Dual stage control of a servo system consisting of a piezoelectric actuator and a linear motor for electrical discharge machining

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Abstract. Gap width is the most important factor that affects the stability of the electrical discharge machining (EDM) process, material removal rate and surface finish of the workpiece. This research is to develop a new hybrid positioning system which consists of a linear servo motor and a piezoelectric actuator (PZT) for high efficiency EDM processes. In this new system, the servo motor provides the macro feeding for the workpiece while the PZT feeds the workpiece in micro scale at high frequency. To reduce the delay caused by separate movements of the linear motor and PZT, a new control algorithm was developed to synchronize the movements of both the motor and PZT. Cutting experiment shows that an increase in MRR of 1.5 times was achieved by using the proposed algorithm.

1. Introduction
Due to the ultra-hardness of polycrystalline diamond (PCD), electrical discharge grinding (EDG), one variation of electrical discharge machining (EDM) process, is considered the most effective machining technique to manufacture PCD products used in biomedical and manufacturing industry [1, 2, 3]. EDG overcomes the most common problems in the traditional grinding process, such as tool wear, significant grinding force and low material removal rate [4, 5]. However, since EDM is a stochastic process which depends on multiple interactive independent parameters, it makes the maintaining of a favorable spark gap extremely difficult. The spark gap between the workpiece and the electrode is the main factor that affects the machining performance [6]. The unstable gap distance will result in abnormal discharge pulses and the accumulation of debris in the gap which, in turn, negatively affect the stability of the machining process [7]. Therefore, keeping a constant gap distance is critical in the control of a stable and efficient EDM process.

2. Dual stage feeding mechanism
Various actuators have been used to feed the workpiece in EDM process, for example, linear servo motor, DC motor and stepper motor. Due to the very small spark gap which is in the range of 20-50µm and the high frequency changes in the working condition in the gap, the need for more accurate and fast actuators is continuously increasing. The piezoelectric actuator (PZT) is one of the most suitable actuators because of its high precision and high response frequency. However, the working range of
PZT is usually very short. A feeding system which consists of PZT alone does not meet practical requirements. An EDG process should have both high response frequency and long working range.

A hybrid dual stage feeding mechanism which consists of a servo motor to satisfy the long-range requirement and one PZT to realize high frequency response was recently developed by Hu et al. [8], and different algorithms have been developed to distribute the movements between the linear motor and the piezoelectric actuator. For example, Tong et al. [9] used a novel algorithm by stopping one actuator (PZT) to move the other (a linear motor); this method did increase the machining speed, however, because the PZT and the linear motor could not move simultaneously, the time was still wasted when the PZT actuator paused for the linear motor to move to compensate the distance after the PZT reached its full range. Kunieda et al. [10] built a simulator in order to investigate the effect of using PZT on the machining speed and stability. The PZT was used to respond to the machining process and the linear motor to keep a dynamic range of the PZT to around 16µm, but it is unclear how both actuators will move to perform the required tasks. Zhu et al. [11] used PZT as a capacitor, based on inverse piezoelectric effect to adjust the discharge gap; the feeding process was dependent on the charging and discharging of two capacitors (PZT and external adjustable capacitor). Once the discharge happened, the PZT would retract and it would move forward again after the charging of the capacitors. This process could undoubtedly increase the stability of the machining by preventing the arc and short circuit from happening, however, it was unable to ensure enough power delivered to the gap in order to complete the machining process, therefore it is unable to significantly increase the speed and efficiency.

In order to satisfy the need for large stroke and high precision, a piezoelectric actuator had been combined with step motor to form a drive with high positioning accuracy and repeatability [12]. Piezoelectric actuator was used as a micro driven system with micro steps which was mounted on a macro driven table for macro steps. Based on inverse piezoelectric effect the piezoactuator was used to adjust the discharge gap. Due to the short range of PZT, the retract distance, in case arcing, was not sufficient to eliminate that spark status. We propose a new algorithm to drive the dual stage mechanism consisting of a linear servo motor and a piezoelectric actuator. In this system, the linear motor is responsible for long travel distance while the PZT is responsible for fast feeding. The new control strategy of macro-micro feeding obtains the best machining efficiency. Experiments were conducted to validate the effectiveness of new system by measuring the machining speed.

3. New dual stage control method
The proposed dual stage feeding mechanism consists of a linear motor as macro drive and a piezoelectric actuator as micro drive. The workpiece was hold by the PZT. The PZT was mounted on the top of the linear motor which moved in the same direction. The main goal of this structure was to maintain a stable machining process by controlling the gap width at desired level. The linear motor fed the piezoelectric actuator to guarantee the PZT has a buffer distance from the electrode which was in the in the range from 25µm to 100µm. The buffer range ensured that at any machining status the piezoelectric actuator has a minimum distance of 25µm to respond to any short circuit spark, and the piezo has enough backward and forward range to move the workpiece and respond to the changes in the spark gap. Once the PZT reached its forward limit (100µm), it was required to return to the left limit (25µm) and start another cycle. At the same time when the PZT was returning to the “25µm” position, the linear motor would compensate the difference in workpiece position by 75µm to ensure that the workpiece is always at a distance 20µm away from the tool, as shown in figure 1.

4. Experimental setup
The EDG experimental system consists of five sub-systems: power source system, the rotating electrode, fluid system, the dual stage feeding mechanism and control system, as shown in figure 2. The main power supply is a transistor type power supply with 90V as Voc and 10A the maximum current. Fluid system contains the machining tank, which would be filled up with the dielectric before
the machining starts. This fluid is flushed from a storage to the tank by a pump. The rotating electrode disk is mounted on a hydraulic motor.

**Figure 1.** Schematic drawing for the feeding process of the dual stage feeding mechanism. (a) initial position where the PZT is at zero position and linear motor at 45μm from the rotating disk. (b) the PZT moved by 25μm to make the gap being 20μm. (c) the machining started by moving both actuators PZT and linear motor. (d) the PZT reached the full range position. (e) the PZT moved backward to the 25μm position. (f) the linear motor moved forward to reduce the gap to 20μm and the machining started again.

**Figure 2.** Set up of the EDG experiment system.

Dual stage feeding mechanism consists of a linear motor and a piezo electric actuator, positioned on the top of the linear motor. Workpiece is mounted on the tip of the feeding mechanism. The main controller was built by using LabView software. Linear motor was controlled through AKD factory-built power controller. Position feedback signal was read by a linear encoder through an analog circuit. Piezoelectric actuator was controlled through THORLAB controller which provided the actuator with the required power and read the position using strain gauges. This controller is connected to the main controller device using USB port.
Frequency is an essential parameter to determine the effectiveness of using the PZT in high-speed applications. The bandwidth of a piezo controller can be estimated based on the following parameters:

- The maximum current the controllers can produce (0.5A).
- The load capacitance of the piezo. (20μF)
- The desired signal amplitude (V).

The absolute maximum bandwidth of the driver, which is independent of the load being driven. The band width of the PZT is calculated using Slew rate, the change in the charge with respect to time is:

\[ \text{slew rate} = \frac{dv}{dt} = \frac{l_{max}}{C} \]  

(1)
\[ \text{slew rate} = \frac{0.5A}{20 \mu F} = 25V/ms \]  

(2)

The bandwidth of the system usually refers to the system's response to a sinusoidal signal of a given amplitude A.

\[ V(t) = A \sin 2\pi f t + A \]  

(3)
\[ \frac{dv}{dt}_{t=2\pi f} = 2\pi Af_{max} \]  

(4)

Using Equations 1 and 4, the maximum frequency can be calculated as:

\[ f_{max} = \frac{l_{max}}{2\pi AC} = \frac{l_{max}}{\pi V_{pp}C} \]  

(5)

Substituting the values of \( l_{max}, V_{p-p} \) and C

\[ f_{max} = \frac{l_{max}}{\pi V_{pp}C} = \frac{0.5A}{\pi (20\mu F)(75V)} \approx 106Hz \]  

(6)

5. Control and test performance of EDG

The spark gap is critical in controlling the EDM process, therefore, it is important to control the feeding mechanism to keep the gap at the desired value. Proposed control algorithm was based on the simultaneous moving of the linear motor and the piezoelectric actuator to respond to the changes in spark status. As shown in figure 3, the control process starts by putting both actuators (PZT and linear motor) at the zero position. Then the linear motor moves to the position of 45 μm from the workpiece, while the piezo moves to the position of 25 μm (this gives the PZT a backward buffer of 25μm to use if short circuit, or arcing status occurs). This makes 20μm gap between the workpiece and the tool.

During the machining process the piezoelectric actuator will respond to the changes in gap caused by the volume of removed material, from the workpiece, and the changes in debris concentration in the gap. Since PZT will move forward, the position of PZT will increase from 25μm to 100μm eventually. During this movement the linear motor will move slowly to compensate the enlarged distance caused by removed material. The position of PZT will always be more than 25μm, which gives the PZT enough range to move backward with high speed, responding to the short circuit status.

In the case of arc spark, the PZT will move backward by about 10μm to increase the spark gap allowing the current to decrease and the spark back to normal status.

In order to test the performance of the new algorithm, experiments were conducted and machining results of using the current algorithms [7] were compared with the results of our algorithm with the same machining parameters. The current control algorithm is based on moving each actuator individually. The PZT will respond to the changes in the spark status. When PZT reaches its limit, it will stop and return to its zero-position waiting for the other actuator, linear motor, to move and compensate the distance of materials removed by the PZT (figure 4).
Figure 3. Block diagram of the proposed control of dual stage feeding mechanism.

Figure 4. Conventional control of dual stage feeding system.

6. Results and discussions
In this experiment, workpiece was a copper strip with the dimension of 3mm x 1mm (figure 5). The machining parameters are shown in table 1:

Table 1. EDM machining parameters.

| Parameter                  | Value  |
|----------------------------|--------|
| Discharge Voltage          | 90V    |
| Pulse on time (T_{on})     | 40us   |
| Pulse off time (T_{off})   | 80us   |
| Discharge current          | 4Amp   |

Figure 5. Machined copper strip used in the experiment.
Novel algorithms were implemented using LABVIEW software. We are using average gap voltage as feedback variable for the machining process. Positions of both actuators were measured during the discharging process. Machining time was also measured in order to investigate performances of both algorithms.

Figure 6 shows the position of the actuators based on the proposed algorithm. The blue line represents the position of the linear motor during the machining process whereas the orange one represents the PZT position. The linear motor was moving forward with a constant speed while the PZT was responding to spark status. As shown in the figure, when the PZT reached its maximum range the PZT would backward to zero and the linear position increased by the PZT range (100µm). During the entire machining distance of 1300µm, the PZT reached its maximum range 4 times, and the overall machining time was 440 sec.

![Figure 6. PZT and linear motor position while feeding 1300µm (the proposed algorithm).](image)

The results of using conventional algorithm was shown in figure 7. As shown in the figure, the PZT reached its maximum limit around 10 times, which required the PZT to stop and the linear motor to move. It consumed 660 sec to machine the same specimen length (1300µm).

![Figure 7. PZT and linear motor position while feeding 1300µm (existing algorithm).](image)

The material removal rate (MRR) of the new algorithm was 2.95µm/s, while MRR of the conventional algorithm was 1.96µm/s. This difference in the MRR was due to the excess time caused by the stop of the PZT waiting for the linear to move. There was no discharging during this waiting time. Therefore, the more times the PZT stopped, the more efficient the new algorithm would be.
7. Conclusion
In this paper a new dual stage control algorithm was proposed to drive the linear motor and PZT. Two machining processes were conducted using the conventional and the new algorithms. The new algorithm was found to be 1.5 times faster than the conventional one, and MRR was one and half bigger compared with the conventional one for machining the same copper strip under the same machining conditions.

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