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Comparison between Bang-Bang, PID and LQR Controller for Electrical Discharge Machining Process

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Abstract: During the Electric Discharge Machining process, ensuring that there is the appropriate amount of spark gap between the tool and the workpiece is one of the most important factors in determining how well the machine will perform. With the assistance of Simulink models, this work will compare the effects of a Bang-Bang Controller, a Proportional-Integral-Derivative (PID) Controller, and a Linear Quadratic Regulator (LQR) Controller on a dynamic EDM process. Through the use of simulation, it was possible to observe the effectiveness of each controller in correctly maintaining the spark gap distance. This effectiveness was then used to determine the approximate values by which the controller could be implemented on the physical EDM setup.

In light of the fact that the EDM is a model of a non-linear process, it has been established beyond a reasonable doubt that LQR is the controller of choice for this process. The various controllers for the EDM Process Model were compared, and supporting graphs are provided to strengthen the claims made in the article.

Keywords: Bang-Bang Controller, Electrical Discharge Machining, LQR Controller, Mean Spark Gap Voltage, Modelling, PID Controller, Servo-control.

I. INTRODUCTION

In a traditional EDM process, metal is subtracted from the workpiece through a melting and evaporation process. This is caused as a result of electrical discharges that happen in a small space between the workpiece and the tool, which acts as positive and negative electrodes, respectively.

This machining method creates thermoelectric energy by bringing a submerged electrode and workpiece closer together. During the EDM process, the tool (cathode) and the workpiece (anode) do not touch each other. Instead, the sparks that come from the discharge make the material on the workpiece melt away.

With EDM, both the part material and the electrode material tool heat up a lot, quickly and often makes a small pool of molten metal or scraps on the part's surface. [5] EDM is often seen as an efficient way to manufacture parts because of the low cost involved with its ownership. It makes it possible to make parts from unusual materials with complex geometries that are hard to make with other standard machining methods.

A. Application of EDM

EDM is popular in small-volume production because it enables milling, turning, small-hole drilling, and wire cutting. EDM is most commonly used for manufacturing fuel injection nozzles for automobiles.

B. Existing System and Proposed System

The existing systems are rather outdated and employ a controller mechanism that is not very effective. This work aims to increase accuracy and implement PID and LQR control to improve the process. Feedforward control for the servo motor is used to make the process more efficient.

A closed loop feedback mechanism is used to regulate a DC Step-Servo motor using PID and LQR control algorithms to increase accuracy by maintaining a sufficient spark gap distance between the tool and workpiece. [4] Increased emphasis on actuation improves the efficiency of the control mechanisms and the overall process.

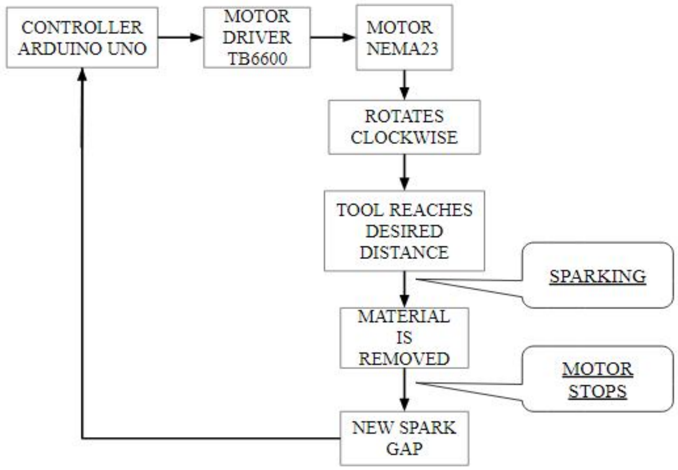

Fig. 1 Flow of Process

C. Challenges of EDM

Machining takes an excessively long time because of the relatively poor rate of metal removal. Tool-wearing is another issue. Pre-built machines have high power consumption and lack modularity and repairability.

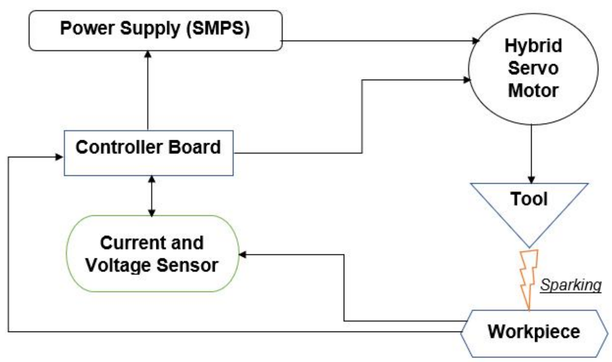

Fig. 2 System Block Diagram

II. LITERATURE SURVEY

Today's industry desires higher precision with greater quality of finished products. Hence, the servo tool feed control system in EDM plays a vital role in maintaining the appropriate spark gap distance between tool and workpiece for attaining efficient machining.

V.C Uchegbu et al. [1] studied the mathematical model of the EDM method for improved gap voltage performance. Their studies give us a deep understanding of the EDM parameters involved while modelling the system. Their work also highlighted the various equations and subsystems in the EDM Simulink model which included the equations for the DC servo motor block and the EDM process model block. Using basic Kirchhoff's equations, an EDM pulse generator model was also created. Experimental simulations from this paper shows us that in absence of a PID compensator the response plot was critically damped, which is similar to that of a sluggish system but, when a fine-tuned PID compensator was used, the response time reduced significantly from 0.19µs to 0.0185µs making it evident that PID controller is rather better in an EDM process for higher control, in comparison to not using any controller at all.

A. Yahya and C.D. Manning [2] developed the model of the EDM system which could accurately foresee the material removal rate [MRR] for any particular tool and work piece. This paper also discusses the servo system controller in terms of a multi loop control system. The MRR constant α had been identified in this paper and empirical analysis was carried out in the Simulink workspace. It was also noted that different material properties for the EDM process gave dissimilar erosion rates, as noted here it was seen that the value of α for the graphite-steel material was moderately greater in comparison to the copper-steel material.

Paulinus Chinaenye Eze et al. [3] developed the mathematical model for the servo positioning system. In this instance, a dependable PID controller was developed and incorporated with the EDM servo motor block in order to enhance the system's capacity to respond to transient conditions.

This experiment's simulation results demonstrated that the designed controller significantly improved the position process's transient performance. The designed controller resulted in an overshoot of 5.06 %, a settling time of 0.17s, a rise time of 0.0526s, and a steady state error of zero.

Elnaz Karimpour et al. [4] Their work presents a simulation of an EDM system that is composed of three primary loops. For the purpose of this study, an indirect measurement procedure was developed and implemented with the aid of a voltage average gap model. This study's primary objective was to replicate the dynamic behaviour of the entire EDM system. In addition, this research revealed that the MRR has a direct correlation with the discharge voltage, discharge current, and pulse on time, but an inverse correlation with the pulse off time. It was also noted that MRR in the EDM process is mainly dependent on evaporation and burst of bubbles.

T. Muthuramalingam and Mohan B [5] discuss the significance of improving electrical process parameters to increase EDM process efficiency. Further studies were also conducted on how crucial process parameters such as discharge energy, electrical variable and pulse shape play a vital role on factors such surface roughness, MRR and electrode wear rate. During their study it was found that lower energy pulses vastly improved the surface finish of the workpiece, while on the other hand higher energy pulses improved the MRR significantly.

It was also found that the duration of pulse plays a significant role in machining characteristics that include tool wear, MRR and surface finish. It was also noticed that the dimension and the size of the craters on the workpiece had been relatively similar at lower energy discharge sparks whereas, the higher energy pulses lead to micro surface crack on the workpiece which often led to improper machining.

It was also discovered that RC Pulse Generators produced a more even surface finish when compared to Transistor Pulse Generators. This was attributed to the fact that the RC Pulse Generators had a lower discharge energy distribution over the surface of tungsten carbide.

Muthuramalingam et al. [6] studied the importance of having an effective gap control mechanism and the effects of various tool electrodes while machining Titanium (Ti-6Al-4V) alloy in the EDM process. In this study a servo tool feed control mechanism was developed, where the distance between the tool and workpiece was measured using a calibrated (HCSR04) sensor which was used to optimize the tool movement time.

It was found that when the stand-off distance (SOD) was kept between the 0.01 mm and 0.1mm range the response time was found to be 0.1 microseconds. In this setup a calibrated ultrasonic (HCSR04) sensor was used to optimize the tool movement time. It was also noted that various input parameters like discharge current, gap voltage and duty factor played a significant role in determining the efficacy of the EDM process. Through the experiments performed it was also noticed that arcing happens at a lower voltage, while on the other hand sparking happens when there is a significant amount of current and voltage, also sudden spikes were observed as a result of sudden inductive kick-back occurrence while shifting between arcing to sparking and vice versa. It was also inferred that lower the spark energy, the lesser was the surface roughness, while on the contrary greater the spark energy of the pulses, the poorer was the surface quality. It was also observed that due to the brass tool’s higher melting point it failed to create a greater surface finish in comparison to the copper tool anode.

T. Muthuramalingam and Mohan B [7] conducted research on how the discharge current pulse influences the machinability of the material during the EDM process. According to the findings of this research, the amount of discharge energy plays a significant part in deciding the size and volume of the crater. According to the findings of their studies, a significant reduction in surface roughness could be achieved through the application of an even distribution of charge generated by the authors' modified fuzzy-based ISO current pulse generator. With the assistance of a current sensing element, the width of the pulse was regulated in this case by utilizing two consecutive zero current crossings as a control mechanism. The material which was machined in this study was that of an AISI 202 stainless steel material. It was also observed that varying the time duration while maintaining a constant discharge current leads to variation in the discharge energy of the pulse. Other important inferences included that the discharge energy must be kept minimum in order to maintain a tiny crater size. It was also seen that adopting a RC pulse generator produced smaller crater size due to its lower frequency of operation but it failed to generate a uniform energy distribution while on the contrary, the ISO current pulse generator produced tiny craters and also had a uniform energy distribution and hence lead to higher MRR and better surface finish in comparison to conventional pulse generators.

III.DESIGN SPECIFICATION

A. Controller Theory

A Bang-Bang controller, also called a hysteresis controller or Variable Structure Controller, is a feedback controller with a cause and an effect. Bang-Bang controllers have only two states: ON and OFF, and switching between activities is quick.

PID controllers include P-Proportional, I-Integral, and D-Derivative also known as Three Term Controllers. When operating in a closed loop, the PID controller will keep the output constant to ensure that the process variables and setpoints remain equal. When comparing the plant output to a reference, the PID controller uses closed loop feedback to reduce the error and stabilize the plant input. PID controllers are favoured due to their manageability, precision, and consistency in operation.

The EDM process is nonlinear in nature. Any real-world test of a PID controller requires linearization. LQR uses nonlinear models to solve PID problems instead of linear equations. When used as a design guide, a retreat horizon allows for the prediction of future output at each time step, which results in a reduction in the overall cost criterion and function. In some systems, LQR saves energy over PID.

TABLE I
PHYSICAL PARAMETERS

S/N	Parameter	Symbol	Value
1	Motor Inductance	L	$3*10^{-3}$ H
2	Motor Resistance	R	0.9Ω
3	Torque Constant	K_t	0.75Nm/A
4	Back EMF Constant	K_e	0.75 V. s/rad
5	Viscous Friction Coefficient	K_f	$6*10^{-3}$
6	Motor Viscosity Friction Constant	b	$6*10^{-3}$
7	Moment of Inertia	J	0.7 Kg/m^2
8	Dimensionless Constant	C	1.74
8	Alpha	α	$2e^{-12}m^3$ /J
10	Gap Voltage	V_{arc}	1.98V
11	Maximum Voltage	V_{max}	25V
12	Gap Current	I_{gap}	4.2A
13	Frequency	F^s	$5e^{-5}$KHz
14	Pulse ON Time	T_{on}	$1e^{-3}$s
15	Pulse OFF Time	T_{off}	$1e^{-3}$s
16	Ignition Delay Time	T_d	$114.2e^{-6}$s
17	Time- Filter Constant	Tau	$10e^{6}$s
18	Gap Width	Sigma	$2e^{-6}$
20	Constant	v	1.04
21	Material Removal Properties	A_p	$2e^{-12}$

B. Performance Criteria

The unit step response parameters to be achieved in this work for an optimized EDM process spark gap include the following:

1) Less than 10% overshoot.
2) Less than 5 seconds of settling time.
3) Less than 2 seconds of Rise time.
4) Less than 0.5% of Steady State Error.
5) Ignition Delay Time being less than 2ms.
6) Spark gap width less than 2mm.
7) Damping ratio to be 0.5.
8) Natural Frequency of the system to be 0.314 rad/s

C. Transfer Function Calculation

Transfer Function of Step-Servo Motor is

$G(s) = \dfrac{K_t}{(L \times J \times s^2) + (L \times b \times s + J \times R \times s) + (b \times R + K_e \times K_t)}$………Equation 1

$Sd = -\zeta\omega_n + j\omega_n\sqrt{1-\zeta^2}$ ……Equation 2

Substituting values in Equation 2 and calculating, D = -0.157 & β = -60°

Simplifying Equation 1, $G(s) = \dfrac{0.75}{(0.0021 s^2) + (0.63 s) + (0.5679)} = \dfrac{0.75}{(s+299.1)(s+0.90272)}$………Equation 3

Poles of the system are -0.90272 and -299.1. Since there is no pole in the right half of the plane, it follows that the system is stable when it is operating in an open loop.

Substituting Equation 2 in Equation 3, $G(s) = \dfrac{0.75}{(0.744+0.272j)(298.9+0.272j)}$

$A_d = \dfrac{0.75}{(0.744 \times 289.9)} = 3.3495 \times 10^{-3}$

$\Phi_d = (-0.054-20.082) = -20.091$

Getting values from simulation for the system in MATLAB,

$K_p = 122$; $K_d = 53$; $K_i = 65$

$G_c(s) = G(s) \times G_o(s) = \left(\dfrac{K_i}{(s)} + K_p + K_d s\right) \times G_o(s)$

$= \dfrac{0.75(65s^2+122s+53)}{s(s+299.1)(s+0.90272)}$

State Space Matrix Representation

$$A = \begin{matrix} -300 & -270.4286 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{matrix}$$

$$B = \begin{matrix} 1 \\ 0 \\ 0 \end{matrix}$$

$$C = \begin{matrix} 23214 & 43571 & 18929 \end{matrix}$$

$$D = 0$$

$|Q_c| = 1$; $|Q_o| \neq 0$, Rank = 3

By its very nature, the system is controllable and observable which is proved using Kalman's test. Using the Linear Quadratic Regulation Method, the State-Feedback Control Gain Matrix K and feed-forward system gain G can be determined. Another approach is to use the Riccati algebraic equation, which defines a time-invariant infinite horizon solution for the LQR and can be used to solve it.

D. System design

This section contains detailed specifications for all Simulink models created to meet the major goal of this project, which is to maintain the right spark cavity gap between the anode and cathode. The transfer function of the motor, as well as a comprehensive overview of the numerous Simulink blocks and their functions, are covered in the section below. This segment uses the Bang-Bang controller, the PID controller, and the LQR controller on the entire EDM system.

E. EDM Process Model Subsystem

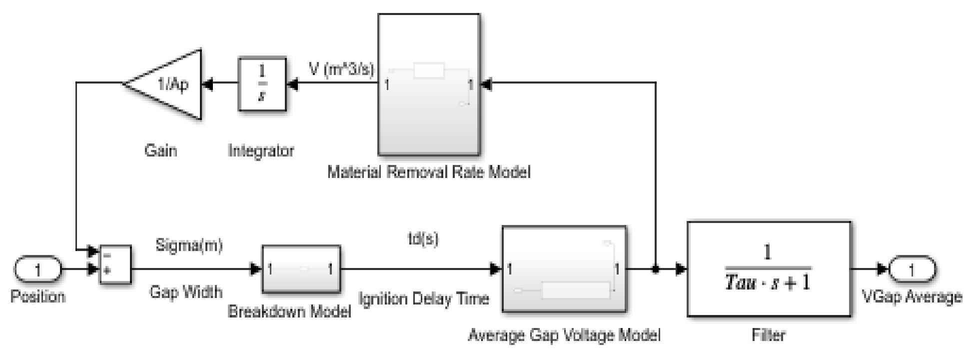

Fig. 3 EDM Process Subsystem

As seen in Fig. 3 MRR Model, Breakdown Model, and Mean Gap Voltage Model make up the EDM Process Model. Secondary blocks in this subsystem include the Integrator, Gain, and Filter. [1] The filter at the end of this subsystem reduces and filters out disturbances from other components to produce a clean output. The EDM process model gets its position input from the Servo motor subsystem block, which is then processed through the various blocks and then the signal is amplified using a gain block which is then filtered using a filter finally the output which is the Spark Gap Distance is observed and a closed loop feedback is taken at the end of this subsystem and is re-fed back to the PID Controller for processing anomalies and appropriate action.

1) MRR Model Block

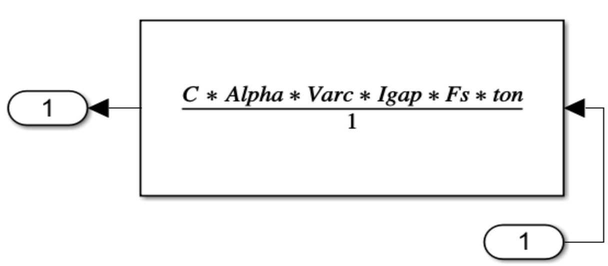

Fig. 4 Material Removal Rate Block

In order to find the most effective and efficient way to remove material in EDM the MRR Model Block as seen in Fig. 4 was developed using dimensional analysis [2]. MRR determines how much of the workpiece is machined in a given time for optimal machining [4]. Multiplying 6 variables yields the optimal MRR equation for EDM; those include C, Alpha, V_{arc}, I_{gap}, F_s, T_{on}.

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2) Mean Gap Voltage Model Block

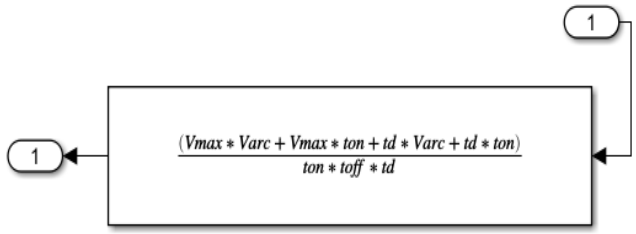

Fig. 5 Mean Gap Voltage Block

As seen in Fig. 5 this block maintains the Mean gap voltage, which regulates the tool-to-workpiece distance. Optimal EDM machining requires a suitable spark gap, hence this equation was developed. [1] The above equation was used in the simulation, and a real-time response was achieved that was similar to the prototype while maintaining the optimal sparking distance for machining.

3) Breakdown Model Block

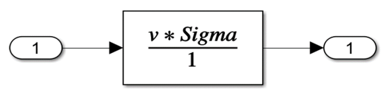

Fig. 6 Breakdown Model

As seen in Fig. 6 this model calculates the ignition delay time that is the time taken to reach the discharge voltage [1]. The ignition delay time is also utilized in order to avoid excessively high starting torque. High starting torque often damages the motor's windings and burns out other magnetic components, reducing its reliability and accuracy. [4] In this equation, here v=1.04*10^{25} and Sigma (material properties) were taken into consideration.

4) Hybrid Step-Servo Motor Block Model

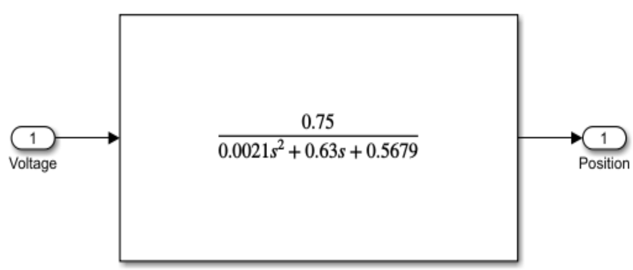

Fig. 7 Hybrid Step-Servo Motor Block

Fig. 7 depicts a simplified version of the transfer function as shown above for the step - servo motor of the 2nd order, which was utilized in the calculations presented above. Armature control was utilized, along with the values of a NEMA 23 motor, in order to derive the transfer function. This block mimics the real servo motor used in the physical prototype and is therefore the heart of the EDM process. In the prototype, actuating the motor coils energizes the motor shaft, which drives the lead screw connected to the tool (electrode), allowing machining to occur. This subsystem receives its primary input from the Pulse Generator, which mimics the Arduino Uno's square pulse to drive the servo motor. This block also receives the corrected voltage input from the PID controller which was optimally tuned using the Ziegler Nichols Tuning Method. During machining, this PID Controller controls the motor's input voltage. That block then processes the shaft position to achieve an appropriate spark cavity space between the brass tool and the mild-steel workpiece.

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IV. RESULTS AND DISCUSSION

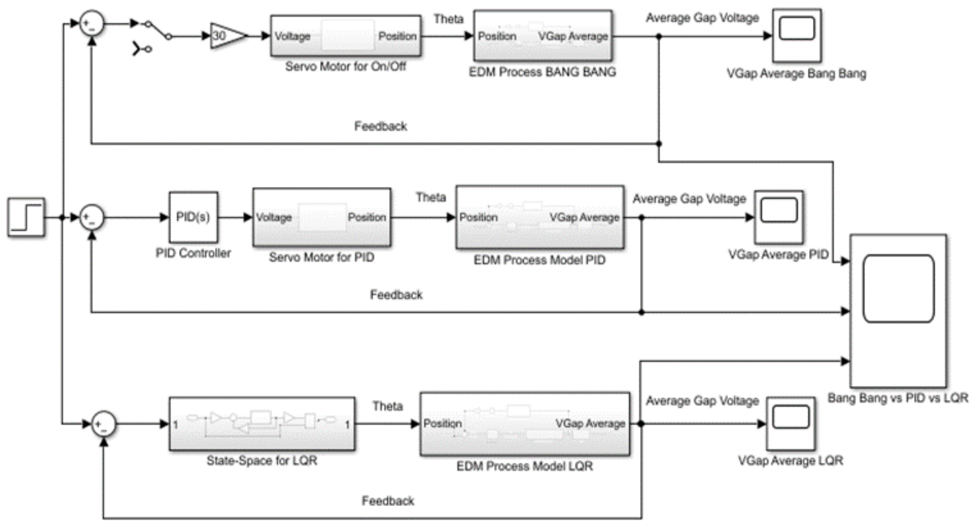

Fig. 8 Model for Comparison of Controllers

A. Effect of Bang-Bang Controller

Bang-Bang controller solely controls by toggling between the ON and OFF states. Through simulation, a bang-bang controller is connected to the Servo Motor Block to switch motor ON and OFF and to capture the machining data. By adjusting a manual switch in physical prototype and simulation, Bang-Bang controller is typically slow and delivers a poor response. As time proceeds from 0µs to 0.9µs during the operation, the motor permits the tool to descend down towards the workpiece, causing sparking at 70V. As time progresses, the graph starts to sink due to the controller's firm character, which achieves control between two states. The controller's controllability is degraded as a result of the observed irregularities in the graph, and the controller's high overshoot percentage contributes to its decreased stability and precision. Bang-Bang is the least desirable controller for improving the machining process due to its stiff configuration, erratic behavior, slow rise time, and high settling time. This control mechanism often requires microlevel switching at specified intervals, thus making it common for errors to slip in, in the physical setup as well.

B. Effect of PID Controller

Using simulation [3], a PID controller is integrated with the EDM Process System to test its controllability and efficacy in the EDM machining process. The PID controller was implemented to create better servo motor controllability than the Bang-Bang Controller. During the process, the change from 0µs to 1.5µs causes the motor to allow the tool to move closer and closer to the workpiece, which results in a spark with a peak voltage of 48.5V and indicates that a sufficient spark gap has been achieved Due to the PID controller's excellent controllability and steadiness, the graph linearizes from 2µs to 10µs, suggesting the tool can maintain a consistent sparking distance and voltage during milling. The PID Controller takes 1.3µs to obtain the optimal spark gap distance, compared to 0.8µs for the Bang-Bang controller. Despite taking 0.5µs longer to obtain the appropriate spark gap distance, the PID Controller reduces the spark gap voltage from 70V to 48.5V. The PID Controller is appropriate for this EDM process due to its smaller overshoot, faster rise and settling time, higher accuracy, and tunability. This controller is widely used in all industries for machining.

C. Effect of LQR Controller

As the rank of the system is 3 it is both observable and controllable. At 3.4µs and 22.5V, the tool hovers over the workpiece and sparks, signifying machining. Due to the LQR controller's optimum control qualities and great stability, the graph linearizes from 5.5µs to 10µs, suggesting the tool can maintain a consistent sparking distance and voltage. LQR controller is the best for EDM due to its versatility, controllability, and noise resistance. The LQR Controller needs the least voltage (22.5V) to obtain the appropriate spark gap location. The Bang-Bang Controller takes 3.4µs to attain the optimal sparking distance, compared to the PID Controller that takes 1.3µs.

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The time taken by the LQR Controller to reach the appropriate sparking distance is longer; however, it requires a significantly lower control voltage to maintain the ideal spark cavity between the tool and the workpiece during machining. This, in combination with its greater flexibility, controllability, and a lower susceptibility to noise, makes it an ideal option for this EDM process.

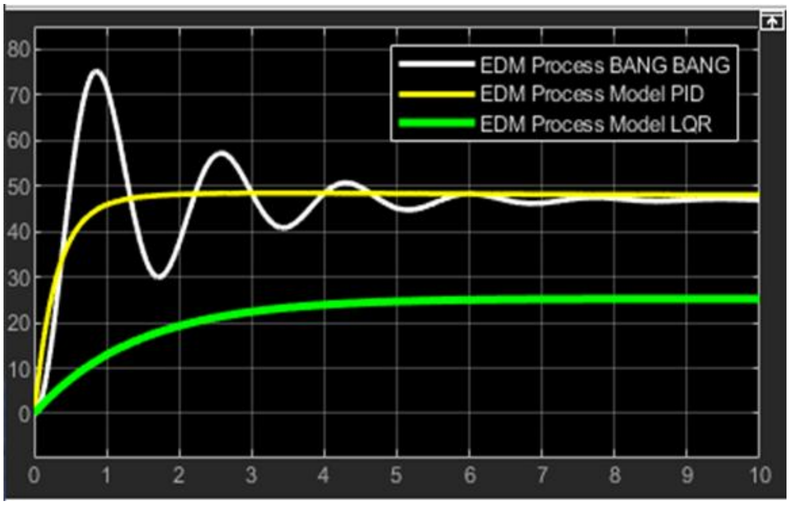

Fig. 9 Mean Gap Voltage for Bang-Bang, PID and LQR

The LQR Controller (green) provides the best control to the motor as shown by the graph in Fig. 9. It takes 3.4µs for the tool to reach the work piece, causing a spark. Compared to Bang-Bang (white) and PID (yellow) controllers, LQR takes 2.6µs and 2.1µs more to reach the required spark gap distance. However, the voltage needed to maintain the spark gap has been reduced significantly from 70V to 22.5V with the Bang-Bang Controller and from 48.5V to 22.5V with the Three Term Controller. The response time of the LQR Controller is also much faster than that of the Bang-Bang and PID controllers. Also, in comparison to Bang-Bang and PID Controllers, LQR Controllers have a lower rise time. Since Bang-Bang overshoots more, LQR eliminates it. Implementing the PID and LQR controllers eliminate the Bang-Bang controller's irregular response. The LQR Controller takes longer to reach the proper sparking distance, but reduces its control voltage by maintaining the optimal spark cavity between the cathode and anode during the material removal process, making it highly desirable for this EDM process. Fig. 11 shows how prototype machining with a brass tool created a cavity in a mild steel workpiece. LQR controllers are the best in any EDM process because they have more controllability and are less sensitive to noise.

TABLE II
TABULAR COMPARISONS BETWEEN BANG-BANG, PID AND LQR CONTROLLER

Parameters	Bang-Bang Controller	PID Controller	LQR Controller
Spark Gap Voltage	70V	48.5V	22.5V
Time to Reach Optimal Sparking Distance	0.8µs	1.3µs	3.4µs
Rise Time	High	Moderate	Low
Settling Time	High	Low	Low
Overshoot Percentage	High	Low	Low
Accuracy	Low	High	High
Controllability	Low	High	High

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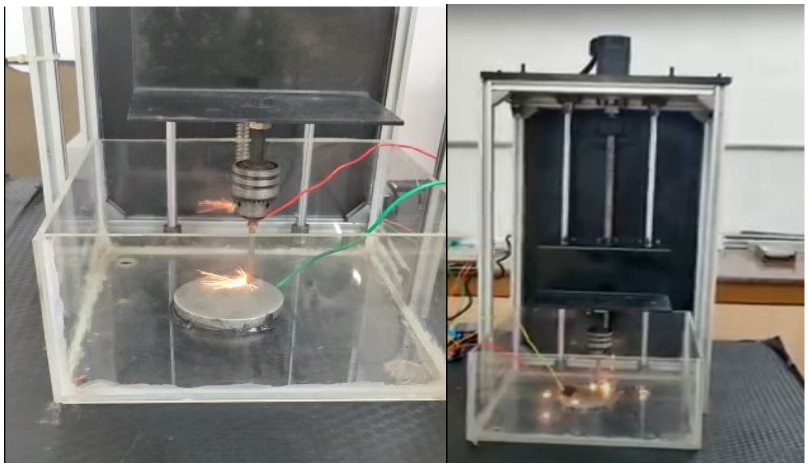

Fig. 10 Experimental Setup Sparking

V. CONCLUSIONS

As seen in Fig. 11, the prototype machining resulted in cavity formation in the mild steel workpiece with the help of a brass tool. Using MATLAB/Simulink, the LQR system for EDM was created and fine-tuned to provide faster and more exact response. The State-Space LQR system was integrated with an EDM dynamics focused on gap voltage optimization for constructing a control system. The technology was tuned to improve EDM reaction time. During prototype build, Bang-Bang and PID control for the EDM process were successfully executed using PID-EDM Simulink values. The simulation showed that the LQR controller created the spark gap or discharge gap quickly and accurately while running at a lower voltage, depending on the materials and ambient circumstances. The LQR controller's simulated settling time, percentage overshoot, steady state error, and rising time were all longer than the traditional controllers.

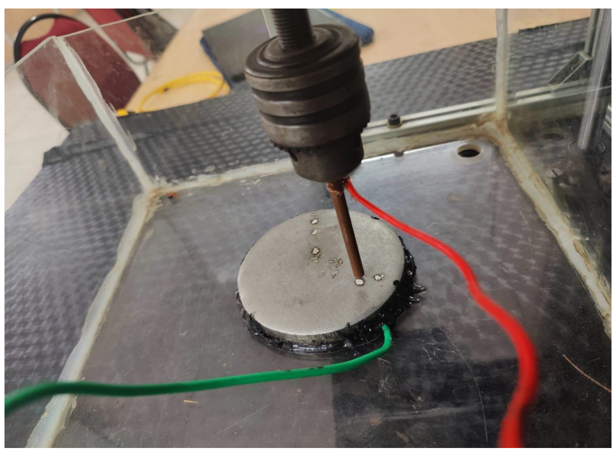

Fig. 11 Cavity formed by Dry-EDM

A. Future Scope

Various other control techniques, such as intelligent and adaptable systems, may be implemented in the near future. With the use of LQR-PID, LQR-LQG, or LEQG controller instead of the LQR controller, EDM process can be made more durable and faster. Optimizing the motor could allow for better micro adjustments, resulting in a lower spark gap distance.

VI. ACKNOWLEDGMENT

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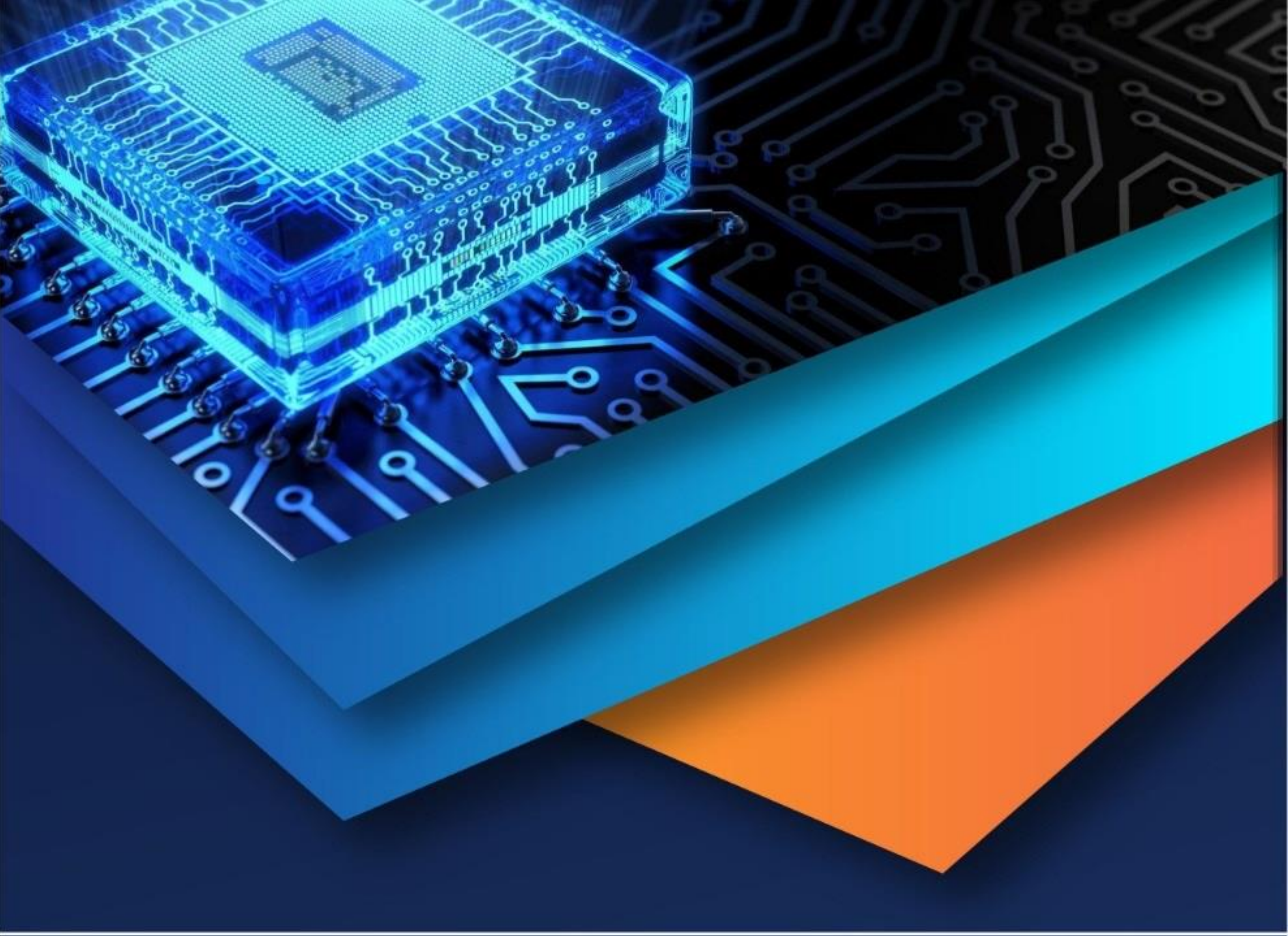

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