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# Design of a Wire Cut EDM End-Effector with Strict Robotic Constraints

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**Abstract.** Wire Electric Discharge Machining (WEDM) stands out as a non-contact and nearly force-free machining technique able to cut complex workpieces, delivering dimensional accuracy and superior surface finishing, especially for exotic super-hard materials. On the other hand, machining with six-axis industrial robots (IR) has received much attention due to its notorious advantages over CNC machines to deliver cost efficiency, large envelope, and complex tool kinematics. However, robot machining suffers from severe limitations regarding the tool payload, chatter, repeatability, accuracy error, complex programming and frequently poor surface finishing. This paper investigates the benefits of combining a robot with WEDM to exploit the advantages of both techniques. However, the new system design is not trivial and will involve a transdisciplinary approach and inventive problem solving to design and control a WEDM end-effector. The present study adopts the TRIZ algorithm approach to design a novel WEDM end-effector and define actions to be taken to achieve a flexible and accurate robotic machining system for hard-to-cut materials.

**Keywords.** Wire Electric Discharge Machining, Robotic WEDM machining, WEDM end-effector, TRIZ, transdisciplinary design

## Introduction

Technological progress has pushed the boundaries of materials and design. The demand for high-performance materials such as superalloys, composites, ceramics, semi and superconductors are a hot topic. However, the same properties that make these materials appropriate for high-end applications imposed significant cutting challenges while using traditional machining techniques [1]. As a solution, electric discharge machining (EDM) has been successfully adopted to cut any hard material offering at least 0.01 S/cm of electric conductivity [2]. The process consists of an electrode steering a series of high-frequency electric discharges that gradually melts the workpiece's surface into small particles flushed by the dielectric fluid. In EDM, there is no contact between the electrode and the workpiece and nearly no forces. Thus, stresses, chatter and vibrations from traditional machining can be avoided. Up to the present day, to control the electrode path, EDM is configured on computer numerically controlled (CNC) machines. However, CNC machines are designed for stiffness to cope with the high forces and vibration of traditional machining. As a result, CNC has a limited working envelope that frequently leads the workpiece to be segmented in

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multiple stages, demanding tricky fixtures, resulting in lower precision and additional costs [3].

To overcome CNC limitations, traditional machining using 6-axis industrial robots (IR) have been extensively investigated, looking for cost-efficiency and design freedom [4]. Besides, since IRs can attach a plethora of different end-effector tools (EE), sensors and control mechanisms, IRs can deliver multi-functionality with improved productivity [5]. Nevertheless, due to IR's intrinsic design, they lack stiffness and cannot hold heavy loads either cope with high forces of traditional machining, particularly on exotic hard-to-cut material. That is why most of the correlated research efforts focus on solving IR machining problems originated from the lack of IR stiffness resulting in machining vibration, poor surface finishing, lack of precision and repeatability [6].

On the other hand, the EDM process, particularly wire EDM (WEDM), has been suggested as a promising solution for IR lack of stiffness and limited forces [7]. Other technical obstacles persist and are fundamentally spread by their transdisciplinary nature. Among the most notorious, the following are a few: limited payload, complicated programming, accuracy error, and complex control. Therefore, the present research will adopt the Theory of Inventive Problem Solving (TRIZ) algorithms to find conceptual transdisciplinary engineering solutions to design a WEDM end-effector with strict robotic constraints. The research is organised as follows. Section 2 describes the methodology. Section 3 presents the results, and lately, section 4 is the conclusion.

## 1. Methodology for End-Effector design by TRIZ

Initially developed by G.S. Altshuller in the 1940s, the technique of TRIZ has been exploited more fully in the 1990s. It consists of algorithms and 40 transdisciplinary principles for driving creative thinking on problem-solving, rather than an intuitive and monodisciplinary trial and error approach. Therefore, the first step in our methodology is to map the usual problems from IR machining and WEDM to apply the TRIZ approach.

Classical TRIZ have available several different tools whose selection depends on the problem and context, making it challenging to select the appropriate tools. To properly formulate an inventive problem that forms a contradiction and respective application of TRIZ principles, we adopt the algorithm suggested by Cameron [8] to later incorporate the concepts into the WEDM end-effector design. Figure 1 summarises the adopted methodology.

To map the problems and main aims, a systematic review [9] on literature from 2010 to 2020 was conducted from scientific databases as well as patents, industry articles, and reports not included in academic repositories.

## 2. Results

### 2.1. Problem mapping on wire EDM and robotic machining

The literature was tabulated in chronological order to find recurrent problems on WEDM and potential sources of TRIZ contradictions. Next, the problems were classified into identified five main categories of material removal rate (MRR), surface roughness (SR), wire break or performance (W.P.), design freedom (D.F.) and dimensional or geometrical error (DGE). Table 1 summarises the findings.

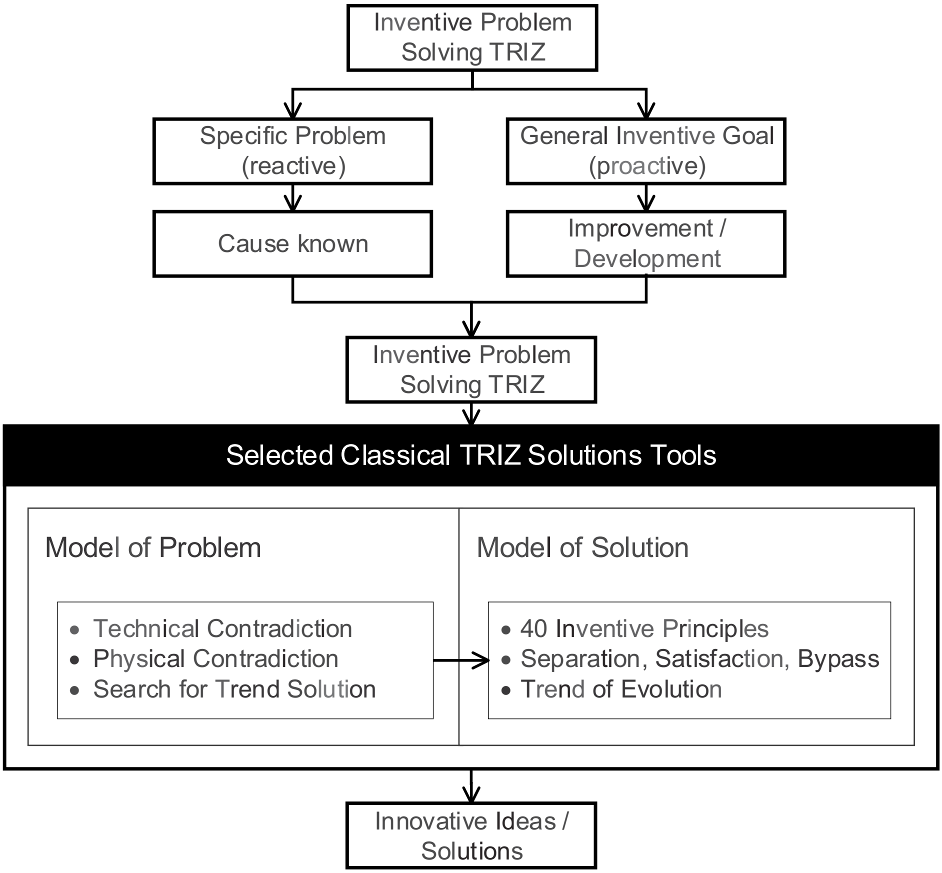


**Figure 1.** Algorithm for the use of narrowed TRIZ tools.

Similarly, to find recurrent problems on robotic machining and discover potential sources of TRIZ contradictions, the literature was again tabulated in chronological order while robotic machining problems classified into identified four main categories of accuracy, vibration, and compensation and low stiffness. Table 2 summarises the findings.

**Table 1.** Recurrent aims and problems on WEDM.

| **Year** | **Reference** | **Main aim** | **Problem** | | | | |
|---|---|---|---|---|---|---|---|
| | | | MRR | SR | WP | DF | DGE |
| **2010** | [10] | Adaptive fuzzy servo control to avoid wire breakage | • | • | • | | |
| **2012** | [11] | Process optimisation of aluminium composite | • | • | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **2013** | [12] | WEDM control to avoid wire rupture in high thickness cut | ● | ● | | | ● |
| **2014** | [13] | Review on process optimisation | ● | ● | | | ● |
| **2015** | [14] | Process optimisation for SR based on wire geometry/speed & current | ● | ● | ● | | |
| | [15] | Adaptive real-time control for MRR, SR and stability | ● | ● | | | |
| | [16] | Process optimisation by adaptive neuro-fuzzy inference | ● | ● | | | |
| | [17] | Process optimisation for taper cutting | ● | ● | | ● | ● |
| | [18] | Adaptive servo control based on current pulse probability | ● | ● | ● | | |
| | [19] | Real-Time control system for MRR | ● | | ● | | ● |
| **2016** | [20] | Identify the most significant parameter for MRR and SR | ● | ● | | | |
| | [21] | Investigate wire movements and workpiece location | | | ● | | ● |
| | [22] | Process optimisation for tapered parts | ● | ● | | ● | ● |
| | [23] | Investigate burning surface in High-speed WEDM parameters | ● | ● | | | |
| **2017** | [24] | Machining parameters against harmful wire vibration | ● | ● | ● | | ● |
| | [25] | New wire mechanism for improved SR and M.R. in tapper | | ● | | ● | ● |
| | [26] | Improved accuracy and MRR with ultrasonically activated wire | ● | ● | ● | | ● |
| | [27] | Adaptive servo control for variable thickness | ● | | ● | | |
| **2018** | [28] | New HS-WEDM with long wire with process parametrisation | ● | ● | ● | | |
| | [29] | Processes optimisation for Titanium Grade 6 | ● | ● | ● | | ● |
| | [30] | Influence of cut direction in SR | ● | ● | | | |
| | [31] | Processes optimisation for angular error in taper cutting | | | | | ● |
| **2019** | [32] | Processes optimisation for Al (6082)/tungsten carbide composite | ● | ● | | | ● |
| | [33] | High-performance wire | ● | ● | ● | | ● |
| | [34] | Investigates different control strategies in wire EDM | ● | ● | | | ● |
| **2020** | [35] | Processes optimization for Inconel 625 | ● | ● | | | |

**Table 2.** Recurrent aims and problems on robotic machining.

| **Year** | **Reference** | **Main aim** | **Problem** | | | |
|---|---|---|---|---|---|---|
| | | | Accuracy | Vibration | Compensation | Low stiffness |
| **2010** | [36] | Investigate errors due to tool displacement | ● | | ● | ● |
| | [37] | Real-time dynamic error compensation | ● | | ● | ● |
| **2011** | [38] | Review on error sources in IR machining | ● | ● | ● | ● |
| **2012** | [39] | Robotic wire cutting process with design freedom | ● | | | ● |
| | [40] | Automated robotic deburring | ● | | ● | |
| | [41] | Real-time compensation control | ● | ● | | ● |
| **2013** | [42] | Contact sensing-based for grinding process | ● | | ● | ● |
| | [43] | Propose CNC-like machining | ● | | ● | ● |
| | [44] | Multi-process programming | ● | | ● | ● |
| | [45] | Automated robotic deburring | ● | | ● | |
| | [6] | Map primary sources of IR machining error | ● | ● | ● | ● |
| | [46] | Real-time compensation using piezo actuators | ● | | ● | ● |
| **2014** | [47] | Robot stiffness | ● | | ● | ● |
| **2015** | [48] | Automatic tool changing system | ● | | | |
| **2016** | [49] | CNC-like machining | ● | | | ● |
| **2017** | [50] | Robot stiffness | ● | | ● | ● |
| | [51] | Wire cutting process | ● | | | |
| | [52] | Trajectory (cutting path) for the grinding process | ● | | ● | ● |
| **2018** | [53] | Geometric design freedom | ● | | | |
| | [54] | 3D workpiece into wire cutting program | ● | | | |
| **2019** | [55] | Contact sensing-based for grinding process | ● | ● | ● | ● |
| | [56] | Real-time control | ● | | | ● |
| | [4] | Literature review IR machining | ● | ● | ● | ● |
| **2020** | [57] | Evaluate dynamic and static stiffness models for robot pose | ● | ● | | ● |

### 2.2. Transdisciplinary End-Effector conceptualisation by TRIZ

To conceptualise the end-effector, we focus on two primary sources. First, common problems in both WEDM and Robotic machining. Second, we list those problems with a high probability to occur due to this novel combination. As a result, a list of broad and transdisciplinary causes is found.

Once the problems were identified, TRIZ [8] is adopted to approach the problems and trigger innovative concepts to be later incorporated into the WEDM end-effector design. **Table 3** presents the results.

**Table 3.** Concepts for designing a robotic WEDM end-effector.

| **Problem description** | **TRIZ** | | |
|---|---|---|---|
| | **Model problem** | **Principle** | **Model solution(s)** |
| **1.** Wire erosion | **(T.C.)** Create intense erosion without being eroded | • Regeneration<br><br>• Universalisation | • Debris stick to the wire creating a protective layer renewed along with the erosion process.<br>• Apply graphite brush to provide electric power and compensate wear by filling up wire craters. |
| **2.** Flushing debris | **(T.C.)** Travel deep into the kerf but get out fast | • Mechanical vibration<br><br>• Add a force field | • Use ultrasonic activation to achieve a stationary wire wave to stabilise and overcome wire warping.<br>• The dielectric fluid nozzle is designed to create a laminar field flow. |
| **3.** Servo delay during short circuit | **(TrE)** Move away from to workpiece and back with nearly no time | • Segmentation | • Add to the servo system a piezo actuator able to move high frequency and microscale only for short-circuit events. |
| **4.** Wire tension | **(PhC)** Achieve a gravity field in any direction allowing robotic freedom | • Replace a mechanical system | • Use ferromagnetic brakes to create an attached magnetic field that moves with the end-effector |
| **5.** Wire composition | **(T.C.)** Needs combined materials in complex shapes yet less complexity | • Increase segmentation | • Use off-the-shelf technology from the electric or lifting industry to interlace single wires with different materials. |
| **6.** End-Effector weight | It needs a ticker and yet light structure | • Porous materials<br><br>• Increase segmentation and dynamism from solid to jointed | • Adopt topologic optimisation and lattice structure made of 3D print<br>• Segment the wire winding system to be on the floor. Next, use flexible shafts to transfer to the end-effector only the wire. |
| **7.** Surface burning in high-speed WEDM | **(T.C.)** Use the entire wire with no change in rotation | • Increase dynamism from solid to jointed<br>• Think in time and scale, and transfer to the supersystem | • The wire has its ends precisely welded, running continuously in the same direction.<br>• The robot detects the end of the wire, stop, move out, revolve 180º and restart cutting in the same direction. |
| **8.** Trade-off SR vs MRR | **(PhC)** Needs High energy pulse for more MRR at the same timeless for better SR | • Think in time and scale to separate in time | • Pulse generator with higher frequency removes more material per time unity yet using lower energy for better SR |
| **9.** Hard to reach the back of the workpiece | | • Increase segmentation and dynamism, and separate in time | The additional 7$^{th}$ axis acts as a rotating table and work synchronised with the robot and allows full access to workpiece geometry. |

| | | | |
|---|---|---|---|
| **10.** Hard to flush in a tilt position | **(T.C.)** Flow misaligned with the gravity field | • Blessing in disguise | Add a nozzle directly into the end-effector for constant flow-wire alignment while the robot cuts in a constant optimum diagonal angle, always top to bottom. |

Legend: **(TC)** Technical Contradiction **(PhC)** Physical Contradiction **(TrE)** Trend of Evolution

### 2.3. Designed WEDM end-effector

Following the finding of the TRIZ transdisciplinary approach, , CATIA V5-6 CAD software is adopted, and the system is completely designed. As a proof of concept, the most miniature ABB IRB120 robot system is selected to verify the current robots' ability in coping with WEDM forces and vibrations. The IR payload is only 3kg yet delivering nearly 0.7 m³ of working space. Figure 2 depicts the robot.

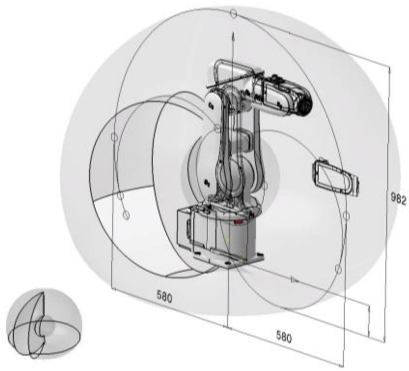


**Figure 2.** Size and workspace of ABB IRB120 for WEDM combination.

Figure 3 presents the mains subsystem of (1) WEDM end-effector, (2) separated wire winding system, (3) rotating 7$^{th}$ axis table, (4) pulse generator, (5) 6-axis industrial robot.

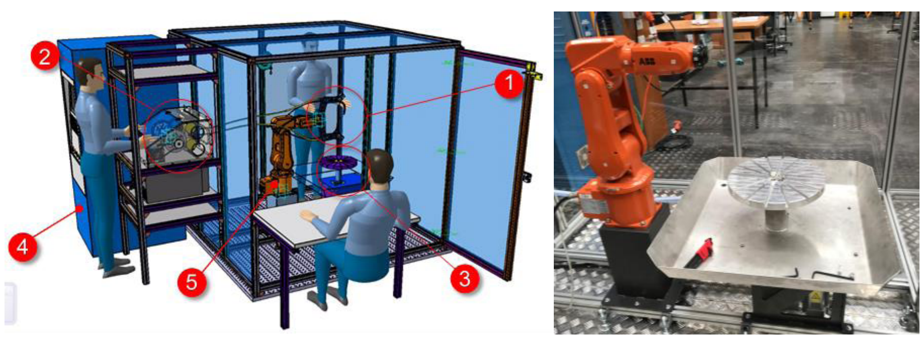


**Figure 3.** Robotic WEDM cell apparatus and main subsystems.

Next, in Figure 4, balloon 7, 3D-printed nozzles are designed to create a dielectric laminar flow travelling parallel to the wire to go deeper in the kerf for improved flushing. In balloon 6, a dual-axis piezo actuator is used to activate a stationary wave vibration on the wire. Also, it is possible to see the electric brush's use in direct contact with the wire providing power and, at the same time, regenerating the wire by filling craters with graphite.

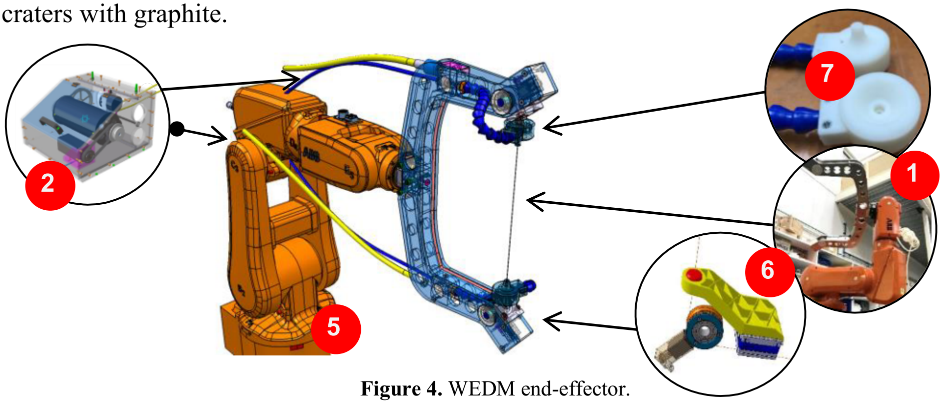


**Figure 4.** WEDM end-effector.

To verify the robotic system's ability to cope with wire EDM vibrations, ANSYS R19 software is used to perform modal harmonic simulation response while the robot is in a pose of low stiffness. It was found that the designed system can perform WEDM and yet avoid harmful vibrations if the pulse frequency is controlled. Figure 5-A displays severe vibration with amplitudes of 27mm under the natural frequency of 103 Hz. Figure 5-B shows that the maximal vibration amplitude is found over the wire yet lower than 1 micron when the frequency is above 6 kHz.

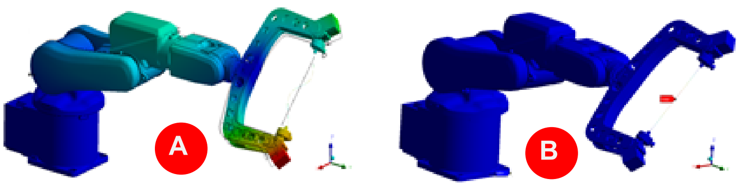


**Figure 5.** Robotic WEDM vibration response for ABB IRB120.

In Figure 6, a pulse generator with low-intensity iso-energy and pulse frequency up to 1GHz is prepared.


**Figure 6.** WEDM high-frequency pulse generator.

Although the TRIZ approach has innovative solutions, some ideas have been limited due to the lack of appropriate technologies to put them into the proposed design. For example, no feasible technology to weld a thin wire, yet keeping the external diameter (i.e. 0.15mm) was found. The next steps of the present research are to finish building the apparatus and perform a series of experiments to verify the capabilities of robotic WEDM regarding design freedom, vibration, MRR, SR, and precision.

## 3. Conclusion

Traditionally, WEDM has nothing to do with robots due to the nature of the process and structure of the equipment. The idea of combining these two totally different processes creates a series of transdisciplinary problems between mechanical, electronic, manufacturing engineering. There is a lack of prior researches on the challenges of combining these two systems. This paper presents a novel approach to scrutinise robotic and WEDM literature to discover recurrent and new obstacles in system design. TRIZ approach, which has been used extensively for user-oriented product design, is applied to analyse literature. The application of the TRIZ technique in this design process played a key role in finding the best combination and features of the robotic WEDM. The novel adaptation of TRIZ methodology has successfully designed a new combined process system that has the best chance to fulfil the expected system requirements and will deliver two main benefits: first, to cut exotic materials for complex, large, and monolithic workpieces; second, achieving robotic machining free of prohibitive chatter and vibrations, which have been reported to be detrimental to complex robotic compensation, such as backlash, pose, and dumping technics.

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