recognised research hot topic [13,73,74].

3.1.3. EDM Systematic Literature Review

The literature was selected by adopting as a final criterion the papers were a new method, a new process, or a new tool is found. Table 2 presents the chronologic evolutional synthesis of identified MPTs, their aims and approaches.

Table 2. Summarised framework on EDM methods, processes, and tools.

		Main Targets					Used Means					M.P.T.s			Deliverable
Year	**Reference**	**Material Rate Removal**	**Surface Roughness**	**Wire Performance**	**Design Freedom**	**Accuracy**	**Process Optimisation**	**Electrode Speed or Composition**	**Process Prediction**	**Dielectric Composition**	**Taper Angle**	**Methods**	**Processes**	**Tools**	
2010	[75]			✔				✔					✔		Review on wire electrodes
2012	[76]	✔	✔				✔			✔		✔	✔		Process optimisation of 6061Al/Al2O3p/20p Al composite
	[57]	✔	✔				✔			✔		✔	✔		Review on many powders as additives in EDM dielectric

Table 2. *Cont.*

Year	Reference	Main Targets: Material Rate Removal	Main Targets: Surface Roughness	Main Targets: Wire Performance	Main Targets: Design Freedom	Main Targets: Accuracy	Used Means: Process Optimisation	Used Means: Electrode Speed or Composition	Used Means: Process Prediction	Used Means: Dielectric Composition	Used Means: Taper Angle	M.P.T.s: Methods	M.P.T.s: Processes	M.P.T.s: Tools	Deliverable
2014	[77]	✔	✔			✔	✔		✔			✔			Review on process optimisation
	[46]	✔	✔	✔		✔	✔	✔					✔		Review on wire electrodes
	[78]	✔	✔	✔			✔					✔			Explains the influence of thickness, current and wire-speed on SR
	[79]	✔	✔	✔			✔		✔			✔			Process optimisation for SR based on current, wire speed and Ø
	[32]	✔	✔				✔							✔	Design of real-time system control for MRR, SR and stability
	[80]	✔	✔				✔		✔			✔			Process optimisation by Adaptive neuro-fuzzy inference system
	[81]	✔	✔	✔			✔		✔			✔			Process optimisation for SR and MRR with minimum cost
2015	[82]	✔	✔				✔		✔			✔			Process optimisation for taper cutting
	[83]	✔	✔				✔		✔			✔			Process optimisation for Nimonic-263 alloy
	[84]	✔	✔			✔	✔		✔			✔			Process optimisation for HSLA steel
	[85]	✔	✔			✔	✔		✔			✔			Process optimisation for HCHCr
	[86]	✔	✔				✔					✔		✔	A tool and a method for process optimisation
	[58]	✔	✔				✔		✔	✔		✔	✔		Mirror surface finishing by nanotubes & dielectric mix
	[87]	✔	✔			✔	✔						✔	✔	Improved SR and MRR by pulse generators in high frequency
	[88]		✔				✔			✔		✔			Dielectric fluid for hydrophobic material
	[47]	✔		✔		✔								✔	Real-Time system for MRR
	[89]	✔					✔	✔						✔	Wire servo system to cope with semiconductors
	[36]	✔	✔				✔		✔			✔			Pulse on time as most significant for MRR and SR
	[45]				✔									✔	Review on EDM for machining curved hole
	[90]	✔					✔		✔			✔			Prediction accuracy 93.62% for SR and MRR
	[91]			✔		✔	✔	✔				✔			Clarify wire movements and suggest workpiece location
	[92]	✔	✔				✔		✔			✔			Maximized WEDM cutting speed
	[93]	✔	✔				✔		✔			✔			Process optimisation for INCONEL 600
2016	[3]	✔		✔			✔	✔				✔			Explains wire deformation and degradation
	[94]	✔	✔	✔			✔				✔		✔		Review on EDM applications of ultrasonic vibrations
	[95]	✔					✔		✔			✔			Process optimisation for metal matrix composite
	[96]	✔	✔		✔		✔		✔		✔	✔			Process optimisation for tapered parts
	[63]	✔	✔				✔	✔				✔			Burning courses in HS-WEDM suggesting best parameters
	[97]	✔											✔		Environmental review with cons of additives and pros of dry-EDM
	[98]	✔	✔											✔	New pulse generator for rough cut and better SR

Table 2. *Cont.*

Year	Reference	Main Targets					Used Means					M.P.T.s			Deliverable
		Material Rate Removal	Surface Roughness	Wire Performance	Design Freedom	Accuracy	Process Optimisation	Electrode Speed or Composition	Process Prediction	Dielectric Composition	Taper Angle	Methods	Processes	Tools	
	[99]		✔		✔			✔						✔	Investigate wire breakage cutting polymeric foams
	[100]	✔	✔			✔	✔		✔			✔			Review on processes optimisation by Response Surface
	[101]	✔	✔				✔		✔			✔			Review on processes optimisation
	[55]	✔	✔			✔	✔			✔	✔		✔		Dielectric temperature with higher MRR (30%) and better SR
	[102]	✔	✔	✔		✔	✔	✔				✔			Machining parameters against harmful wire vibration
	[103]		✔		✔	✔					✔			✔	New wire mechanism for improved SR and MR in tapper
	[1]	✔	✔				✔			✔		✔			High-speed EDM using air as a dielectric
2017	[104]	✔	✔			✔	✔		✔			✔			The performance index for high MRR
	[48]				✔	✔	✔						✔	✔	Review on Micro-electrode fabrication processes
	[105]	✔	✔				✔		✔			✔			Process optimisation for Udimet-L605
	[13]	✔	✔	✔									✔		Investigate fluid behaviour with ultrasonically activated wire
	[74]	✔	✔	✔		✔							✔		Improved accuracy and MRR with ultrasonically activated wire
	[106]	✔	✔							✔			✔		A dielectric formulation for higher MRR and energy in HS-WEDM
	[107]	✔	✔	✔		✔	✔					✔			Review on causes of wire electrode wear
	[108]	✔	✔				✔		✔			✔	✔		Process optimisation for titanium Ti-6Al-4V
	[109]	✔	✔	✔			✔						✔		Ultrasonic wire and process parameters for different materials
	[62]	✔	✔				✔		✔			✔	✔		Process optimisation for stainless-clad steel
	[110]	✔	✔				✔		✔			✔			Process optimisation for nano-TiO2 dispersed austenite steel
	[111]	✔	✔				✔		✔			✔			Process optimisation for H21 tool steel
	[112]	✔	✔	✔			✔	✔					✔	✔	New HS-WEDM with long wire with process parametrisation
	[113]	✔	✔				✔		✔			✔			Process optimisation for Indian RAFM steel
	[5]	✔	✔				✔		✔			✔			Process optimisation for Pure Titanium
	[114]	✔	✔				✔		✔			✔			Process optimisation for Inconel 825
2018	[33]	✔	✔				✔		✔			✔			Review on processes optimisation for titanium and its alloys
	[115]	✔	✔	✔		✔	✔		✔			✔			Review on processes optimisation for Metal Matrix Composites
	[116]	✔	✔				✔		✔			✔			Processes optimisation for NiTi Superelastic Alloy
	[117]	✔	✔				✔		✔			✔			Processes optimisation for Inconel 718
	[118]	✔	✔				✔		✔			✔			Processes optimisation for high-speed steel (HSS) M2
	[119]	✔	✔	✔		✔	✔		✔			✔		✔	Processes optimisation for Titanium Grade 6
	[120]	✔	✔				✔		✔			✔			Processes optimisation for Ni-Ti shape memory alloy

Table 2. *Cont.*

		Main Targets					Used Means				M.P.T.s				Deliverable
Year	**Reference**	**Material Rate Removal**	**Surface Roughness**	**Wire Performance**	**Design Freedom**	**Accuracy**	**Process Optimisation**	**Electrode Speed or Composition**	**Process Prediction**	**Dielectric Composition**	**Taper Angle**	**Methods**	**Processes**	**Tools**	
	[121]	✔	✔				✔					✔			Influence of cut direction in SR
	[122]					✔	✔		✔		✔	✔			Processes optimisation for angular error in taper cutting
	[123]	✔	✔				✔		✔			✔			Processes optimisation for Ti50Ni48Co2 Shape Memory Alloy
	[124]	✔	✔				✔		✔			✔			Processes optimisation for AA 7075 Aluminium Alloy
	[125]	✔	✔				✔		✔			✔			Processes optimisation for cladded material
	[14]	✔	✔					✔					✔		Review of new materials for sinking EDM electrodes
	[126]	✔	✔				✔		✔			✔			Processes optimisation for Maraging steel
	[127]	✔	✔				✔		✔			✔			Processes optimisation for Ti-6Al-4V alloy
	[128]	✔	✔				✔		✔			✔			The thickness and servo voltage are the most influencing in a taper cut
	[129]			✔		✔								✔	Prediction for consumables and wear parts
	[130]	✔	✔				✔		✔			✔			Processes optimisation for 16MnCr5 Alloy steel
	[131]	✔	✔				✔		✔			✔			Processes optimisation for Magnesium metal matrix composite
	[4]	✔	✔			✔	✔		✔			✔			Processes optimisation for Al (6082)/tungsten carbide composite
	[132]	✔	✔	✔		✔	✔						✔		High-performance wire increasing MRR (~29%) and SR (~10%)
2019	[133]	✔					✔		✔			✔			Processes optimisation for Ti–6Al–4V by Artificial Intelligence
	[134]	✔	✔				✔		✔			✔			Processes optimisation for Ti50Ni49Co1 Shape Memory Alloy
	[135]	✔	✔				✔		✔			✔			Processes optimisation for Al5083/7%
	[136]	✔	✔	✔			✔				✔		✔		Review on EDM applications of ultrasonic vibrations
	[137]				✔									✔	Additive manufacture of EDM electrodes delivers design freedom

According to Figure 2, WEDM is subject to a trend of intensive research, with new methods and process optimisation being the more prominent research fields in EDM. Meanwhile, Figure 3 shows that new methods are typically followed to outcome, with 43%. However, as demonstrated in Figures 4 and 5, research is primarily process-related, being frequently limited to the proposal of new approaches to cope with stochastic EDM process parameters in optimisation or prediction. Besides, it was possible to find that most of the researchers carried out the study of process parametric effects on single or multi-response optimisation [91], being differentiated primarily based on varying the workpiece material to suggest next narrowed improved parameters [101]. Hence, the derivative research for optimal process parametrisation is the majority and trend of publication. Even saturated, the subject is still a hot topic suggesting that new ways to increase process efficiency are necessary. In this sense, the hybridisation of EDM is a trending solution where ultrasonic combination [73,74,112,138] and powder addition to dielectric [57,58,76] are the most promising fields.

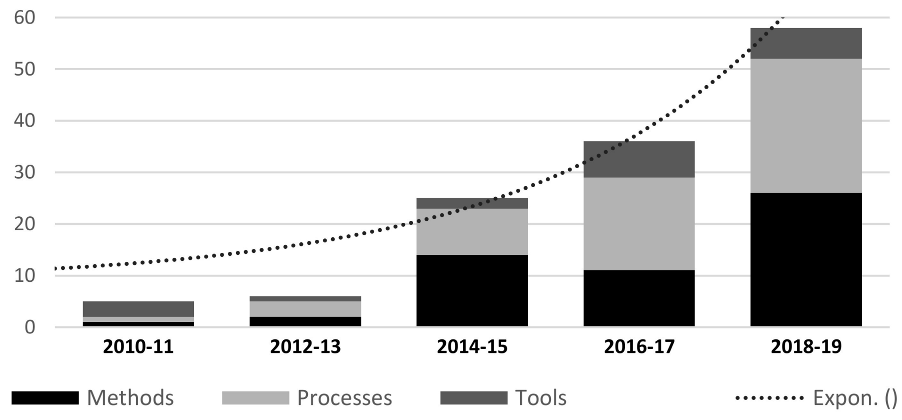


Figure 2. EDM literature evolution.

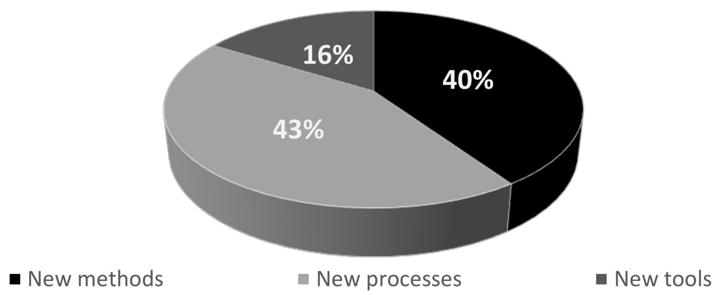


Figure 3. WEDM overall literature distribution.

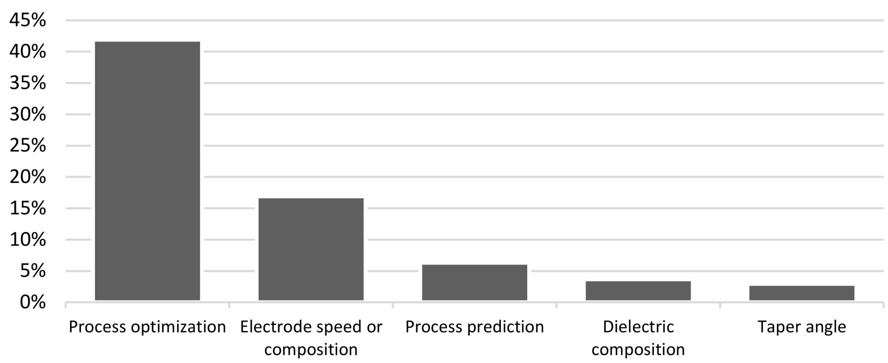


Figure 4. Main approaches to improve EDM.

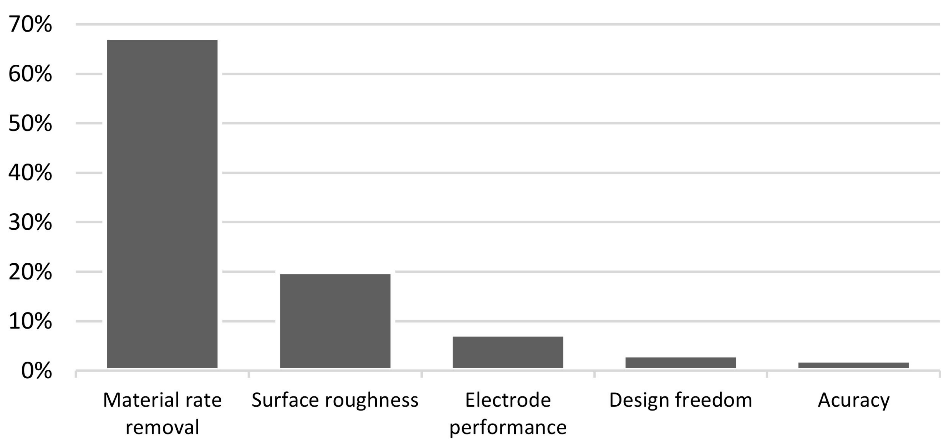


Figure 5. Primary targets in EDM.

By analysing the use of tools, it was possible to observe that fundamental new innovative tools account for only 16% of total research being developed. Regarding SR and MRR, the most promising relies on new pulse generators based on high frequency and lower energy pulse. Moreover, research innovations often focus on the electrode (i.e., wire) or dielectric composition, with few exceptions on taper angle and real-time process control. The latter also focuses on process parameters. Therefore, it is possible to suggest that the current literature lacks tools to improve the EDM application.

In Figure 5, a breakdown of the literature objectives shows that 67% of studies focus on MRR and SR or a trade-off. In this sense, there is an agreement that MRR and SR are frequently opposed to each other. Thus, the improvement of MRR is mainly observed, followed by SR deterioration. Regarding simulations, several mathematical methods have been identified to predict processes with 90–95% accuracy [90]. However, current work in EDM is deficient in process simulation, such as finite element analysis in dry EDM [139], thus revealing a research opportunity. Except for EDM in microscale [48,51,53,54] and taper angle issues [103], no research was found focusing on dimensional accuracy. Therefore, it is possible to suggest that EDM variants of sink EDM and WEDM deliver enough dimensional quality. However, design freedom is still limited by CNC boundaries, and current solutions deliver reduced shape and accuracy [103], thus configuring a research opportunity. Since process optimisation has reached a high level of saturation [38,101], other researchers focused their innovation efforts on four primary areas of (1) wire performance [46,140], (2) dielectric fluids [1,13], (3) enhanced electrode design by additive manufacturing [137], and (4) investigating MRR and SR by combining ultrasonic [74,94].

The most prominent innovative process is vibration assisted EDM, mainly aiming to improve MRR, EWR, and SRR, also investigating the effects over electrode wear [136]. Such technic has been successfully applied in all EDM variants except for micro EDM, where high frequencies can damage the electrode [141].

By evaluating the advances on electrode wires, higher performance was achieved with up to 20% more MRR than the commonly applied round brass wire. However, high-performance wires rely on complex shaping and rare metals, resulting in wires characterised by high cost, prone to damage the wire scrap chopper, presenting straightness issues [142] and environmental hazards [46].

On the other hand, the evolution of pure brass wire to core brass-alloys next added with reduced Zinc content in coating alloys provides enhanced cooling and flushability compared to conventional brass wires. That is why round core brass wires persist as the best trade-off for cost, cut speed, surface roughness, and endurance for most of hard to cut materials [112]. As a solution to the high wire cost, an increase in HS-WEDM interest is noticed. However, in HS-WEDM, when the MRR is near 150 mm^2/min, the workpiece surface presents severe burns and a high frequency of wire breakage [106]. That is why researchers investigated and found that the leading cause is remaining debris not flushed due to dielectric prematurely vaporised when the cutting energy is high. The problem was solved by changing forward and reverse wire speed. However, keeping the MRR not higher than 155 mm^2/min [63]. Focusing on wire usage and improved SR, a new HS-WEDM wire system uses a reciprocated ultra-long 10 km molybdenum alloy wire to achieve a similar SR of low-speed WEDM (LS-WEDM) and yet, with possible wire reuse. However, even optimised, the MRR of HS-WEDM is an average of 40% lower than conventional LS-WEDM [112]. Lately, as evidence that wire breakage is not solved, research aimed to mitigate the problem by proposing an automatic wire thread [143]. For the above, it is possible to suggest that high-performance wires with a lower cost and extended usage are a recurrent concern and MRR improvements for HS-WEDM are still necessary [106].

Regarding dielectric fluids, the common ways to attempt improving MRR and SR are thought to be cooled fluids [55], additives [1,57,58], and flushing combined with ultrasonic field [13]. By addressing the surface burning problem, a new type of dielectric fluid with a higher vaporisation point was developed for HS-WEDM. The results have shown an increased MRR of 330 mm^2/min and higher average current of 15 A with stable machining efficiency [106]. Concerning ultrasonic combination, the principle behind the wire electrode activated with ultrasonic is to reduce or even eliminate the undesired effects of electromagnetic field, resulting in higher dimensional and shape accuracy and reduced wire breakage and a more stable process [74]. Regarding flush operation, the ultrasonic field helps to cope with the effects of gravity when the wire is working on non-vertical straight cutting [121]. Therefore, it also helps achieve higher MRR [74,109] and polished surfaces [144].

Regarding design freedom, sink EDM has focused on metallic additive manufacturing to deliver more complex shaped electrodes [137]. On the other hand, a great attempt has been made on curved holes while conceptual mechanisms are proposed to deliver uneven curved holes by complex kinematics of sink EDM electrodes [45]. However, this remains severely limited by the complexity of the mechanical system and the necessary control. Another advancement in design freedom is milling EDM, where complex forms have been successfully machined in micro-scale using electrodes running as traditional tools in cutting paths [48]. Nevertheless, no recent attempts have been made at large scale, configuring a research opportunity [49].

WEDM embodied in CNC machines present significant taper angle limitations due to wire run-out of guide and deficient dielectric flow into the machining region along with the wire electrode in tilt directions [103]. As a result, difficulties are noticed to cut faces starting and above 5° [103], with limit angles suggested up to 45° [15]. To amend these limitations, researchers have proposed complex mechanical solutions [103], new numerical models to predict and compensate errors [96,122,128], and specific dielectric formulations [15]. Moreover, conventional machining software does not solve the particular needs of wire cutting path programming. That is why new software has been studied to convert CAD workpiece shapes into CNC WEDM cutting path programmes [145]. These efforts suggest that both CNC programming and envelope have constrained the workpiece design; therefore, new solutions should be found.

Lately, the reviewed studies were classified according to the type. The findings have shown that 96% is found within Academia in the form of journal articles (85%), conference papers (9%), and one book section (1%). It is worth noting that all found patents refer to wire development while only one journal article is directly related to the industry. The latter, a WEDM CNC machine, is improved, and advantages argued include taper angle, increased workpiece thickness, and automatic wiring [143]. This distribution, combined with Figure 5, suggests that research focusing on new tools rather than processes parameters may be more relevant to the current industry needs.

3.2. *State of the Art in IR Machining*

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn.

3.2.1. Industrial Robots (IR) Fundamentals

Robots are found in various configurations being classified by their mechanisms, DOF, actuation, workspace, control, kinematics and type of application [26].

In the context of machining, standard IRs refers to a serial system of rigid bodies interconnected by joint mechanisms with six degrees of freedom (DOF), also known as a kinematic chain [146]. Machining IRs can perform programmable trajectories in three-dimensional space with the described configuration while containing arbitrary position and orientation for any object or end-effector [147]. In IRs, the joints can be of a revolute or prismatic type, while the link can be either rigid or flexible. The serial IRs have the axis numbered based on the first joint fixed on the base ending on the 6th link, free to move in space. Figure 6a depicts the six-axis principle, while Figure 6b shows how it is embedded in the current IR structure.

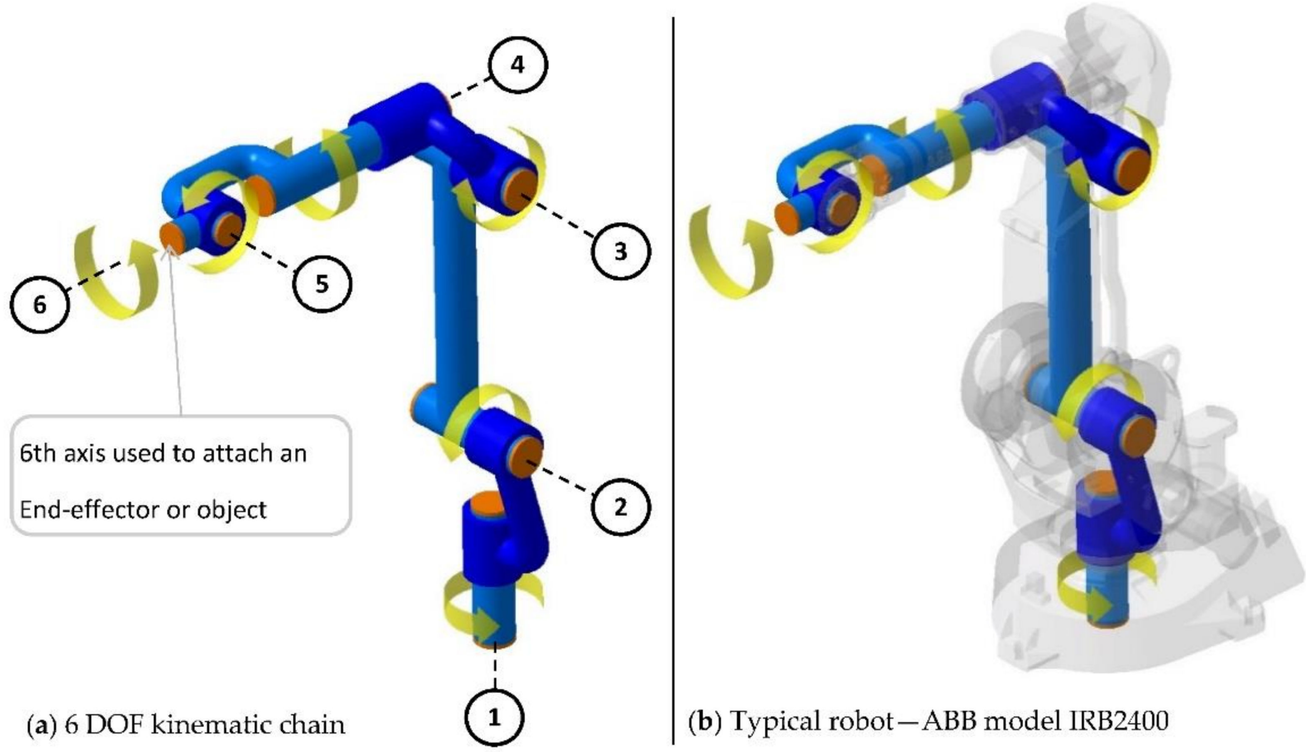


Figure 6. Typical six-axis industrial robot for machining processes.

As a result, even a small six-axis IR can deliver large revolute working envelopes [148]. For example, the most miniature payload model of 3 kg found in the ABB IRB120 can deliver nearly 0.7 m^3 of working space, as in Figure 7.

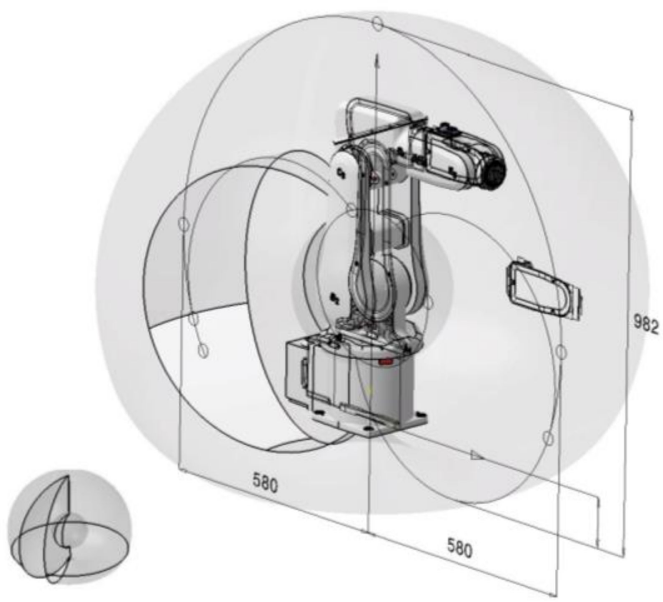


Figure 7. ABB IRB120—revolute working envelope.

3.2.2. IR Systematic Literature Review

Once again, the criteria adopted to select the final literature sample on IR machining were new methods, new processes, and new tools. Table 3 presents the chronologic evolutional synthesis of identified MPTs, their objectives and approaches.

Table 3. Summarised framework on IR machining methods, processes, and tools.

		Main Targets				Used Means				M.P.T.s			
Year	**Reference**	**Improve Accuracy**	**Mitigate Vibration**	**Propose Compensation**	**Mitigate Low Stiffness**	**Damping Tools**	**Simulation**	**Coupling Mechanisms**	**Control Strategies**	**Methods**	**Processes**	**Tools**	**Deliverable**
2006	[149]	✔	✔		✔	✔						✔	Damping tool
2007	[150]	✔	✔	✔	✔	✔	✔		✔	✔			Damping attenuation
2009	[151]	✔	✔	✔	✔		✔		✔	✔			Real-time compensation
2010	[152]	✔		✔	✔		✔		✔	✔			Tool displacement simulation
	[153]	✔		✔	✔		✔		✔	✔			Dynamic compensation
2011	[154]	✔	✔	✔	✔	✔	✔		✔		✔		Literature review IR machining
2012	[155]						✔	✔				✔	Wire cutting process with design freedom
	[156]	✔		✔					✔	✔			Automated robotic deburring
	[157]	✔	✔		✔		✔		✔			✔	Real-time control
2013	[158]	✔	✔		✔		✔	✔		✔	✔	✔	Literature review on IR as a CNC-like machine
	[159]	✔		✔	✔				✔			✔	Contact sensing-based for grinding process
	[160]	✔		✔	✔	✔	✔		✔				CNC-like machining
	[21]						✔	✔	✔		✔		Multi-process programming
	[161]	✔					✔		✔	✔			Offline programming
	[162]						✔	✔	✔		✔		Wire cutting process
	[25]	✔		✔			✔		✔		✔		Automated robotic deburring
	[26]	✔	✔	✔	✔	✔		✔	✔			✔	Map main sources of IR machining error
	[22]	✔					✔		✔			✔	Improved deburring process
	[163]	✔		✔	✔			✔	✔			✔	Dynamic compensation by piezo actuators
2014	[164]	✔		✔	✔		✔			✔			Robot stiffness
	[165]	✔					✔				✔		Image-based print process path
2015	[166]	✔	✔	✔	✔	✔	✔	✔	✔	✔		✔	Literature review IR machining
	[167]	✔						✔				✔	Automatic tool changing system
	[168]	✔	✔	✔	✔	✔	✔	✔	✔	✔			Literature review IR machining
	[16]	✔		✔				✔	✔			✔	Polish end-effector
2016	[169]	✔					✔	✔	✔	✔			CNC-like machining
2017	[170]	✔		✔	✔		✔			✔			Robot stiffness
	[171]	✔					✔			✔			Wire cutting process
	[172]	✔		✔			✔	✔	✔	✔			Polishing
	[148]	✔			✔		✔	✔		✔			Robot stiffness
	[173]	✔		✔	✔		✔				✔		Trajectory (cutting path) for the grinding process
	[174]	✔					✔			✔			A mathematical model for plasma coating
2018	[175]	✔							✔			✔	3D vision
	[176]	✔					✔	✔			✔		Geometric design freedom
	[177]	✔					✔			✔			3D workpiece into wire cutting program
	[178]	✔		✔	✔		✔			✔			Robot stiffness
	[179]												Coupling mechanisms
2019	[180]	✔	✔	✔	✔		✔		✔	✔			Contact sensing-based for grinding process
	[181]	✔			✔		✔		✔	✔			Real-time control
	[23]	✔	✔	✔	✔	✔	✔		✔	✔		✔	Literature review IR machining
	[182]	✔					✔			✔			Wire cutting process

As shown in Figure 8, IR machining is a rising research topic. Besides, the review allows us to confirm that nearly all publications aimed to improve stiffness and suppress machining vibration [23] being frequently found among the found literature review. However, as demonstrated in Figure 9, solving the lack of stiffness and suppressing machining vibration are intermediary paths to improve machining accuracy and overall efficiency.

Moreover, since substantial research exists to compensate errors, it is possible to suggest that the lack of IR stiffness and ways to avoid machining vibrations are not solved. According to Figure 10, new methods are the most frequent topic (52%), followed by new tools (29%) and new processes (19%).

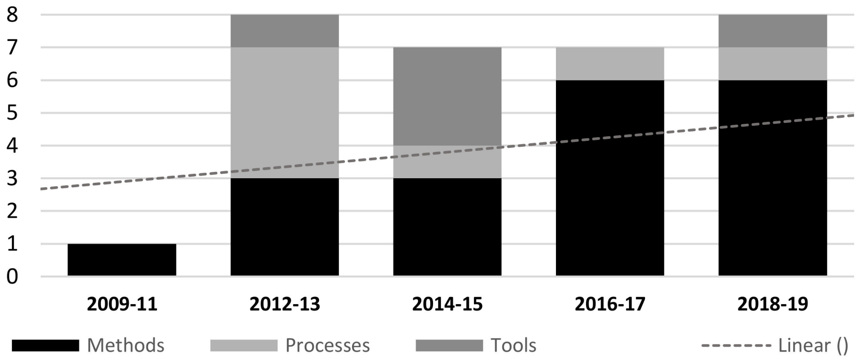


Figure 8. IR machining literature evolution.

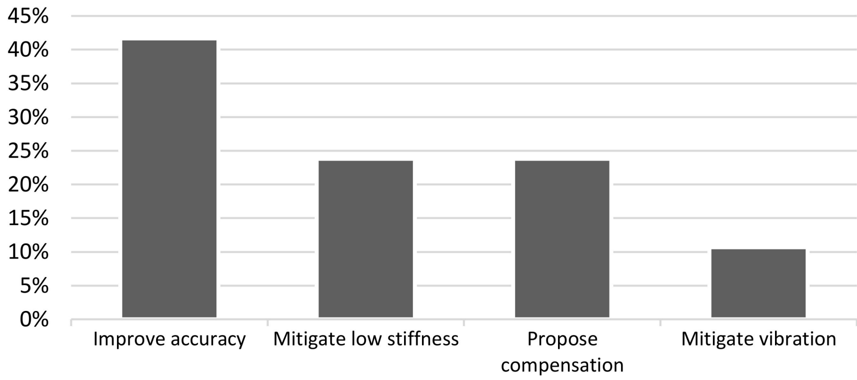


Figure 9. Primary targets in IR machining.

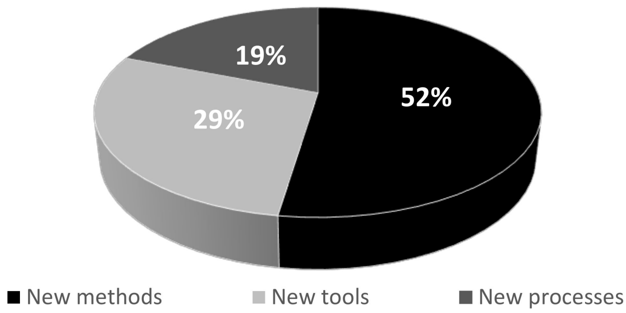


Figure 10. IR overall literature distribution.

Meanwhile, few studies focused on machining efficiency in terms of MRR [16] or SR [183]. On the contrary, improvements of MRR and SR are secondary effects eventually observed when vibration, stiffness and simulation are adequately managed [180,184]. Thus, it is possible to suggest that new ways to solve IR limitations must be achieved upon looking for similar efficiency to conventional machining processes. As depicted in Figure 11, the common approaches for improving IR machining can be found in four groups. The first and common group relies on simulations that allow offline programming [161], as well as allow to convert complex 3D workpieces into cutting programs [177] and avoid trajectory collision and IR singularities [173]. Hence, simulations that deliver robot pose for maximised stiffness [148,164,170,178] and embedded error compensation are tailored for the robot model and manufacturer [178]. Another prominent subject on IR machining focuses on control strategies in real-time during robot machining [157,166,181]. Most of the control strategies are contact sensing-based [159,180] that measure and react to forces or vibrations during the machining operation with pre-determined programming routines. However, artificial vision based on 3D scanning has also been conducted. While common objectives of force sensing are improved SR and precision, artificial vision focuses on collision avoidance [175] and absorbing workpiece dimensional variation in post-processing operations such as automated robotic deburring [25,156]. The third group explores IR flexibility employing coupling mechanisms. Coupling mechanisms play a key role in connecting the IR to the end of effect tool (EE), thus defining the machining process and exploring the flexibility of IRs. Coupling tools have received attention due to their capacity to embedded dumping tools to reduce vibration [149]. Moreover, sensing tolls such as reaction forces [159,180] that will make feasible real-time control as well as provide data used in compensation methods are embodied in cutting path programming software [148,164,170,178].

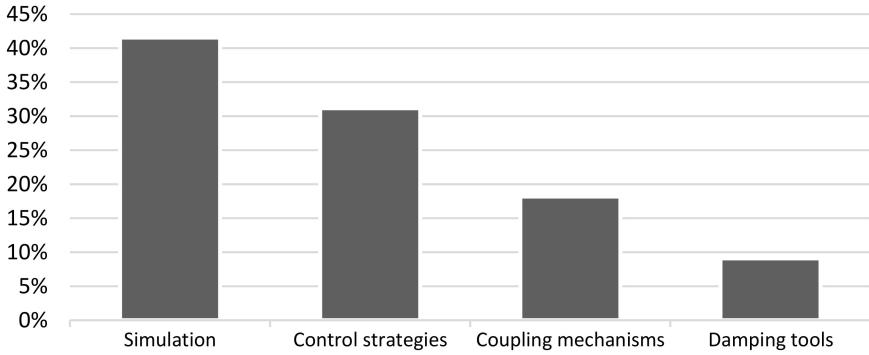


Figure 11. Improving approaches in IR machining.

4. Narrowing Potential Combinations

To move forward, it is necessary to choose an EDM variant considered advantageous for an end-effector design. In this sense, dry EDM, powder EDM, and hybrid EDM were suppressed since they are conditions applied in one of the other EDM variants rather than a proper EDM process. As adopted criteria, robot constraints and capabilities were taken into consideration as follows.

As shown in Table 4, according to the alignment of each EDM variant, it was attributed to a binary note of 0 or 1, where wire EDM is selected. Wire EDM is slightly more aligned than milling EDM due to the electrode as a wire having the capability of being reused as in HS-WEDM, thus better exploiting the robot able to work several unattended hours [46]. It worth noting that, despite the lighter weight of the electrode as a wire, WEDM cannot work without a complex structure for running and tensioning the light and flexible wire electrode. Therefore, the assumption that WEDM can deliver a lighter end-effector is misleading, as later demonstrated with the proposed design.

Table 4. Selection of EDM variant for end-effector design.

	Six-Axis Robots Characteristics	Die sink EDM	Micro EDM	Milling EDM	Wire EDM
(−)	Low stiffness under force or vibrations	1	1	1	1
(−)	Limited accuracy	0	0	0	0
(−)	Limited end-effector weight	0	1	0	1
(−)	Limited sealing against fluids	0	0	1	1
+	Provides a large working envelope	0	0	1	1
+	Able to work for many hours	1	0	1	1
+	Can offer increased design freedom	1	0	1	1
+	Offer complex cutting path programming	1	1	1	1
+	Offer several options for process sensing and control	0	1	1	1
	Best alignment	4	4	7	8

4.1. Combination Plausibility Calculation and Discussions

Firstly, by focusing on strengths and weaknesses [30] extracted from the literature review on IR and the selected WEDM, four SWOT interaction scenarios are created in Table 5.

Table 5. SWOT combination scenarios.

		SWOT scenarios	Wire EDM in CNC Machines: Strengths +WE S1. High accuracy +WE S2. High SR quality +WE S3. Ability to cut hard materials +WE S4. No vibration or forces	Wire EDM in CNC Machines: Weaknesses (−)WE W1. Low MRR (−)WE W2. Low design freedom (−)WE W3. Limited envelope (−)WE W4. Expensive wire usage	(+) Desirable
Machining Robots	Strengths	+IR S1. Large envelope +IR S2. Design freedom +IR S3. Path programming +IR S4. Easier sensing	Scenario #1 Strengths combinations	Scenario #2 WEDM's Weaknesses & IR's Strengths	
	Weaknesses	(−) IR W1. Low stiffness (−) IR W2. Low accuracy (−) IR W3. Unable to cut hard materials (−) IR W4. Limited EE weight	Scenario #3 IR's Weaknesses & WEDM's Strengths	Scenario #4 Weaknesses combinations	Undesirable
			(+) Desirable	Undesirable	(−)

Next, to quantify the plausibility of each group of weaknesses or strengths that have to prevail, the AHP is applied [185]. Table 6 summarises the plausibility for each group of strengths and weaknesses in both axes.

Table 6. Pairwise comparison of WEDM and IR strengths.

	SWOT Scenarios Groups	W.E.D.M. −WEDM	W.E.D.M. +WEDM	IR −IR	IR +IR	Plausibility Results
WEDM	(−)WEDM Weaknesses	1.00	0.69	1.44	0.41	18.1%
	+WEDM Strengths	1.44	1.00	2.08	0.48	25.0%
IR	(−)IR Weaknesses	0.69	0.48	1.00	0.41	13.9%
	+IR Strengths	2.47	2.08	2.47	1.00	43.1%
	Consistency Ratio			1.1%		

As shown in Table 6, since the strengths of WEDM (27.4%) and IR (49.9%) are expected to prevail, it is possible to anticipate that the combinations of IR and WEDM shall deliver promising results. Parallelly, some weaknesses of WEDM (14.0%) and IR (8.6%) are prone to persist and thus require appropriate care during the design conception. Due to the combined strengths, the resulting process should achieve improved design freedom, enlarged machining envelops (thicker workpieces). Furthermore, IR mature programming software can assist flexible processes configurations, and increased sensing is applied for EDM stochastic parameters. For example, solutions could arise to cope with wire breakage by changing the WEDM end-effector using IR intelligent coupling and subroutine programming, delivering faster and free human operation. Another combination group relies on two quadrants on weakness and strengths from both IR and WEDM. As a result, some risks and many synergistic interactions are observed. One could argue in inevitable WEDM dimensional degradation. However, this conclusion is not straightforward. As most IR dimensional error originates from conventional machining contact forces and resulting vibration, the WEDM characteristic of non-contact and nearly zero forces shall improve IR precision machining. However, the precision level is yet to be investigated since a few papers have investigated machining error sources from the IR exclusively [26]. It is worth noting that in fields such as architecture applications, where the current IR precision is acceptable, IR machining research has flourished in the direction of design freedom [177] rather than coping with errors. Moreover, in architecture applications, wire cutting is a noticed predominant end-effector. Many researchers are finding ways to convert complex geometry into efficient robot programming adapted to WEDM [162,169,177,182].

For the WEDM process, kinematics is widely recognised as a critical process parameter [143,183]. In this sense, adapting WEDM into a robot shall enable complex electrode movement with higher smoothness [186,187]. As an ultimate result, the combinations promise to include IR machining, so far mainly restricted to low precision and easy-to-cut materials, as a viable tool within the field of precise and hard-to-cut materials. Lately, as an identified risk, the WEDM feeding system is complex and potentially heavy to act as an EE for the IR. In this sense, a possible solution would be to adopt the HS-WEDM type that reuses the wire and thus, presents more possibilities to be reconfigured in a lighter design and yet deliver reduced wire costs for WEDM.

Lately, since many weaknesses on WEDM are amended by IR, and vice versa, most combined deficiencies do not necessarily result in deteriorated outcomes. For instance, the low MRR of WEDM is prone not to be improved by IR. However, the low MRR will impose a low level of speed to the IR, which is desirable to the IR operation since it has been demonstrated that IR high speed is a recognised source of dimensional error.

4.2. Innovative End-Effector Ideation Based on TRIZ

Regarding how to combine WEDM into an IR, the literature does not provide a straightforward answer. To accommodate more consideration of this combination, we focus on potential and known problems of both WEDM and robotic machining. Next, we adopt TRIZ [31] to approach the issues listed and trigger innovative concepts later incorporated into the WEDM end-effector design. Table 7 summarises the TRIZ findings.

4.3. WEDM End-Effector

Adopting CATIA V5-6 [189], the entire system was modelled, and its mass calculated. Next, the design results and the selected WEDM end-effector will be presented. As depicted in Figure 12, the proposed end-effector weighs 7.852 kg and demands a robot with a payload of at least 8 kg. By adopting the ABB range of robots [190], a suitable robot payload starts with model IRB1300, which correspond to the 4th robot model in a range of 26 models that goes from 3 kg to 800 kg payload. Thus, the suggested end-effector can be considered light enough for a robot considered small to average size.

Table 7. Innovative concepts for the WEDM end-effector.

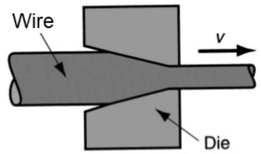
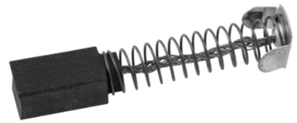
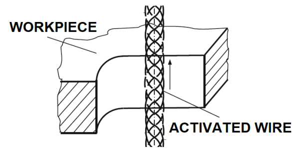
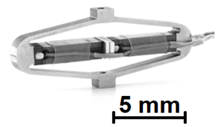
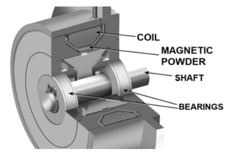
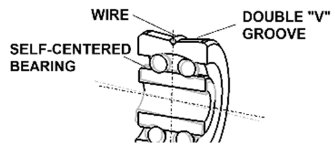
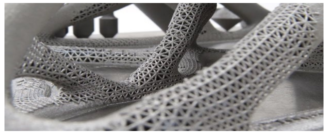
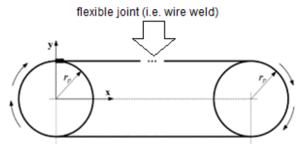
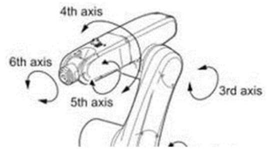
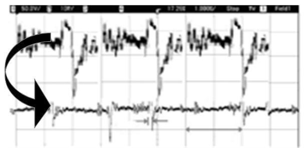
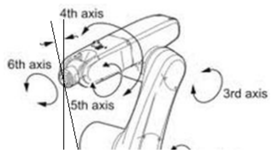
No.	Problem or Component	TRIZ Problem Modelling			TRIZ Principle	Conceptual Solution	
		Technical Contradiction	Physical Contradiction	Trend of Evolution			
1	Wire erosion in HS-WEDM	Provide intense and prolonged erosion on the workpiece without being eroded	-	-	- Regeneration	Add a process able to regenerate and compensate for the wire erosion. Here, a light wire drawing may accommodate raised edges and pits, thus prolonging the wire life	
2	In HS-WEDM, wire erosion creates sharp edges and pits on the surface		-	-	- Regeneration-Universalisation	Use a conductive graphite brush to compensate for erosion and connected directly to the pulley and in contact with the wire	
3	Dielectric flushing efficiency	It needs to go deep into the kerf but get out fast	-	-	- Mechanical vibration	Use ultrasonic wire activation to improve fluid atomisation from a spray nozzle	[74] 
4	Wire short circuit	It needs to be a large wire to cut more extensive parts but a short wire to avoid bending				Use stationary wave on the wire to stabilise and overcome wire bending by attraction to the workpiece	
5	Waste of time due to wire short circuit	Needs to move away from to workpiece and back with nearly no time	-	-		Adopt piezo actuator able to move with high frequency as well as in microscale	
6	Control in wire tension	It needs to provide tensioning currently by a gravity field, but in any direction	-	-	- Replace a mechanical system	Use ferromagnetic powder, which apparent viscosity, to create an attached magnetic field controlled by the coil current	
7	The wire running out of the pulley	Need to be fixed to align the wire but mobile to accommodate disturbances	-	-	- Universalisation	The wire drives itself by self-centred bearings with integrated double V groove	

Table 7. *Cont.*

No.	Problem or Component	TRIZ Problem Modelling			TRIZ Principle	Conceptual Solution
		Technical Contradiction	Physical Contradiction	Trend of Evolution		
8	Wire composition	Need different combined materials in complex shapes yet less complexity	-	- Increasing segmentation	- Object segmentation	Use mature technology from the electric or lifting industry to compose complex combinations of segmented wire materials and functions 
9	The high weight of End-Effector	It needs to be stiff but light	- Ticker and yet light components	-	- Porous materials	Adopt topologic optimisation and lattice structure made of 3D print 
10	Surface burning in HS-WEDM	Use all wire extension with no change in the rotation direction	-	- Increasing Dynamism	- Evolve from solid to jointed system	The wire has its ends precisely attached, allowing it to run continuously in the same direction 
11			-	-	- Thinking in Time and Scale- The wire reciprocates by the supersystem	The robot detects the end of the wire, stop, move out, revolve the 6th axis end-effector in 180° and restart cutting in the same direction 
12	Low SR with high MRR	It needs a high energy pulse for more MRR and less for better SR	-	-	- Thinking in Time and Scale to Separate in Time	Pulse generator with higher frequency removes more material per time unity with lower energy resulting in better SR keeping high MRR [188] 
13	Difficult to flush in tilt positions due to gravity (Phenomenon of unilateral water curtain)	Wire move to taper angles while dielectric flows in the vertical direction	- Flow against gravity	-	- Blessing in disguise (harm to benefit)	Robot cuts with wire in a constant optimum diagonal angle X°, and always top to bottom, thus gravity assures flooding and flushing the kerf 

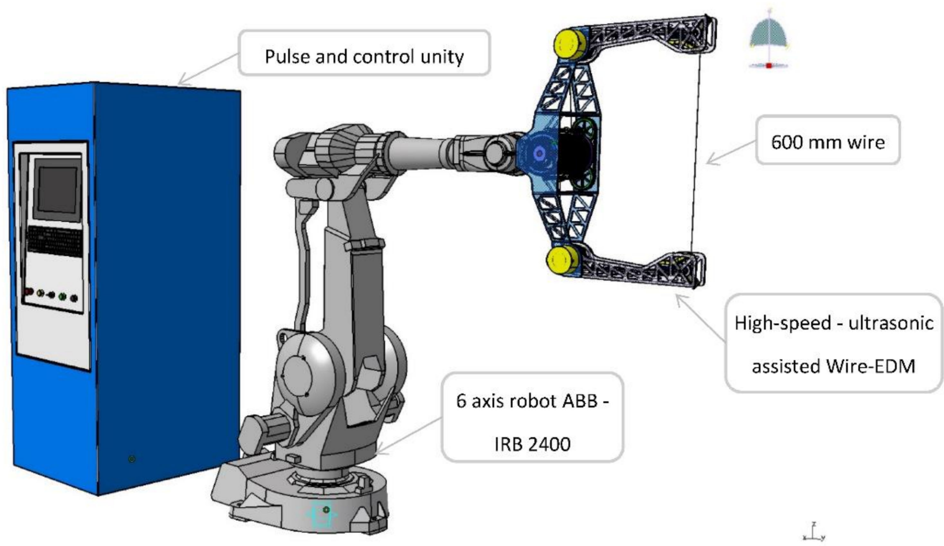


Figure 12. Robotic High speed—ultrasonic-assisted Wire EDM into an ABB robot IRB 2400.

Regarding the control unity centre, it has reunited and configured the following sub-systems:

- Six-axis IR robot control ABB—IRB 2400 with payload 10–16 kg and reach of 1.55 m
- Wire EDM pulse generator
- Dielectric cooling and flow control
- Wire tension control
- Wire-speed control

According to Figure 13, the proposed wire EDM end-effector has embedded the following:

- In Figure 13a, a high-speed reciprocating wire EDM unity can use a range of wires diameters from 0.15 to 0.3 mm and speed from 0.1 to 12 m/s. The system embodied a mechanical wire winding system that guarantees perfect synchronism between the wire portion being released and tractioned. Moreover, the servo motor is built inside the wire drum, with the motion being transferred by gears. As a result, this approach has provided a compact design with lower collisions risks and more significant envelop usage, as well as appropriate gravity centre to the end-effector.
- In Figure 13b, a holding structure optimised by topologic analysis and internal hollow lattice structure allows for flowing the dielectric through the structure to cool the workpiece and the structure and sensitive components such as the tension control. Moreover, the structure is designed so that the exposed wire electrode is 600 mm large, which is nearly the limit of most WEDM machines cutting thickness in the market.
- In Figure 13c, the tension breaker can provide uniform tension up to 30 N. This allows creating a magnetic field controlled by coil current based on ferromagnetic powder, providing constant tension independently of positioning or wire direction of wire speed. Moreover, the pulley design incorporates a propeller that generates an airflow to cool the system and helps to reduce contact with dielectric fluid or debris;
- In Figure 13d, we have a high-frequency piezoelectric actuator able to work in two directions (X, Y) to provide a wide range of ultrasonic wire excitation in frequency and combined wave orientation. Hence, the actuator works to promote automatic, fast, and accurate wire retraction and repositioning in the case of wire short-circuit.
- Still, in Figure 13d, it is possible to see that conductive graphite brushes are adopted to provide continuous and stable electric power transition to the wire. Hence, it is expected and yet to be confirmed if this approach can reduce wire erosion by filling wire craters with graphite conductive material. Moreover, the titanium pulleys are designed with deep grooves and self-centred bearings to avoid wear, vibration, and wire run-out.

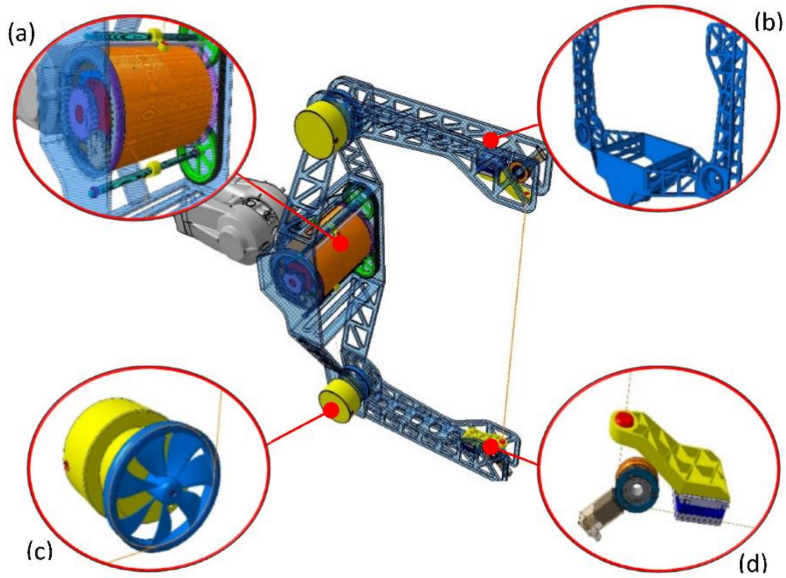


Figure 13. Novel High speed—ultrasonic-assisted Wire EDM end-effector. (**a**) Wire winding (**b**) Topologic optimized structure (**c**) Magnetic brake (**d**) X,Y axis piezo actuator.

5. Conclusions

The advantages of industrial robots are clear. However, up to this day, robot arms cannot cope with traditional machining processes' fundamental forces and vibrations compared with CNC machines. Therefore, this study has scrutinised EDM and robotic machining literature and delivered a suitable end-effector design with a synergistic combination of wire EDM and a six-axis robot into a novel force-free robotic machining process. The TRIZ approach has proven helpful in finding innovative solutions. However, some of the ideas found have been limited due to the lack of appropriate technologies to put them into the proposed design. For example, we did not find a feasible technology to weld a tungsten wire yet keep the wire's 0.15mm external diameter. Moreover, a pulse generator with low intensity and high frequency has been suggested in the literature but is not in commercial use today. The following research steps are to conduct a series of experiments to verify the system's capabilities in design freedom, stability, MRR, SR, and precision. The latter represents a recognised main obstacle of current robotic machining using traditional contact and force intensive processes.

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Abbreviations

A.H.P.	Analytic Hierarchy Process
C.N.C.	Computer Numeric Control
D.O.F.	Degrees of freedom
EDM	Electric Discharge Machining
EE	End Effector tool
EWR	electrode wear rate
IR	6 Axis Industrial Robot
M.P.T.	Methods, Processes and Tools
M.R.R.	Material Rate Removal
PM-EDM	Powder-mixed electrical discharge machining
SR	Surface roughness
SWOT	Strengths, Weaknesses, Opportunities and Threats
T.R.I.Z.	Theory of inventive problem-solving technique
W.E.D.M.	Wired Electro Discharge Machining

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